



Effect of Graphene Embedment on Fiber–Matrix Interface and Tensile Properties of FRCC Composites

DOI:

[10.1061/JCCOF2.CCENG-4462](https://doi.org/10.1061/JCCOF2.CCENG-4462)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Wang, Z., Nguyen, D., Su, M., & Wang, Y. (2024). Effect of Graphene Embedment on Fiber–Matrix Interface and Tensile Properties of FRCC Composites. *Journal of Composites for Construction*, 28(4). <https://doi.org/10.1061/JCCOF2.CCENG-4462>

Published in:

Journal of Composites for Construction

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.



Effect of graphene embedment on fibre-matrix interface and tensile properties of FRCM composites

Zhaohua Wang¹, Dung Nguyen², Meini Su^{3*}, Yong Wang⁴

¹PhD Candidate, School of Engineering, The University of Manchester, Engineering Building A, Booth Street, Manchester, UK, M13, Email: Zhaohua.wang@manchester.ac.uk

²Postdoctoral Research Fellow, School of Engineering, The University of Manchester, Engineering Building A, Booth Street, Manchester, UK, M13, Email: Nguyen.dung@manchester.ac.uk

^{3*}Senior Lecturer, School of Engineering, The University of Manchester, Engineering Building A, Booth Street, Manchester, UK, M13, Email: Meini.su@manchester.ac.uk (Corresponding author):

⁴Professor, School of Engineering, The University of Manchester, Engineering Building A, Booth Street, Manchester, UK, M13, Email: Yong.wang@manchester.ac.uk

Abstract

This paper presents the results of an experimental study to investigate the effects of using two types of graphene, dried graphene (DG) and hydrated graphene (HG), on enhancing the interfacial and tensile mechanical properties of fabric-reinforced cementitious matrix (FRCM) composites. It has been found that inclusion of both DG and HG can produce an improvement in the tensile strength of FRCM composites by increasing the tensile strength of the mortar paste and the amount of fibres participating in loadbearing due to increased penetration of mortar (cement hydrates) into the fibre bundle. The better dispersion of HG produces better results than DG. The maximum increases in overall tensile strengths of the FRCM composites with DG and HG are 18% and 31% respectively, with the majority of these improvements coming from the increase in the amount of fibres participating in loadbearing. Microstructure images indicate increases of up to 20% and 44% in mortar penetration thickness into fibre bundles by using DG and HG, respectively.

Keywords: Bonding mechanism; Graphene enhanced cementitious matrix; Interfacial bond behaviour; Pull-out test; Tensile test.

30 **Introduction**

31 Fabric-reinforced cementitious matrix (FRCM) composites, consisting of bundles of carbon
32 fibres embedded in a cementitious matrix, have emerged as a promising method for strengthening
33 reinforced concrete (RC) structures (Babaeidarabad et al. 2014; Ebead et al. 2017; Pino et al.
34 2017; Guo et al. 2020). Owing to their light weight-to-high strength ratio and good compatibility
35 with the concrete substrate, FRCM composites can be used to restore RC structures to desirable
36 mechanical and physical properties, while achieving enhanced resistance to aggressive
37 environments (Pino et al. 2017; Raza and Qureshi 2021; Liu et al. 2022).

38 Fig.1 (a) shows the cross-section of a unit of a FRCM composite, consisting of fibre filaments
39 and a cementitious matrix. Fig.1 (b) illustrates the load transfer mechanism within the FRCM
40 composite when subjected to a tensile load. Under this loading condition, only the fibres directly
41 bonded to the mortar (referred to as “sleeve filaments” in Fig.1 (a)) participate in load bearing.
42 The other fibres (the “core filaments” in Fig.1 (a) and (b)) are not impregnated and their limited
43 loadbearing resistance comes from friction between the core and sleeve filaments, via systematic
44 slipping of the fibres in a load carrying mechanism referred to as “telescopic failure” (Banholzer
45 2004; Alexandre et al. 2023). However, it should be pointed out that in many practical
46 applications, FRCM composites are attached to RC beams which are subjected to bending. In
47 these cases, due to deflection of the beams, there would exist normal stresses at the
48 FRCM/concrete interface as observed by Li et al. (1990) and Calabrese et al. (2020). The normal
49 stresses force the structure to behave in a mixed fracture mechanics Mode I/II loading condition,
50 and can also increase the interface bond resistance (Calabrese et al. 2020 & 2021). This effect is
51 called snubbing-friction (Li et al. 1990; Fu and Lauke, 1997). Nevertheless, in both the
52 aforementioned loading conditions (pure tension and bending), the strength of the FRCM
53 composite is still mainly provided by the sleeve filaments (Silva et al. 2014; Ascione et al. 2015).
54 This research focuses on the pure tensile loading condition, with the failure mode being fracture
55 mechanics Mode II.

56 Since the tensile strength and fracture strain of carbon fibres are much greater than that of

57 the mortar, the tensile strength of FRCM composite is dominated by the volume fraction of the
58 loadbearing fibres in the FRCM composite, which is crucially a function of the thickness of the
59 sleeve filaments. This thickness is referred to as the penetration depth (Ozturk and Chung 2021).
60 Therefore, the most important factor in improving the tensile strength of FRCM composite is to
61 increase the penetration thickness of mortar into the fibres.

62 In FRCM composites, the mechanism to engage fibres in loadbearing is by mortar
63 penetration into fibre filaments. The dissolved cement ions are small enough to diffuse through
64 the space between the fibre filaments, as illustrated in Fig. 2. However, when cement hydrates
65 precipitate on the surface of the unhydrated cement particles, they block further contact between
66 the unhydrated cement particles and water, preventing further dissolution of the unhydrated
67 cement particles. The unhydrated cement particles are large and cannot penetrate into the fibre
68 bundles. While the dissolved ions can move into the space, they are limited within the fibre
69 bundles due to the low hydration degree of cement. Therefore, the penetration of cementitious
70 mortar into fibre bundles is limited in conventional FRCM composites.

71 Without any measure, the volume of the core filaments is approximately 60-70% of the full
72 bundle (Jesse 2004; Hartig et al. 2008; Aljewifi et al. 2010; Zhu et al. 2021), leaving only 30-
73 40% of the fibres as sleeve filaments to participate in loadbearing. This is not materially and
74 structurally efficient. Consequently, efforts are being made to find means to increase the volume
75 of loadbearing fibres in FRCM composites.

76 One method is to include short fibres in the cementitious matrix (Zhang and Deng 2022).
77 Short glass fibres could improve the bond between multifilament yarns and the surrounding
78 matrix by means of new cross-links between the cementitious matrix and fabric yarn, and
79 bridging effects that delay the development of cracks (Butler et al. 2011; Barhum and
80 Mechtcherine 2012). However, using short fibres has a number of problems, including fibre
81 concentration to form fibre balls, labour intensive mixing (Emdadi et al. 2015) and reduced
82 workability (Boulekbache et al. 2010). Another method is to change the water/cement ratio to
83 improve flowability of the cement paste to alleviate the aforementioned dissolution problem of

84 large unhydrated cement particles (Peled et al. 2008). However, increasing the water/cement ratio
85 of cementitious materials compromises their mechanical strengths. Although plasticizers are
86 commonly used as an alternative to water to improve the fluidity of cement while preserving
87 mechanical properties, it is important to recognize that this approach does not enhance the
88 penetration thickness of cement into fibre bundles because this method does not reduce the sizes
89 of hydrate particles.

90 Another alternative method to enhance bonding between the cementitious matrix and the
91 fibre bundles in FRCM composites is silica suspension coating on the fibre yarn (Guo et al. 2022).
92 The absorption of active silica on the fibre yarn surface promotes the formation of C-(A)-S-H
93 and leading to an increase in the composite's properties. However, the complexity of silica
94 suspension treatment hinders its application as a construction material. Similarly, plasma
95 modification (Zhao et al. 2020) or the employment of a peeling process to improve fabric
96 adhesion to the cementitious matrix (Rambo et al. 2021) are only applicable to highly demanding
97 applications where cost is not a key governing issue.

98 Among the various existing methods, epoxy impregnation of the fabric (Xu et al. 2004;
99 Donnini et al. 2016) is the most feasible. Epoxy coating is an effective method for enhancing the
100 mechanical properties of composites (Signorini et al. 2020). The low viscosity of epoxy allows a
101 thin coating to be deposited on the fibres and improves the bond, thereby reducing the amount of
102 resin and consequently high temperature sensitivity (Signorini et al. 2020). However, reducing
103 the viscosity of epoxy resin often requires the addition of acetone (Signorini et al. 2020). This
104 technique has a number of drawbacks when the material is used in construction, including the
105 risk of fire, health problems associated with acetone usage, and cost. With regard to fire safety,
106 research by the same group (Messori et al. 2019) demonstrated that the post-fire mechanical
107 performance of the materials decreased drastically when the temperature exceeded 200 °C. In fire
108 conditions, the material temperature would be much higher. Thus, a cement-based approach is
109 preferred.

110 In summary, the penetration thickness of cement paste into fibre bundles in FRCM
111 composites depends on many factors including filament size and spacing, the hydrophilic
112 characteristics of the filaments, mortar flowability, and the size of the cement particles and their
113 degree of hydration. Because of the many influential parameters and the complexity of their
114 effects, effective enhancement of cement paste penetration into fibre bundles is challenging. All
115 the existing methods have significant shortcomings and further research is needed to find easily
116 implementable methods of increasing fibre participation in loadbearing without compromising
117 the mechanical properties of the composite.

118 A more promising and simpler approach is to improve the degree of cement hydration, which
119 can be enhanced by incorporation of graphene into cement, and this is the focus of the research
120 reported in this paper. The emergence of graphene as a possible additive to construction materials
121 has opened a door to solving the problem of limited bonding between cementitious matrix and
122 fibre bundles. The benefits of graphene in cement mortar go beyond the commonly recognized
123 benefits, such as improved mechanical properties (Du et al. 2016) and acting as bridging elements
124 to delay the initiation and propagation of cracks at the nanoscale (Contamine et al. 2011; Santis
125 et al. 2018; Mahmoudi et al. 2022).

126 Graphene, a two-dimensional material of carbon atoms, can act as nucleation sites to
127 accelerate hydration of cement (Jing et al. 2017; Baomin and Shuang 2019; Ho et al. 2020; Lin
128 and Du 2020). When graphene nanoparticles are dispersed in the cement paste, they act as
129 nucleation seeding to stimulate the precipitation of cement hydrates on their surfaces away from
130 the unhydrated cement particles, as illustrated in (Fig. 3). This process decreases the diffusion
131 barrier of cement hydrates around the unhydrated cement particles (Thomas et al. 2009; Land and
132 Stephan 2012; Artioli et al. 2014), thereby releasing more dissolved cement ions to the
133 surrounding aqueous medium. The elevated concentration of ions allows a greater number of
134 dissolved cement ions into the fibre bundles than without graphene, which in turn promotes the
135 generation of hydration products within the fibre bundles and increases the penetration thickness
136 of cement in fibre bundles.

137 Despite the abovementioned potentials of using graphene to enhance various aspects of the
138 mechanical properties of cementitious matrix, as has been comprehensively reviewed by Yang et
139 al. (2017), there is a lack of reported research in the literature that focuses on the fibre/mortar
140 interface, necessitating the research to be reported in this paper. Whilst there have been numerous
141 research studies on using nanoparticles to improve the mechanical properties of composites, such
142 as (Signorini and Nobili 2021) who used carbon nanotubes and silica nano coating to improve
143 the bonding behaviour at the interface, this research explores the effects of graphene as nucleation
144 seedings to enhance the hydration of cement and the penetration thickness of cement into the
145 fibre bundles of FRCM composites.

146 This paper will investigate the effects of two types of graphene (i.e., dry graphene (DG) and
147 hydrated graphene (HG)). HG is an intermediate-product of DG and is supplied in paste form
148 without drying, in contrast to DG which is supplied in dried form. Consequently, HG is less
149 expensive and has a lower carbon footprint than DG. Furthermore, due to the greater number of
150 free platelets, HG will facilitate SP adsorption more efficiently than DG.

151 Both the interfacial and tensile properties of FRCM are needed in the design of beams
152 strengthened by FRCM, depending on the type of failure modes. As has been mentioned earlier,
153 the focus of this research is the sleeve filaments in tension. Therefore, in this research, the FRCM
154 composite specimens were subject to pure tensile loading. Therefore, further discussions of this
155 paper will only consider fracture mechanics Mode II behaviour.

156 The specific objectives of this research are to:

- 157 (a) Demonstrate the beneficial effects of using graphene to increase the mechanical properties
158 of FRCM composites and quantify the increases;
- 159 (b) Demonstrate the effects of using graphene to increase the penetration thickness of cement
160 mortar into the fibre bundles of FRCM composites and quantify the penetration thickness;
- 161 (c) Quantify the increase in mechanical properties of cement mortar due to using graphene;
- 162 (d) Quantify the increase in mechanical properties of the participating fibre bundles.

163

164 **Materials and experimental methodology**

165 To meet the above objectives, tensile mechanical tests were carried out on cement mortar, the
166 interface between mortar and fibres as well as FRCM composites. Scanning electron microscopy
167 (SEM) image analysis was also performed to support understanding. These tests will be described
168 in detail later.

169

170 **Material components**

171 In total, the test specimens include the following material components: cementitious matrix
172 (mortar), graphene and carbon fibres. This section provides their properties.

173

174 Cementitious matrix (mortar)

175 The cementitious matrix used in this research was made of Portland cement (PC), superplasticizer,
176 water, and river sand. The Portland cement was CEM2 42.5N with a specific surface area of 362
177 m²/kg, and its chemical composition is provided in Table 1.

178 The river sand with particle size less than 1.18 mm was washed to remove any ionic
179 contaminants and dried in ambient air prior to mixing.

180 A polycarboxylate-based superplasticizer (SP) (ADVA 650) was used to enhance the
181 workability of the cementitious matrix and the effectiveness of dispersion and stabilization of
182 graphene in the mixing water. The ratio of PC: water: sand: SP was 1:0.4:1.4:0.01.

183

184 Graphene

185 Graphene used in this project was in two forms: DG and HG. Except for the drying process, both
186 DG and HG platelets had undergone the same manufacturing process and hence they had the
187 same physical dimensions as shown in Table 2. HG is an intermediate product of DG, consisting

188 of 80% water and 20% DG, and is supplied as a paste form without drying. In contrast, DG is
189 dried. HG is cheaper and more readily available than DG, which makes it advantageous in terms
190 of lower cost and lower environmental impact. Moreover, HG has the potential to be better
191 dispersed in FRCM composites because it can more easily facilitate the adsorption of
192 superplasticizer due to a higher number of free platelets compared to DG.

193

194 Carbon fibres

195 The carbon fabric mesh (C-Mesh 84/84) used in this study was in bundle form. Fig. 4 shows the
196 arrangement and dimensions of longitudinal and transverse fibres. Table 3 lists its geometrical
197 and mechanical properties. The corresponding properties of the carbon fibre filament are also
198 provided in Table 3 for reference.

199

200 **Test specimens**

201 Cementitious matrix (mortar)

202 A total of five mortar mixtures were investigated, consisting of the control mixture without
203 graphene, and two dosages (0.035% and 0.07%) each of DG and HG types of graphene, as listed
204 in Table 4. These two dosages were based on a previous preliminary study (Ho et al. 2020) that
205 determined the optimal graphene dosage that would achieve the greatest increase in the
206 mechanical properties of mortar. The tiny amount of graphene had no adverse effect on
207 workability (Ho et al. 2020).

208 The graphene mortar specimens were made by adding graphene to water and the SP solution,
209 followed by sonication using an RS Pro ultrasonic cleaner (200W) for 30 minutes, as described
210 in (Dung et al. 2023). Afterwards, the graphene suspension was mixed with the dry mix of cement
211 and sand for 2 minutes. As verified by UV-vis tests, this dispersion approach was satisfactory
212 after 1 hour (Dung et al. 2023). The mixture was cast into dogbone-shaped moulds and
213 consolidated on a vibrating table and finished with a trowel. The specimens were demoulded

214 after 24 hours of casting, cured in lime water for 28 days prior to testing for mechanical strengths.
215 The lime water was a saturated solution of calcium hydroxide to provide a highly alkaline
216 environment. For each mix, a set of triplicate specimens were tested.

217

218 FRCM composite plate

219 Each FRCM composite specimen for tensile and pull-out testing consisted of two layers of
220 cementitious matrix and one layer of carbon fabric, as shown in Fig. 5. The FRCM composite
221 plates had a total thickness of 10 mm and planar dimensions of 300 mm × 500 mm. The specimens
222 were prepared on a wooden formwork.

223 After the fresh cementitious mortar was prepared as described in the previous section, it was
224 poured onto the wooden formwork to form a 5mm thick layer of cementitious mortar, and then
225 the surface was levelled. Immediately afterwards, a layer of carbon fabric was placed on top of
226 the mortar and stretched. Once this was done, the second 5mm thick layer of the same
227 cementitious mortar was cast and levelled with a metal trowel. The FRCM plate was covered
228 with a plastic wrap for 24 hours before demoulding. Afterwards, the FRCM plates were cured in
229 lime water at ambient temperature (20 ± 2 °C) for 28 days prior to cutting into specimens for pull-
230 out and tensile tests. In order to minimize the effects of vibration on the specimens due to cutting,
231 a high precision diamond blade (Premium Diamond Disc Cutter Blade PD300SEG-CS) from
232 Evolution Power Tools, UK, was used. After cutting, no debonding at the fibre/mortar interface
233 was observed, and neither was there any debonding between layers of mortar after mechanical
234 testing.

235 The nominal dimensions of the pull-out test specimens were 250 mm × 30 mm × 10 mm to
236 ensure three carbon bundles inside the cross-section. The nominal dimensions of the tensile test
237 specimens were 500 mm × 50 mm × 10 mm so that they had five warp-carbon bundles inside the
238 cross-section.

239 Since the fabric mesh had fibre bundles in two perpendicular directions, only the fibres in
240 the direction of the applied load should be included when calculating the fibre reinforcement ratio

241 (Carloni et al. 2018).

242

243 **Test Methodology**

244 *Tensile testing cementitious matrix*

245 Direct tension tests were performed on dogbone-shaped specimens (Fig. 6) with a cross-section
246 of 15 mm × 30 mm (Kamal et al. 2008; Mahmoudi et al. 2022). Each specimen had two LVDTs
247 with a 50 mm gauge length on both sides, as illustrated in Fig. 6. The direct tension test was
248 conducted on a servo-hydraulic test frame with a loading capacity of 5 kN. Displacement control
249 was used for the loading at 0.05 mm/min. Three nominally identical specimens were tested for
250 each mix.

251

252 *Pull-out tests*

253 The pull-out tests followed the methodology described in (Zhu et al. 2021; Zhang and Deng 2022)
254 and Fig. 7 shows the specimen dimensions. At the middle of the test specimen (i.e., cross-section
255 B), all materials (i.e., mortar and fibre bundles) except the central fibre bundle were cut off. At
256 cross-section A which is 70 mm away from Cross-section B, the central fibre bundle was cut off.
257 This arrangement ensured that the central bundle of fibres would be loaded and pulled out from
258 the upper part, as the embedded length in the upper part (70 mm) was shorter than that in the
259 lower part (130 mm). The clamping parts at both ends were reinforced with FRP wraps to prevent
260 the mortar from crushing. During each test, a linear potentiometer was used to measure the
261 displacement of the specimen. Displacement control was used and the loading rate of the servo-
262 hydraulic test frame was set at 0.2 mm/min. Again, three identical specimens were tested for each
263 mix.

264

265 ***FRCM composite tensile tests***

266 Fig. 8 shows the FRCM specimen dimensions, and Fig. 9 shows how the test was conducted
267 using a clevis-grip system in accordance with AC434 (ICC 2013). At both ends, perforated steel
268 tabs with dimensions of 200 mm × 50 mm × 3 mm were bonded to the mortar surface by epoxy
269 resin to protect the specimen ends from crushing due to gripping. This test arrangement avoids
270 lateral pressure being applied to the specimen and prevents the specimen from being subjected to
271 bending (Contamine et al. 2011). Two linear potentiometers were attached to the two sides of the
272 specimen to measure displacements. The load was applied by displacement control by a servo-
273 hydraulic test frame with a maximum capacity of 10 kN (Fig. 9), and the loading rate was set at
274 0.2 mm/min. Three identical specimens were tested for each type of FRCM composite.

275

276 ***Microstructure Images***

277 SEM images were taken of the mortar specimens, the pull-out specimens and the FRCM
278 composite tensile test specimens. The SEM samples were 20-30 mm in diameter and were
279 cleaned and stored in isopropanol to avoid further hydration before SEM imaging. To prepare the
280 SEM analysis samples, the test material was vacuum-dried and the surfaces were polished, using
281 sandpapers prior to final polishing with diamond suspensions (6, 3, and 1 μm). After polishing,
282 the samples were cleaned twice with isopropanol in an ultrasonic bath, and then vacuumed for 24
283 hours. Prior to the SEM analysis, the polished samples were subjected to a compressed air jet to
284 remove any dust from their surfaces before being mounted onto aluminium stubs using double-
285 sided adhesive carbon discs and coated with gold by a Quorum Q150T ES Sputter coater. A
286 Tescan Mira3 SC microscope was utilized for the SEM analysis with magnifications of 5000×
287 and 1000×.

288 The measurement of penetration thickness was conducted by analysing the SEM images. A
289 total of 60 random points were measured across a single cross section of the test specimens. After
290 discounting the maximum and minimum values, the remaining measured values were used to

291 calculate the statistical data for the penetration thickness. This methodology was used in prior
292 research by others, such as (Aljewifi et al. 2010; Donnini et al. 2016 & 2017; Zamir et al. 2019).

293

294 **Results and Discussions**

295 **Tensile strength and modulus of cementitious matrix**

296 Table 5 lists the average (of three identical specimens) tensile strength and modulus of elasticity
297 of the cementitious matrix. The stress-strain response of cement mortar under uniaxial direct
298 tensile test can be characterized by a linear ascending curve up to the point of failure. Therefore,
299 the tensile modulus of elasticity is determined by curve fitting to the middle third of the linear
300 portion of the tensile stress-strain response curve, as illustrated in Fig. 10. The gradient of the line
301 with the highest R^2 value is the tensile modulus of elasticity.

302 As expected, inclusion of graphene made some improvement to the mechanical properties
303 of the cementitious matrix. The improvement in the tensile strength of cement mortar due to
304 adding graphene is consistent and noticeable (18-29 % increase at 0.035 and 0.07 % graphene
305 dosage). However, the changes in modulus of elasticity are small and variable (-22 % and 7 % at
306 0.035 % and 0.07 % graphene dosages, respectively). The limited improvement in Young's
307 modulus due to graphene is because this property is measured at a low stress level, during which
308 the mechanical properties of the cement mortar follow the mixture law of composites where the
309 tiny dosage of graphene makes negligible difference. The inconsistency in modulus of elasticity
310 is within the range of measurement error.

311

312 **Results of penetration thickness**

313 Fig. 11 shows images of the interfaces between fibre and cementitious matrix of different FRCM
314 composite specimens. A cross-section of a test specimen was measured at 60 random points to
315 determine the penetration thickness. The standard deviation values for the penetration thickness
316 of CS, DG1, DG2, HG1, and HG2 specimens were $4.92 \mu\text{m}$, $4.16 \mu\text{m}$, $3.87 \mu\text{m}$, $4.11 \mu\text{m}$, and 3.92

317 μm , respectively. These results suggest a comparable accuracy level among the different
318 specimens.

319 Fig. 12 depicts the effects of graphene on increasing the penetration thickness of cementitious
320 matrix into carbon fibre bundles. Both types of graphene increased the penetration thickness but
321 the improved dispersion of HG gave better results than DG (Dung et al. 2023). The percentage
322 increases in penetration thickness are 6% and 20% for 0.035% and 0.07% DG graphene dosage;
323 35% and 44% for 0.035% and 0.07% HG graphene dosage.

324 From the penetration thickness values, the volume fractions of fibre in the sleeve filaments
325 of the FRCM composites (i.e., the ratio of sleeve fibre area and total fibre area) can be calculated
326 to be 29%, 32% & 34%, 40% & 43% for CS, DG with 0.035% graphene dosage & 0.07%
327 graphene dosages, and HG with 0.035% graphene dosage & 0.07% graphene dosages respectively.

328

329 **Pull-out test results**

330 For the pull-out tests, two failure modes are possible: (a) fibre bundle pull out, and (b) fracture
331 of fibres in the sleeve filaments.

332 For failure mode (a), the pull-out stress can be calculated using the following equation:

$$333 \quad \sigma_{interface} = \frac{P_{pull-out}}{L_e C_f} \quad (1)$$

334 where $P_{pull-out}$ is the peak pull-out force, L_e is the effective embedded length of the fibre fabric
335 (i.e., 70 mm) and C_f is the perimeter of the embedded fabric bundle.

336 For failure mode (b), the peak load at failure ($P_{pull-out,u}$) is calculated according to Eq. (2)
337 because only the sleeve filaments are fractured.

$$338 \quad P_{pull-out,u} = \varepsilon_f E_f A_{f_s} \quad (2)$$

339 in which A_{f_s} is the cross-section area of the sleeve filaments in the pull-out specimens, which
340 can be determined from the penetration thickness based on SEM images; E_f is the Elastic modulus

341 of carbon fibre; and ε_f is the fracture strain of the fibres.

342 Fig. 13 shows the typical failure mode of the pull-out test specimens. Due to high bond
343 strength, the observed failure mode in all the tests was fracture of the sleeve filaments and
344 slippage between core and sleeve filaments (Fig. 13). Therefore, the peak loads in the pull-out
345 tests represent the tensile strength of the sleeve filaments instead of interfacial shear stress.

346 Fig. 14 presents the experimental load-displacement curves for all pull-out tests. They show
347 three stages of behaviour as illustrated in Fig. 15: Initially, the load-displacement curves exhibit
348 a nearly linear ascending trend, which indicates elastic behaviour, including undamaged and
349 elastic bond between the fibre bundle and the mortar matrix. During this stage, all the filaments
350 remain intact. As the curve becomes non-linear, it marks debonding of the fibres from the mortar
351 in the sleeve filaments, which continues up to the point where the peak load (P_{max}) is reached.
352 During this stage, sleeve filament ruptures occur. Therefore, the peak load is critically affected
353 by the mortar penetration thickness, or the thickness of the sleeve filaments of the fibre bundle.
354 The load drop thereafter is attributed to progressive fracture of the sleeve filaments. Finally, the
355 curve reached a relatively stable plateau. At this stage, the resistance of the plate is provided by
356 friction between the core filaments and the sleeve filaments. This unique failure is known as
357 ‘telescopic debonding’. The contribution of the frictional load provides an enhancement to the
358 bond resistance, and helps to increase the ductility and residual adhesive resistance of the plate.
359 Similar findings were reported by Cogen and Peled (2012); Liu et al. (2020); Focacci et al. (2022)
360 and Alexandre et al. (2023).

361 Table 6 summarises the pull-out test results. It is important to consider the magnitude of the
362 standard deviation compared to the mean value when assessing the significance of these
363 differences. The differences in peak load values between the CS group and the DG1, DG2, HG1,
364 and HG2 groups are significantly greater than their respective standard deviations, indicating
365 statistical significance in the difference between these groups.

366 When compared with the CS, the ultimate loads of samples DG1 and DG2 increased by ~13%
367 and ~20%, respectively, while for samples HG1 and HG2, the improvements are even more

368 significant, at 17% and 30%, respectively. These improvements are consistent with the results of
369 microstructure images observed in the previous section associated with increased penetration
370 thickness of mortar into fibre bundles. The results can be seen in Fig. 16 which plots increases in
371 strength of the interfacial bonding between carbon fibre bundles and cementitious matrix.

372 CS, DG, and HG specimens have standard deviations of 32 N (CS), 5 N (DG1), 15 N (DG2),
373 55 N (HG1), and 12 N (HG2). DG and HG specimens have smaller standard deviations than CS
374 samples, which indicates consistent performance of graphene modified FRCM composites. In
375 comparison, the approach used by (Donnini et al. 2016), which involved impregnation of fibres
376 in epoxy resin at various levels, followed by application of a quartz sand layer to mitigate fibre
377 slippage within the mortar matrix, produced inconsistent results. While some coated samples
378 exhibited noticeable improved tensile strengths (e.g., 10 to 29% for transition tensile strength and
379 52 to 82% for ultimate tensile strength), some coated samples had notably lower tensile strengths
380 than those of the corresponding untreated samples (e.g., -21% for transition tensile strength and
381 -4% for ultimate tensile strength).

382

383 **FRCM tensile test results**

384 Three typical failure modes of the FRCM composites were found, including (I) failure at the ends
385 of the gripping area; (II) breakage of fibres in the middle part together with cracks along the
386 length; (III) slippage of fibre together with partial fibre fracture (see Fig. 17). Among the total of
387 15 test specimens, two failure modes were observed as shown in Fig. 17, including: (I) 2 cases
388 of failure at the ends of the gripping area and (II) 13 cases of breakage of fibres in the middle part
389 together with cracking along the length. Failure Mode I has no relevance to this research and its
390 results were excluded from the subsequent further analysis. Although the failure mode does not
391 change with the addition of graphene, there were more secondary cracks with smaller spacing
392 between them along the length of the test specimens, as explained below.

393 For a FRCM composite coupon subjected to tensile loading, the first crack will occur when
394 the stress applied to the matrix is equal to the matrix tensile strength. Once the first two cracks

395 are fully open, the axial force is transferred from the gripped parts to the free part of the coupon
396 by the sleeve filaments through the cracked cross sections. A new crack will form if the distance
397 between two adjacent cracks is longer than a critical distance and when the maximum stress in
398 the matrix equals the matrix tensile strength. This process continues until the distance between
399 two cracks is smaller than the critical distance (Focacci et al. 2022). After the formation of
400 sufficient cracks at increasing tensile stress, the bridging capacity of the sleeve filaments at one
401 of the cracked sections is exceeded thereby causing failure of the specimen (Ranade et al. 2014).
402 During the crack formation process, energy is dissipated when a new crack occurs. Owing to the
403 benefit of graphene in enhancing the tensile strength of the matrix in graphene modified FRCM
404 composites, an increased amount of energy is needed to break the matrix when forming a new
405 crack.

406 Using graphene also increases the penetration thickness of mortar into the fibre bundle. As
407 a result, the maximum force that can be transferred from the matrix to the fibres by the sleeve
408 filaments is increased. The effect of graphene in increasing the penetration thickness is greater
409 than the effect of graphene in increasing the dissipated energy in forming new cracks. Therefore,
410 the critical distance between cracks becomes smaller, resulting in denser cracks in the graphene
411 enhanced FRCM composite. Similar findings have been reported by others (Dvorkin et al. 2013;
412 Trainor et al. 2013; Wu et al. 2021; Guo et al. 2022;) who investigated other means of increasing
413 the penetration thickness. The increases in energy dissipation and penetration thickness of
414 graphene modified FRCM composites are exhibited as larger areas under the stress-strain curves
415 and increased deformation capacity, which was similarly reported by Focacci et al. (2020).

416 The detailed results in Fig. 18-19 can be used to quantitatively demonstrate the above-
417 mentioned effects. Consider the average values in Fig. 18 of the three nominally identical tests.
418 The first segment of the curves until point A is governed by the tensile properties of the mortar
419 until mortar cracking. Using graphene increased the tensile strength of the mortar, and hence the
420 average peak stresses at point A for the graphene modified samples (DG & HG) are higher than
421 that of the control sample (CS). After mortar cracking, the stress drops during the transitional
422 period for the applied stress in the mortar to transfer to the fibres in the sleeve, before it rises

423 again as the fibres in the sleeve take up load. The higher average peak loads at point B of the
424 curves for graphene modified samples (DG and HG) are a direct result of the increased
425 penetration thickness of mortar in the fibre bundles. Furthermore, due to better dispersion of
426 graphene in the HG sample than in the DG sample, the average peak stress of the HG sample is
427 higher than that of the DG sample. After the peak stress at point B, all the test samples follow a
428 trend of decreasing stress at increasing strain due to progressive breakage of the fibres in the
429 sleeve. The general trend of the stress-strain curves follow that reported in (Donnini et al. 2016),
430 but the key quantities are highly influenced by the presence of graphene. The tensile failure modes
431 of the coupons are shown in Fig. 19.

432 The obtained results are consistent with the results of previous studies by others (Donnini et
433 al. 2016; Santis et al. 2018), including: (a) a linear ascending part until Point A (the transition
434 point) which marks the occurrence of first cracking of the cementitious matrix; and (b) a strain
435 hardening part where the stress in the fibres keeps increasing until tensile fracture of the sleeve
436 filaments as marked by point B (the ultimate point). Therefore, the load at point A includes
437 contributions of both the mortar and the sleeve fibres at the same strain level as that of the fracture
438 strain of the mortar, whereas the load at Point B is that of the sleeve fibres at fracture only. These
439 two loads can be calculated as follows

440 For point A:

$$441 \quad P_{FRCM,1} = \varepsilon_m E_m A_m + \varepsilon_m E_f A_{f_s} \quad (3)$$

442 where A_m , E_m and ε_m are the cross-section area, the Elastic modulus and the fracture strains
443 of the mortar in the FRCM composite, respectively.

444 For point B:

445 After cracking, the mortar matrix does not contribute to the resistance of the composite.
446 Therefore, the ultimate load of the FRCM composite comprises of two parts: the tensile strength
447 of the sleeve filaments and the friction force provided by the core filaments. Since the friction
448 force is small, it is reasonable to take the tensile strength of the sleeve filaments as the load

449 carrying capacity of the FRCM composite, as expressed in Eq. (4).

$$450 \quad P_{FRCM,2} = \varepsilon_f E_f A_{fs} \quad (4)$$

451 Fig. 20 (a) and (b) show the effects of graphene content on tensile resistances at the transition
452 point (point A in Fig. 18) and the ultimate point (point B in Fig. 18), respectively. The transition
453 point resistance of the FRCM composite specimens is enhanced by 14 to 18% and 17 to 19%
454 when adding DG and HG, respectively, and the ultimate tensile resistances are increased by 3 to
455 14% and 26 to 31%, respectively.

456 The observed increases in transition and tensile strengths of FRCM composites can be
457 attributed to graphene's role as a nucleation seeding (Dung et al. 2023). First, graphene facilitated
458 cement hydration, leading to an improvement in cementitious matrix strength (Table 2). Second,
459 this improved hydration process resulted in elevated concentrations of dissolved cement ions,
460 which promoted the ingress of more dissolved cement ions into the fibre bundles (Fig. 11),
461 thereby further strengthening the transition and tensile strengths of the FRCM composites.

462 The dispersion of HG within the cementitious matrix was better than that of DG graphene
463 (Dung et al. 2023), leading to better performance of the FRCM composites incorporating HG
464 than those incorporating DG.

465 The improvement in penetration thickness by using the proposed method of adding graphene
466 in this research ranges from 6% to 44%, leading to 13% to 30% increases in interfacial bonding
467 resistances obtained from pull-out tests. Similar improvements in resistances have been achieved
468 by others (these researchers did not measure the penetration thickness) including 19% and 33%
469 improvements by Cohen and Peled (2012) who used 200-nm silica fume coated AR-glass
470 composites produced by dry and wet processes respectively, 18% increase in the tensile strength
471 of composites by Quadflieg et al. (2018) by using potassium silicate-coated AR-glass fabric, 32%
472 increase by Signorini et al. (2019) who employed 150-nm micro silica coated uniaxial high-
473 tenacity carbon fabric (with AR-glass yarns in the weft). However, for similar improvements, the
474 graphene-based approach in this study is considered a promising method for practical
475 applications.

476 The improvements in Fig. 20 (a) and (b) can be predicted using the mixture law equations
477 for fibre composites, as expressed in Eq. 3 and Eq. 4 for the transition strength and the ultimate
478 strength respectively, as confirmed in Fig. 21 (a) and (b) respectively, which show good
479 agreement between the calculation results using Eq. 3 and Eq. 4 and the test results.

480 The improvement in the ultimate strength of graphene modified FRCM composites are
481 almost entirely due to the increase in penetration thickness of mortar into fibre bundles enabled
482 by graphene. This can be clearly seen in Fig. 22 which shows the relationship between the
483 increases in the ultimate tensile strength with the increases in penetration thickness.

484 Fig. 23 shows the comparison of peak loads of each fibre bundle obtained from FRCM tensile
485 tests and pull-out tests. As expected, the utilisation efficiency of fibres in pull-out specimens is
486 generally higher than FRCM composites; this is because the stress distribution among the five
487 bundles in FRCM composites is not uniform. Some of the fibre bundles contribute less than others.

488

489 **Conclusions**

490 This study has investigated the effects of using two different types of graphene on the mechanical
491 properties of mortar matrix, pull-out test results for the fibre and mortar interfaces, and tensile
492 test results of FRCM composites. The two types of graphene were Dry Graphene powder (DG)
493 and Hydrated Graphene (HG) paste and their dosages were 0.035 and 0.07%. The main
494 conclusions of this study are:

495 (a) Using DG and HG increased the tensile strength of cementitious matrix by up to 18 and 31%,
496 respectively;

497 (b) Compared to the FRCM specimens without graphene, the penetration thickness of cement
498 mortar into fibre filaments increased by 6% to 44% due to graphene inclusion.

499 (c) The increased penetration thickness almost accounts for the entire increase in both transition
500 tensile strength and ultimate tensile strength of the FRCM composites. Increases of 6 - 20%
501 and 35 - 44% in penetration thickness for DG and HG samples resulted in corresponding
502 increases of 14 - 18% and 3 - 14% increases in transition and ultimate tensile strengths of the

503 DG specimens, and increases of 17 - 19%, and 26 - 31% increases in transition and ultimate
504 tensile strengths of the HG specimens.

505 (d) The intermediate state graphene product HG appears to give better results than the dry
506 powder state product DG. The intermediate HG state is also less costly. Therefore, HG should
507 be preferred to DG.

508

509 **Data Availability Statement**

510 All data, models, or code that support the findings of this study are available from the
511 corresponding author upon reasonable request.

512

513 **Acknowledgements**

514 The authors acknowledge the financial support provided by the Engineering and Physical
515 Sciences Research Council (EPSRC) Fund (EP/T021748/1) for the completion of this research.
516 Acknowledgement should also be given to material suppliers for their in-kind contribution to the
517 research: the Portland cement was supplied by Breedon-UK, the Graphene was supplied by First
518 Graphene (UK) and the carbon fabric mesh was provided by Ruregold (Italy).

519

520 **References**

521 Alan Strauss Rambo, D., Umbinger de Oliveira, C., Pícolo Salvador, R., Dias Toledo Filho, R.,
522 da Fonseca Martins Gomes, O., de Andrade Silva, F., and de Melo Vieira, M. (2021). "Sisal textile
523 reinforced concrete: Improving tensile strength and bonding through peeling and nano-silica
524 treatment." *Construction and Building Materials*, 301, 124300.

525 Alexandre, V. J. F., Boshoff, W. P., and Combrinck, R. (2023). "Damage evaluation and
526 mechanisms of textile reinforced concrete during telescopic failure." *Construction and Building
527 Materials*, 403, 133055.

528 Aljewifi, H., Fiorio, B., and Gallias, J.-L. (2010). "Characterization of the impregnation by a
529 cementitious matrix of five glass multi-filament yarns." *European Journal of Environmental and
530 Civil Engineering*, 14(5), 529-544.

531 Artioli, G., Valentini, L., Dalconi, M. C., Parisatto, M., Voltolini, M., Russo, V., and Ferrari, G.
532 (2014). "Imaging of nano-seeded nucleation in cement pastes by X-ray diffraction tomography."
533 *International Journal of Materials Research*, 105(7), 628-631.

534 Ascione, L., de Felice, G., and De Santis, S. (2015). "A qualification method for externally
535 bonded Fibre Reinforced Cementitious Matrix (FRCM) strengthening systems." *Composites Part*
536 *B: Engineering*, 78, 497-506.

537 Babaeidarabad, S., Loreto, G., and Nanni, A. (2014). "Flexural Strengthening of RC Beams with
538 an Externally Bonded Fabric-Reinforced Cementitious Matrix." *Journal of Composites for*
539 *Construction*, 18(5), 04014009.

540 Banholzer, B., 2004. Bond behaviour of a multi-filament yarn embedded in a cementitious matrix
541 (Doctoral dissertation, Bibliothek der RWTH Aachen).

542 Baomin, W., and Shuang, D. (2019). "Effect and mechanism of graphene nanoplatelets on
543 hydration reaction, mechanical properties and microstructure of cement composites."
544 *Construction and Building Materials*, 228, 116720.

545 Barhum, R., and Mechtcherine, V. (2012). "Effect of short, dispersed glass and carbon fibres on
546 the behaviour of textile-reinforced concrete under tensile loading." *Engineering Fracture*
547 *Mechanics*, 92, 56-71.

548 Boulekbache, B., Hamrat, M., Chemrouk, M., and Amziane, S. (2010). "Flowability of fibre-
549 reinforced concrete and its effect on the mechanical properties of the material." *Construction and*
550 *Building Materials*, 24(9), 1664-1671.

551 Butler, M., Hempel, S., and Mechtcherine, V. (2011). "Modelling of ageing effects on crack-
552 bridging behaviour of AR-glass multifilament yarns embedded in cement-based matrix." *Cement*
553 *and Concrete Research*, 41(4), 403-411.

554 Calabrese, A.S., D'Antino, T., Colombi, P. and Poggi, C., 2020. Study of the influence of interface
555 normal stresses on the bond behavior of FRCM composites using direct shear and modified beam
556 tests. *Construction and Building Materials*, 262, p.120029.

557 Calabrese, A.S., D'Antino, T. and Colombi, P., 2021. Experimental and analytical investigation
558 of PBO FRCM-concrete bond behavior using direct and indirect shear test set-ups. *Composite*
559 *Structures*, 267, p.113672.

560 Carloni, C., D'Antino, T., Sneed, L. H., and Pellegrino, C. (2018). "Three-Dimensional
561 Numerical Modeling of Single-Lap Direct Shear Tests of FRCM-Concrete Joints Using a
562 Cohesive Damaged Contact Approach." *Journal of Composites for Construction*, 22(1),
563 04017048.

564 Cohen, Z., and Peled, A. (2010). "Controlled telescopic reinforcement system of fabric-cement
565 composites — Durability concerns." *Cement and Concrete Research*, 40(10), 1495-1506.

566 Cohen, Z. and Peled, A., 2012. Effect of nanofillers and production methods to control the
567 interfacial characteristics of glass bundles in textile fabric cement-based composites. *Composites*
568 *Part A: Applied Science and Manufacturing*, 43(6), pp.962-972.

569 Contamine, R., Si Larbi, A., and Hamelin, P. (2011). "Contribution to direct tensile testing of
570 textile reinforced concrete (TRC) composites." *Materials Science and Engineering: A*, 528(29),
571 8589-8598.

572 Donnini, J., Corinaldesi, V., and Nanni, A. (2016). "Mechanical properties of FRCC using carbon
573 fabrics with different coating treatments." *Composites Part B: Engineering*, 88, 220-228.

574 Du, H., Gao, H. J., and Pang, S. D. (2016). "Improvement in concrete resistance against water
575 and chloride ingress by adding graphene nanoplatelet." *Cement and Concrete Research*, 83, 114-
576 123.

577 Dung, N. T., Su, M., Watson, M., and Wang, Y. (2023). "Effects of using aqueous graphene on
578 behavior and mechanical performance of cement-based composites." *Construction and Building*
579 *Materials*, 368, 130466.

580 Dvorkin, D., Poursaeed, A., Peled, A. and Weiss, W.J., 2013. Influence of bundle coating on the
581 tensile behavior, bonding, cracking and fluid transport of fabric cement-based composites.
582 *Cement and Concrete Composites*, 42, pp.9-19.

583 Ebead, U., Shrestha, K. C., Afzal, M. S., Refai, A. E., and Nanni, A. (2017). "Effectiveness of
584 Fabric-Reinforced Cementitious Matrix in Strengthening Reinforced Concrete Beams." *Journal*
585 *of Composites for Construction*, 21(2), 04016084.

586 Emdadi, A., Mehdipour, I., Libre, N. A., and Shekarchi, M. (2015). "Optimized workability and
587 mechanical properties of FRCC by using fiber factor approach: theoretical and experimental
588 study." *Materials and Structures*, 48(4), 1149-1161.

589 Focacci, F., D'Antino, T. and Carloni, C., 2020. The role of the fiber–matrix interfacial properties
590 on the tensile behavior of FRCC coupons. *Construction and Building Materials*, 265, p.120263.

591 Focacci, F., D'Antino, T. and Carloni, C., 2022. Tensile testing of FRCC coupons for material
592 characterization: discussion of critical aspects. *Journal of Composites for Construction*, 26(4),
593 p.04022039.

594 Fu, S.Y. and Lauke, B., 1997. The fibre pull-out energy of misaligned short fibre composites.
595 *Journal of materials science*, 32(8), pp.1985-1993.

596 Guo, W., Hu, J., Ma, Y., Huang, H., Yin, S., Wei, J., and Yu, Q. (2020). "The application of novel
597 lightweight functional aggregates on the mitigation of acidification damage in the external anode
598 mortar during cathodic protection for reinforced concrete." *Corrosion Science*, 165, 108366.

599 Guo, S., Ren, J., Yang, T., Rahman, M. Z., Shi, C., and Zhu, D. (2022). "Influences of surface
600 treatment on the mechanical performances of carbon and basalt textiles-reinforced concretes
601 under harsh environments." *Composites Part B: Engineering*, 246, 110195.

602 Hartig, J., Häußler-Combe, U., and Schicktzanz, K. (2008). "Influence of bond properties on the
603 tensile behaviour of Textile Reinforced Concrete." *Cement and Concrete Composites*, 30(10),
604 898-906.

605 Ho, V. D., Ng, C.-T., Coghlan, C. J., Goodwin, A., Mc Guckin, C., Ozbakkaloglu, T., and Losic,

606 D. (2020). "Electrochemically produced graphene with ultra large particles enhances mechanical
607 properties of Portland cement mortar." *Construction and Building Materials*, 234, 117403.

608 Jesse, F. (2004). "Load bearing behaviour of filament yarns in a cementitious matrix."
609 *Unpublished doctoral dissertation, Technische Universität Dresden, Germany. Retrieved from*
610 <http://nbn-resolving.de/urn:nbn:de:swb,14-1122970>.

611 ICC (International Code Council). 2013. Acceptance criteria for masonry and concrete
612 strengthening using fiber-reinforced cementitious matrix (FRCM) composite systems. AC434.
613 ICC Evaluation Service. Washington, DC: ICC.

614 Jin, Y., Liu, J., Xie, X., and Zhai, L. (2018). "Comparison between epoxy resin concrete and
615 traditional materials under high temperature." *IOP Conference Series: Earth and Environmental*
616 *Science*, 186(2), 012039.

617 Jing, G., Ye, Z., Lu, X., and Hou, P. (2017). "Effect of graphene nanoplatelets on hydration
618 behaviour of Portland cement by thermal analysis." *Advances in Cement Research*, 29(2), 63-70.

619 Kamal, A., Kunieda, M., Ueda, N., and Nakamura, H. (2008). "Evaluation of crack opening
620 performance of a repair material with strain hardening behavior." *Cement and Concrete*
621 *Composites*, 30(10), 863-871.

622 Land, G., and Stephan, D. "Nanoparticles as accelerators for cement hydration." *Proc., Proc. of*
623 *the 3rd International Symposium on UHPC and nanotechnology in Construction*, 93-99.

624 Li, V.C., Wang, Y. and Backer, S., 1990. Effect of inclining angle, bundling and surface treatment
625 on synthetic fibre pull-out from a cement matrix. *Composites*, 21(2), pp.132-140.

626 Lin, Y., and Du, H. (2020). "Graphene reinforced cement composites: A review." *Construction*
627 *and Building Materials*, 265, 120312.

628 Liu, S., Rawat, P., Chen, Z., Guo, S., Shi, C. and Zhu, D., 2020. Pullout behaviors of single yarn
629 and textile in cement matrix at elevated temperatures with varying loading speeds. *Composites*
630 *Part B: Engineering*, 199, 108251.

631 Liu, P., Feng, R., Wang, F., Xu, Y., and Zhu, J.-H. (2022). "Fatigue testing of corroded RC
632 continuous beams strengthened with polarized C-FRCM plate under ICCP-SS dual-function
633 retrofitting system." *Structures*, 43, 12-27.

634 Mahmoudi, F., Abdalla, J. A., Hawileh, R. A., and Zhang, Z. (2022). "An overview of mechanical
635 properties of engineered cementitious composite (ECC) with different percentages of GGBS."
636 *Materials Today: Proceedings*, 65, 2077-2080.

637 Messori, M., Nobili, A., Signorini, C. and Sola, A., 2019. Effect of high temperature exposure on
638 epoxy-coated glass textile reinforced mortar (GTRM) composites. *Construction and Building*
639 *Materials*, 212, pp.765-774.

640 Nadiy, R., Peled, A., Mechtcherine, V., Hempel, S., and Schroefl, C. (2017). "Micro- and
641 nanoparticle mineral coating for enhanced properties of carbon multifilament yarn cement-based
642 composites." *Composites Part B: Engineering*, 111, 179-189.

643 Ozturk, M., and Chung, D. D. L. (2021). "Enhancing the electromagnetic interference shielding
644 effectiveness of carbon-fiber reinforced cement paste by coating the carbon fiber with nickel."
645 *Journal of Building Engineering*, 41, 102757.

646 Peled, A., Zaguri, E., and Marom, G. (2008). "Bonding characteristics of multifilament polymer
647 yarns and cement matrices." *Composites Part A: Applied Science and Manufacturing*, 39(6), 930-
648 939.

649 Pino, V., Hadad, H. A., Basalo, F. D. C. y., Nanni, A., Ebead, U. A., and Refai, A. E. (2017).
650 "Performance of FRCM-Strengthened RC Beams Subject to Fatigue." *Journal of Bridge*
651 *Engineering*, 22(10), 04017079.

652 Pino, V., Nanni, A., Arboleda, D., Roberts-Wollmann, C., and Cousins, T. (2017). "Repair of
653 Damaged Prestressed Concrete Girders with FRP and FRCM Composites." *Journal of*
654 *Composites for Construction*, 21(3), 04016111.

655 Quadflieg, T., Leimbrink, S., Gries, T. and Stolyarov, O., 2018. Effect of coating type on the
656 mechanical performance of warp-knitted fabrics and cement-based composites. *Journal of*
657 *Composite Materials*, 52(19), pp.2563-2576.

658 Raza, S. S., and Qureshi, L. A. (2021). "Effect of carbon fiber on mechanical properties of reactive
659 powder concrete exposed to elevated temperatures." *Journal of Building Engineering*, 42, 102503.

660 Ranade, R., Zhang, J., Lynch, J.P. and Li, V.C., 2014. Influence of micro-cracking on the
661 composite resistivity of engineered cementitious composites. *Cement and Concrete Research*, 58,
662 pp.1-12.

663 Santis, S. D., Hadad, H. A., Basalo, F. D. C. y., Felice, G. d., and Nanni, A. (2018). "Acceptance
664 Criteria for Tensile Characterization of Fabric-Reinforced Cementitious Matrix Systems for
665 Concrete and Masonry Repair." *Journal of Composites for Construction*, 22(6), 04018048.

666 Signorini, C., Sola, A., Nobili, A. and Siligardi, C., 2019. Lime-cement textile reinforced mortar
667 (TRM) with modified interphase. *Journal of Applied Biomaterials & Functional Materials*, 17(1),
668 2280800019827823.

669 Signorini, C., Nobili, A., Sola, A., and Messori, M. (2020). "Designing epoxy viscosity for
670 optimal mechanical performance of coated Glass Textile Reinforced Mortar (GTRM)
671 composites." *Construction and Building Materials*, 233, 117325.

672 Signorini, C., and Nobili, A. (2021). "Targeting functionalised carbon nanotubes at the interphase
673 of Textile Reinforced Mortar (TRM) composites." *Composites Part A: Applied Science and*
674 *Manufacturing*, 144, 106330.

675 Silva, F. d. A., Butler, M., Hempel, S., Toledo Filho, R. D., and Mechtcherine, V. (2014). "Effects
676 of elevated temperatures on the interface properties of carbon textile-reinforced concrete."
677 *Cement and Concrete Composites*, 48, 26-34.

678 Thomas, J. J., Jennings, H. M., and Chen, J. J. (2009). "Influence of Nucleation Seeding on the
679 Hydration Mechanisms of Tricalcium Silicate and Cement." *The Journal of Physical Chemistry*
680 *C*, 113(11), 4327-4334.

681 Trainor, K.J., Foust, B.W. and Landis, E.N., 2013. Measurement of energy dissipation
682 mechanisms in fracture of fiber-reinforced ultrahigh-strength cement-based composites. *Journal*
683 *of engineering mechanics*, 139(7), pp.771-779.

684 Wang, Z., Dai, J.-G., Wang, M., Chen, L., Zhang, F., and Xu, Q. (2021). "Residual bond strengths
685 of epoxy and cement-bonded CFRP reinforcements to concrete interfaces after elevated
686 temperature exposure." *Fire Safety Journal*, 124, 103393.

687 Wu, S., Qureshi, T. and Wang, G., 2021. Application of graphene in fiber-reinforced cementitious
688 composites: A review. *Energies*, 14(15), p.4614.

689 Xu, S., Krüger, M., Reinhardt, H.-W., and Ožbolt, J. (2004). "Bond Characteristics of Carbon,
690 Alkali Resistant Glass, and Aramid Textiles in Mortar." *Journal of Materials in Civil Engineering*,
691 16(4), 356-364.

692 Yang, H., Cui, H., Tang, W., Li, Z., Han, N., and Xing, F. (2017). "A critical review on research
693 progress of graphene/cement based composites." *Composites Part A: Applied Science and*
694 *Manufacturing*, 102, 273-296.

695 Zhang, M., and Deng, M. (2022). "Fabric-to-cementitious matrix bond behavior in carbon fabric
696 reinforced cementitious matrix (FRCM) composites with added short fibers." *Composite*
697 *Structures*, 300, 116173.

698 Zhao, J., Liebscher, M., Michel, A., Schneider, K., Foest, R., Fröhlich, M., Quade, A., and
699 Mechtcherine, V. (2020). "Plasma-generated silicon oxide coatings of carbon fibres for improved
700 bonding to mineral-based impregnation materials and concrete matrices." *Cement and Concrete*
701 *Composites*, 114, 103667.

702 Zhu, M., Zhu, J.-H., Ueda, T., Matsumoto, K., and Su, M. (2021). "Bond behavior of carbon
703 fabric reinforced cementitious matrix (FRCM) composites considering matrix impregnation."
704 *Composite Structures*, 262, 113350.

705

706

707

708

709

710

711

712