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Durability of Steel Fibre Reinforced Rubberised Concrete Exposed to Chlorides

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Abstract

This study assesses the durability and transport properties of low water/binder ratio (0.35) steel fibre reinforced rubberised concrete (SFRRuC) mixes, which are proposed to be used as flexible concrete pavements. Waste tyre rubber is incorporated in concrete as fine and coarse aggregate replacement and blends of manufactured steel fibres and recycled tyre steel fibres are used as internal reinforcement. The fresh, mechanical and transport properties of plain concrete are compared with those of SFRRuC mixes having different substitutions of rubber aggregates (0, 30 and 60% by volume). The chloride corrosion effects due to exposure to a simulated accelerated marine environment (intermittent wet-dry cycles in 3% NaCl solution) is also evaluated. The results show that, although water permeability (e.g. volume of permeable voids and sorptivity) and chloride ingress increase with rubber content, this increase is minor and water and chlorides permeability are generally within the range of highly durable concrete mixes. No visual signs of deterioration or cracking (except superficial rust) were observed on the surface of the concrete specimens subjected to 150 or 300 days of accelerated chloride corrosion exposure and a slight increase in the mechanical properties is observed. This study shows that the examined low water/binder SFRRuC mixes promote good durability characteristics, making these composite materials suitable for flexible concrete pavement applications.

35 **Keywords:** *Rubberised concrete; Steel fibre reinforced concrete; Flexible concrete pavement; Hybrid*
36 *reinforcement.*

37 1 Introduction

38

39 Several factors are considered when designing road pavements including traffic loading, sub-
40 grade status, environmental conditions, as well as cost and availability of construction
41 materials. Two different systems of pavements are conventionally used in roads construction:
42 flexible asphalt or rigid concrete. A flexible pavement typically consists of a series of layers
43 and its design is based on distributing the load through the component layers. On the other
44 hand, a rigid pavement typically consists of one Portland cement concrete structural layer and
45 its design is based on the flexural resistance of this layer. Flexible asphalt pavements have low
46 stiffness and as such they can better accommodate deformations arising from temperature
47 changes, loads and soil movements, however, lack the durability resistance of rigid concrete
48 pavements which are longer lasting [1]. It is therefore desirable to develop a pavement system
49 with comparable flexibility to asphalt pavement, and ability to withstand higher stresses as well
50 as environmental attack during its service life. One attractive alternative proposed by the
51 authors is concrete pavements that include high amounts of recycled rubber particles (chips
52 and/or crumbs), as a partial replacement of natural aggregates, and recycled steel fibre
53 reinforcement. These composite concretes, referred to as steel fibre reinforced rubberised
54 concretes (SFRRuC), can be designed to have high flexibility similar to asphalt and flexural
55 strengths similar to steel fibre reinforced concrete (SFRC) [1].

56

57 Over the past two decades, research interest in the potential use of waste tyre rubber (WTR)
58 as partial replacement of natural aggregates in the production of concretes (rubberised
59 concretes – RuC) has steadily grown [2-6]. RuC present reduced workability and increased
60 air content, compared to conventional concretes, as a result of the rough surface texture of the
61 rubber particles [4, 7-9]. Though RuC can show higher ductility and increased toughness
62 compared to conventional concrete [8-10], this is at the expense of loss in strength and
63 stiffness [11, 12]. Different strategies to improve the mechanical performance of RuC have
64 been investigated in recent years, including the addition of supplementary cementitious
65 materials to the binder mix to reduce the porosity and aid early age strength development. For
66 example, Raffoul et al. [9] observed a 40% enhancement in the compressive strength of RuC
67 when 20 wt.% of cement was replaced with equal amount of silica fume and fly ash. This
68 enhancement was attributed to the better particle packing and cohesion of the concrete mix
69 as a result of the reactivity of these materials and the consequent pozzolanic reaction.

70 The addition of fibres to RuC can enhance the mechanical performance of these composite
71 concretes. Xie et al. [13] reported that the inclusion of manufactured steel fibres (MSF) in RuC,
72 mitigated the reduction in compressive strength while increasing residual flexural strength.
73 Similar outcomes were reported in other studies by the authors [1, 2] where SFRRuC presented
74 better mechanical properties than plain RuC. Although the fresh and mechanical properties of
75 RuC and SFRRuC have been studied by several researchers, there is still a dearth of data in
76 this field, especially when rubber aggregates are incorporated in the large volumes (exceeding
77 20% replacement by volume of total natural aggregates). It should be noted that, large volumes
78 of rubber aggregates replacements in concrete are necessary to attain flexibility in concrete
79 pavements.

80

81 Few studies examined the durability and transport properties of RuC, with notable
82 discrepancies being reported on the effect of rubber particles on long-term performance. Water
83 permeability and water absorption by immersion generally increase with rubber content [14-
84 16]. This has been attributed to the additional water required in RuC mixes to maintain
85 workability, and the high void volumes between rubber particles and cement paste due to the
86 hydrophobicity of rubber. Conversely, several researchers have observed a reduction in water
87 absorption of RuC (up to 12.5% rubber for fine aggregates) using the method of immersion
88 and related this behaviour to the impervious nature of rubber particles. Benazzouk et al. [17]
89 reports that the addition of rubber crumbs of up to 40% volume in cement pastes reduced
90 sorptivity, hydraulic diffusivity and air permeability. Similar observations are reported by
91 Segre and Joeques [18] who also attributed this behaviour to the hydrophobic nature of rubber.
92 The transport properties of these composite concretes are strongly dependent on the distinctive
93 features of the starting concrete matrix, whose performance can significantly vary as a function
94 of mix design, age and curing conditions, among other factors, which explains the variability
95 in results obtained from different investigations.

96

97 In a recent study, the authors [1] studied the mechanical properties of SFRRuC mixes in which
98 fine and coarse aggregates were partially replaced with rubber (0%, 20%, 40% or 60%
99 replacement by volume), and different types of steel fibres (MSF and/or recycled tyre steel
100 fibres- RTSF) added in volumes of up to 40 kg/ m³. In addition to the increased toughness and
101 flexibility attained, it was observed that all the examined SFRRuC mixes were able to achieve

102 flexural strengths that meet the flexural strength limits prescribed in pavement design EN
103 13877-1 [19]. Concrete pavement slabs, however, are susceptible to several deteriorative
104 processes that can be caused by the ingress of aggressive substances into concrete, such as
105 corrosion due to attack by chlorides or carbonation. The rate of transport of aggressive agents
106 is related to a large degree to the concrete's degree of saturation and air permeability [17].
107 Aggressive substances such as chlorides can also penetrate into concrete due to diffusion and
108 capillary action.

109

110 The chloride permeability in RuC remains largely unknown and studies examining this [20,
111 21] reveal increased chloride permeability with rubber content, which can be significantly
112 reduced with the addition of fly ash and/or silicate fume. This is consistent with the reduced
113 water absorption and permeability achieved in concretes with these additions [15, 20]. To date,
114 there are very few studies on the transport and durability properties of RuC with large volumes
115 of rubber replacement [7, 22, 23], while the transport and durability properties of SFRRuC has
116 not been studied yet. Furthermore, there is limited understanding on the mechanism governing
117 chloride-induced corrosion of steel fibres in RuC and its potential effect on long-term
118 performance. However, there is a good consensus that the main factors controlling durability
119 of SFRC, when exposed to chlorides, include: (i) the age and the exposure conditions, (ii) the
120 steel fibre type and size, (iii) the concrete matrix quality and (iv) the presence of cracks [24].
121 Consequently, it is important to understand the transport and durability properties of SFRRuC
122 before using it in flexible concrete pavements.

123

124 In this study, the fresh state, mechanical strength, and transport properties of SFRC, and
125 SFRRuC are investigated and compared. The fresh properties assessed include workability, air
126 content and fresh density. The mechanical performance is examined in terms of compressive
127 strength and flexural behaviour including flexural strength, elastic modulus and residual
128 flexural strength. The transport properties examined are volume of permeable voids, gas
129 permeability, sorptivity and chloride penetrability (chloride ion penetration depth and
130 diffusion). The chloride corrosion effects due to exposure to a simulated accelerated marine
131 environment (intermittent wet-dry cycles in 3% NaCl solution) are also evaluated.

132

133 **2 Experimental Programme**

134

135 **2.1 Materials and mix designs**

136 **2.1.1 Materials**

137

138 A Portland limestone cement CEM II-52.5 N, in compliance with EN 197-1 [25] and containing
139 80-94% Portland cement clinker, 10 –15% limestone and 0-5% minor additional constituents,
140 was adopted as the primary binder in this study. Silica fume (SF) and fuel ash (FA) were also
141 used (10 wt.% for each) to improve particle packing (or filling) in the mixture [9] as well as to
142 reduce permeability and enhance concrete strength. Two types of high range water reducer
143 HRWR admixtures, plasticiser and superplasticiser, were also added to achieve the desired
144 workability. A water/binder (Portland cements + silica fume + fly ash) ratio of 0.35 was used
145 in all mixes.

146

147 The coarse aggregates were river gravel with particle sizes of 5/10 mm and 10/20 mm, specific
148 gravity (SG) of 2.65 and water absorption (A) of 1.2%. The fine aggregates were river sand
149 with particles sizes of 0/5 mm, SG of 2.64 and A of 0.5%.

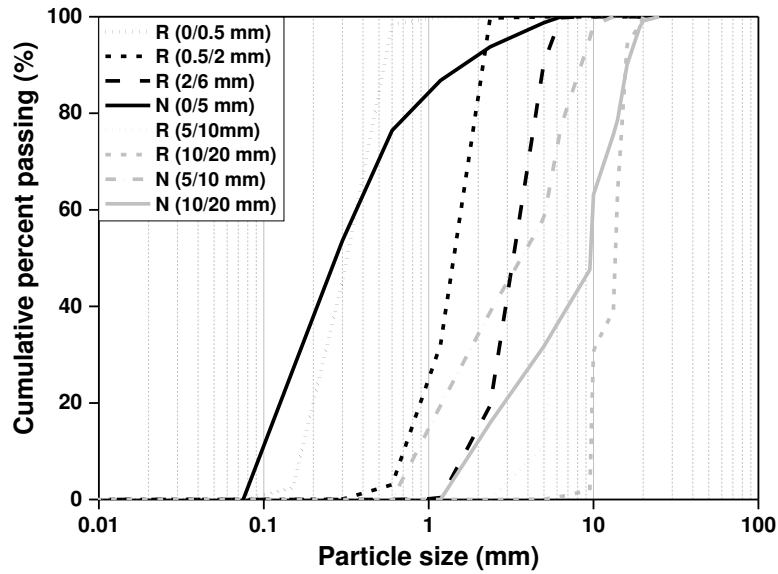
150

151 The rubber aggregates were recovered by the mechanical shredding of vehicular tyres. Rubber
152 particles were sourced in the following size ranges: 0/0.5 mm, 0.5/2 mm and 2/6 mm, 5/10
153 mm, and 10/20 mm. A relative density of 0.8 (measured using a representative volume of
154 rubber) was used for the rubber to determine the appropriate replacement by volume. Fig. 1
155 shows the particles size distribution for the used natural (N) and rubber (R) aggregates,
156 obtained according to ASTM C136 [26].

157

158 A blend of two different types of steel fibres were used: 1) undulated MSF, and b) cleaned and
159 screened recycled tyre steel fibres (RTSF). The physical and mechanical properties of both
160 types of steel fibre are shown in Table 1.

161



162
163 **Fig. 1** Particle size distributions for natural aggregates and rubber particles

164
165 **Table 1.** Physical and mechanical properties of steel fibres

Fibre type	Length (mm)	Diameter (mm)	Density (g/cm ³)	Tensile strength MPa
MSF	55	0.8	7.8	1100
RTSF	15-45 (> 60% by mass)	<0.3	7.8	2000

166
167 **2.1.2 Concrete mix designs**

168
169 An optimized conventional concrete mix design [9] with target cylinder compressive strength
170 of 60 MPa at 28 days of curing, typically used in bridge piers for XD3 exposure class, was
171 adopted in this study. It was confirmed by the authors in a previous study [1] that this mix
172 design suites the replacement up to 60% of WTR and does not cause much degradation in
173 concrete fresh properties, yet maintaining a mechanical performance suitable for pavement
174 construction.

175
176 The key parameters examined experimentally are: (i) the content of rubber (0%, 30% and 60%)
177 replacing both fine and coarse aggregates by volume, (ii) the content of fibres (0 or a blend of
178 20 kg/m³ MSF + 20 kg/m³ RTSF), (iii) the curing conditions (mist room or 3% NaCl), (iv) the
179 age of testing (28, 90, 150 or 300 days).

181 Table 2 shows the rubber replacement ratios and fibre contents of the four mixes examined in
 182 this study. The mix nomenclature is described below: Each mix name follows the format NM,
 183 where N stands for the percentage of aggregate replacement (0 – conventional concrete with
 184 no rubber replacement, 30 or 60%), whilst M shows information about the reinforcement; P
 185 stands for plain concrete without fibres and BF stands for blended fibre mixes consisting 20
 186 kg/m³ of MSF and 20 kg/m³ of RTSF). For example, 60BF mix contains 60% rubber
 187 replacement and contains both MSF (20 kg/m³) and RTSF (20 kg/m³). Table 3 presents the
 188 concrete mix designs per m³ of concrete.

189

Table 2. Concrete mix ID and variables

Concrete mixes ID	% Rubber replacing aggregates by volume		MSF (kg/m ³)	RTSF (kg/m ³)
	Fine	Coarse		
0P	0	0	0	0
0BF	0	0	20	20
30BF	30	30	20	20
60BF	60	60	20	20

190

191

Table 3. Mixes proportions for 1 m³ of fresh concrete

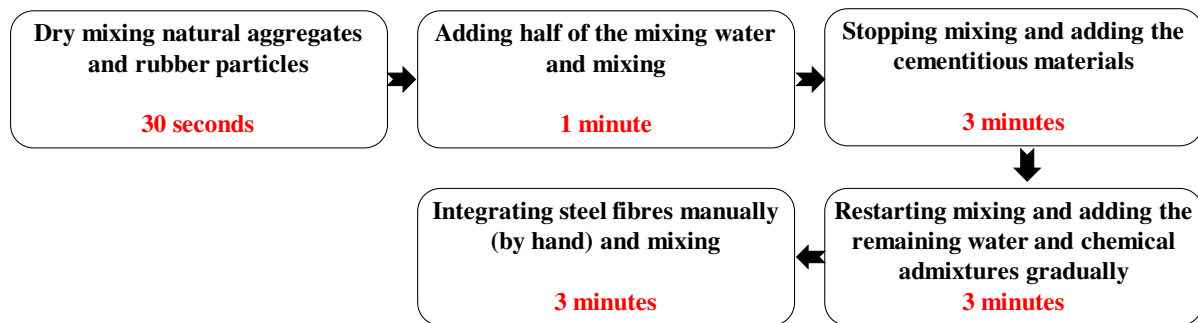
Components	Concrete mixes			
	0P	0BF	30BF	60BF
CEM II (kg/m ³)	340	340	340	340
SF (kg/m ³)	42.5	42.5	42.5	42.5
FA (kg/m ³)	42.5	42.5	42.5	42.5
Water (l/m ³)	150	150	150	150
Plasticiser (l/m ³)	2.5	2.5	3.25	4.25
Superplasticiser (l/m ³)	5.1	5.1	5.1	5.1
Natural aggregates				
0/5 mm (kg/m ³)	820	820	574	328
5/10 mm (kg/m ³)	364	364	254	146
10/20 mm (kg/m ³)	637	637	446	255
Rubber				
0/0.5 mm (kg/m ³)	0	0	16.5	33
0.5/2 mm (kg/m ³)	0	0	24.8	49.6
2/6 mm (kg/m ³)	0	0	33	66
5/10 mm (kg/m ³)	0	0	33	66
10/20 mm (kg/m ³)	0	0	57.7	115.4
Fibres				
MSF (kg/m ³)	0	20	20	20
RTSF (kg/m ³)	0	20	20	20

192 **2.1.3 Mixing, casting and curing procedure**

193

194 Due to the limited capacity of the pan mixer used, each mix was cast in three batches. The
195 concrete constituents were mixed according to the sequence shown in Fig. 2.

196



197

198

Fig. 2 Sequence of mixing

199

200 Concrete was cast in two layers (according to EN 12390-2) [27] and vibrated on a shaking table
201 (25s per layer). The fresh concrete was covered with plastic sheets and left under standard
202 laboratory conditions ($20\text{ }^{\circ}\text{C} \pm 2$ and $50 \pm 5\%$ relative humidity (RH)) for 48 h. The specimens
203 were then demoulded and stored in a mist room ($21\text{ }^{\circ}\text{C} \pm 2$ and $95 \pm 5\%$ RH) to cure for 28
204 days. Following a period of 21 days, the 150 x 300 mm and 100 x 200 mm cylinders were
205 removed from the mist room and sliced up, parallel to the trowelled surface, into five shorter
206 cylinders (150 x 50 mm each) and two shorter cylinders (100 x 100 mm each), respectively.
207 All concrete slices were placed back in the mist room until the end of mist curing (28 days).

208

209 **2.2 Testing methods**

210 **2.2.1 Fresh state properties**

211

212 Fresh concrete properties were assessed in terms of slump, air content and fresh density
213 according to EN 12350-2 [28], EN 12350-7 [29], and EN 12350-6 [30], respectively.

214

215

216

217

218 **2.2.2 Mechanical strength tests**

219

220 Compression and flexural tests were performed on all of the specimens at the end of the drying
221 period (4 days after removal from the mist room or NaCl solution). Three specimens were
222 tested for each mix and environmental conditioning.

223 The Uniaxial compression tests were performed on concrete cubes (100 x 100 mm) according
224 to EN 12390-3:2009 [31] at a loading rate of 0.4 MPa/s. Three-point bending tests were
225 performed on prisms (100 x 100 x 500 mm) with 300 mm span, using an electromagnetic
226 universal testing machine and a set-up similar to that suggested by RILEM [32]. A day before
227 testing, a notch (5 mm thick and 15 mm deep) was sawn at the mid-span of the bottom side of
228 each prism to force the crack to open at mid-span and a clip gauge was mounted across the
229 notch (gauge length 5 mm) to measure the crack mouth opening displacement (CMOD) and
230 control the test. All tests were CMOD-controlled at a constant rate of 0.05 mm/min for CMOD
231 from 0 to 0.1 mm, 0.2 mm/min for CMOD ranging from 0.1 to 4 mm and 0.8 mm/min for
232 CMOD from 4 mm to 8 mm. The net mid-span deflection was measured using two linear
233 variable differential transformers (LVDTs) mounted at the middle of a yoke (one on each side),
234 as suggested by JSCE [33].

235

236 **2.2.3 Gas and water permeability**

237

238 Cylinders of 150 x 50 mm were tested after 28 and 300 days of curing in a mist room. Prior to
239 testing, specimens were pre-conditioned (oven dried) to remove water from the concrete pores.
240 Rather than using the standardised preconditioning temperature of 105 °C, which causes
241 cracking, mainly due to the removal of interlayer and bound water present in the hydration
242 products [34-36], a temperature of 80 °C was initially used on the 28 day specimens in an
243 attempt to minimise cracking. Constant mass was achieved after 7 days of drying, but SFRRuC
244 specimens exhibited cracks of average width around 0.065 mm which can be attributed to the
245 different coefficient of thermal expansion of the rubber aggregates. Although the values
246 obtained from the cracked specimens are not expected to reflect the real permeability of
247 SFRRuC, these values are still reported in the following and commented upon.

248

249

250 To minimise cracking induced during preconditioning, a reduced temperature of 40 °C was
251 adopted for treating the 300 day specimens. As expected, it took much longer to reach constant
252 mass (between 30 to 40 days). Considering the extended time required to dry the concretes, it
253 was decided not to expose the specimens to wet-dry chlorides exposure, as a direct correlation
254 between gas and water permeability measurement and chloride penetrability would not be fair,
255 as the concretes would have completely different ages by the time each of test was conducted.

256

257 Oxygen permeability tests were performed on three 150 x 50 mm cylinders per mix following
258 the procedure recommended by RILEM TC 116-PCD-C [37], also called “Cembureau
259 method”, using 1 Bar of oxygen gas above the atmospheric pressure. Sorptivity measurements
260 were conducted in two cylinders of similar size following the recommendation of the EN 13057
261 [38]. After performing the sorptivity test, the same cylinders were used to measure the volume
262 of permeable voids (VPV) based on the procedures of ASTM C1202 [39], also called the
263 vacuum saturation method.

264

265 **2.2.4 Chloride permeability and corrosion**

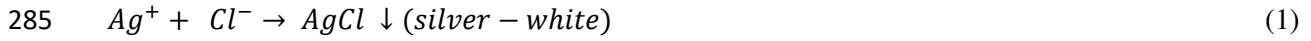
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267 After 28 days of mist curing, chloride permeability was evaluated in two different exposure
268 conditions: (i) fully immersing cylinders (100 x 100 mm) in a 3% NaCl solution (placed in
269 sealed plastic containers in the mist room until testing); and (ii) wet-dry cycles (accelerated
270 chloride corrosion simulation), by immersion in a 3% NaCl for 4 days followed by a drying
271 period in standard laboratory environmental conditions for 3 days. Prisms (100 x 100 x 500
272 mm), cubes (100 mm) and cylinders (100 x 100 mm) were kept apart by at least 10 mm using
273 a specially designed frame. All specimens were preconditioned for ion chloride penetration
274 tests using the unidirectional non-steady state chloride diffusion-immersion method described
275 in EN 12390-11 [40].

276

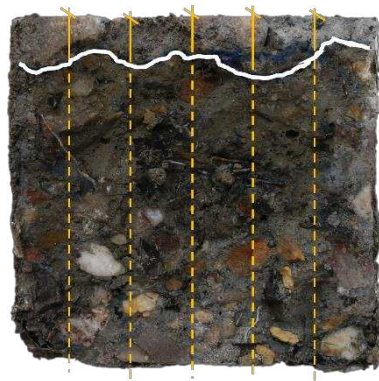
277 After preconditioning for 90, 150 and 300 days in NaCl solution, two 100 x 100 mm cylinders
278 per mix per condition were split into two halves at mid-point according to the colorimetric
279 method [41, 42]. From each freshly split cylinder, the piece with the split section nearly
280 perpendicular to the exposed surface was chosen for the penetration depth measurement, and
281 was immediately sprayed with 0.1 N silver nitrate (AgNO₃) solution. Silver nitrate reacts with

282 the chloride ion present in the hardened matrix to form white AgCl (white in colour); whereas
 283 at greater depth, silver nitrate reacts with the hydroxyl ion to form Ag₂O (dark brown), as
 284 described in formulas (1) and (2) [43].



287

288 Chloride penetration depth was indicated by the boundary colour change within 10-15 minutes
 289 after spraying. The chloride penetration depth was marked at the colour change boundary and
 290 the depth was recorded as the average distance, taken from five sections (Fig. 3). The cylinder
 291 that registered the maximum average depth was selected for analysis and used to drill out binder
 292 powder from the surface and colour change boundary to determine acid-soluble chloride
 293 concentrations.



294

295 **Fig. 3** Representative SFFRuC freshly split, sprayed and marked for determination of
 296 chloride penetration depth

297

298 The acid-soluble (total) chloride concentration was measured at the 134.724 emission line
 299 using a Spectro-Ciros-Vision ICP-OES instrument which was calibrated with standards of
 300 known chloride concentrations made up in 20% nitric acid. The apparent chloride diffusion
 301 coefficients (D_{app}) were roughly estimated using the re-arrange error function solution of Fick's
 302 second law of diffusion shown in Eq. (3) [41, 42]:

303
$$D_{app} = \left(\frac{x}{2 - \operatorname{erf}^{-1}\left(1 - \frac{C_x}{C_s}\right)\sqrt{t}} \right)^2$$
 (3)

304 where x is the maximum average distance of colour change boundary from the concrete
 305 surface; C_x is the total chloride concentration at the colour change boundary at any time t; C_s
 306 is the total chloride concentration at the surface.

307 It should be noted that the D_{app} obtained using the traditional profile method specified in EN
308 12390-11 [40] is more accurate than that of colorimetric method. This is due to the fact that
309 the measurements and calculations of chloride concentration using colorimetric method can
310 be influenced by many factors including concrete alkalinity, the amount and concentration of
311 the sprayed $AgNO_3$ solution, pore solution volume of concrete, sampling method as well as
312 method used for measuring the chloride content [42]. However, the colorimetric method is a
313 quick, simple and relevant method for assessing the kinetics of chloride penetration in
314 concrete specimens when non-steady state chloride diffusion test is carried out in laboratory
315 condition. Many studies [41, 42, 44] have proven its feasibility to determine the average
316 chloride penetration depth (the depth associated with the assumed “critical” chloride
317 concentration with respect to corrosion risk $\sim 0.4\%$ by unit mass of binder) and assess the
318 D_{app} .

319 **3 Results and Discussion**

320

321 **3.1 Fresh state properties**

322

323 The slump, air content and fresh density of the concretes studied are presented in Table 4. The
324 addition of fibres reduced the workability of the concrete, and this effect is more notable with
325 the inclusion of both fibres and rubber in the SFRRuC mixes. For mixes 0BF, 30BF and 60BF,
326 the slump drops by 5%, 13% and 56%, respectively, when compared with the plain concrete,
327 0P. The tendency of steel fibres to agglomerate contributed to the slump reduction. The
328 decrease in slump as a result of adding rubber particles can be explained by the higher level of
329 inter-particle friction between rubber particles and the other concrete constituents (owing to
330 the rough surface texture and high coefficient of friction of rubber particles) [1, 4, 7-9].
331 Nevertheless, all mixes satisfy the slump requirements described in pavement design standard
332 EN 13877-1 [19]. Moreover, similar to the finding in Ref. [9], no signs of segregation, bleeding
333 or excessive “balling” were observed in any of the mixes.

334

335

336

337

338

339 **Table 4.** Fresh state properties of SFRRuC evaluated. Values in parenthesis correspond to
 340 one standard deviation of three measurements

Properties	Concrete mix			
	0P	0BF	30BF	60BF
Slump (mm)	223 (14)	212 (10)	193 (15)	98 (25)
Air content (%)	1.3 (0.5)	1.4 (0.1)	3.4 (1.1)	3.2 (0.2)
Fresh density (kg/m ³)	2405 (5)	2424 (9)	2124 (6)	1859 (4)

341

342 The addition of fibres alone did not induce notable changes in the air content of the concrete.
 343 The substitution of natural aggregate by rubber (mixes 30BF and 60 BF) in SFRC, however,
 344 significantly increased the air content of the fresh concrete by more than 100%. The rough and
 345 hydrophobic nature of rubber particles tends to repel water and therefore increases the amount
 346 of entrapped air in the mix. The increased friction between fibres and rubber also cause fibres
 347 to agglomerate and trap more air [1, 45].

348

349 The fresh density of the SFRC mix, 0BF, is slightly higher than that of the plain concrete mix,
 350 0P, (Table 1) owing to the high specific gravity of the added fibres. The density of the fresh
 351 mix is significantly reduced when rubber particles are used to replace natural aggregates as a
 352 result of their lower density (Section 2.1.1). For the SFRRuC, 30BF and 60BF, the density
 353 decreases by 13% and 30%, respectively, compared to the plain concrete.

354

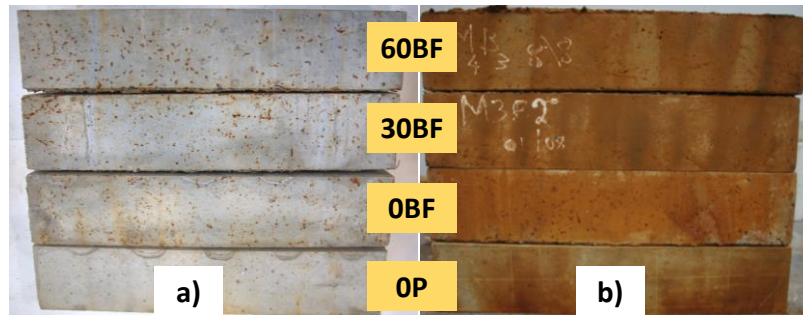
355 **3.2 Effect of chloride exposure in mechanical performance**

356 **3.2.1 Visual inspection**

357

358 Figs. 4 a) and b) show the appearance of specimens after 150 and 300 day exposure to
 359 accelerated chloride corrosion conditions, respectively. Prior to chloride exposure, there were
 360 no signs of rust on the concrete surface, which implies that the fibres were protected by a thin
 361 layer of cement paste. At the end of 150 days of wet-dry chloride exposure, however, the
 362 specimens showed minor signs of superficial rust (Fig. 4a) in regions where the fibres were
 363 near the concrete surface. A large amount of rust is observed on the surface of the specimens
 364 exposed for 300 days (Fig. 4b), mainly as a consequence of the corrosion of the steel frame

365 used to hold the specimens. Nevertheless, at all periods of the accelerated chloride corrosion
366 exposure, no sign of deterioration or cracks were observed on the concretes.



367

368 **Fig. 4** SFRRuC specimens after a) 150 days, and b) 300 days of wet-dry chloride exposure

369

370 Fig. 5 shows the internal appearance of a SFRRuC splitted cube, 30BF, after 300 days of wet-
371 dry chloride exposure. Despite the external rusty appearance (Fig. 4b), no evidence of rust is
372 observed on the fibres embedded in these concretes. This indicates that steel reinforcement did
373 not corrode to any significant extent under the wet-dry chloride exposure. This performance
374 may be explained by the reduced chloride permeability of the concretes, as it will be discussed
375 in detail in the following sections, and the discrete nature of steel fibres embedded in the matrix,
376 generating smaller potential differences along the steel surface and reduced cathode/anode
377 ratios compared to conventional steel rebars [24].



378

379 **Fig. 5** Section through a SFRRuC specimen after 300 days of wet-dry chloride exposure

380

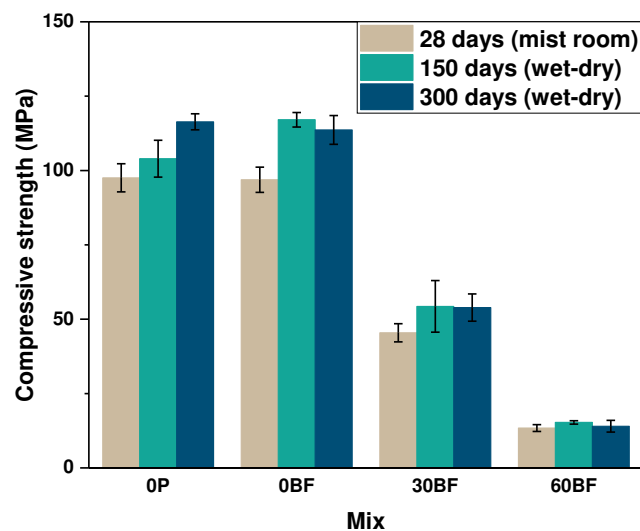
381 In addition, the dense and uniform fibre-matrix interfacial transition zone (ITZ), composed
382 mainly of rich segregated lime, acts as a high alkalinity barrier and protects fibres in the bulk
383 SFRC against chloride and oxygen ingress [24].

384 3.3 Compressive strength

385

386 The influence of wet-dry chloride exposure on the compressive strength of SFRRuC is
387 presented in Fig. 6. Error bars represent one standard deviation of three measurements.
388 Comparable compressive strength values are seen for the plain concrete, 0P, and the SFRC,
389 0BF, before and after chloride exposure. As expected, the replacement of natural aggregates
390 with rubber particles led to a substantial reduction in compressive strength. Prior to chloride
391 exposure, reductions of up to 54% and 86% in compressive strength, respectively, with respect
392 to 0BF. The loss in compressive strength is mainly due to the lower stiffness and higher Poisson
393 ratio of rubber in comparison to that of natural aggregates. The weak adhesion between cement
394 paste and rubber particles may also contribute to the strength degradation, as discussed by the
395 authors in Ref. [1] and Khaloo et al. in Ref. [12].

396



397

398 **Fig. 6** Compressive strength of concretes assessed before and after 150 and 300 days of wet-
399 dry chloride exposure

400 All mixes after 150 and 300 days of wet-dry chloride exposure present a slightly increased
401 compressive strength, compared to the 28-day values measured prior to the chloride exposure.
402 The increase in strength is attributed to the continuous hydration of the cementitious paste over
403 the period of exposure, owing to the high amount of pozzolanic materials used for replacing
404 Portland cement in all the concrete mixes.

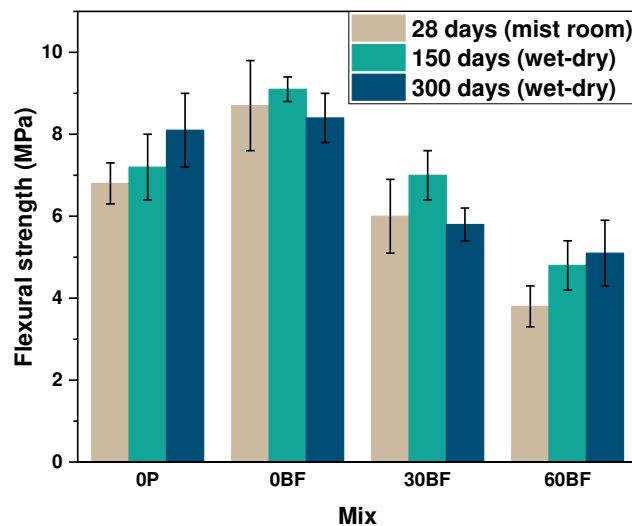
405

406

3.4 Flexural behaviour

408

409 The mean values of flexural strength at 28 days and after 150 and 300 days of wet-dry chloride
410 exposure are presented in Fig. 7. Error bars represent one standard deviation of three
411 measurements. The addition of fibres to plain concrete, mix 0BF, enhances the 28-day flexural
412 strength by 28%, compared to 0P. The partial replacement of natural aggregates by rubber
413 particles reduced the flexural strength of the tested concretes, but to a lesser extent than the
414 compressive strength (Fig. 6). The 28-day flexural strength reduction of SFRRuC mixes, 30BF
415 and 60BF, in comparison to 0BF is 31% and 56%, respectively. The contribution of steel fibres
416 in enhancing the flexural strength was anticipated as the thin fibres, RTSF, tend to “sew” the
417 micro-cracks that develop in the matrix during loading, while the thick fibres, MSF, tend to
418 control the propagation of wider cracks and redistribute stresses [1, 46].



419

420 **Fig. 7** Flexural strength of concretes assessed before and after 150 and 300 days of wet-dry
421 chloride exposure

422

423 For all mixes, the flexural strength results are higher at the end of 150 days of wet-dry chloride
424 exposure than those of 28-day mist cured specimens, as a consequence of the ongoing hydration
425 of the cement in the concretes.

426

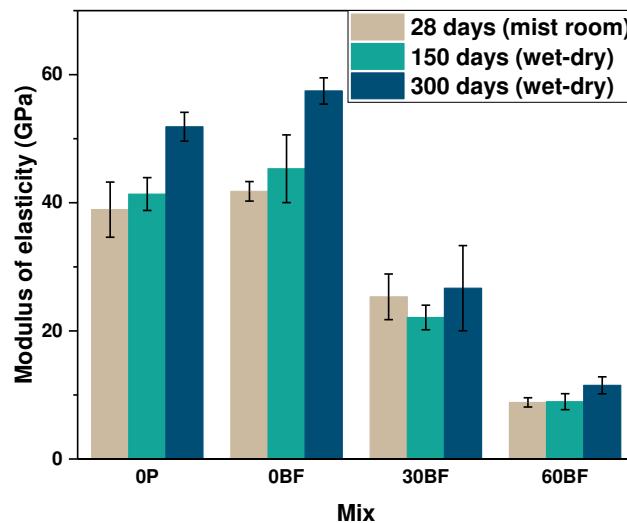
427 No clear trend can be identified in the flexural strength values of the specimens at the end of
428 300 days of wet-dry cycles. While 0P and 60BF mixes present higher flexural strength values,
429 compared to those of 150 days of wet-dry cycles, the flexural strength values of 0BF and 30BF

430 mixes are even lower than their respective strength at 28-days. This variation may be the result
431 of the high natural variability in these specimens. It is unlikely that the flexural strength of 0BF
432 and 30BF specimens was reduced due corrosion attack, as evidence of rust in the fibres
433 embedded in these specimens was not observed (see Section 3.2.1).

434

435 Fig. 8 shows the average elastic modulus obtained from three prisms per mix over the three
436 periods of testing. Error bars represent one standard deviation of three measurements. Flexural
437 elastic modulus was determined based on the theory elastic deflection and by using the secant
438 modulus of the load-deflection curves (from 0 to 30% of the peak load).

439



440

441 **Fig. 8** Elastic modulus of all tested concrete specimens before and after 150 and 300 days of
442 wet-dry chloride exposure

443

444 The addition of 40 kg/m³ of fibres did not affect the elastic modulus of concrete by much.
445 However, a notable decrease in the elastic modulus is observed from the replacement of natural
446 aggregates with rubber particles; reductions up to 38% for 30BF and 79% for 60BF compared
447 to 0BF. The reduction in the elastic modulus is mainly caused by the low stiffness of the rubber
448 particles and to a lower degree by the high air content in these concretes, as discussed in section
449 3.1. The low elastic modulus of 60BF, however, is still comparable to that of typical of flexible
450 pavements, i.e. around 8 GPa [47].

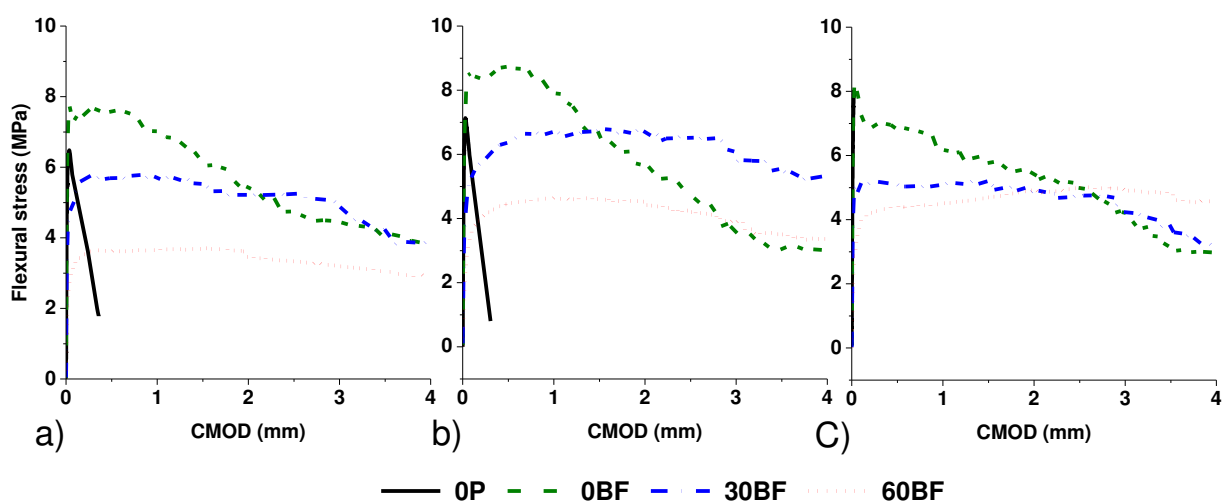
451

452 A general increase in the average elastic modulus of all mixes after 150 and 300 days of wet-
 453 dry cycles was identified, compared to 28-day compressive strength. Although enhancement
 454 in elastic modulus was expected as the compressive strength increases with time, the large
 455 increase seen for normal concrete after 300 days can be partly attributed to variability between
 456 the three prisms which came from three different batches, and partly to the fact that the elastic
 457 modulus is determined indirectly from deflections.

458

459 Fig. 9 presents the average flexural stress-CMOD curves registered in all prisms over the three
 460 periods of testing. The sudden stress loss after the peak load for the plain concrete mixes
 461 indicates their brittle behaviour in tension. On the other hand, all SFRC and SFRRuC mixes
 462 show enhanced post-cracking load bearing capacity and significant energy absorption. This is
 463 a result of the fibres bridging the cracks and controlling their propagation even after the peak
 464 load, dissipating energy through pull-out and mobilising and fracturing a larger volume of
 465 concrete. It is also evident that the post-peak energy absorption behaviour of the SFRC and
 466 SFRRuC specimens is not reduced after exposure to wet-dry cycles. This confirms that steel
 467 reinforcement did not corrode to any significant extent under the wet-dry chloride exposure
 468 adopted in this study.

469



470

471 **Fig. 9** Flexural stress-CMOD curves of the tested concrete specimens a) before, and after
 472 wet-dry chlorides exposure for b) 150 and c) 300 days

473

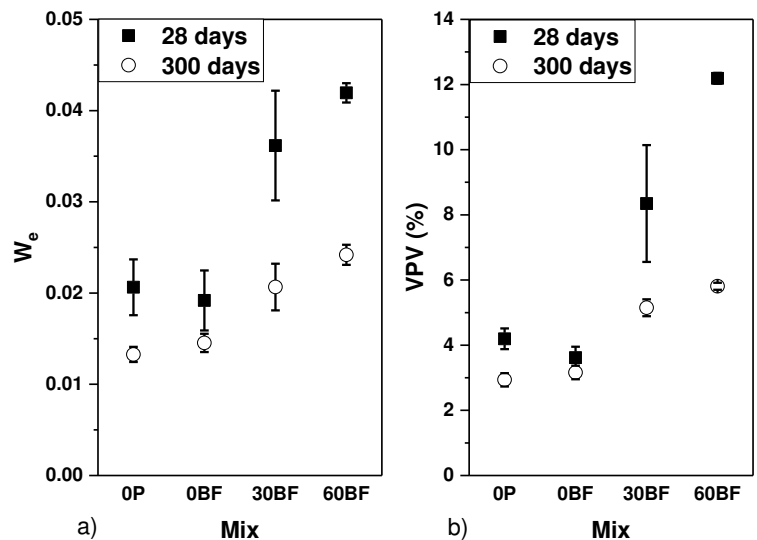
474

475 **3.5 Transport properties**

476 **3.5.1 Evaporable moisture and volume of permeable voids**

477

478 The loss of mass due to water evaporation after preconditioning the specimens at 80 °C (28 day
479 cured) and 40 °C (300 day cured) was determined as the ratio between the total amount of
480 evaporated water and the dry mass of the specimen. The mean values (average of five
481 measurements) of evaporable moisture concentrations results, W_e , are shown in Fig. 10a, and
482 the volume of permeable voids, VPV, are presented in Fig. 10b. Error bars correspond to one
483 standard deviation of five measurements for W_e and two measurements for VPV. A direct
484 relationship between the W_e and VPV is observed for all the tested concretes, independently of
485 the preconditioning temperature and curing age, where higher values of evaporated water are
486 obtained in more porous concretes.



487

488 **Figs. 10** a) Evaporable moisture, and b) volume of permeable voids of all tested concretes

489

490 The addition of fibres generally results in reduced shrinkage cracking and in the establishment
491 of more tortuous and disconnected pore network [48], thus reducing VPV. For 28 days cured
492 samples, OBF mix exhibits, as expected, a decrease in VPV, though marginal and within the
493 observed experimental error (average of 13%), whereas the SFRRuC mixes exhibit a large
494 increase in VPV. This can be attributed to the rubber particles, the rough surface and
495 hydrophobic nature of which can help trap air on their surface and make their interface more
496 porous and highly absorptive to water [49, 50].

497

498 Minor changes in the VPV values are observed in concretes 0P and 0BF for the two curing
499 conditions. This is unexpected as more mature concretes typically have lower permeability, but
500 it may be the result of the already high quality of the concrete matrix which makes it dense to
501 start with. In concrete composites with rubber aggregates, 30BF and 60BF, extended curing
502 times reduce the VPV values by 24% and 93%, respectively. It should be pointed out that
503 SFRRuC specimens exhibited severe cracking upon preconditioning at 80°C, which increased
504 their permeability and caused the high VPV results recorded.

505

506 Baroghel-Bouny [51] proposed a classification of the durability of reinforced concrete
507 structures based on "universal" durability indicators determined on a broad range of concretes
508 cured in water. According to the proposed system, concrete mixes with VPV between 6-9%
509 are categorised as highly durable. The VPV values of all the mixes examined in this study are
510 lower than 6%, after 300 days of curing, even when rubber particles are used as partial
511 aggregate replacement, which puts them in the highly durable category.

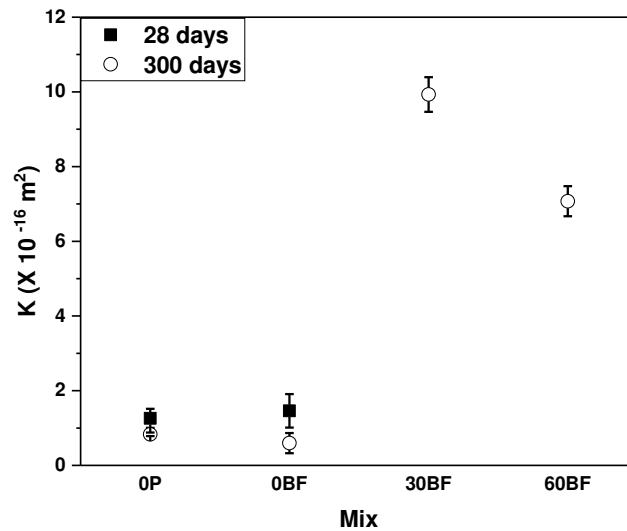
512

513 **3.5.2 Oxygen permeability**

514

515 The oxygen permeability is not only influenced by the overall porosity, but also by the
516 proportion of continuity of larger pores where most of the flow will occur [52, 53]. Fig. 11
517 shows the oxygen permeability results for 28 day cured specimens (preconditioned at 80 °C)
518 and 300 day cured specimens (preconditioned at 40 °C), expressed as the intrinsic permeability
519 'K'. Error bars correspond to one standard deviation of three measurements. Due to the
520 extremely high permeability of the specimens resulting from the surface cracking upon
521 preconditioning at 80°C, the gas permeability for the 28 day cured specimens with rubber
522 particles could not be determined (the oxygen found its way out very quickly).

523



524
525 **Fig. 11** Oxygen permeability results for all tested mixes

526

527 Considering the standard deviations as well as the experimental errors for both 28 and 300 days
528 results, the oxygen permeability values for SFRC specimens, 0BF, are comparable with those
529 of plain concrete, 0P, indicating that the fibres did not modify much the permeability of the
530 concretes tested. SFRRuC specimens, 30BF and 60BF, on the other hand, show significantly
531 higher permeability values, up to 12 and 8.5 times respectively, with respect to the plain
532 concrete mix, 0P. These concretes presented comparable air contents (Table 4) and VPV values
533 (Fig 10b), despite the differences in rubber content. The increased oxygen permeability
534 recorded for the assessed specimens may be attributed to the compressibility of rubber particles
535 when pressure is applied. As rubber deforms, the oxygen gas can more easily find its way
536 through the specimen and around the rubber particles. If that is the case, then gas permeability
537 may not be the best way to determine the permeability of RuC.

538

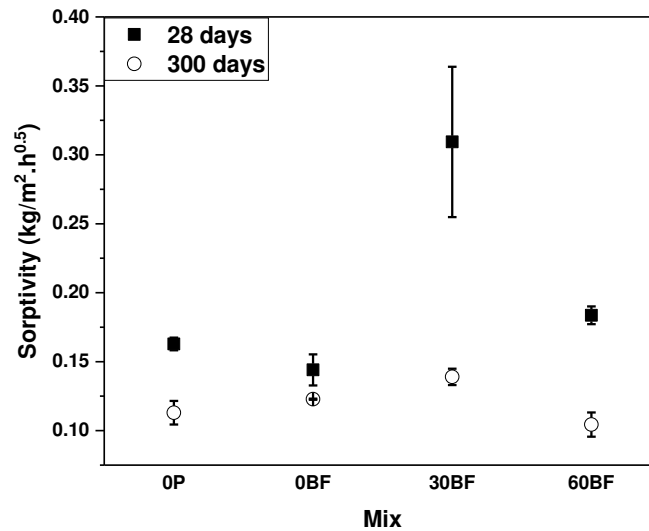
539 **3.5.3 Water sorptivity**

540

541 The main mechanism that governs sorptivity is capillary suction of water when a specimen is
542 partially saturated [52, 54]. The difference in pressure causes the movement of water front
543 through a porous material. Hence, sorptivity is derived by measuring the slope of the amount
544 of water uptake per unit area as a function of the square root of time. The sorptivity results
545 measured for 28 and 300 days cured specimens are shown in Fig. 12. Error bars correspond to
546 one standard deviation of two measurements

547

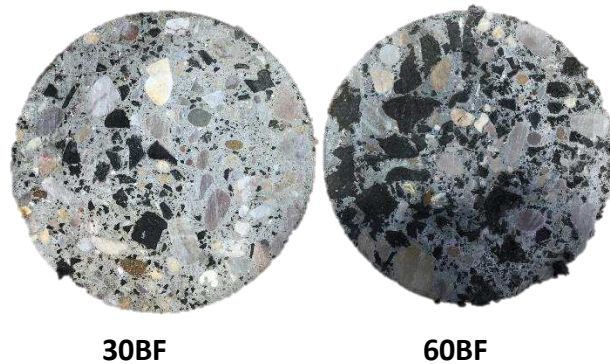
548 For the 28 day cured samples, the addition of fibres to plain concrete, mix 0BF, causes marginal
 549 decrease in the sorptivity value, with an average of 12% with respect to the plain concrete mix,
 550 0P. For 300 day, however, 0BF specimens record marginally higher sorptivity values, with an
 551 average of 9%, than that of 0P specimens. These results are in good agreement with the VPV
 552 values (Fig 10.b) confirming that the extended curing time had only a minor effect on the
 553 sorptivity and on the already high quality of the concrete matrix evaluated in this study.



554
 555 **Fig. 12** Sorptivity values of all tested mixes
 556

557 The 28 days sorptivity results of the SFRRuC specimens show different trends. While the 30BF
 558 specimens record the highest sorptivity values, an average 90% higher than 0P mix, 60BF
 559 specimens shows slightly higher sorptivity value, average of 13% compared to 0P. Unlike VPV
 560 and chloride penetration tests, where the specimens are fully immersed for a long period of
 561 time, specimens evaluated for sorptivity were partially immersed in water (2 mm depth from
 562 the trowelled surface) and the water uptake measurements were recorded during the first 24
 563 hours of first immersion, as specified in EN 13057 [38]. Therefore, the quality of the concrete
 564 surface that is in contact with water plays a major role in imbibing the water through the fine
 565 capillary pores. As it has been reported previously [45, 50], the rough texture of rubber particles
 566 cause both fine and coarse pores to increase with increasing rubber content. Hence, in addition
 567 to the surface cracking upon preconditioning at 80°C, the authors hypothesised that the high
 568 values of sorptivity for the 30BF specimens may be attributed to the large amount of fine pores
 569 which dominated the initial sorptivity behaviour. On the other hand, the high amount of large
 570 coarse rubber particles in the 60BF specimens located on the concrete surface in contact with
 571 water (see Fig. 13) could have limited the water absorption rate (owing to the non-sorptive

572 nature of rubber particles) and dominated the initial sorptivity behaviour. To confirm this, the
573 specimens were left partially immersed for a longer period (15 days) and the water uptake was
574 measured. Similar to VPV, it was observed that the sorptivity of the concrete is higher with
575 increasing the rubber content. This suggests that when water imbibed through the contact
576 surface in 60BF, the amount of fine pores also dominated the water ingress into the sample
577 consistent with the differences in pore network between the surface and the core of the
578 specimens.



579

580

581 **Fig. 13** Cross section view of the SFRRuC specimens used for the sorptivity test

582

583 Extending the curing time for 30BF and 60BF, i.e. 300 days, cause significant reduction in the
584 sorptivity values, with average of 67% and 20%, respectively, when compared with the values
585 registered for concretes cured for 28 days. This is mainly related to the absence of surface
586 cracking upon preconditioning at 40°C which results in more realistic sorptivity values.

587

588 When calculating the concrete sorptivity using the depth penetration approach [52, 55, 56], all
589 mixes examined here record sorptivity values less than $6 \text{ mm/h}^{0.5}$, which places them in the
590 excellent durability class based on the durability index proposed by Alexander et al. [57] and
591 adopted in Refs. [52, 55, 56].

592

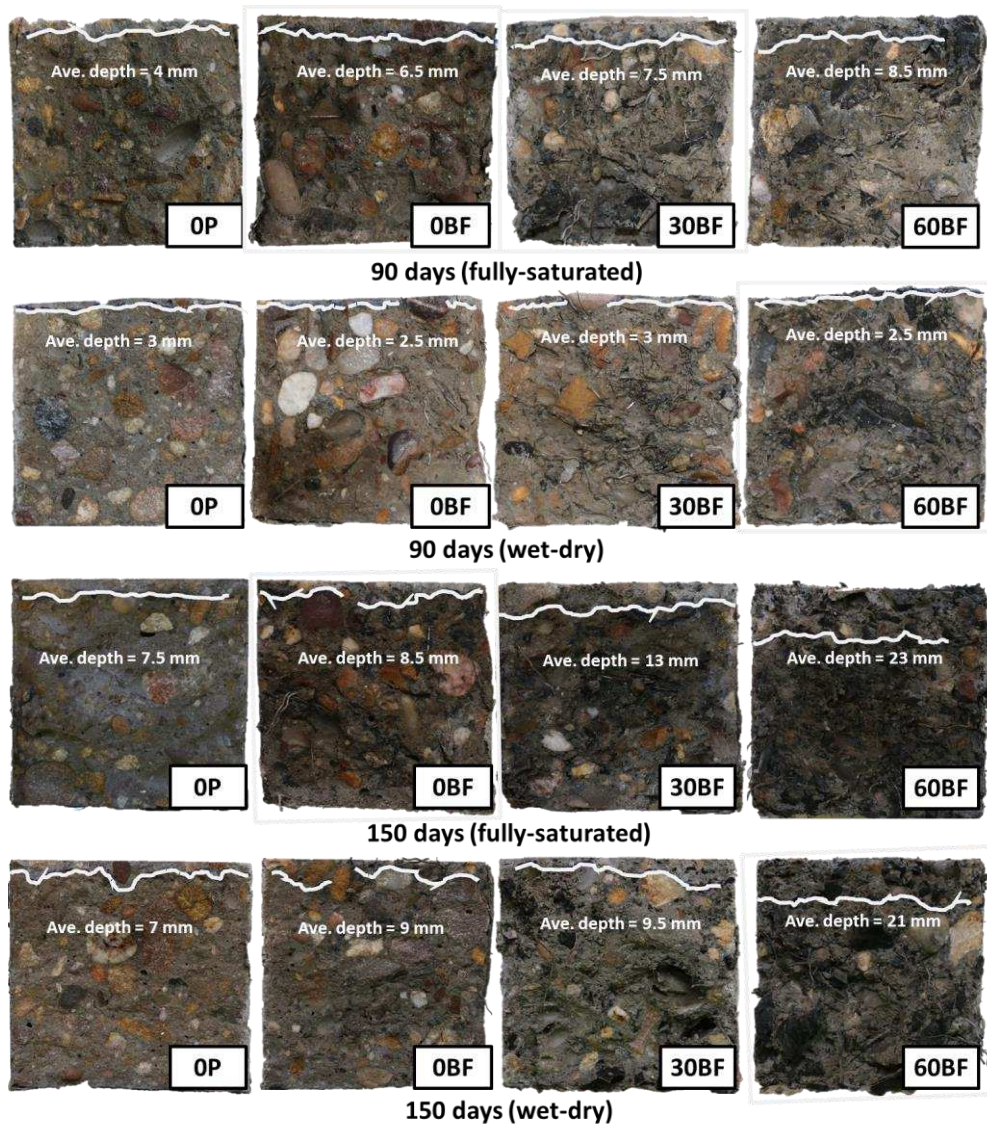
593 **3.6. Chloride ion penetration**

594

595 Fig. 14 shows the chloride penetration zone after spraying 0.1 N AgNO_3 at the end of 90 and
596 150 days of chloride exposure in fully-saturated and wet-dry conditions. As the continuous
597 hydration of concrete specimens that contain high amount of silica fume gradually darken the

598 colour of the matrix (see Fig. 14), it was not possible to detect the penetration zone in any of
 599 the specimens exposed to chlorides for 300 days due to the similarity in colour between matrix
 600 and the rubber particles. This drawback of the colorimetric method for assessing chloride
 601 permeability in concretes containing blended cement and silica fume has also been previously
 602 reported [58].

603



604

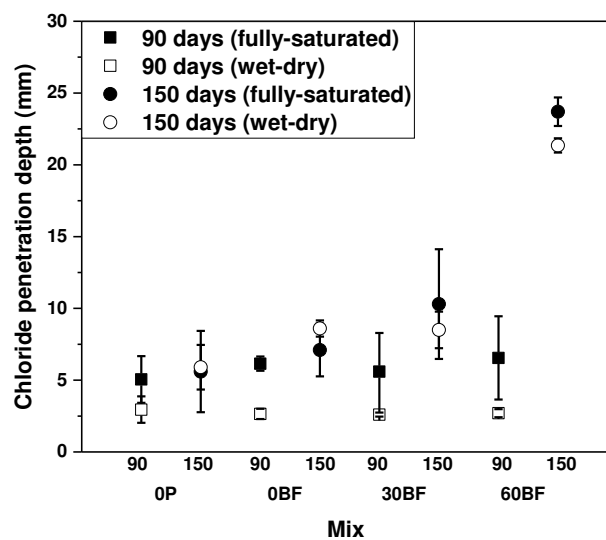
605 **Fig. 14** Chloride contaminated zone of all concrete mixes at the end of 90 and 150 days of
 606 chloride exposure in fully-saturated and wet-dry conditions

607

608 Fig. 15 shows a comparison between the average chloride penetration depths for all concrete
 609 specimens. Error bars correspond to one standard deviation of the average depth measured in
 610 two different specimens. For concretes exposed to wet-dry cycles, the chloride penetration

611 depth is in general lower than those of fully-saturated specimens. In fully-saturated specimens
 612 the chloride ingress is mainly governed by the diffusion mechanism. The process of chloride
 613 ingress into concrete exposed to wet-dry cycles is a combination of diffusion and absorption,
 614 as in partially saturated concretes the chloride solution is absorbed by capillary suction and
 615 concentrated by evaporation of water [59]. These results somehow contradict what has been
 616 reported for other blended cement concretes [59], where the wet-dry cycle exposure to
 617 chlorides typically leads to deeper chloride penetration compared to fully-saturated ones. The
 618 duration of the wet-dry cycles, and particularly the degree of dryness achieved, controls the
 619 extent of ingress of chlorides, as higher degrees of dryness facilitate deeper chloride penetration
 620 during subsequent wet cycles [60]. Due to the low permeability of these concretes, it seems the
 621 drying cycle was not sufficient to remove water beyond the concrete surface, hindering
 622 capillary sorption of chlorides rich solution into the concrete.

623



624

625 **Fig. 15** Chloride penetration depth for all concrete mixes assessed at the end of 90 and 150
 626 days of chloride exposure in fully-saturated and wet-dry conditions

627

628 The data presented in Fig. 15 also indicate that the chloride penetration depth at the end of 90
 629 days of exposure was small and comparable, being in the range of 5–7 mm for the fully-
 630 saturated specimens, and 2–3 mm for the wet-dry specimens. This suggests that up to 90 days
 631 of chloride exposure, the penetration rate was not aggravated by the addition of rubber. At the
 632 end of 150 days of chloride exposure, however, the depth of chloride penetration in both

633 conditions generally increased with rubber content. This is consistent with the higher values of
 634 VPV obtained for SFRRuC specimens (sections 3.5.1).

635

636 For practical purposes, due to the small chloride penetration depths at 90 days and difficulty in
 637 identifying chloride penetration depths at 300 days of chloride exposure, only specimens at 150
 638 days of exposure (in both conditions) were considered for the determination of total chloride
 639 concentration and apparent chloride diffusion coefficient. Table 5 presents the total chloride
 640 concentrations by weight of binder as well as the roughly estimated apparent chloride diffusion
 641 coefficient measured at the colour change boundary for all of the assessed concretes. The
 642 chloride concentrations for the plain concrete and SFRC mixes, 0P and 0BF, were less than 10
 643 ppm (i.e. the detection limit of the instrument used), hence it was not possible to detect the
 644 exact total chloride concentrations and then calculate the apparent diffusion coefficients for
 645 these mixes.

646

647 **Table 5.** Chloride concentration and the roughly estimated apparent chloride diffusion
 648 coefficient in concretes after 150 days of chlorides exposure

Mix	Maximum average chloride penetration depth, x (mm)		Chloride concentration at surface, C_s (wt% of binder)		Chloride concentration at colour change boundary, C_x (wt% of binder)		Apparent diffusion coefficient (10^{-12} m ² /s)	
	fully-saturated	wet-dry	fully-saturated	wet-dry	fully-saturated	wet-dry	fully-saturated	wet-dry
0P	7.6	7	0.159	0.640	<10 ppm	<10 ppm	-	-
0BF	8.58	9	0.339	0.248	<10 ppm	<10 ppm	-	-
30BF	13	9.5	1.752	2.229	0.109	0.234	1.87	1.33
60BF	23	21	1.398	2.858	0.151	0.157	7.90	4.62

649

650 SFRRuC mixes, 30BF and 60BF, present lower chloride concentrations values (at both
 651 conditions) than 0.4% by weight of cement, which is the most commonly assumed critical total
 652 chloride concentration value inducing corrosion [58, 61]. This indicates that even with the
 653 increased VPV and sorptivity caused by the replacement of natural aggregates with rubber
 654 particles (Section 3.5.1 and 3.5.3), the assessed concretes present high resistance to chloride
 655 penetration for 150 days of chloride exposure.

656

657 SFRRuC mixes, 30BF and 60BF, show an increase in the apparent chloride diffusion
658 coefficient at higher rubber contents, possibly due to their higher VPV and sorptivity. The
659 apparent chloride diffusion coefficients of the fully-saturated and wet-dry specimens are
660 comparable for the 30BF mixes, indicating that under the testing conditions used in this study,
661 the drying cycle had a negligible effect on chloride penetration. Similar results have been
662 identified in high quality Portland cement based concretes produced with silica fume, due to
663 their refined porosity requiring longer drying times to obtain a particular moisture content [59].
664 Moreover, Kim et al. [44] evaluated the D_{app} at colour change boundary, following colorimetric
665 method, for ordinary Portland concrete specimens made with 0.4 w/c ratio and immersed in
666 marine environment for 6 months. It was found that the D_{app} was around $1.7 (10^{-12} \text{ m}^2/\text{s})$, in
667 line with the values obtained here for 30BF. On the other hand, 60BF specimen in fully-
668 saturated condition registers almost twice the diffusion coefficient than that in wet-dry
669 condition. Nevertheless, with the apparent diffusion coefficients values observed here,
670 SFRRuC mixes can be considered as medium to highly durable concrete mixes according to
671 the durability indicators suggested in [51, 62].

672

673 For inspection purposes, the authors collected concrete samples at 50 mm depth from the
674 exposed surface from those specimens exposed to chloride for 300 days, in both conditions,
675 and the total chloride concentrations were measured. The total chloride concentrations for all
676 of the examined samples were less than 10 ppm. This confirms the good resistance to chloride
677 penetrability of all mixes.

678

679 **4 Conclusion**

680

681 This study examined the fresh, mechanical and transport properties as well as chloride
682 corrosion effects in SFRRuC due to exposure to a simulated marine environment. Natural
683 aggregates were partially replaced with waste tyre rubber particles and blends of MSF and
684 RTSF were used as internal steel reinforcement. The following can be concluded:

- 685 • The addition of fibres marginally decreases workability and increases air content and unit
686 weight. The substitution of rubber aggregates in SFRRuC mixes significantly reduces
687 workability and unit weight (due to the lower density of rubber) and increases air content
688 by more than 100%.

689

690 • No visual signs of deterioration or cracks (except superficial rust) were observed on the
691 surface of concrete specimens subjected to 150 or 300 days of accelerated chloride exposure.
692 Furthermore, no evidence of rust is observed internally on the fibres embedded in concretes
693 indicating that steel reinforcement did not corrode to any significant extent under the wet-
694 dry chloride exposure. This shows that blend fibres make a positive contribution to the
695 durability of both conventional and RuC.

696

697 • The use of increasingly higher volumes of rubber aggregate in SFRRuC mixes reduces
698 progressively the compressive strength and elastic modulus of concrete. Flexural strength is
699 also affected, though to a lesser extent due to the presence of fibres. Hence, fibres are an
700 essential component in the design of flexible concrete pavements.

701

702 • As a consequence of the ongoing hydration of the cementitious materials, a slight general
703 increase in the mechanical properties of all mixes after 150 and 300 days of wet-dry chloride
704 exposure was identified in comparison to the 28-day mechanical properties.

705

706 • While VPV and sorptivity generally increase with increased rubber content, the change with
707 respect to plain concrete is minor. All mixes examined after 300 days of mist curing show
708 VPV values lower than 6% and sorptivity values lower than $6 \text{ mm/h}^{0.5}$, which means that
709 they can be classified as highly durable concrete mixes.

710

711 • The depth of chloride penetration in both conditions (fully-saturated and wet-dry) generally
712 increases with rubber content. At the colour change boundary, 30BF and 60BF specimens
713 record lower chloride concentrations than 0.4% by weight of cement (critical concentration
714 inducing corrosion) and present apparent diffusion coefficients values within the range of
715 highly durable concrete mixes.

716

717 It is concluded that the combination of rubber particles, up to 60%, and steel fibres can lead to
718 an innovative concrete with increased ductility and flexibility as well as good transport
719 characteristics. Future work should be focused on examining the capability of this promising
720 concrete to withstand aggressive environments such as freeze-thaw resistance and fatigue
721 performance.

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722
723

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731

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