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Mechanical Performance of Steel Fibre Reinforced Rubberised Concrete for Flexible Concrete Pavements

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Abstract

This work aims to develop materials for flexible concrete pavements as an alternative to asphalt concrete or polymer-bound rubber surfaces and presents a study on steel fibre reinforced rubberised concrete (SFRRuC). The main objective of this study is to investigate the effect of steel fibres (manufactured and/or recycled fibres) on the fresh and mechanical properties of rubberised concrete (RuC) comprising waste tyre rubber (WTR). Free shrinkage is also examined. The main parameters investigated through ten different mixes are WTR and fibre contents. The results show that the addition of fibres in RuC mixes with WTR replacement substantially mitigates the loss in flexural strength due to the rubber content (from 50% to 9.6% loss, compared to conventional concrete). The use of fibres in RuC can also enable the development of sufficient flexural strength and enhance strain capacity and post-peak energy absorption behaviour, thus making SFRRuC an ideal alternative construction material for flexible pavements.

Keywords: *Recycled fibres; Rubberised concrete; Steel fibre concrete; Rubberised steel fibre concrete; Hybrid reinforcement; Flexible concrete; Flexible pavements.*

27 **1. Introduction and Background**

28 Road pavements and slabs on grade are constructed either with flexible asphalt or rigid concrete.
29 Flexible pavements can better accommodate local deformations, but lack the durability of
30 concrete which is by nature much stiffer. A flexible concrete pavement could combine the
31 advantages of both types of pavements, however, requires a radical change in how it is
32 constructed. Rubberised concrete which can be design to have stiffness values similar to that of
33 asphalt, can be used as an alternative construction material for flexible pavements. It is well
34 known, however, that the use of rubber in substantial enough quantities can also adversely affect
35 all of the other mechanical properties of Portland-based concrete. Furthermore, virgin rubber
36 aggregates are significantly more expensive than natural aggregates. To address these issues, this
37 study aims to use recycled materials derived from waste tyre rubber (WTR) not only to provide
38 economically and structurally sound alternatives, but also to enable the development of a
39 sustainable flexible concrete pavement solution.

40

41 **1.1 Waste tyre materials**

42 According to The European Tyre Recycling Association [1], approximately 1.5 billion tyres are
43 produced worldwide each year and a quarter of this amount is arisen in EU countries. It is also
44 estimated that for every tyre brought to the market, another tyre reaches its service life and
45 becomes waste. The European Directive 1991/31/EC [2] introduced a set of strict regulations to
46 prevent the disposal of waste tyres in landfills as a means of preventing environmental pollution
47 and mitigating health and fire hazard [3-5]. As a result, in the EU any type of waste tyre disposal
48 in the natural environment has been banned since 2006. The European Directive 2008/98/EC [6]
49 has also established a disposal hierarchy leading to a serious effort for effective waste tyre
50 management, minimising energy consumption.

51 Typical car or truck tyres comprise 75-90% rubber, 5-15% high-strength corded steel wire and
52 5-20% polymer textile. WTR is currently used as fuel, in particular in cement kilns. It is also used
53 in applications, such as synthetic turf fields, artificial reefs, sound proof panels, playground
54 surfaces and protective lining systems for underground infrastructure [7, 8]. While these
55 applications make a positive contribution to recycling WTR, demand with respect to the volume
56 of waste tyres is still small. Since cement-based materials constitute the largest portion of
57 construction materials worldwide, recycling WTR in concrete is a positive way to respond to the
58 environmental challenge and to the significant redundant volumes of waste materials.

59

60 **1.2 Rubberised concrete**

61 In the past two decades, several studies have investigated the addition of WTR in concrete, but
62 only recently for structural applications [9-12]. Concretes containing rubber particles present high
63 ductility and strain capacity, increased toughness and energy dissipation [11, 13, 14]. These
64 properties, along with the material's high impact and skid resistance, sound absorption, thermal
65 and electrical insulation [5, 15-17] make rubberised concretes (RuC) a very attractive building
66 material for non-structural applications.

67

68 Despite the good mechanical properties of rubber, production of RuC has several important
69 drawbacks: (a) reduction in workability associated with the surface texture of the rubber particles
70 [3, 11, 18, 19], (b) increased air content as the rough and non-polar surface of rubber particles
71 tend to repel water and increase the amount of entrapped air [20-22], and (c) reduction in the
72 compressive strength (up to approximately 90% reduction with 100% replacement of natural
73 aggregates), tensile strength and stiffness [11, 23]. The reduction in mechanical properties is
74 mainly attributed to the lower stiffness and higher Poisson's ratio of rubber (nearly 0.5) compared

75 to the other materials in the mixture, and the weak bond between cement paste and rubber
76 particles [21, 24, 25]. One of the potential alternatives to enhance the mechanical performance of
77 RuC is the addition of fibres.

78

79 **1.3 Steel fibre reinforced concrete using recycled fibres**

80 The steel cord used as tyre reinforcement is a very high strength cord of fine wires (0.1- 0.3 mm).
81 The same cord is currently being used in limited volumes to reinforce concrete in high value
82 security applications, such as vaults and safe rooms. At the same time when extracted from tyres,
83 the cord is either discarded or at best re-melted. Commercially available steel fibre reinforcement
84 for concrete comprises thin fibres with a diameter ranging from 0.3 to 1 mm and has a sizable
85 market mainly in tunnel and slabs on grade applications. Hence, it is natural to consider tyre wire
86 for concrete applications [26], as using recycled tyre steel fibres (RTSF) from waste tyres, instead
87 of manufactured steel fibres (MSF), can reduce costs and positively contribute to sustainability
88 by reducing the emissions of CO₂ generated from manufacturing steel fibres [27, 28]. Recently,
89 many studies have examined the use of recycled steel fibres in concrete [27, 29-32]. By assessing
90 mechanical properties, most of these studies confirm the ability of classified RTSF to reinforce
91 concrete.

92

93 **1.4 Steel fibre reinforced rubberised concrete**

94 Despite the fact that there are many studies on RuC and SFRC, there are very few studies
95 examining the effect of using steel fibres and rubber particles together in concrete, and most of
96 these focus on cement-based mortars or self-compacted concrete (SCC) [33-37]. Turatsinze et al.
97 [33] investigated the synergistic effect of MSF and rubber particles, in particular replacing sand
98 in cement-mortars. They observed that the addition of steel fibres improved the flexural post-

99 cracking behaviour, while the addition of rubber (up to 30% by volume of sand) significantly
100 increased the deflection at peak load. Ganesan et al. [35] studied the influence of incorporating
101 crumb rubber and MSF in SCC. Compared to conventional SCC, they reported a 35% increase
102 in flexural strength when 15% of sand (by volume) was replaced with crumb rubber and 0.75%
103 (by volume) fraction of steel fibres was added. Xie et al. [36] conducted an experimental study
104 on the compressive and flexural behaviour of MSF reinforced recycled aggregate concrete with
105 crumb rubber. They found that as the amount of rubber content was increased, the reduction in
106 the compressive strength was smaller compared to other studies, and they attributed this
107 behaviour to the inclusion of steel fibres. They also concluded that steel fibres played a significant
108 role in enhancing the residual flexural strength, which was slightly affected by the increase in
109 rubber content. Finally, Medina et al. [37] examined the mechanical properties of concrete
110 incorporating crumb rubber and steel or plastic fibres coated with rubber. They observed that
111 concrete with rubber and fibres presents better compressive and flexural behaviour as well as
112 impact energy absorption than plain rubberised concrete.

113

114 To the best of the authors' knowledge only limited information is available on the mechanical
115 behaviour of steel fibre reinforced rubberised concrete (SFRRuC) where both fine and coarse
116 aggregates are replaced with rubber particles in significant volumes (exceeding 20% by volume
117 of total aggregates) and further studies are needed to understand its performance where much
118 larger rubber volumes are used. Large volumes of rubber are necessary to achieve more flexible
119 concrete pavements. In addition, the behaviour of SFRRuC in which RTSF are used alone or in
120 a blend with MSF, has not been studied yet.

121

122 This study investigates the fresh properties as well as the compressive and flexural behaviour of
123 several SFRRuC mixes with the aim of developing optimized mixes suitable for pavement
124 applications. Coarse and fine aggregates are partially replaced by different sizes and percentages
125 of tyre rubber particles and various dosages and blends of steel fibres, MSF and/or RTSF, are
126 used as fibre reinforcement. Details of the experimental programme and the main experimental
127 results are presented and discussed in the following sections. This study contributes to the
128 objectives of the EU-funded collaborative project Anagennisi (<http://www.anagennisi.org/>) that
129 aims to develop innovative solutions to reuse all waste tyre components.

130

131 **2. Experimental Programme**

132 **2.1 Parameters under investigation**

133 The parameters assessed in this study were: (i) the rubber content used as partial replacement of
134 both fine and coarse aggregates (0%, 20%, 40% or 60% replacement by volume), and (ii) steel
135 fibre content (0 or 20 kg/m³ MSF + 20 kg/m³ RTSF, or 40 kg/m³ RTSF). A total of 10 different
136 mixes were prepared. For each mix, three cubes (150 mm-size), three cylinders (100 mm-
137 diameter and 200 mm-length), and three prisms (100x100 mm-cross section and 500 mm-length)
138 were cast. The cubes and cylinders were used to obtain the uniaxial compressive strength and the
139 compressive stress-strain curve, respectively, whereas the prisms were cured in different
140 conditions to evaluate free shrinkage strain (autogenous and drying) and then subjected to three-
141 point bending. Table 1 summarises the different mix characteristics and the ID assigned to the
142 mixes. The mix ID follows the format NX, where N denotes the amount of rubber content used
143 as partial replacement of both fine and coarse aggregates (0, 20, 40 or 60%), while X represents
144 the type of steel fibre reinforcement and can be either P, BF or RF (Plain, Blend of Fibres or
145 Recycled Fibres, respectively). For instance, 60BF is the rubberised concrete mix that contains

146 60% of rubber particles as conventional aggregate replacement and consists of blend fibres (20
 147 kg/m³ MSF and 20 kg/m³ RTSF).

148

149 Table 1. Concrete mix ID, and quantities of rubber and steel fibres added in each mix

Mix No.	Mix ID	% Rubber replacing aggregates by volume		Fine rubber (kg/m ³)	Coarse rubber (kg/m ³)	MSF (kg/m ³)	RTSF (kg/m ³)
		Fine	Coarse				
1	<i>0P</i>	0	0	0	0	0	0
2	<i>0BF</i>	0	0	0	0	20	20
3	<i>0RF</i>	0	0	0	0	0	40
4	<i>20P</i>	20	20	49.5	60.4	0	0
5	<i>20BF</i>	20	20	49.5	60.4	20	20
6	<i>40P</i>	40	40	99	120.9	0	0
7	<i>40BF</i>	40	40	99	120.9	20	20
8	<i>60P</i>	60	60	148.5	181.3	0	0
9	<i>60BF</i>	60	60	148.5	181.3	20	20
10	<i>60RF</i>	60	60	148.5	181.3	0	40

150

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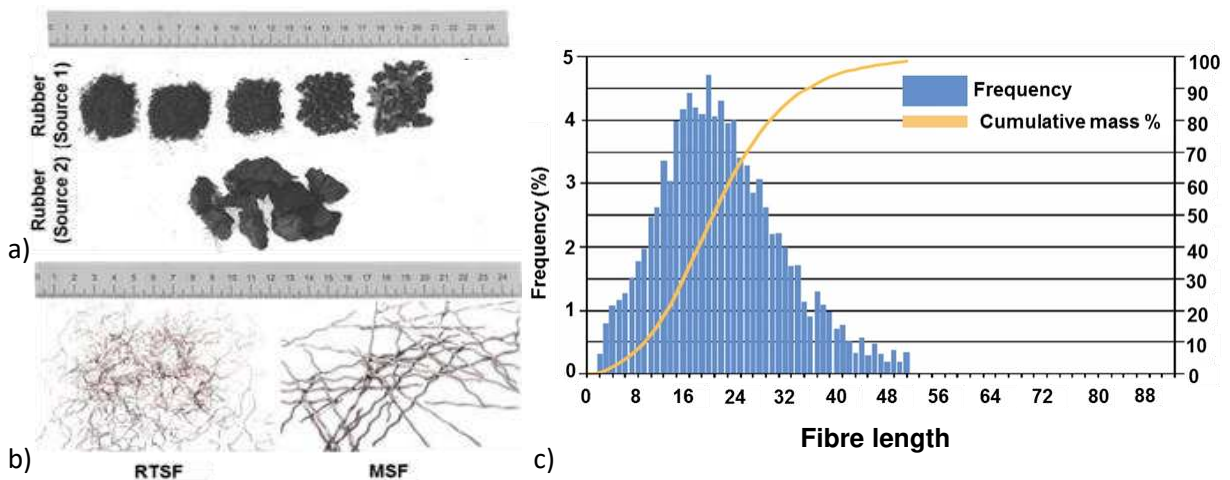
152 2.2 Materials and mix preparation

153 2.2.1 Materials

154 2.2.1.1 Rubberised concrete

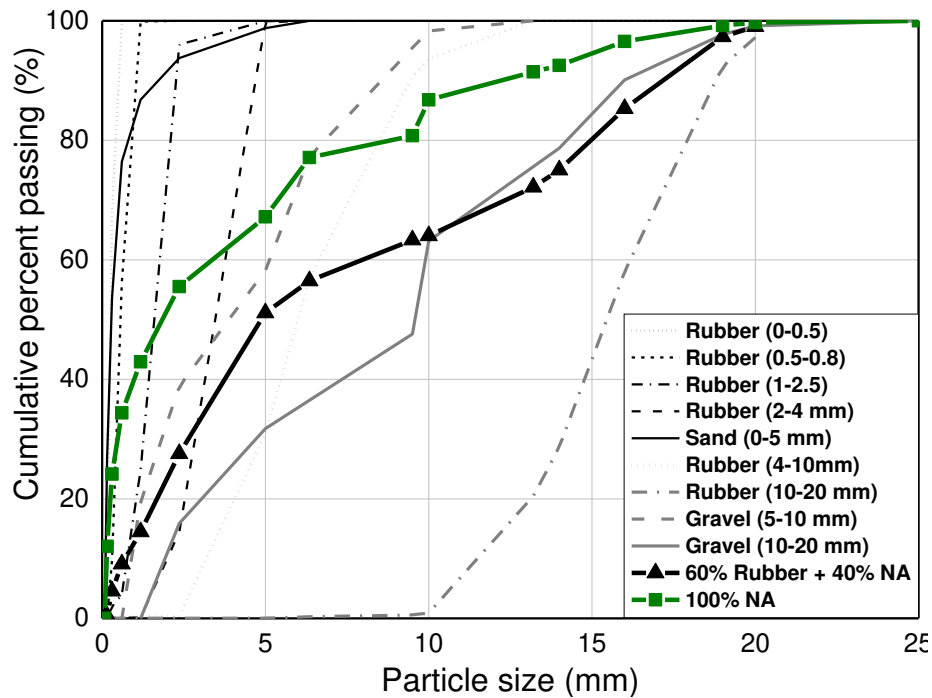
155 A high strength commercial Portland Lime Cement CEM II-52.5 N containing around 10–15%
 156 Limestone in compliance with BS EN 197-1 [38] was used as binder. The coarse aggregates used
 157 comprised natural round river washed gravel with particle sizes of 5-10 mm and 10-20 mm
 158 [specific gravity (SG)=2.65, absorption (A) =1.2%]. The fine aggregates used comprised medium
 159 grade river washed sand with particle sizes of 0-5 mm (SG=2.65, A=0.5%). Pulverised fuel ash
 160 (PFA) and silica fume (SF) were used as partial replacement of cement (10% by weight for each)
 161 to enhance the fresh and mechanical properties of the mixes. Plasticiser and superplasticiser were
 162 also added to improve cohesion and mechanical properties (mix details are given in Section
 163 2.2.2).

164 The rubber particles used in this study were recovered through the shredding process of waste
 165 tyres at ambient temperature and where obtained from two different sources. As depicted in
 166 Figure 1a, the fine rubber particles were provided in the ranges of 0-0.5 mm, 0.5-0.8 mm, 1-2.5
 167 mm and 2-4 mm and were used in the concrete mix in the ratio 12:12:32:44 of the total added
 168 fine rubber content, while the course rubber particles were supplied in the ranges of 4-10 mm and
 169 10-20 mm and were utilized in the concrete mix in the ratio 50:50 of the total added course rubber
 170 content. Figure 2 presents the particle size distribution of the natural aggregates (NA) and rubber
 171 particles used, obtained according to ASTM-C136 [39]. To limit the influence of rubber size on
 172 concrete particle packing, conventional aggregates were replaced with rubber particles of roughly
 173 similar size distribution to minimise the impact on the packing of the concrete mix constituents.
 174 A relative density of 0.8 was used to calculate the mass of rubber replacing natural aggregates,
 175 as determined using a large rubber sample that was accurately cut and measured.
 176



177
 178
 179
 180

Figure. 1 a)Rubber particles, b) MSF and RTSF used in this study and c) length distribution analysis of RTSF



181
182
183 **Figure. 2** Particle size distribution for conventional aggregates and rubber
184

185 Table 2 reports the physical properties of the coarse aggregates (5-20 mm) and the coarse rubber
186 particles (4-20 mm), obtained through a series of tests: (a) particle density and water absorption
187 according to EN 1097-6 [40], (b) loose bulk density according to EN 1097-3 [41], and (c) particle
188 shape-flakiness index according to EN 933-3 [42]. The physical properties of the fine aggregates
189 and fine rubber particles were not evaluated due to difficulties in performing the tests on fine
190 rubber particles as they floated when submerged in water.

191
192 As it was not possible to complete the flakiness tests for all particle sizes, in the end this
193 information was not used directly in the mix design. It should be noted though that the higher
194 flakiness influenced the optimisation of the mix design and more fines and supplementary
195 materials were necessary, as reported in [11].
196

197

Table 2. Physical properties of coarse aggregates and coarse rubber particles

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Physical properties/Type of rubber	Rubber - Source 1 4-10 mm	Rubber - Source 2 10-20 mm	Natural aggregates 5-10 mm	Natural aggregates 10-20 mm
Apparent particle density, kg/m ³	1136	1103	2685	2685
Oven-dried density, kg/m ³	1032	1090	2599	2599
Saturated and surface-dried particle density, kg/m ³	1123	1101	2631	2631
Water absorption after 24h, %	5.3-8.8	0.8-1.3	1.2	1.2
Bulk specific gravity	1.1	1.1	2.6	2.6
Bulk density, kg/m ³	454	485	1511	1583
Flakiness index	6.64	17.48	7.05	9.7

205 2.2.1.2 Steel Fibres

206 The MSF were crimped type steel fibres with a length of 55 mm, diameter of 0.8 mm and tensile
 207 strength of 1100 MPa. The RTSF were cleaned and screened fibres (typically containing < 2%
 208 of residual rubber) and had lengths in the range of 15-45 mm (at least 60% by mass), diameters
 209 <0.3 mm and tensile strength of 2000 MPa. Figure 1b presents both types of fibres (MSF and
 210 RTSF) used in this study and Figure 1c illustrates the length distribution of the RTSF based on a
 211 digital optical correlation method that combines photogrammetry and advanced pattern
 212 recognition to determine the length of individual fibre from high speed image of free falling
 213 dispersed fibres [43].

214

215 2.2.2 Mix design

216 The mix design used in this experimental study (adopted from Raffoul et al. [11]) was optimised
 217 to be used for typical concrete bridge piers targeting a compressive strength of 60 MPa (cylinder),
 218 and suited the replacement of 0%, 20%, 40% and 60% of WTR without excessive degradation in
 219 fresh and mechanical properties. The optimised mix proportions for 0% rubber content
 220 (conventional concrete), are shown in Table 3.

221

Table 3. Concrete mix proportions (without rubber content)

Material	Quantity
CEM II – 52.5 MPa	340 kg/m ³
Silica fume (SF)	42.5 kg/m ³
Pulverised fuel ash (PFA)	42.5 kg/m ³
Natural fine aggregates 0-5 mm	820 kg/m ³
Natural coarse aggregates 5-10 mm	364 kg/m ³
Natural coarse aggregates 10-20 mm	637 kg/m ³
Water	150 l/m ³
Plasticiser	2.5 l/m ³ *
Superplasticiser	5.1 l/m ³

222

*It was increased at higher amounts of rubber and fibres were added to the concrete (2.5-4.75 l/m³)

223

224 *2.2.3 Mixing, casting and curing procedure*

225

A 200 litre pan mixer was used for all mixes. The procedure used for mixing the concrete started

226

with conventional aggregates dry mixed for 30 seconds together with the rubber particles.

227

Subsequently, half of the total amount of water was added and mixed for about 1 minute. The

228

mix was allowed to rest for 3 minutes allowing the conventional aggregates to get saturated. After

229

that, the cementitious materials (Portland cement, silica fume and fly ash) were added, followed

230

by the remaining water and the chemical admixtures. The fresh concrete was finally mixed for

231

another 3 minutes. For those concrete mixes with steel fibres, fibres were manually integrated

232

into the concrete during mixing at the last mixing stage.

233

234

The concrete fresh properties, including slump, air content and fresh density, were then assessed

235

for each mix according to the standardised methods described in EN 12350-2 [44], EN 12350-7

236

[45], and EN 12350-6 [46], respectively. The concrete specimens were cast in plastic cube (150

237

mm) and cylinder moulds (100x200 mm), and prismatic steel moulds (100x100x500 mm)

238

according to EN 12390-2 [47] and EN 14651 [48]. The specimens were cast in two layers and

239 vibrated (25s per layer) on a vibrating table. After casting, specimens were covered with plastic
240 sheets to prevent moisture loss, and left under standard laboratory conditions for 48h until
241 demoulding. The specimens were then kept in a mist room ($21\text{ }^{\circ}\text{C} \pm 2$ and $95 \pm 5\%$ relative
242 humidity (RH)) for 28 days, except for the prisms used for shrinkage measurements that were left
243 in the mist room for 7 days and then stored in a control room ($24\text{ }^{\circ}\text{C} \pm 2$ and 42 ± 5 RH) for 50
244 days. After the curing period, the specimens were kept under standard laboratory conditions (20
245 $^{\circ}\text{C} \pm 2$ and 50 ± 5 RH) until testing.

246

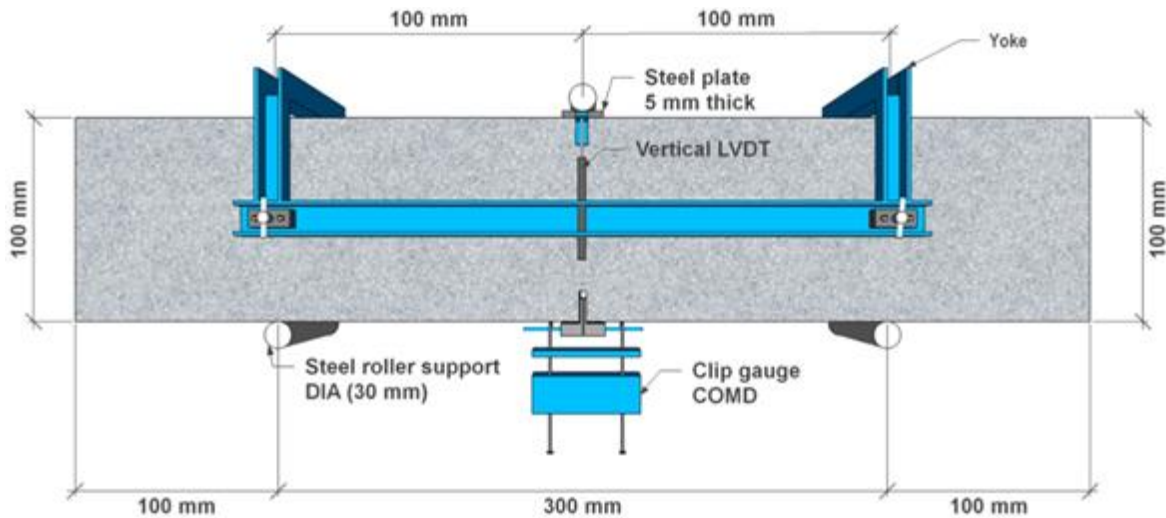
247 **3. Test set-up and procedure**

248 **3.1 Compression testing**

249 Prior to testing, the top faces of the cylinders were cut and ground according to EN 12390-3 [49].
250 For the RuC cylinders, extra measures were taken to prevent local failure during testing by
251 confining their two ends with high-ductility post-tensioned straps, as proposed by Garcia et al.
252 [50]. Axial compression tests were performed on concrete cubes and cylinders according to EN
253 12390-3 [49] under monotonic loading until failure. For all tested cylinders, the compression tests
254 were performed using a servo-hydraulic universal testing machine with a load capacity of 1000
255 kN. The load was applied on the cylinders at a displacement rate of 0.3 mm/min. The local axial
256 strain was measured using two diagonally opposite strain gauges at mid-height. The global axial
257 strain was measured using three laser sensors, with an accuracy of $40\mu\epsilon$, placed radially around
258 the specimens (120° apart) using two metallic rings. The metallic rings were attached to the
259 specimens using four clamp screws, covering the middle zone of the cylinder and resulting in 100
260 mm gauge length. The tests on cubes were carried out using a standard compression machine
261 with a load capacity of 3000 kN at a loading rate of 0.4 MPa/s.

262 **3.2 Three-point bending tests**

263 The flexural behaviour of the concrete specimens was assessed by performing three-point
264 bending tests using an electromagnetic universal testing machine with a load capacity of 300 kN.
265 A detailed schematic of the test setup is provided in Figure 3. The loading point allowed for both
266 the in-plane and out-of-plane rotation of the prism. Two LVDTs were mounted at the middle of
267 a yoke (one on each side) as suggested by the JCI [51] to measure the net deflection at mid-span.



268

269 **Figure. 3** Schematic representation of the flexural test set-up

270

271 A clip gauge of 12.5 mm-length was fixed at the middle of the bottom side of the prism, where a
272 5 mm-wide and 15 mm-deep notch had been sawn. The clip gauge measurement (crack mouth
273 opening displacement -CMOD) was used to control the loading rate as suggested by RILEM [52].
274 All tests were performed under a rate of 50 $\mu\text{m}/\text{min}$ for CMOD ranging from 0 to 0.1 mm, 200
275 $\mu\text{m}/\text{min}$ for CMOD ranging from 0.1 to 4 mm, and 8000 $\mu\text{m}/\text{min}$ for CMOD higher than 4 mm.

276

277 **3.3 Free-shrinkage**

278 The autogenous and drying shrinkage tests were performed according to EN-126174 [53].
279 However, to avoid issues of fibre alignment along the mould boundaries, the size of the prismatic

280 specimens was increased from 40x40x160 mm (as suggested by the standard) to 100x100x500
281 mm. Specimens were demoulded two days after casting and fitted with steel “Demec” points
282 (locating discs) using plastic padding. Two Demec points were fixed 300 mm apart on each of
283 the vertical (as cast) sides of the prism.

284

285 The first strain measurement was recorded after 30 minutes to allow for the hardening of the
286 adhesive. For autogenous shrinkage, the specimens were kept in a mist room with controlled
287 temperature and humidity conditions ($21\text{ }^{\circ}\text{C} \pm 2$ and $95 \pm 5\%$ RH) and measurements were taken
288 at the ages of 1, 2, 3 and 7 days after demoulding. For drying shrinkage, specimens were stored
289 in a chamber with controlled temperature and humidity conditions ($24\text{ }^{\circ}\text{C} \pm 2$ and 40 ± 5 RH)
290 and measurements were taken at the ages of 10, 14, and 28 and 56 days after demoulding.

291

292 **4. Experimental Results and Discussion**

293 **4.1 Fresh state properties**

294 *4.1.1 Workability*

295 To assess the workability of rubberised concrete, most researchers (including the authors of this
296 paper) use the slump test which appears to be a consistent and easy-to-apply method in practice
297 [3, 7, 10, 11, 19]. Table 4 shows the slump results of all mixes as well as their corresponding
298 slump classes, all of which fulfil the consistency requirements as described in pavement design
299 standard BS EN 13877-1[54] and the normative reference BS EN 206-1 [55] either for fixed-
300 form or slip-form (class S1) paving . The desired slump class was targeted to be at least S3 (slump
301 ≥ 90 mm), by modifying the plasticiser dosage which was increased proportionally to the amount
302 of rubber and steel fibres in each mix. All mixes achieved the targeted slump, however, the

303 workability for mixes *60BF* and *60RF* was quite low (40 and 35 mm, respectively) although high
 304 amounts of plasticiser and superplasticiser were added (4 per m³ and 5.1 per m³ of concrete,
 305 respectively). Nevertheless, this low workability did not raise any issues during handling, placing
 306 or finishing of the mixes due to the high rubber dosage (60%). No signs of segregation, bleeding
 307 or excessive “balling” were observed in any of the mixes.

308

309 **Table 4.** Fresh concrete properties for all concrete mixes

Mix No.	Mix ID	Extra plasticiser added L/m ³	Slump (mm)	Slump class	Air content %	Bulk density (kg/m ³)	Theoretical density (kg/m ³)
1	<i>OP</i>	0	240	S5	1.35	2406	2426
2	<i>0BF</i>	0	195	S4	1.5	2452	2454
3	<i>0RF</i>	0	195	S4	1.15	2447	2454
4	<i>20P</i>	0.25	200	S4	1.9	2258	2211
5	<i>20BF</i>	0.5	170	S4	3	2269	2239
6	<i>40P</i>	0.5	170	S4	3.15	2046	1996
7	<i>40BF</i>	1	130	S3	3.35	2086	2025
8	<i>60P</i>	1	150	S3	2.35	1869	1780
9	<i>60BF</i>	1.5	40	S1	3.35	1889	1811
10	<i>60RF</i>	1.5	35	S1	4.15	1884	1811

310

311 The results show that slump decreases with the addition of steel fibres, and further decreases with
 312 the inclusion of rubber, even though the amount of plasticiser was increased proportionally. By
 313 comparing the slump values of the control mix with the SFRC mixes without rubber (*0BF* and
 314 *0RF*), it can be seen that fibres caused a slump drop of 18.8% for both SFRC mixes. This decrease
 315 may be caused by increased friction between the RTSF, which have a large specific surface area,
 316 and the concrete constituents during mixing. Additionally, the tendency of steel fibres to
 317 agglomerate also has an adverse effect on workability.

318

319 The slump of the RuC mixes without steel fibres, *20P*, *40P* and *60P*, also decreased by 16.6%,
320 29.1% and 37.5%, respectively, in comparison to the control mix. The surface shape and texture
321 of rubber appear to have increased friction compared to conventional aggregates. Furthermore,
322 fine impurities (i.e. rubber dust and fluff) on the rubber particles may also have reduced the free
323 water in the fresh concrete mix.

324

325 The combined effects of both steel fibres and rubber on reducing the workability can be clearly
326 seen from the slump values of SFRRuC mixes, *20BF*, *40BF*, *60BF* and *60RF*, where the slump
327 significantly dropped by 29.1%, 45.8%, 83.3% and 85.4%, respectively, in comparison to the
328 control mix.

329

330 *4.1.2 Air content and unit weight*

331 Air content has been shown to increase with the addition of fibres and/or rubber in concrete [56,
332 57] and a similar trend is observed in this study. As indicated in Table 4, the air content (entrapped
333 air) in the concrete in general rises when increasing the rubber content, and further increases with
334 the addition of fibres (except for mixes *ORF* and *60P* which can be considered outliers). The
335 increase in the air content is possibly due to the rough and non-polar surface of rubber particles
336 which tend to repel water and increase the amount of entrapped air in the mix. The large specific
337 surface area of the fibres and their tendency to occasionally agglomerate can also contribute to
338 increase air entrapment.

339

340 It was expected that the air content of the concrete mix with a blend of fibres (MSF and RTSF)
341 would be less than the air content of the concrete mix with RTSF alone as the blend fibres mix
342 has lower amount of fibres, hence lower specific surface area of fibres. However, as shown in

343 Table 4, there is no clear trend in this respect and more work is needed before firm conclusions
344 can be made.

345

346 From Table 4, it is clear that, as expected, the measured density of the concretes assessed
347 significantly decreases with increasing rubber content. Although this was mainly due to the lower
348 specific gravity of rubber particles (0.8) compared to the specific gravity of fine and coarse
349 aggregates (2.65), density was also slightly affected by the increase in air content. On the other
350 hand, the addition of steel fibres resulted in a marginal increase in the density (in both
351 conventional and RuC) due to the higher specific gravity of steel fibres (7.8). The last column in
352 Table 4 presents the theoretical density of each mix, assuming that there is no air content. A good
353 correlation between the theoretical and experimental values is observed. The measured density
354 values dropped by 148-215 kg/m³ for each 20% addition of rubber replacement, whereas the
355 theoretical decline was 215 kg/m³. The difference between these two is attributed to air content
356 and the assumed specific gravity value used for rubber (0.8), which might not be accurate for all
357 rubber particles used, as tyres arise from various sources.

358

359 **4.2 Compressive behaviour**

360 The mean (average from three cubes and three cylinders, respectively) compressive strength and
361 elastic modulus values are shown in Table 5. The modulus of elasticity values were obtained by
362 using the secant modulus of the stress-strain curves (from 0 to 30% of the peak stress) similar to
363 fib 2010 model code [58]. Standard deviation values are given in brackets below the mean values.

364

365

366

367
368

Table 5. Mechanical properties of all concrete mixes tested under compression

Mix ID	<i>0P</i>	<i>0BF</i>	<i>0RF</i>	<i>20P</i>	<i>20BF</i>	<i>40P</i>	<i>40BF</i>	<i>60P</i>	<i>60BF</i>	<i>60RF</i>
Age of testing (days)	30	30	31	31	32	32	33	33	34	34
Cube strength (MPa)	78.2 (4.5)	93.7 (3.5)	101.5 (2.9)	51.1 (1.5)	52.0 (3.0)	23.3 (0.2)	25.1 (1.6)	10.6 (0.5)	11.7 (1.4)	11.9 (0.2)
Cylinder strength (MPa)	68.9 (20.7)	94.8 (7.0)	78.8 (5.0)	33.1 (5.1)	33.9 (4.4)	10.8 (0.4)	16.5 (1.4)	7.6 (1.0)	8.2 (1.4)	7.8 (0.3)
Modulus of elasticity (GPa)	44.3 (4.0)	43.0 (1.2)	45.7 (1.2)	30.7 (5.1)	20.0 (0.0)	22.0 (5.3)	17.3 (1.5)	8.0 (0.0)	8.3 (1.5)	4.7 (1.2)

369

370 *4.2.1 Cube strength*

371 It can be observed that the addition of steel fibres in conventional concrete increases the
372 compressive strength by 20% when a blend of MSF and RTSF (20 kg/m³ and 20 kg/m³) is used,
373 and by 30% when only RTSF is used (40 kg/m³). Steel fibres enhanced the compressive strength
374 by controlling the tensile transverse strains developed, due to the Poisson effect during axial
375 loading, thus delaying micro-crack coalescence and eventually unstable propagation that causes
376 compression failure. RTSF are particularly effective in this respect, possibly due to their random
377 geometry and better distribution in the mix due to their small diameters.

378

379 The replacement of fine and coarse aggregates with rubber particles had, as expected, a significant
380 adverse effect on the compressive strength. The drop in the compressive strength, with respect to
381 the control mix, was around 35%, 70% and 86% for mixes with 20%, 40% and 60% aggregate
382 replacement, respectively. The reduction in compressive strength can be mainly attributed to the
383 lower stiffness and higher Poisson ratio of rubber compared to conventional aggregates, and the
384 weak bond between cement paste and rubber [20, 21]. Under axial load, rubber particles develop
385 large lateral deformations (due to Poisson effect) which cause lateral tensile stresses and micro-

386 cracks in the cement paste, thus accelerating the unstable propagation of cracks and causing
387 failure at a lower load compared to conventional concrete. The differences in elastic
388 characteristics and possibly poor bonding conditions between cement paste and rubber particles
389 may also lead to uneven stress distribution in the concrete.

390

391 The addition of fibres into the RuC mixes did not have a significant effect on the compressive
392 strength. Compared to the RuC mixes that had the same amount of rubber and did not contain
393 fibres, the increase in the compressive strength as a result of the addition of MSF and/or RTSF
394 was 1.7% for *20BF*, 7.6% for *40BF*, 10% for *60BF* and 12% for *60RF*. This indicates that the
395 compressive strength of the SFRRuC is dominated by the amount of rubber, while sensitivity to
396 steel fibre content is very low.

397

398 *4.2.2 Stress-strain characteristics*

399 Figure 4 shows representative axial stress-strain curves (up to the peak stress) for selected tested
400 cylinders. As there are considerable local strain variations and global bending issues, the
401 cylinders that displayed better agreement between global and local axial strains and lower level
402 of bending during loading were chosen. As pointed out by other researchers [11, 25], there is a
403 very high variability in the recorded results, mainly due to large accidental bending, resulting
404 from uneven bearing surfaces and/or due to the non-uniform distribution of the rubber particles
405 in the concrete mass.

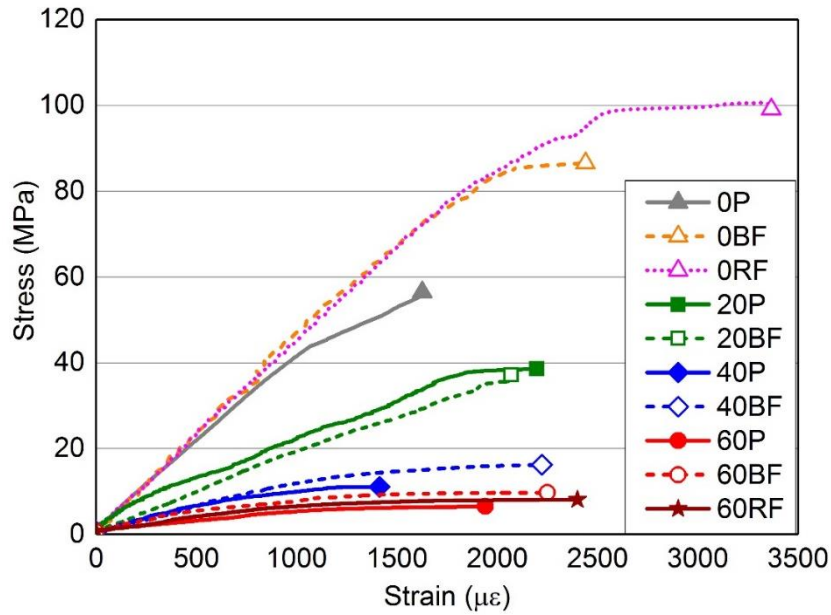


Figure. 4 Stress-strain curves of the concrete assessed

406

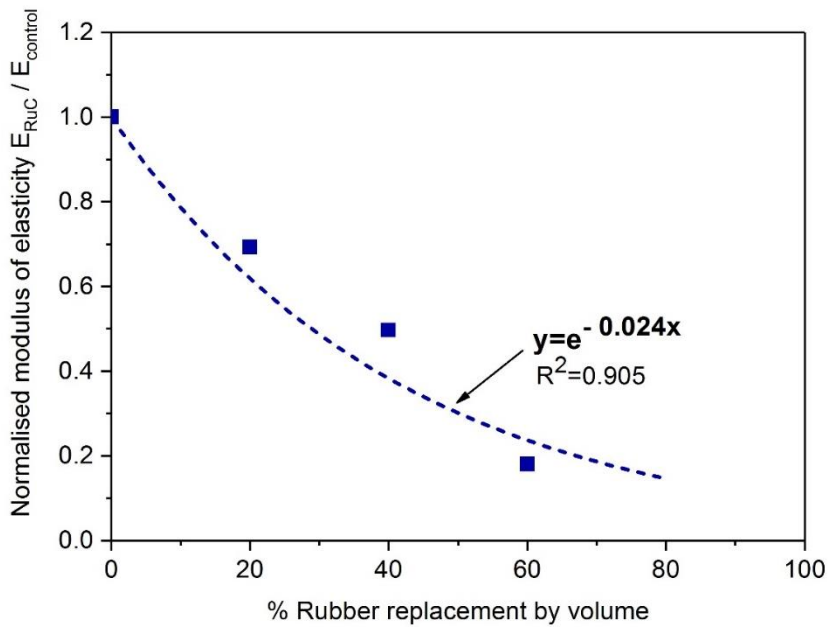
407

408

409 It can be seen from Table 5 and Figure 4 that as the rubber content increases, the peak stress and
 410 the initial slope of the stress-strain curves substantially decreases. For the applications considered
 411 in this study (i.e. concrete pavements and slabs on grade), the loss in compression strength is not
 412 as important as the increase in deformability, provided that sufficient flexural strength is
 413 maintained.

414

415 Figure 5 shows that the modulus of elasticity of rubberised concretes (E_{RuC}) without fibre
 416 addition, normalised with respect to the control concrete mix ($E_{Control}$), reduces with an increased
 417 rubber content. Such reduction in stiffness can be attributed to the lower stiffness of rubber
 418 particles (compared to conventional aggregates) and to the higher air content, as confirmed in
 419 section 4.1.2. An exponential curve is also shown to provide an equation for the estimation of
 420 modulus of elasticity. The reduction in elastic stiffness may be undesirable in some structural
 421 applications, but it can help develop new structural solutions, in particular at the soil structure
 422 interaction level.



423

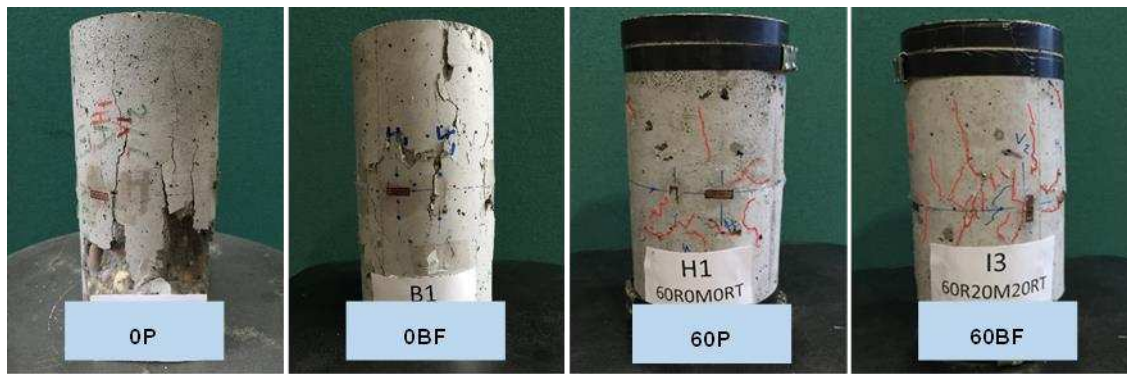
424 **Figure 5.** Correlation between the normalized modulus of elasticity of rubberised concretes as a
 425 function of rubber aggregate content

426

427 As shown in Table 5, the effect of steel fibres on compressive stiffness is not conclusive.
 428 However, steel fibres overall tend to increase the peak stress and corresponding strain (apart from
 429 mix *20BF*). This enhancement is expected due to the steel fibre ability to control the development
 430 of transverse deformations.

431

432 The addition of rubber and steel fibres had a more significant effect on the failure mode (Figure
 433 6). Whilst the plain concrete specimens failed in a sudden and brittle manner, the RuC specimens
 434 failed in a much more ductile manner. This can be attributed to the relatively low elastic modulus
 435 of the rubber particles, which increases the deformation capacity before cracking, but also to the
 436 tensile resistance of rubber aggregates. The RuC specimens with steel fibres exhibited more (and
 437 thinner) vertical cracks at failure, compared to the ones without fibres. This suggests that ductility
 438 was also improved somewhat by adding fibres.



439

440

Figure 6. Typical compression failure of tested concrete cylinders

441

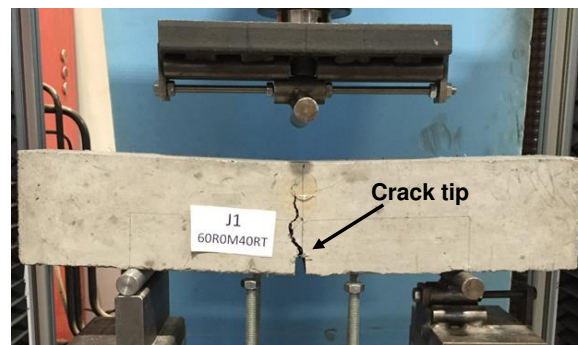
442 **4.3 Flexural behaviour**

443 The failure mode was the same for all specimens and a typical example is shown in Figure 7; a

444 single crack initiated at the notch of the mid-span section and propagated vertically towards the

445 compression zone.

446



447

Figure 7. Photograph showing a typical flexural failure of the tested concrete prisms

449

450 The mean values (average of three prisms) of strain capacity, flexural strength and elastic

451 modulus are shown in Table 6. The elastic theory was used to determine the flexural modulus of

452 elasticity by using the secant modulus of the load-deflection curves (from 0 to 30% of the peak

453 load).

454

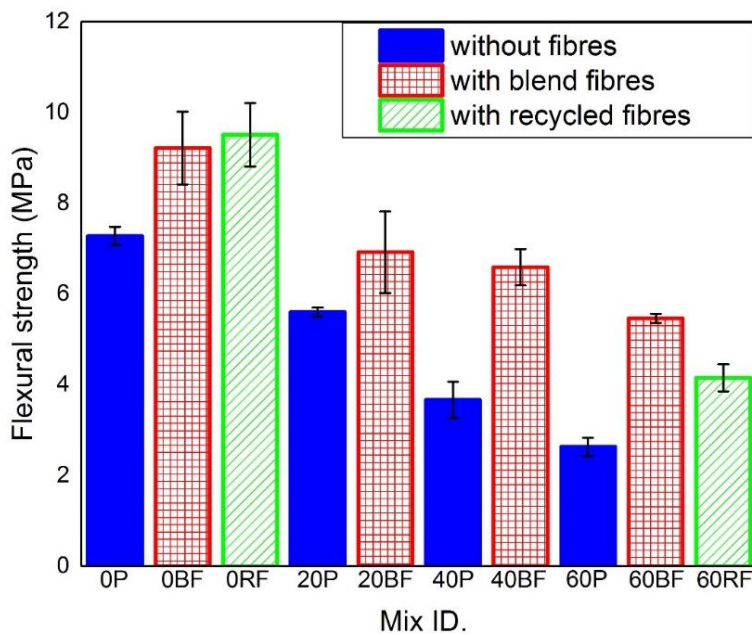
Table 6. Mechanical properties of all concrete mixes tested in flexural

Mix ID	<i>OP</i>	<i>OBF</i>	<i>ORF</i>	<i>20P</i>	<i>20BF</i>	<i>40P</i>	<i>40BF</i>	<i>60P</i>	<i>60BF</i>	<i>60RF</i>
Age of testing (days)	60	60	61	61	62	62	63	63	64	64
Flexural strength (MPa)	7.3 (0.2)	9.2 (0.8)	9.5 (0.7)	5.6 (0.1)	6.9 (0.9)	3.7 (0.4)	6.6 (0.4)	2.6 (0.2)	5.5 (0.1)	4.2 (0.3)
Modulus of elasticity (GPa)	46.8 (2.1)	47.5 (1.0)	48.3 (3.34)	29.3 (2.31)	34.0 (3.1)	18.3 (2.6)	23.5 (5.9)	8.1 (1.6)	8.3 (1.1)	10.1 (2.5)
Strain capacity, δ_{max} (mm)	0.04 (0.01)	0.06 (0.02)	0.22 (0.07)	0.05 (0.01)	0.26 (0.32)	0.06 (0.01)	1.34 (0.21)	0.14 (0.03)	1.32 (0.74)	0.55 (0.36)

455

456 **4.3.1 Flexural Strength**

457 Flexural strength values are compared in Figure 8. The addition of steel fibres enhanced the
 458 flexural strength by 26% for *OBF* and 30% for *ORF*, with respect to the control mix. This
 459 improvement was anticipated as the steel fibres act as flexural reinforcement.



460

Figure 8. Flexural strength of the tested concrete mixes

461

462

463 Consistent with the reported by other authors [25, 36, 59], replacing the fine and coarse
 464 aggregates with rubber particles had an adverse effect on flexural strength. The flexural strength

465 of the RuC mixes without fibres, *20P*, *40P* and *60P*, was 23%, 49% and 64% lower than that of
466 the conventional concrete, respectively. As for the compressive strength, the reduction in flexural
467 strength may be attributed to the lack of good bonding conditions between the rubber particles
468 and the cement paste, as well as the low stiffness and higher Poisson's ratio of rubber (nearly 0.5)
469 compared to conventional aggregates [20, 21]. The high Poisson's ratio means that the rubber
470 once in tension will contract faster than concrete in the lateral direction, facilitating loss of bond.
471 The low stiffness also means that the rubber contributes very little in tension at the low strain at
472 which the cement matrix cracks.

473

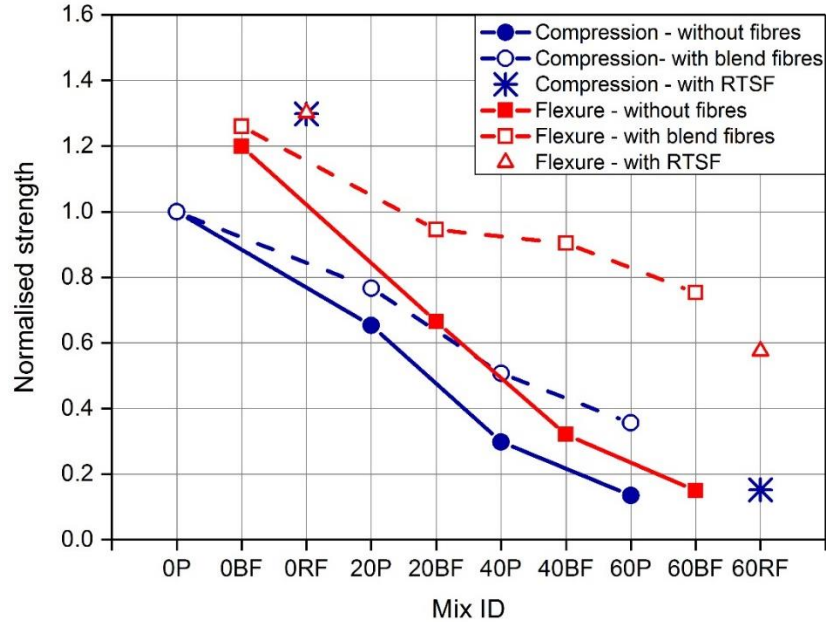
474 The addition of steel fibres in the RuC resulted in a substantial enhancement of its flexural
475 strength, therefore mitigating the adverse effect of partially replaced natural aggregates by
476 recycled rubber particles. By comparing the flexural strength of the SFRRuC mixes, *20BF*, *40BF*,
477 *60BF* and *6ORF*, with the flexural strength of the RuC mixes without fibres, *20P*, *40P* and *60P*,
478 it is noted that the flexural strength was increased by 23%, 78%, 111.5% and 61.5%, respectively.
479 Although the flexural strength gain of the *6ORF* mix is not as high as the *60BF* mix, it still
480 provides sufficient flexural strength for SFRRuC pavements and slabs on grade and can
481 potentially lead to more sustainable solutions by eliminating the need for virgin materials.

482

483 Figure 9 shows the normalised compressive and flexural strength for all mixes, with respect to
484 the control mix (concrete without fibres and/or rubber). It is clear that the loss in compressive
485 strength as a result of the addition of rubber is more pronounced than the flexural strength loss.
486 Even without the fibres, the loss in flexural resistance of the RuC is less than the loss in
487 compressive strength; this indicates that the rubber is making a modest contribution to the tensile
488 capacity of the concrete in tension. When fibres are added, the tensile resistance is further

489 enhanced and hence, considerable flexural resistance is developed even when large volumes of
490 rubber are present.

491



492

493 **Figure. 9** Normalised strength as a function of rubber volume in the concrete

494

495 4.3.2 Modulus of elasticity

496 The values obtained from the flexural tests are in general similar to those from the compressive
497 tests. As expected, there is a small increase (up to 3%) in the elastic modulus when fibres are
498 added. A significant reduction in the elastic modulus is also found for the RuC mixes, with the
499 decrease being almost proportional to the amount of rubber content. In particular, the modulus of
500 elasticity of the RuC mixes without fibres, 20P, 40P and 60P, was 37.4%, 60.9% and 82.7%
501 lower than that of the control mix, respectively. The addition of steel fibres into RuC mixes
502 recovered only marginally part of the modulus of elasticity loss. This confirms that, within the
503 elastic domain, the inclusion of rubber particles plays a dominant role on flexural stiffness,
504 whereas the steel fibres make a minimal contribution.

505 4.3.3 Strain capacity

506 The flexural strain capacity was assessed by examining the stress-deflection curves. The
507 deflection δ_{fmax} corresponding to the peak stress, f_{max} , is taken as a relevant indicator of strain
508 capacity [33]. It is evident from table 6 that the strain capacity is enhanced by the addition of
509 fibres. For instance, the δ_{fmax} value for the control mix, *OP*, was 0.04 mm, while the δ_{fmax} values
510 for *OBF* and *ORF* mixes were 0.06 and 0.22 mm, respectively. This enhancement can be explained
511 by the bridging action of the fibres. The strain capacity of the RTSF mix, *ORF*, was higher than
512 that of the blend fibres mix, *OBF*, possibly due to the larger number of RTSF fibres bridging the
513 cracks.

514

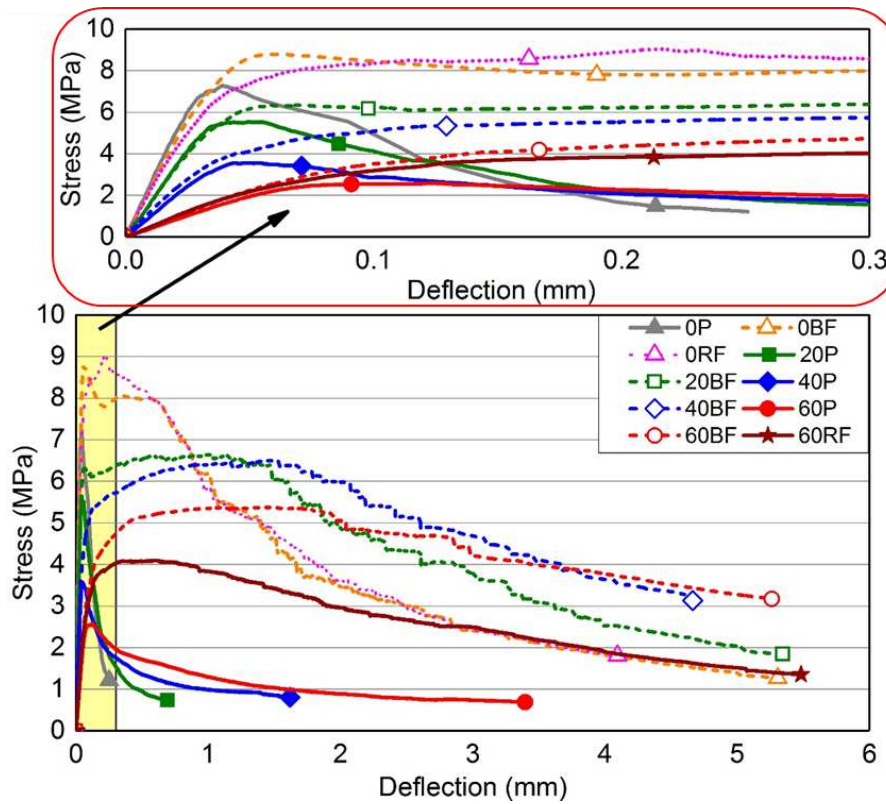
515 The strain capacity also increases with higher rubber contents in the concrete. Compared to the
516 control mix, *OP*, the δ_{fmax} of the RuC mixes was increased by 25%, 50% and 250% for *20P*, *40P*
517 and *60P*, respectively. Turatsinze et al. [33] explained such behaviour by the ability of rubber
518 particles to reduce stress concentration at the crack tip, thus delaying the coalescence and
519 propagation of micro-cracks. Mixes with steel fibres and rubber developed the highest strain
520 capacity values, indicating a synergy between rubber and steel fibres in enhancing strain capacity.

521

522 4.3.4 Residual flexural strength and energy absorption behaviour

523 The load versus deflection curves shown in Figure 10 confirm that the post-peak branches of the
524 SFRC prisms without rubber were significantly enhanced as a result of the inclusion of fibres.
525 The fibres continue bridging the cracks and resisting their opening even after the peak load,
526 dissipating energy through the pull-out mechanism.

527



528

529

Figure. 10 Average stress versus deflection curves for all concrete mixes studied

530

531 Although rubber particles had an adverse effect on the flexural strength of the concrete prisms,
 532 they improved slightly the post-peak energy absorption. This enhancement can be explained by
 533 the ability of the rubber particles to undergo large deformation in tension and promote high
 534 energy absorption. As a result of the interlocking and friction at fibre–matrix and fibre-rubber
 535 interfaces, steel fibres substantially enhanced the post-peak energy absorption and dissipation of
 536 RuC mixes, which at large displacements show higher flexural capacity than the specimens
 537 without rubber.

538

539 As expected, concrete prisms with a blend of fibres (MSF and RTSF) show superior post-peak
 540 energy absorption behaviour than those with RTSF alone. RTSF are overall better distributed and
 541 in general help control micro-cracks, while MSF are better at controlling cracks once they open

542 and develop. Though the difference in performance is not obvious for normal concrete in Figure
 543 10, this is well demonstrated at 60% rubber content when the 60BF controls the cracks much
 544 better than 60RF. In another study [43], the mixes with blend fibres are shown to outperform both
 545 the RTSF and MSF only mixes.

546

547 To further examine the post-peak energy absorption behaviour of the mixes, the residual flexural
 548 strength (f_{Ri}) and the characteristic residual flexural strength values ($f_{Ri,c}$) were obtained (see
 549 Table 7) at given intervals of CMOD (0.5, 1.5, 2.5, 3.5) according to RILEM recommendation
 550 [52]. The residual flexural strength can be considered a measure of toughness or even ductility of
 551 the SFRC mixes. Higher values of f_{Ri} mean higher post-cracking load carrying capacity and
 552 higher ductility. The characteristic residual flexural strength $f_{Ri,c}$ accounts for the variability of
 553 the residual flexural strength results. SFRRuC mixes showed a lower rate of reduction in residual
 554 strength than FRC mixes. This may be attributed to the presence of rubber particles that prolong
 555 the crack path and increase the contact area of the failure surface with the rubber particles, which
 556 make some contribution to the tensile strength, but also enable the steel fibres to engage better
 557 across the crack.

558

559 **Table 7.** Residual and characteristic flexural strength values of concrete assessed

Mix No.	Mix ID	f_{Ri} (MPa)				$f_{Ri,c}$ (MPa)				fib (2010) classification	
		f_{R1}	f_{R2}	f_{R3}	f_{R4}	$f_{R1,c}$	$f_{R2,c}$	$f_{R3,c}$	$f_{R4,c}$	$f_{R3,c}/f_{R1,c}$	Class
1	0P	-	-	-	-	-	-	-	-	-	-
2	0BF	8.1	5.3	3.5	2.7	6.1	3.5	2.4	1.2	0.39	- (< 0.5)
3	0RF	8.4	5.2	3.7	2.8	8.3	4.7	2.9	1.8	0.35	- (< 0.5)
4	20P	-	-	-	-	-	-	-	-	-	-
5	20BF	6.5	6.6	5.4	4.3	4.4	4.9	3.3	2.3	0.75	4.4 b
6	40P	-	-	-	-	-	-	-	-	-	-
7	40BF	5.9	6.4	6.4	5.4	4.9	5.8	5.6	4.6	1.14	4.9 d
8	60P	-	-	-	-	-	-	-	-	-	-
9	60BF	5.1	5.4	5.3	4.7	4.4	5.2	5.1	3.8	1.16	4.4 d
10	60RF	4.1	3.7	3.1	2.6	3.6	3.2	2.8	2.6	0.78	3.6 b

560 * **a** if $0.5 < f_{R3,c}/f_{R1,c} < 0.7$; **b** if $0.7 \leq f_{R3,c}/f_{R1,c} \leq 0.9$; **c** if $0.9 \leq f_{R3,c}/f_{R1,c} \leq 1.1$; **d** if $1.1 \leq f_{R3,c}/f_{R1,c} \leq 3$; **e** if $1.3 \leq f_{R3,c}/f_{R1,c}$

561 According to fib model code [58] for structural applications with normal and high-strength
562 concrete, SFRC can be classified according to the post-cracking residual strength (considering
563 the value of $f_{R1,c}$), and the ratio $f_{R3,c}/f_{R1,c}$. The higher the value of $f_{R1,c}$ and/or the ratio $f_{R3,c}/f_{R1,c}$,
564 the higher the class. As observed in Table 7, mixes *40BF* and *60BF* show the best overall
565 performance among all mixes, whereas SFRC mixes (without rubber) can not be classified as
566 their $f_{R3,c}/f_{R1,c}$ ratio is less than 0.5. Nevertheless, all SFRC mixes (conventional and rubberised)
567 fulfilled the requirements of EN 14889-1 [60] – 1.5 MPa at 0.5 mm CMOD and 1.0 MPa at 3.5
568 mm CMOD – and could be used for practical applications.

569

570 The aim of this study is to develop a more flexible Portland cement concrete pavement. However,
571 as flexible pavement standards/specifications relate to asphalt concrete, it is not possible to use
572 them for a direct comparison, though the flexural performance of SFRRuC is far superior to that
573 of asphalt concrete. Hence, SFRRuC pavements, though flexible, should comply with
574 standards/specifications for rigid pavements. The major issue here is that the rigid pavement
575 standards rely on the compressive and flexural strengths. Though all SFRRuC mixes studied
576 here meet the flexural strength characteristics, as described in pavement design standard BS EN
577 13877-1[54], not all of them can meet the compressive requirements. However, provided that
578 durability requirements are met, this should not be a big issue but would require modification on
579 the standard.

580

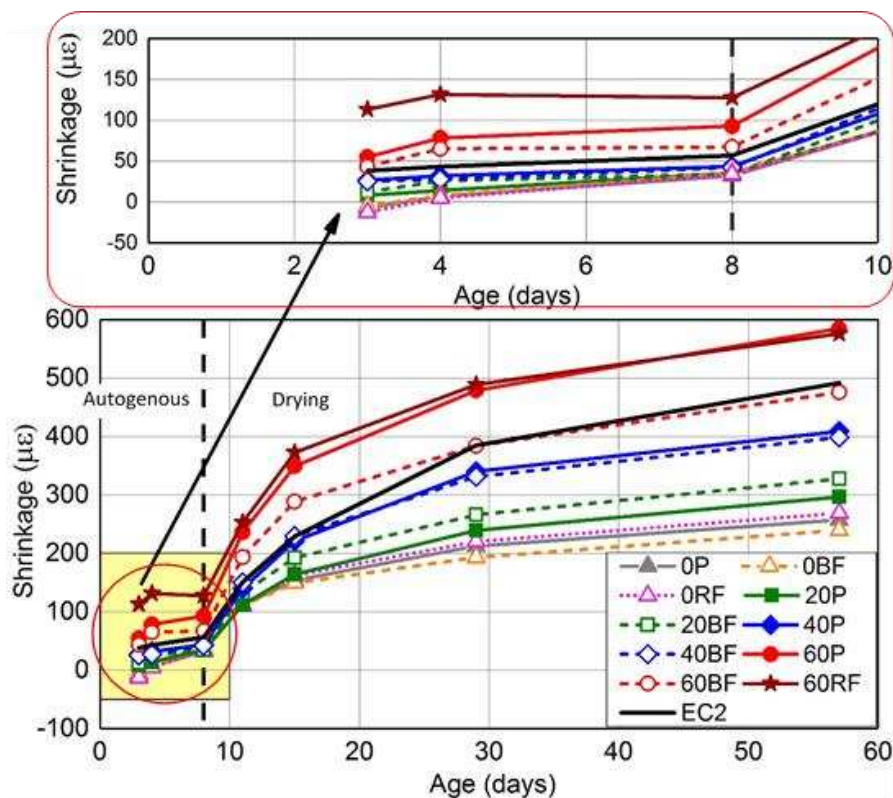
581 **4.4 Free shrinkage behaviour**

582 Typical curves of total shrinkage versus time are shown in Figure 11. The vertical dotted line
583 shown at 8 days indicates the start of drying shrinkage. The values predicted according to

584 Eurocode 2 [61] for conventional concrete (accounting for temperature and humidity) are also
585 included for comparison.

586

587 Both conventional concrete and SFRC mixes show lower autogenous and drying shrinkage
588 strains than those predicted by Eurocode 2 (EC2). The difference between predicted and actual
589 values for these mixes can be attributed to the presence of high quantities of silica fume and fly
590 ash, not accounted for in the Eurocode 2 equation. It is also clear that the addition of rubber
591 increases the overall shrinkage strains at 57 days by 15.5% for 20P, 59% for 40P and 127% for
592 60P. This increase in free shrinkage strain with increasing rubber content is due to the lower
593 stiffness of rubber particles compared to conventional aggregates, which reduces the overall
594 internal restraint. The higher porosity and diffusivity of rubberised concrete prisms can also
595 contribute to increasing the rate of moisture loss and accelerating drying shrinkage.



596

597

598

Figure. 11 Total free shrinkage for all concrete mixes

599 **5 Conclusions**

600 This study assessed the fresh state and mechanical properties of steel-fibre reinforced rubberised
601 concretes (SFRRuC), in which waste tyre rubber partially replaced aggregates, and blends of
602 manufactured and recycled tyre steel fibres were used as reinforcement. Based on the
603 experimental results, the following conclusions can be drawn:

- 604 ▪ The replacement of conventional aggregates with rubber particles reduces workability and
605 unit weight, and increases air content of the fresh concrete mixes. Steel fibres further
606 lower workability and increase air content, whilst marginally increasing unit weight.
- 607 ▪ The mechanical properties (compressive and flexural strength, as well as the modulus of
608 elasticity) decrease with increasing rubber content. Steel fibres in appropriate amounts
609 (up to 40 kg/m³) enhance the mechanical properties of conventional concrete (up to 30%
610 compressive strength) and provide modest increases in the modulus of elasticity.
- 611 ▪ Free shrinkage strain increases with increasing rubber content as a result of the lower
612 stiffness of rubber particles.
- 613 ▪ In rubberised concrete, the addition of steel fibre reinforcement mitigates the loss in
614 flexural strength (from 50% to 9.6% loss, compared to conventional concrete) and slightly
615 improves compressive strength and modulus of elasticity (up to 12.5% and 28.4%,
616 respectively), hence, they are an important component when RuC is to be used for
617 structural purposes.
- 618 ▪ Concrete strain capacity and post-peak energy absorption behaviour are enhanced by the
619 addition of fibres and are further improved by the inclusion of rubber, completely
620 transforming the flexural performance of RuC and enabling it to resist structural loads.
- 621 ▪ A high performance (class d according to fib 2010 model code [58]) and highly flexible
622 steel fibre reinforce rubberised concrete can be produced with 60% rubber content and

623 blended fibres (20 kg/m³ of MSF and 20 kg/m³ of RTSF), suitable for pavement
624 applications.

625 It is concluded that SFRRuC is a promising candidate material for use in structural concrete
626 applications with increased toughness and flexibility requirements, such as road pavements and
627 slabs on grade. Future work should be directed towards investigating the long-term performance
628 of this innovative concrete in aggressive environments.

629

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637

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