

Mechanical Properties and Air Permeability of Concrete Containing Waste

Tyres Extracts

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49 **Abstract**

50 The safe disposal of waste tyres has been seen as having a negative impact on the
51 environment. To mitigate this impact, the components of waste tyres can be used in the
52 production of green concrete. This study explores the effects of the curing and drying regime on
53 the mechanical properties and permeation characteristics of concrete containing both crumbed
54 rubber and steel fibres that are removed from waste tyres. Five concrete mixes were designed
55 and concrete cubes, cylinders, and prisms were cast using waste tyres extracts. Crumb rubber
56 was treated by submersion in sodium hydroxide and then used to partially replace 10% and 30%
57 of fine aggregates in the concrete mix. Extracted steel fibres were added at the rate of 1% and
58 2% per volume of each mix. Compressive, indirect splitting tensile as well as flexural strengths
59 were conducted after normal curing while observing several drying conditions. Additionally, air
60 permeability was assessed using a portable apparatus which was developed to assess
61 permeability easily. For the concrete test specimens containing 10% partial replacement of fine
62 aggregate by crumb rubber and 1% steel fibres, it was discovered that the splitting tensile
63 strength and flexural strength were higher than that of the control mix by 21% and 22.6%,
64 respectively. For specimens, that included the 10% crumb rubber and 1% steel fibres, when
65 exposed to oven drying at 105°C for 12 hours, the compressive strength results increased by 17%
66 compared to the control specimens exposed to the same conditions. Unlike the compressive
67 strength results, the splitting tensile and flexural strength results decreased after exposing the
68 specimens to elevated temperature. The addition of crumb rubber and steel fibres as a partial
69 fine aggregate replacement resulted in increasing the air permeability of the concrete to different
70 degrees depending on the percentages used. The oven drying curing regime improved the
71 permeability by reducing it in specimens containing the 10% crumb rubber and 1% steel fibres as

72 indicated by increasing their permeability time index by 15% when compared to air-dried
73 specimens. Using waste tyre extracts as a partial replacement of concrete fine aggregate can be
74 recommended for both indoor and outdoor applications. This study showed that this was a viable,
75 economic and environmentally friendly method for reducing carbon footprint.

76

77 **Keywords:** concrete; waste tyres; steel fibres; mechanical properties; air permeability

78

79 **1. Introduction**

80 In the UK, the waste tyre management industry have been taking great steps in the last
81 ten years to build its proficiency and duty of best practice with safety and environmental
82 legislation (Wrap, 2006). Siddique and Naik (2004) mentioned that over 270 million scrap tyres
83 are deposited in the United States per year. As the potential to reproduce green sustainable
84 concrete, researchers (Ibrahim and Razak, 2016; Tam et al., 2016; Carsana et al., 2013; Aghae
85 et al., 2015; Rodríguez et al., 2016; Tam et al., 2016; Adeboje et al., 2018-2020) investigated the
86 use of tyre waste in concrete for construction. The advantages gained by using tyre waste in
87 concrete included minimizing the environmental impact, reducing the usage of natural aggregate
88 and reducing the space volume used for disposals in landfills. Sofi (2018) reported that using
89 tyre waste as coarse or fine aggregate would adversely affect the mechanical properties as well
90 as durability of the concrete because the interfacial zones between the rubber and cement may
91 act as a micro-crack due to weak bonding between the two materials. However, Dobrotál and
92 Paraschiv (2017) recommended in their study that good enhancement in physical and mechanical
93 characteristics was achieved after thermal treatment of the rubber using an autoclave.

94 Aslani and Gedeon (2019) studied rubberized concrete containing 0.25% - 1%
95 polypropylene, steel fibres and crumb rubber replacement of 20% of fine aggregate. The work
96 reported that the addition of steel fibres from 0.75% led to improved tensile strength of
97 overheated rubberized concrete having 10% crumb rubber compared to normal concrete.
98 Sharobim et al., (2018) reported a higher reduction of tensile strength for specimens overheated
99 in the oven at 300°C. They found a 30% reduction in the splitting tensile strength of overheated
100 rubberized concrete having 10% crumb rubber compared to that of normal concrete. Abdullah et
101 al., (2018) reported that the split tensile strength linearly decreased with rubber content above
102 6%. The strength then declined at further replacement rates for overheated specimens (200°C-
103 600°C). On the other hand, Aiello et al., (2009), Centonze et al., (2012), Sengul (2016)
104 investigated the utilization of steel from waste tyres without adding waste rubber. These studies
105 found that workability of fibre reinforced concrete was lower than that of normal concrete.
106 Compressive, tensile, and flexural strengths were increased with the addition of fibre. Crack
107 spacing and crack width were reduced by adding 1% waste steel fibres compared to those of the
108 control specimens.

109 Treatment of crumb rubber with sodium hydroxide (NaOH) solution has been widely
110 used to increase the bond between cement and rubber resulting in increased strength (Segre and
111 Joekes, 2000; Chou et al., 2007; Liu and Zhang, 2015; Guo et al., 2017). Segre et al., (2002) and
112 Mohammadi et al., (2016) suggested that NaOH treatment converts the zinc stearate compound
113 which was used in tyre manufacturing to a soluble form of sodium stearate which can be
114 removed by washing with water. Zukri et al., (2017) studied the effect of treated crumb rubber
115 with the addition of steel fibre on the concrete properties. This resulted in good bonding between
116 cement pastes and crumb rubber after treatment with sodium hydroxide (NaOH). The treatment

117 of the crumb rubber was carried out by submerging it in 8 mole of sodium hydroxide for 10
118 minutes, then dried by a stream of warm air before adding it to the concrete mixes. Roychand et
119 al., (2020) reported similar enhancement in the mechanical properties of the concrete when using
120 treated rubber by sodium hydroxide NaOH.

121 The quality of concrete can be defined by its durability (Bungey (1989). The durability is
122 usually presented by destructive and non-destructive properties that can be attained. The quality
123 of concrete cover is considered the first line of defense for steel reinforcement against aggressive
124 exposure to substance and environment (Dhir et al., 1993; Claisse et al., 1999a and b; 2003).
125 The water and air permeability of concrete can be used to estimate quality of concrete cover
126 (Yang et al., 2018; Katpady et al., 2018). However, not all permeability tests can be applied on
127 site successfully as they are destructive and sometimes their mobility and setup may be difficult.
128 Simple indicators such as in-situ permeation tests are reasonable and easy tools to measure the
129 amount of fluid or air transmitted through the concrete surface and near surface (concrete cover).

130 Figg (1973) developed tests for determining water and air permeability of concrete in the
131 laboratory and in-situ conditions. The test was based on a hole drilled into the concrete surface.
132 Low pressure was applied to the drilled hole into the surface concrete using a hypodermic
133 needle. The pressure was generated by implementing a vacuum by hand. For the Figg Air test, a
134 hand vacuum pump was used to draw air from a sealed cavity. The Figg air permeability test is
135 measured and evaluated when the pressure recovers from 55 to 50 kPa below the atmospheric
136 pressure in a given time period. However, the apparatus used in this testing method was of
137 considerable expense; further, the hypodermic needle can clog up with debris while applying the
138 pressure. Cather et al., (1984) modified Figg's method by increasing the hole dimensions to 13
139 mm in diameter and 50 mm in depth. Parrott and Hong, (1991) investigated the air permeability

140 of concrete. They measured the pressure drop from 100 to 95 kPa, for a given period of time,
141 above atmospheric pressure in a sealed cavity; this is known as Permeability Index. However,
142 this test is expensive and difficult to handle on site. Claisse et al., (2003) drilled three holes in
143 their specimens, rather than a single hole as initially proposed for the Figg testing method, which
144 resulted in repeatable and consistent results.

145 Air permeability apparatus for laboratory and in-situ testing based on the vacuum
146 technique was developed to overcome the disadvantages of handling and operation cost (Dhir et
147 al., 1993; Dhir et al., 1995; Claisse et al., 1997; Claisse et al., 1999 b; Torrent and Gebauer,
148 1994; Ebensperger and Torrent, 2012). The vacuum technique has been based on vacuum
149 preconditioning and permeability by monitoring pressure decay in concrete cover (concrete near
150 surface). Torrent and Frenzer, (1995); Claisse et al. (1999b); Katapady et al., (2018) found that
151 there were direct relationships between air permeability, pore volume, and durability aspects
152 such as depth of carbonation, chloride diffusion, and also the compressive strength results. It
153 became apparent that the air permeability of concrete containing crumb rubber and waste steel
154 fibres either preconditioned by drying in the oven or by drying at room temperature had not been
155 investigated.

156 **2. Research Significance**

157 In this investigation, correlation between the mechanical properties and the non-
158 destructive testing represented in air permeability of rubberized concrete including the steel fibre
159 extracted from tyre wastes was assessed. A simple easy to use non-destructive portable air
160 permeability apparatus was developed to measure concrete near surface air permeation
161 successfully. The relationship between the mechanical properties and air permeability was
162 evaluated for the studied mixes to explore useful indicators. The analysis of these experimental

163 results will be able to advance the disposal of waste tyres and lead to a more sustainable,
164 economical, and durable concrete for infrastructure and structural applications in construction.

165 **3. Experimental Program**

166 In this study, five mixes were considered. The mixes contained specimens for oven dried
167 curing (preconditioning) as well as normal curing. In addition to the tests to assess the
168 mechanical properties (compression, splitting tensile, and flexural) of the concrete, a non-
169 destructive air permeability test was used to assess permeation characteristics of studied
170 specimens and to correlate the results with those of the mechanical properties tests. This also
171 provided a simple method for detecting the quality of the rubberized concrete. A detailed
172 discussion now follows.

173 **3.1 Materials**

174 The design of the control mix (without crumb rubber and steel fibres) was carried out to
175 achieve a target compressive strength of 30 MPa at 28 days in standard water curing. This target
176 strength represents what has been considered here as a reasonable concrete strength for concrete
177 applications. The maximum aggregate size was 20 mm. For comparison purposes, the
178 water/cement ratio was constant for all mixes with a ratio value of 0.5. The different portions of
179 concrete mix components to produce one cubic meter of concrete are listed in Table 1. The
180 slump values ranged from 40 to 80 mm depending on the percentages of crumb rubber and steel
181 fibres as indicated in Table 1. It can be observed from Table 1 that as the crumb rubber
182 percentage increased, the slump increased. However, when the percentage of steel fibres was
183 increased, the slump was reduced in mix, M10@2 but increased in mix M30@2.

184 **3.1.1 Crumb Rubber and Treatment**

185 Crumb rubber was provided in sizes ranging from 2-4 mm by Allcock & Sons Ltd, who
186 specialize in recycling waste tyres and grinding these into crumbs. Figure 1 (a) shows the crumb
187 rubber used in this investigation. Pre- treatment of the rubber crumb was carried out in this
188 research based on the recommendations of Segre and Joekes (2000); Segre et al. (2002); Chou et
189 al. (2007); Liu and Zhang (2015); Mohammadi et al. (2016); Guo et al. (2017; Zukri et al. (2017)
190 by submerging crumb rubber for 30 minutes in “1 N NaOH” solution (one mole concentration of
191 sodium hydroxide solution) at room temperature. After treatment with the NaOH solution, the
192 rubber particles were washed with potable water for a period of 5 minutes until the pH of the
193 washing water became neutral. The crumbs were then dried by a stream of warm air before
194 adding to the concrete mixes.

195 **3.1.2 Preparation of Steel Fibres**

196 The steel fibres extracted from the waste tyres were cut into nominal lengths of 40 mm
197 using a cut wire method. The fibres were extracted by magnetic separator after burning, similar
198 to the method described by Rashid and Balouch (2017). The Steel fibres were corrugated with
199 nominal lengths equal to 40 mm, a nominal diameter of 1.0 mm and aspect ratio of 40. Steel
200 fibres were added to the mixes manually in the form of fine aggregate together with the crumb
201 rubber according to ACI 544.1R (2002). Figure 1 (b) illustrates the steel fibres after extraction
202 and separation.

203 **3.1.3 Cement**

204 Masterceret UK provided the cement that met all of the conformity criteria to BS EN
205 197-1.

206 **3.1.4 Sand**

207 The fine aggregate used can be classified as ordinary sand with a yellow and rough
208 texture. The fineness modulus was measured by sieve analysis and found to be 2.7. The density
209 was measured using a pycnometer: the cement density obtained was 2630 kg/m³, while the
210 natural bulk density of the sand was 1700 kg/m³.

211 **3.2 Samples Preparation**

212 A total of five mixes were designed: a control mix and four samples mixes with two
213 different percentages of crumb rubber (10% and 30%) and two different percentages of steel
214 fibres (1% and 2%). The crumb rubber partially replaced fine aggregate and the steel fibres were
215 added as a percentage of concrete volume. Thomaset et al., (2016) suggested that the relative
216 specific gravities of the rubber crumb and sand must be considered during the mix design.
217 Therefore, more rubber weight was added compared to the sand replaced. Quantities of
218 materials used for mix design are reported in Table 1 for 1 m³. The specimens were cast in the
219 laboratory and left in their moulds for 24 hours at room temperature.

220 The procedure for mixing took place by firstly adding the dry coarse aggregate, sand,
221 rubber, and steel fibres followed by the cement in that order. The water was lastly added and
222 mixed continuously until a uniform matrix had been achieved.

223 Concrete cube specimens of 150 x 150 x 150 mm, cylinder specimens of 150 mm
224 diameter and 300 mm height, and prism specimens with cross-section dimension of 100 x 100
225 mm and length 500 mm were prepared. The specimens were cured in water for up to 28 days.
226 For the samples preconditioned by drying in the oven, they were kept in the oven for 12 hours at
227 105°C and then cooled in laboratory air before being tested for air permeability or mechanical
228 properties. This time and temperature were chosen to avoid damage of the pore structure while

229 drying (Dhir et al., 1995) and to obtain reliable results. The specimens were tested for
230 compressive strength after two curing time periods: 7 and 28 days (3 samples were tested at each
231 age for each mix and drying condition). For the determination of the tensile and flexural
232 strength, the samples were tested at 28 days (3 samples were tested for each mix and drying
233 condition). The other specimens, which were not dried in the oven, were tested immediately
234 after curing. After curing and or drying (preconditioning), selected cube specimens were drilled
235 with holes of 13 mm diameter and depth of 50 mm in order to insert the probe for measuring the
236 air permeability index (3 samples were tested for each mix and drying condition). In total 150
237 specimens (90 cubes for compressive strength and air permeability testing, 30 cylinders for
238 tensile strength testing and 30 prisms for flexural strength testing) were prepared.

239 **3.3 Test Methods**

240 Concrete cube, cylinder and prism specimens were used to test the compressive, indirect
241 splitting tensile, and flexural strengths as well as air permeability assessment as described in 3.2.

242 **3.3.1 Mechanical Properties Testing**

243 The compressive strength testing of the concrete cubes was as shown in Figure 2 (a).
244 Indirect tensile splitting testing was carried out on the concrete samples according to ASTM
245 C190 (2018) as shown in Figure 2 (b). Flexural strength testing was carried out according to
246 ASTM C348 (2018), as shown in Figure 3.

247 **3.3.2 Development of a Portable Apparatus for Air Permeability Assessment**

248 The air permeability of concrete cover was assessed using a non-destructive portable
249 technique developed especially for this investigation. The effect of drying method, addition of
250 crumb rubber and steel fibres on concrete mixes were assessed using this technique. Air

251 permeability index was assessed based on measuring the pressure decay of compressed air by a
252 portable air compressor to near surface concrete. A hole of 13 mm in diameter and 50 mm in
253 depth was drilled into the specimen surface. The dust was cleared using a small brush. A layer
254 of silicon rubber of approximately 5 mm thickness was applied onto the surface around the hole.
255 On setting, the silicon rubber formed a layer around the hole to eliminate any air leakage at the
256 surface. A new steel probe was developed to obtain repeatable and consistent results. The probe
257 with large washer, as shown in Figure 4 (a), was inserted into the hole and the washer was
258 tightened under a nut to make sure that there was complete air tightness between the washer and
259 the silicon rubber. The probe was connected to the portable air compressor via a reflux non-
260 returnable air valve and a pressure gauge to monitor the air pressure decay. In order to make sure
261 that the decay was only through the concrete hole and there is no leakage from the connections,
262 the apparatus was calibrated by drilling a wooden solid cube, adding the silicon rubber around
263 the hole, inserting the probe, and tighten the nut over the washer. The pressure gauge was
264 monitored for over than one hour and no pressure decay was observed. The latest version of the
265 air permeability portable technique was designed to measure the time index in seconds for the
266 pressure decay from 100 KPa (1 bar) to 10 KPa (0.10 bar). This range of pressure difference was
267 chosen to cover a wide range of studied mixes. The test setup is shown in Figure 4 (b).

268 **4. Experimental Results and Discussion**

269 The concrete mixes were designed to include a partial replacement of the fine aggregate.
270 Mechanical properties air permeability of concrete was measured using the portable non-
271 destructive technique.

272 **4.1 Compressive Strength**

273 This section provides details of the compressive strength results.

274 **4.1.1 Results of the compressive strength test at 7 and 28 days curing**

275 Figures 5 (a and b) show the bar charts together with the error bars for the average of
276 compressive strength results at 7 and 28 days for different mixes. The standard deviations of 3
277 cube samples for each mix were ranged from 0.44 to 0.96 at 7 days age, while the standard
278 deviations were ranged from 0.40 to 1.95 at 28 days as shown in Figure 5. As presented, the
279 standard deviation ranges were relatively low to the corresponding average values of the
280 samples. The maximum coefficient of variation for all the mixes at 7 and 28 days was below 9%
281 which indicated good quality control.

282 **4.1.2 Effect of crumb rubber and steel fibres percentages**

283 The compressive strength results in Figure 5 show that partial replacement of fine
284 aggregate by crumb rubber reduced compressive strength to different degrees depending on the
285 percentage provided. It can be seen from Figure 5 that the 10% partial replacement of fine
286 aggregate by crumb rubber and adding 1% steel fibers to the mix led to compressive strengths of
287 26.4 MPa and 27.63 MPa after water curing for 7 days and 28 days, respectively. These values
288 are slightly lower than those of the control mix exposed to the same curing period and conditions
289 by 6% and 10%, respectively. This observation agrees with Zukri et al., (2017) who found in
290 their study that 10% crumb rubber and 1 % steel fibers had the greatest compressive strength
291 with slight reduction of 6.87%. Increasing steel fibers to 2% of the concrete mix volume while
292 keeping the crumb rubber content at 10%, provided compressive strength values of 27.53 MPa
293 and 28.90 MPa after 7 days and 28 days, respectively. These values are slightly higher than those
294 mentioned above, but they were still lower than those of the control mix exposed to the same
295 curing period and conditions by 1% and 6%, respectively.

296 The increase in the percentage of fine aggregate replaced with crumb rubber to 30% with
297 the addition of 1% steel fibres resulted in concrete with compressive strength of 14.13 and 16.0
298 MPa after 7 and 28 days of water curing, respectively. These results were far lesser than those of
299 the control mix by 49% and 46%, respectively. Increasing steel fibre content to 2% resulted in
300 compressive strength values of 15.23 MPa and 17.40 MPa, which were also far lesser than the
301 control mix by 49% and 43%, respectively, but higher than those of 1% steel fibres subject to the
302 same curing periods and conditions. It can be argued that increasing the crumb rubber to 30%
303 resulted in poor bonding between the cement particles and crumb rubber, and as a result of
304 additional stresses that this caused, weaken the bond between the cement paste and steel fibres.
305 This might lead to the non-uniformity of the applied load and, in turn, reduces the strength
306 dramatically.

307 The current results were in the line with the results of Liu et al., (2018) who reported a
308 slight reduction in the compressive strength with the replacement of sand with crumb rubber.
309 Záleská et al. (2019) reported a further reduction of compressive strength as a result of increasing
310 the percentage of crumb rubber. Sofi (2018) reported that the reduction in compressive strength
311 of the mix with 20% crumb rubber was more than 50% compared to the control mix. It was
312 found that the increase in the steel fibres resulted in an increase in the compressive concrete
313 strength results. For example, compressive strength average value for Mix M10@2 shown in
314 Figure 5 which contained 10% crumb rubber and 2% steel fibres was almost the same as the
315 compressive strength value of the control mix at 94% after water curing for 7 and 28 days,
316 respectively. This is in the line with the findings of Sreeshma and Varghese, (2016) who reported
317 that the increase in the steel fibres percentage when combining them with crumb rubber resulted
318 in an increase in the compressive strength of the concrete compared with normal concrete or

319 concrete that included crumb rubber only. As these previous studies utilized commercial steel
320 fibres, it is interesting to note the see a similar trend with the fibres extracted from waste tyres.

321 **4.1.3 Effect of heating on compressive strength**

322 The effects of heating the samples were studied in the mixes designated with the
323 subscript “h”, as shown in Figure 5 for oven drying curing (preconditioning) at 105°C for 12
324 hours. It can be seen from Figure 5 that the compressive strength values of the control mix
325 specimens after oven drying were less than the samples which were tested immediately after
326 water curing for 7 and 28 days by 18% and 20%, respectively.

327 Unlike normal concrete, rubberized concrete with 10% crumb rubber and 1% steel fibres
328 exposed to oven drying for 12 hours resulted in an increase of the compressive strength for 7 and
329 28 days when water cured. For instance, mix M_h10@1 compressive strength was higher than that
330 of M10@1 by approximately 5% for 7 and 28 days of water curing. This is in agreement with
331 Mousa (2017) who studied rubberized concrete specimens that included silica fume and exposed
332 to heating that ranged from 105°C to 800°C. He reported an increase in the compressive strength
333 when the temperature was below 300°C. This indicates that by adding 1% waste steel fibres in
334 combination with 10 % crumb rubber may have the same effect as adding silica fume to mixes
335 that include crumb rubber. It can be argued that by adding a small percentage of waste steel
336 fibres (1%) as light reinforcement mixed with the waste crumb rubber strengthens the bond with
337 other binding materials. After oven drying, the little expansion of steel fibres and the heated
338 crumb rubber bound with the other concrete particles in the pore structure may led to slight
339 increase in the compressive strength of the cube.

340 For higher percentages of steel fibers (2%), compressive strength values of the mix
341 M_h10@2 were slightly higher than those of the mix M10@2 by 2% and 6% after water curing
342 for 7 and 28 days, respectively. For mixes with higher percentage of crumb rubber (30%
343 replacement) and 1% and 2% steel fibres added to the mix, oven drying for 12 hours, reduced the
344 compressive strength by a range of 10% to 28% at both curing periods of 7 and 28 days. This is
345 in the line with the results reported by Abdullah et al., (2018) who reported that the compressive
346 strength reduces with higher rubber content and an increased temperature of heating. Záleská et
347 al., (2019) reported that the rubberized concrete was stable up to 300°C while they mentioned
348 that the decomposition of rubber-based aggregate and its combustion deteriorated functional
349 properties of the samples exposed to 400°C.

350 **4.2 Indirect Tensile Strength Results**

351 The following sections provide details of the specimens tested for the indirect tensile
352 strength.

353 **4.2.1 Results of the Indirect Tensile Strength test (28 days water curing)**

354 Figure 6 shows the average values and error bars of the indirect tensile strength results
355 for three cylinder specimens per each mix. The standard deviations were ranged from 0.20 to
356 0.58. Figure 2 (b) illustrates the crack pattern and failure of cylinder specimens under indirect
357 split tensile testing.

358 **4.2.2 Effect of crumb rubber and steel fibres percentages**

359 It can be seen from Figure 6 that the tensile strength value for mix M10@1, containing
360 10% crumb rubber as partial replacement of fine aggregate and 1% steel fibres was 2.87 MPa

361 which is higher than that of the control mix by 21%. For the same amount of crumb rubber but
362 increasing the steel fibres to 2%, mix M10@2, the tensile strength value was 3.05 MPa, which is
363 higher than that of the control mix by 29%. The tensile strength value for mix M30@1, having
364 30% crumb rubber and 1% steel fibres, was 1.65 MPa, which is lower than that of the control
365 mix by 30%. Increasing the steel fibres ratio to 2%, mix M30@2, resulted in a slight increase in
366 tensile strength reaching 1.87 MPa, which is still lower than that of the control mix by 21%.
367 This is in agreement with Sreeshma and Varghese (2016) who reported that concrete containing
368 up to 10% replacement of fine aggregate by crumb rubber and commercial steel fibres revealed a
369 higher tensile strength compared to that of the control mix. Thus, utilizing crumb rubber and
370 waste steel fibres is beneficial in applications requiring increased tensile strengths such as rigid
371 pavements or industrial ground floor slabs.

372 It was observed that rubberized concrete with small percentage of rubber and steel fibres
373 extracted from tyres behaved in a similar manner to those containing the commercial equivalent.
374 It was also noted that the increase of steel fibres in the mix from 1 to 2% resulted in a slight
375 increase in the tensile strength due to the partial replacement of fine aggregate with 10% crumb
376 rubber and the higher 30% of crumb rubber led to the reduction in the tensile strength.

377 **4.2.3 Effect of heating on Tensile Strength**

378 The effect of heating the specimens in the oven at 105° C for 12 hours can be observed
379 from the bar charts in Figure 6. Unlike the compressive strength values shown in Figure 5, and
380 discussed earlier in Section 4.1.3, all the tensile strength values decreased after exposing the
381 specimens to elevated temperature regardless the percentages of crumb rubber or steel fibres as
382 shown in Figure 6. For instance, rubberized concrete of 10% crumb rubber partial replacement
383 of fine aggregate and 1% steel fibres in the mix, M_h10@1, specimens exposed to heating in the

384 oven resulted in a reduction of tensile strength value by 23% compared to that of mix M10@1
385 (air dried).

386 For Mix M_h10@2, which included 2% steel fibres had a tensile strength value lower than
387 that of mix M10@2, by 25%. This shows that the reduction of tensile strength for overheated
388 specimens in this study were lower than that observed by Sharobim et al., (2018) who studied
389 specimens containing crumb rubber only heated up to 300°C. However, one of the group
390 specimens studied by them and exposed to 70°C showed an almost similar reduction (24.4%).
391 For mixes, which have crumb rubber replacement of fine aggregate by 30%, the reduction of
392 tensile strength as a result of overheating was higher than that for 10% crumb rubber
393 replacement mixes.

394 Figure 6 shows that tensile strength values for M_h30@1 and M_h30@2 were lower than
395 those of M30@1 and M30@2 by 35% and 37%, respectively. The results in this study show that
396 concrete mixes with crumb rubber and steel fibres extracted from waste tyres may not be suitable
397 for tension applications under high temperature. Similarly, Li et al., (2019) reported that
398 rubberized concrete could improve the thermal insulation of building enclosures saving energy
399 and reduce CO₂ emissions, but was unsuitable for elevated temperature applications in tension.

400 It can be argued that oven drying curing (preconditioning) was harsh for the specimens
401 containing the 30% crumb rubber since the crumb rubber is expected to expand and weaken the
402 bond between the aggregate particles and itself with cement paste. This expansion establishes
403 micro cracks which eventually lead to fracture of the specimen.

404 **4.3 Flexural strength results (28 days water curing)**

405 Details of flexural strength test results are considered in the following section.

406 **4.3.1 Results of the Flexural Strength Test (28 days water curing)**

407 Thirty 100 mm square cross-section prism specimens of 500 mm length, as indicated in
408 Figure 3, were prepared and tested for flexural strength after water curing for 28 days. Half of
409 these prisms were tested immediately after curing, while the other half were left in the oven for
410 12 hours at 105°C. For each mix, 3 prism specimens were tested after the curing period, while,
411 the other three were tested after oven dried and cooling in the room temperature inside the
412 laboratory. The average values of the test results were recorded.

413 **4.3.2 Cracking Behaviour and Failure**

414 Figure 7 shows the flexural failure of a prism specimen. It was observed that crackings
415 occurred prior to failure at the peak load. The recorded peak load was dependent on the crumb
416 rubber and steel fibres percentages. Increasing the crumb rubber resulted in a lower peak load,
417 while, increasing the steel fibres percentage led to increasing the peak load, in the line with Abu
418 Bakar et al., (2017) who studied the effect of the combination of crumb rubber and steel fibres on
419 flexural strength and toughness of concrete. They reported that the post-cracking behaviour of
420 the rubberized concrete slab elements induced more ductility leading to increase in the waste tyre
421 crumb rubber aggregate ratio up to 20%. In addition, Eldin and Senouci (1994) observed that the
422 control specimens were broken into two pieces under loading while the rubberized concrete did
423 not show brittleness under flexural loading. Moreover, Hu et al., (2018) reported that the
424 addition of specific ratios of blended steel fibres in concrete improved the mechanical properties.

425 **4.3.3 Effect of Crumb Rubber and Steel Fibres Percentages**

426 Figure 8 shows the average values of the three specimens per mix and the error bars for
427 the flexural strength results for specimens of different mixes after 28 days water curing. The SD
428 calculated from the test results ranged from 0.15 to 0.67.

429 Figure 8 shows that the flexural strength value for mix M10@1, containing 10% partial
430 replacement of fine aggregate by crumb rubber and 1% steel fibres was 5.85 MPa. This value is
431 higher than that of the control mix by 22.60%. For the same amount of crumb rubber and 2%
432 steel fibres content, mix M10@2, the flexural strength value was 6.10 MPa, which is higher than
433 that of the control mix by 28%. The flexural strength value for mix M30@1, having more crumb
434 rubber of 30%, and 1% steel fibres, was 2.73 MPa. This value is lower than that of the control
435 mix which was 43%. Záleská et al., (2019) reported that the lowest flexural strength was
436 observed for 30% replacement of fine natural aggregates with fine rubber particles. Increasing
437 the steel fibres ratio to 2% while keeping the crumb rubber percentage at 30% for sample
438 M30@2, resulted in a slight increase in the tensile strength ratio to 2.93 MPa, however, it was
439 still lower than that of the control mix by 39%.

440 Abu Bakar et al., (2017) reported that an increase in the steel fibres percentage in the
441 combined crumb rubber and steel fiber mix improved the flexural strength. Sreeshma and
442 Varghese (2016) also reported that combining the crumb rubber by 10% fine aggregate
443 replacement and adding steel fibres provides higher splitting tensile and flexural strengths
444 compared to those of normal concrete mix. Sofi (2018) reported that the flexural strength
445 decreased when the amount of rubber was increased from 20 to 30%. Again, the trend shown
446 here suggests that the percentage of rubber should be limited to under 20%. It is worth
447 mentioning that the addition of steel fibres overcomes the reduction in flexural strength as a
448 result of increasing the crumb rubber percentage.

449 4.3.4 Effect of Heating on Flexural Strength

450 The effect of oven drying of the prism specimens at 105° C for 12 hours can be seen with
451 error bars in Figure 8. All the flexural strength results decreased after being exposed to elevated
452 temperature in a similar manner to those of the indirect splitting tensile strength, as shown in
453 Figure 6. It was observed that the reduction was very extreme and more than those of the
454 indirect splitting tensile strength values. For example, heated rubberized concrete with 10%
455 crumb rubber replacement of fine aggregate and 1% steel fibres in the mix, M_h10@1 had a
456 reduction of flexural strength value by 27% compared to that of the non-heated mix, M10@1.
457 For mix M_h10@2, which included 2% steel fibers, the flexural strength value was lower than that
458 of M10@2 by 35%. For mixes having crumb rubber replacement of fine aggregate by 30%, the
459 reduction of flexural strength as a result of heating was higher than that for 10% crumb rubber
460 replacement mixes.

461 The flexural strength values for mixes M_h30@1 and M_h30@2 were lower than those of
462 mixes M30@1 and M30@2 by 39% and 46%, respectively. This is in the line with the findings
463 of Sharobim et al. (2018) who reported an almost similar reduction for the group of specimens
464 tested after being exposed to 70°C compared with the other group which was tested at 25°C.
465 The results in Figure 8 show that the reduction of flexural strength values for specimens
466 containing 30% crumb rubber, as a result of heating, is higher than that of compressive strength
467 values for specimens containing the same crumb rubber volume shown in Figure 6.

468 Zukri et al., (2017) also found that the reduction of flexural strength of heated rubberized
469 concrete containing steel fibres is higher than the reduction of compressive strength for the same
470 concrete mix. The reduction of compressive and flexural strengths may be attributed to the

471 expansion of the crumb rubber at high temperature (105°C). However, the reduction in flexural
472 strength is higher than that of the compressive strength due to the type of applied load and its
473 effect. In compression, the rubber as a compressible material with Poisson's ratio round 0.5 filled
474 the voids and it was prevented by the existence of the coarse aggregate from excessive expansion
475 even with heat curing conditions.

476 In flexural loading, the tensile forces generated on the rubber increases the possibility of
477 using its inelastic property, that is, (nonlinear elastic stress strain curve of the rubber) reaching
478 fracture of rubber particles. The Poisson effect took place inversely by reducing the size of the
479 particles that were exposed to the tensile forces which, in turn, reduces the strength. In higher
480 temperatures, this inelastic property degraded leading to rapid and more reduction in the flexural
481 strength as observed by Sharobim et al. (2018) for specimens tested after being exposed to
482 400°C.

483 **4.4 Air Permeability Test Results**

484 The repeatability and reliability of the proposed air permeability test method were
485 checked by carrying out the test on fifteen different cubes of the control mix and for the decay
486 from 100 kPa to 10 kPa. Figure 9 shows the air permeability index in seconds against test
487 number. The standard deviation and coefficient of variation were as low as 2.19 and 2.87%,
488 respectively. Figure 10 shows the decay of air pressure over the specified range. It can be seen
489 from Figure 10 that the regression analysis is approximately linear with a high correlation
490 coefficient, $r=0.996$.

491 The variations in the permeability time index for the different mixes studied in this
492 investigation and the error bars are shown in Figure 11. The actual measurements for three

493 specimens per each mix studied were recorded and the average values are indicated in Figure 11.
494 It can be seen that the control specimen that was air dried in the laboratory had the maximum
495 time index with an average value of 75.7 seconds, which is an indication of lowest permeability
496 among the studied specimens.

497 Oven drying control specimens (Control_h) revealed a reduction in time index by 39.2%
498 compared to non-heated samples. Recent advances have shown that the drying regime has a
499 significant effect on the values and repeatability of air permeability results (Yang et al., 2013 and
500 2015). It has been argued that drying specimens in the laboratory room temperature for two days
501 led to non-repeatable and misleading results (Dhir et al, 1995; Claisse et al, 1999b). They
502 reported that oven-drying specimens to 105°C for two days led to stable and repeatable results
503 but they reported that the overheating for two days could alter the pore structure of the tested
504 concrete to different degrees depending on the concrete grade. Achang et al., (2019) reported
505 also the significance effect of moisture content on permeability results.

506 The values of air permeability index for different mixes, shown in Figure 11 revealed that
507 the addition of crumb rubber as a partial replacement of fine aggregate and adding steel fibres to
508 the mix decreases the permeability time index. For example, replacing fine aggregate by 10%
509 crumb rubber and adding 1% steel fibres to the mix, M10@1 resulted in a higher permeability
510 (lower time index) of 23.3% less than that of control specimens. This study shows that oven
511 dried specimens (M_h10@1) had lower permeability (higher time index) before oven drying
512 compared to the normal concrete. This was obtained for the increase in time index to 67 seconds
513 which is the highest time index of those of mixes containing waste tyre extracts. It can be argued
514 that for reasonable partial replacement of fine aggregate with crumb rubber (10%), the rubber
515 expands at high temperatures filling the pores in concrete which expected to reduce the

516 permeability of concrete. Zukri (2017) reported that at high temperature the rubber particles fill
517 the narrow channels in the pore structure and a better pore structured system was observed.

518 It can be seen from the error bars shown in Figure 11 that the standard deviation values of
519 oven-dried specimens were less than those dried at room temperature in the laboratory.
520 Increasing the crumb rubber content to 30% had an adverse effect on concrete permeability and
521 oven-drying specimens having 30% crumb rubber had even lower permeability compared with
522 all other specimens, as shown in Figure 11. This may be attributed to the fact that increasing the
523 crumb rubber content more than 10% with steel fibres resulted in higher porosity, which is the
524 most crucial factor for concrete permeability. Liu et al., (2018) reported that an increase in the
525 crumb rubber content resulted in higher water permeability of rubber-modified concrete.

526 **4.5 Air Permeability Index: Correlation with Other Properties**

527 The above section showed that the developed test successfully provided a good
528 measurement for the relative permeability performance of concrete based on mix contents. The
529 following sections demonstrate the influence of air permeability on the mechanical properties of
530 studied concrete.

531 **4.5.1 Air permeability and compressive strength results trend**

532 Figure 12 was established based on the results shown in Figures 5 and 11. Figure 12
533 shows the relationship between the compressive strength and air permeability index after 28 days
534 of concrete curing for different studied specimens under different drying regimes. As shown
535 from Figures 5, 11, and 12, the permeability time index for any mix increase in compressive
536 strength with a linear relationship regardless of the type of mix or the drying regime. The

537 relationship between the air permeability index and the compressive strength showed good
538 correlation with $r = 0.91$.

539 This is in agreement with Katapady et al., (2018): they showed that the relationship
540 between the compressive strength and the permeability for a blended concrete containing fly ash
541 and slag cement was linear with a high correlation, regardless of the curing conditions.

542 **4.5.2 Air permeability, tensile strength, and flexural strength results trend**

543 The indirect splitting tensile and flexural strengths are distinct measures for strength. As
544 expected, they were significantly different in magnitudes; however, they followed a similar
545 pattern of variation as shown in Figures 6 and 8. Figures 13 and 14 show the indirect splitting
546 tensile strength and air permeability index relationship as well as flexural strength and air
547 permeability index relationship, respectively. The figures show that the relationships in both
548 figures have scattered results with linear relationships of correlation values, $r = 0.78$, and 0.84 ,
549 respectively.

550 These relationships had lower correlation compared to that for compressive strength and
551 air permeability index. This agrees with the findings of Mohamed et al., (2017) where the same
552 pattern and trend of variation between air permeability and both indirect splitting tensile and
553 flexural strengths of concrete having Arabic Gum Biopolymer in its ingredients. Furthermore,
554 Cui et al., (2016) reported also a direct relationship between compressive, flexural strengths and
555 coefficient of permeability.

556 It is worth mentioning that the higher time index indicated lower permeability and this
557 explains why the relationships between permeability and different mechanical properties in this
558 investigation had the same trend.

559 **5. Conclusions**

560 The influence of crumb rubber and steel fibres partial replacement of fine aggregate
561 replacement on the mechanical properties and air permeability of concrete was considered in this
562 study. The crumb rubber used was pre-treated with sodium hydroxide prior to adding to the
563 concrete mix.

564 Five mixes were considered and included 10% and 30% crumb rubber and together with
565 1% and 2% steel fibres extracted from waste tyres as partial fine aggregate replacement.

566 A portable easy to use air permeability apparatus was successfully developed and used to
567 test the concrete samples.

568 The combination of crumb rubber and steel fibres in the concrete mixes led to a reduction
569 of compressive strength and weight of the concrete specimens. An increase in the steel fibres
570 percentage while keeping the rubber content constant resulted in increased compressive strength
571 of concrete. Rubberized concrete of 10% crumb rubber and 1% steel fibres exposed to oven
572 drying at 105°C for 12 hours exhibited an increase in compressive strength.

573 The splitting tensile strength of the concrete specimens containing 10% crumb rubber and
574 1% steel fibres was higher than that of the control mix by 21%. An increase in the steel fibres to
575 2% resulted in slight increase of 9% only. All the splitting tensile strength results decreased after
576 exposing the specimens to an elevated temperature regardless of the percentages of crumb rubber
577 or steel fibres used.

578 Flexural strength results decreased after being exposed to an elevated temperature in a
579 similar manner to those for the splitting tensile strength results.

580 Unlike normal concrete, rubberized concrete containing steel fibres provided warning
581 prior to failure in terms of a wide flexural crack which indicated the existence of ductile
582 behaviour in the specimens. Flexural strength of concrete containing 10% crumb rubber and 1%
583 steel fibres was higher than that of the control mix by 22.6%. Increase in the steel fibers content
584 to 2% resulted in a slight increase of flexural strength by 6% only.

585 Replacing fine aggregate with 10% crumb rubber and 1% steel fibres in the mix resulted
586 in a higher permeability (lower time index) by 23.3% less than that of the control specimens.
587 Oven dried control specimens resulted in a higher permeability (reduction of the average time
588 index) by 39.2% compared to that of their air-dried samples.

589 Oven drying improved the permeability of specimens contain 10% crumb rubber and 1%
590 steel fibres as indicated by a lower permeability (increase in time index) by 15% compared to
591 their air-dried samples. A further increase in the crumb rubber to 30% and oven drying samples
592 had an adverse effect on concrete permeability which was indicated by lower time index (higher
593 permeability).

594 The relationship between the compressive strength and air permeability index values is
595 linear with a good correlation ($r = 0.91$), regardless the type of mix or the drying regime. Other
596 mechanical properties, namely, tensile strength, and flexural strength had lower correlation
597 relationships with air permeability index; however, they had the same trend.

598 The experimental results showed a promising application of extracted steel fibres /crumb
599 rubber combination in reinforced concrete. The steel extracted from the waste tyres exhibited a
600 similar performance as commercial steel fibres employed by other investigators.

601 It is recommended that the rubber content is limited to 10% and 1% steel extract for
602 outdoor structural applications. However, higher percentages of these waste tyre extracts can be
603 used for indoor applications. These mixes can be used for pavements and slab on grade
604 applications, where they it would withstand moderate temperatures and provide reasonable
605 flexure performance.

606 The using of waste tyre materials is considered a sustainable, viable, economic and
607 environmentally friendly method for the production of concrete and would mitigate against the
608 energy used-up in buildings operations as well as reduce carbon footprint.

609

610 **Data Availability**

611 All data, models, and code generated or used during the study appear in the submitted article.

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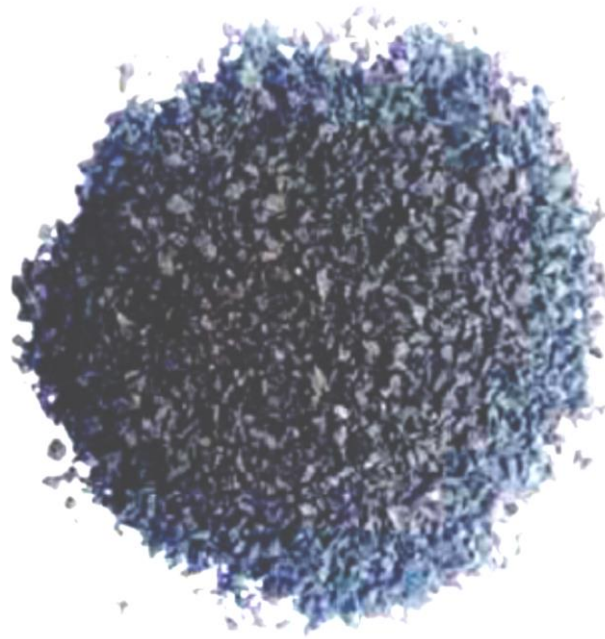
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(a) Crumb rubber particles (0.425- 4.75 mm)



(b) Extracted steel fibres

Figure 1: Materials extracted from waste tyres and used in mixes preparation.



(a) Concrete cube sample

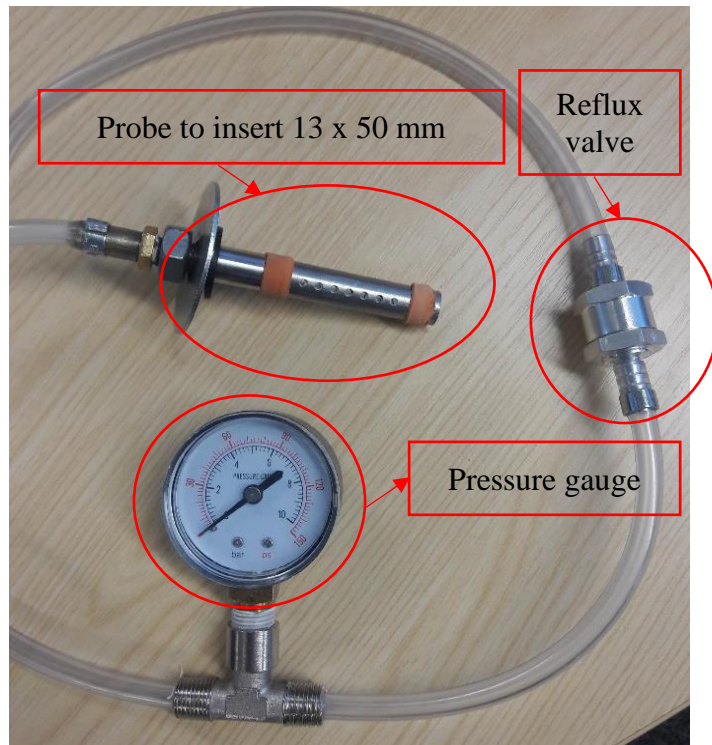


(b) Concrete cylinder sample

Figure 2: samples containing 10% crumb rubber and 1% steel fibres; (a) after compressive strength testing, and (b) after splitting tensile strength testing.



Figure 3: Setup of flexural strength test.

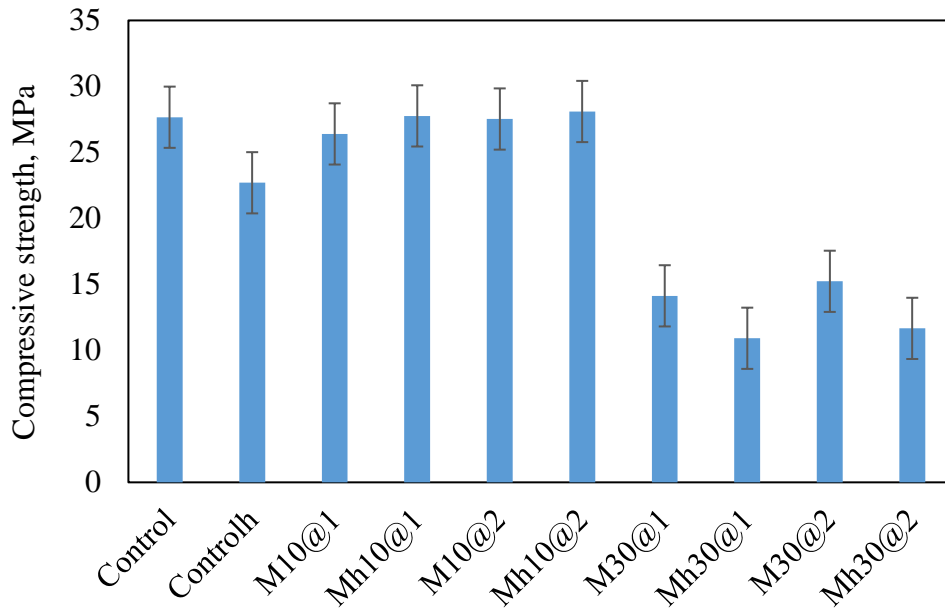


(a) Probe, pressure gauge, and reflux valve.



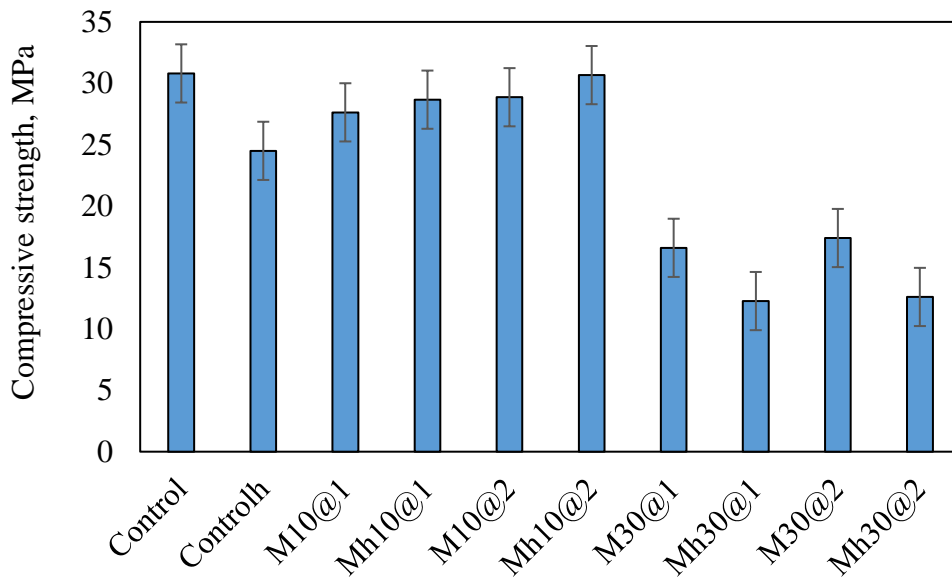
(b) Test apparatus attached to a portable pump.

Figure 4: Developed portable permeability index test apparatus.



Mixes used in the experimental work

a) Testing after curing for 7 days



Mixes used in the experimental work

b) Testing after curing for 28 days

Figure 5: Compressive strength results for different specimens of studied mixes.

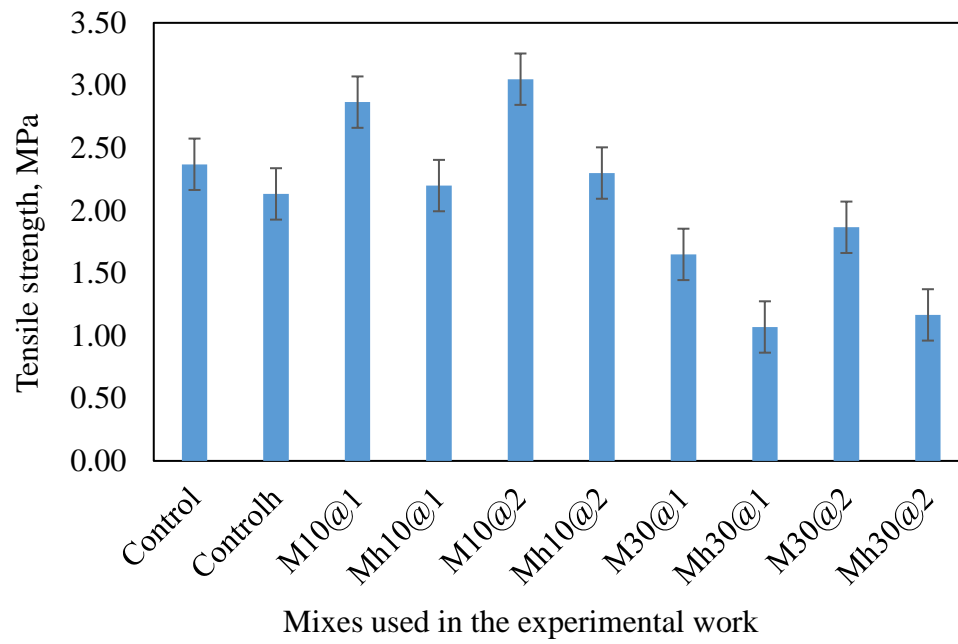


Figure 6: Tensile strength results for different specimens of studied mixes.

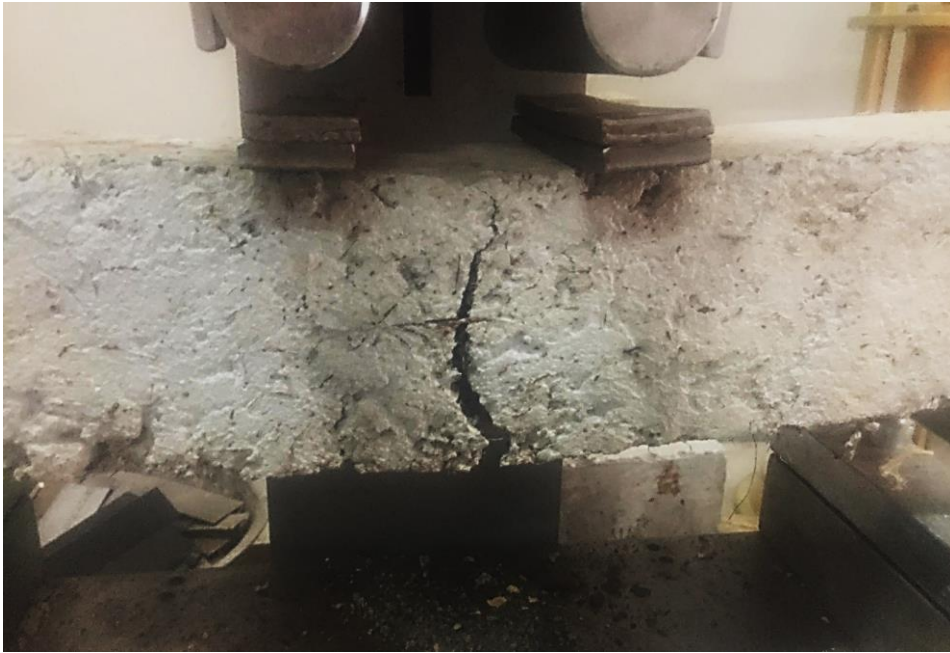


Figure 7: Typical failure mode of prism specimen containing crumb rubber and steel fibres

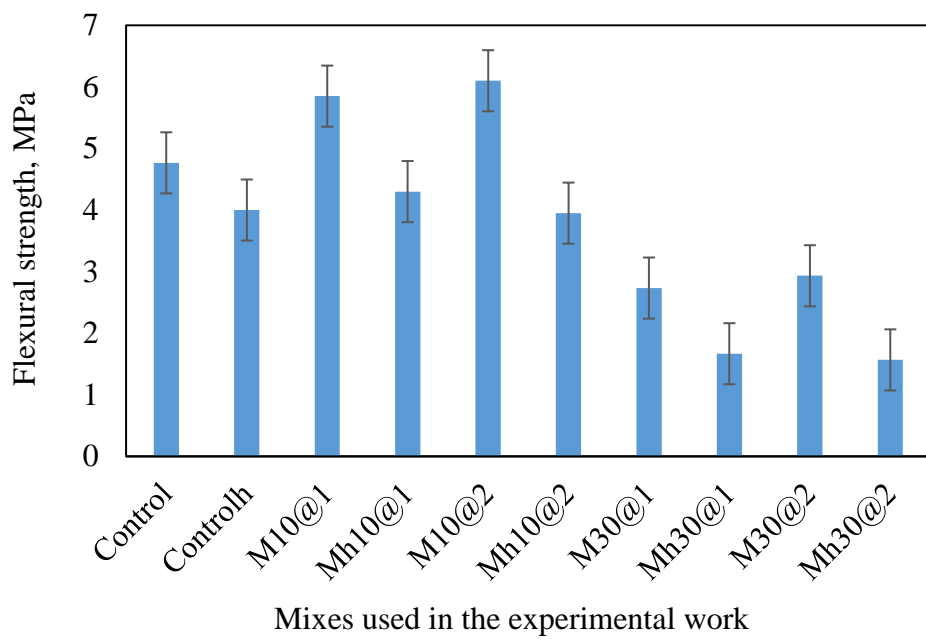


Figure 8: Flexural strength results for different specimens of studied mixes.

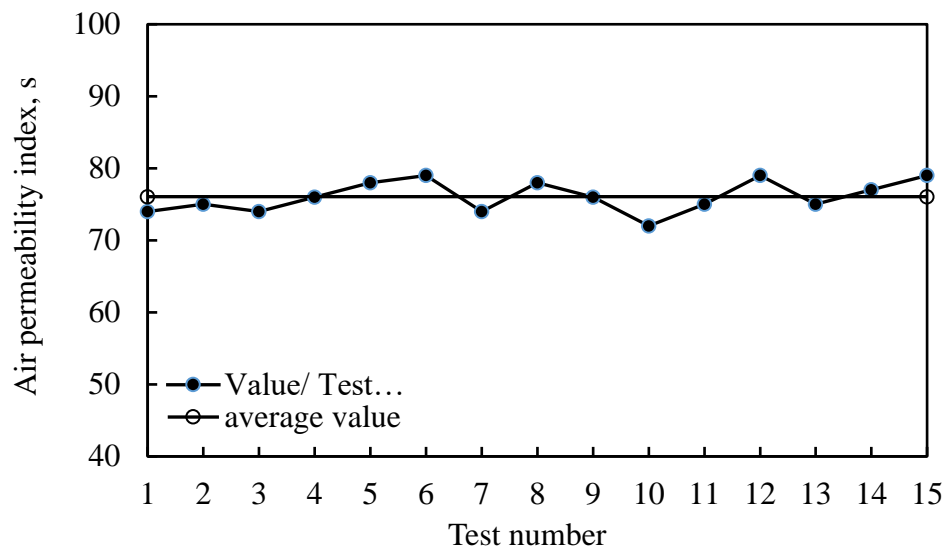


Figure 9: Repeatability of air permeability index for fifteen specimens of the control mix

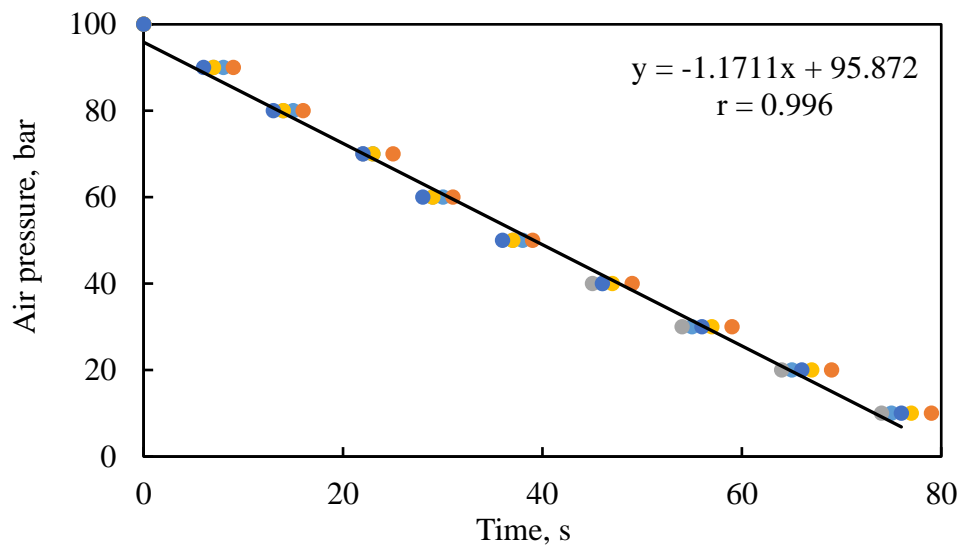


Figure 10: Air pressure decay for many specimens of the control mix

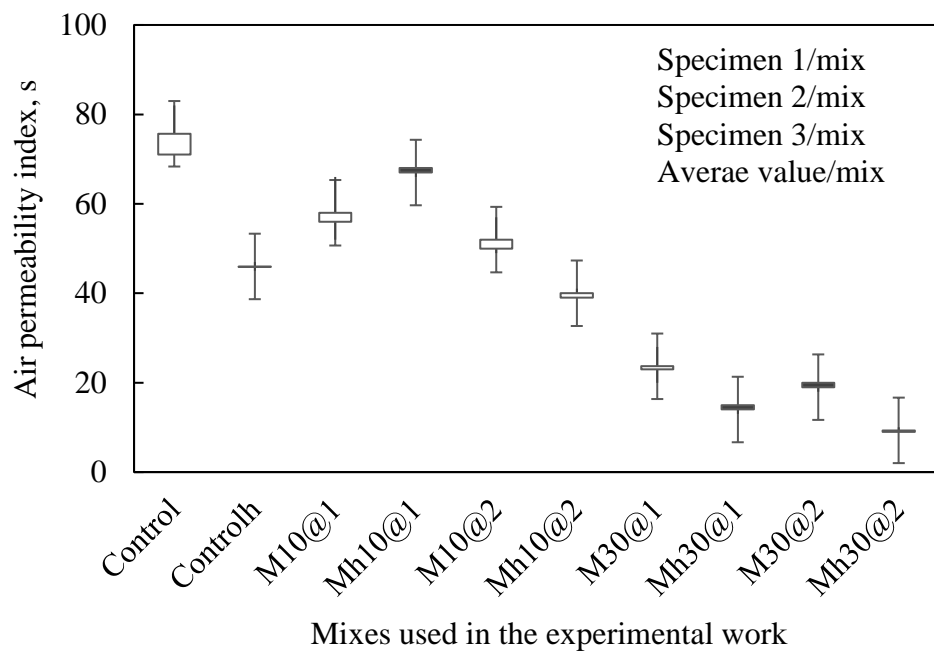


Figure 11: Permeability indices for different specimens of studied mixes.

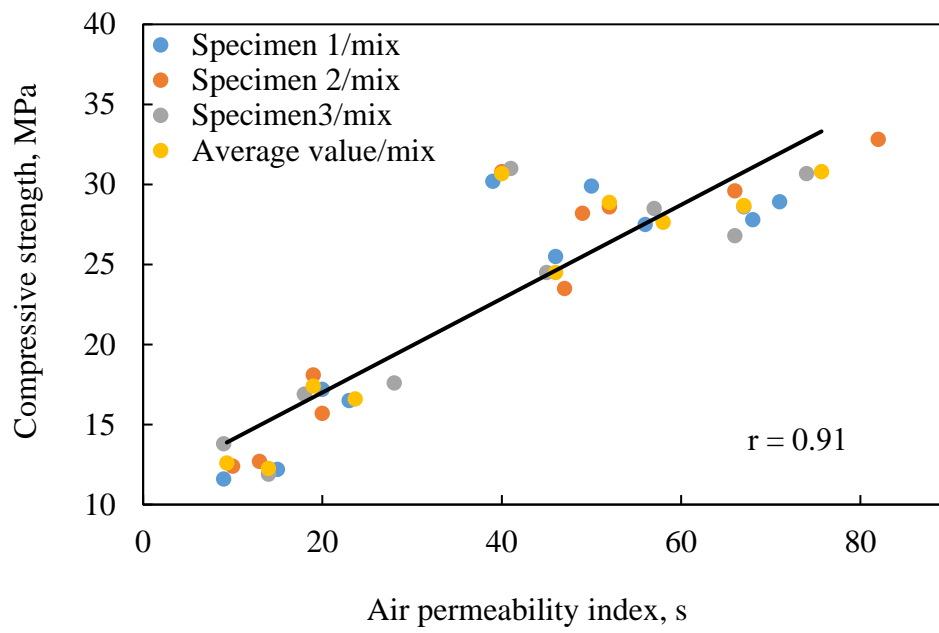


Figure 12: Compressive strength versus air permeability index

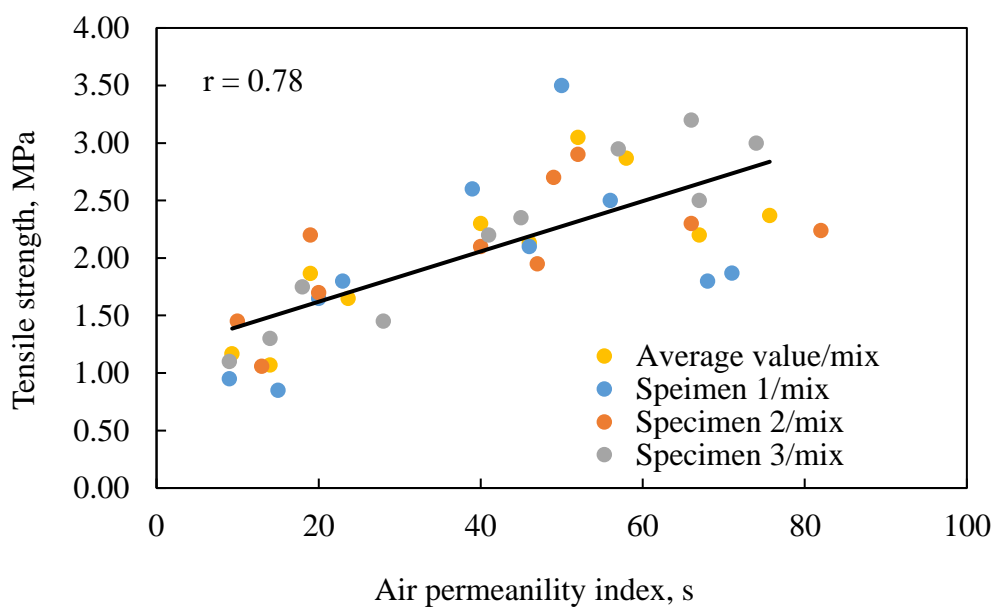


Figure 13: Tensile strength versus air permeability index

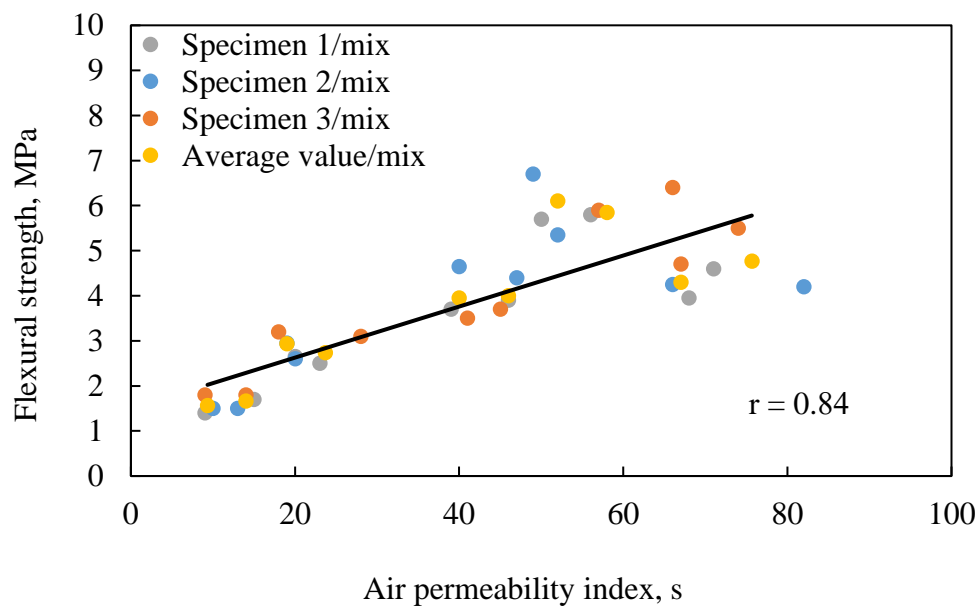


Figure 14: Flexural strength versus air permeability index

Table 1 Material quantities for concrete mix

Mix designation	Solid constituents and proportions, kg/m ³					Water, Liter/ m ³	Water/ cement	Slump, mm
	Cement	Sand**	** Crumb rubber	Steel fibres	Coarse aggregates			
Control*	350	620	--	--	1230	175	0.50	40
M10@1	350	530	30	75	1230	175	0.50	55
M10@2	350	450	30	150	1230	175	0.50	50
M30@1	350	480	90	75	1230	175	0.50	75
M30@2	350	400	90	150	1230	175	0.50	80

*Target Strength, 30 MPa

**The replacement of sand with crumb rubber was by volume (the weights above are for 1 m³)