

## Self-healing concrete

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# 1 Self-healing Concrete

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9  
10 **Abstract:** Concrete is used in the construction area worldwide. However, concrete is generally  
11 brittle and easily to be cracked, especially under a tensile force. Moreover, in order to reduce the  
12 amount being used of sand, waste rubber is tried to be used to replace sand. Nevertheless,  
13 adding rubber induces reductions of mechanical properties. Thus, a kind of fibre named Duras  
14 Easyfinish is tried to be used to offset the negative influence from adding rubber. In this  
15 chapter, specimens with standardized and natural cracks are tested for inspecting self-healing  
16 abilities when different contents of the fibre are added in concrete. Tests proved that mechanical  
17 properties increase to the highest value when 0.2% of the fibre is put in concrete. It can be  
18 explained that the fibre combines cracks to improve strength of concrete. Moreover, Ultrasonic  
19 Pulse Velocity (UPV) results of specimens with standardized cracks show very low self-healing  
20 increase rates which fluctuate from 0.1% to 1%. This chapter has revealed the reason of low  
21 self-healing increments which is the fibre is merely added as an element in concrete instead of  
22 bonding. Self-healing increase rates of specimens with natural cracks ascend from around 3.25%  
23 to 3.5% between 30 days and 36 days, then the values fall down within next six days. The  
24 Natural Frequency test is another indicator for measuring self-healing abilities of concrete.  
25 Natural frequencies of specimens with different depth of cracks have also been highlighted in  
26 this chapter.

27 **Keywords:** Self-healing Concrete; Fibre; Rubber; Ultrasonic Pulse Velocity; Natural Frequencies;  
28 Recycled Concrete

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## 85 1. Introduction

86

### 87 1.1 Background

88 Concrete is made by mixing cement, coarse and fine aggregate and water. It is widely used  
89 and it has high compressive strength, high stiffness, and low cost [1]. The obvious disadvantage  
90 of concrete is the weak tensile strength that can easily induce cracks [2]. Cracks will expand  
91 gradually to be permeability if there is no immediate repair [3]. This means that carbon dioxide,  
92 chloridion, and water in the air can easily attach to steel bars and cause corrosion [4]. Thus,  
93 these cracks not only result in reduction on the strength of concrete, but can also shorten the  
94 durability of buildings [5]. 45% of the annual construction fee is spent on maintenance of  
95 existing buildings in the UK [6]. If cracks can be healed by themselves, then the maintenance fee  
96 of buildings can be dramatically reduced. Moreover, it is difficult to check cracks in places  
97 where access is difficult. It is also really difficult to properly check the stability of buildings,  
98 especially for large-scale structures [7]. Furthermore, manual methods to repair cracks have  
99 limitations, such as using chemical and environmentally unfriendly construction materials [8,  
100 9].

101 In order to protect the environment, crumb rubber is used to replace sand. The number of  
102 discarded tyres, which are out of service, is estimated as the second largest waste material  
103 worldwide [10]. The major component of rubber, Styrene, is bad for the health of environment.  
104 Moreover, it may stimulate eyes and the upper respiratory tract mucosa when it is burned [11].  
105 Furthermore, land is the potential living site of animals that are filled with wasted tyres. It is  
106 urgent to deal with the negative influence from wasted tyres. In this chapter, crumb rubber  
107 made from crushed wasted tyres substitutes a small part of sand to test on mechanical  
108 properties of rubberized concrete.

109 Self-healing concrete has been paid much attention to in past 40 years. There have been  
110 some research works about self-healing with bacterial additions [12]. However, there is no  
111 study on self-healing abilities of crumb rubber concrete with fibre. If the rubberized concrete  
112 with fibre can satisfy strength requirements and has a good performance in terms of  
113 self-healing, it can be used to manufacture sleepers or bearers which are hard to access for  
114 maintenance. Moreover, it is really helpful to keep environment healthy away from pollution of  
115 waste tyres. Thus, it is meaningful to investigate self-healing abilities of rubberized concrete  
116 with fibre. Additionally, in this chapter, a new measurement of self-healing abilities will be  
117 used for the first time, introduced from the crack inspection system.

118

### 119 1.2 Literature Review

#### 120 1.2.1 Crumb Rubber Concrete (CRC)

121 There are three types of rubber which researchers have tested so far. These are ground  
122 rubber, rubber chips and crumb rubber. Comparing the three types of rubber, rubber chips and  
123 ground rubber reduce more compressive strength than crumb rubber [13]. Thus, crumb rubber  
124 is chosen as an additional material in concrete in order to reduce the effect of waste rubber.

125 Different views have been put forward on mechanical properties of rubberized concrete.  
126 There was a kind of concrete with rubber has lower compressive strength than plain concrete  
127 [14, 15]. Nevertheless, Faraz, Jain and Singh [16] obtained a different result that the compressive

128 strength of 5% rubberized concrete was higher than that of plain concrete. The reason of this  
 129 special case is that rubber in concrete generated voids which may reduce bonding strength  
 130 between cement and rubber [17]. Splitting tensile strength and flexural strength will also  
 131 decrease by adding rubber in concrete [18, 19]. Thus, it is significant to find other materials to  
 132 offset influence of adding rubber.

### 133 1.2.2 Fibre in Concrete

134 Fibre is the material which could potentially reduce influence on mechanical properties of  
 135 using rubber. Steel fibre is a kind of fibre which has a good performance on ductility and  
 136 fracture toughness [20]. However, steel fibre is easily corroded when exposed to a high sulphate  
 137 and chloride environment. Thus, another kind of fibre named Duras Easyfinish fibre will be  
 138 used in concrete to avoid corrosions. Furthermore, fibre can act as cores for the precipitation of  
 139 calcium carbonate ( $CaCO_3$ ) [21]. This mechanism can stimulate generation of calcium  
 140 carbonate to improve self-healing performance.

141 In this chapter, Duras Easyfinish fibre is added into concrete to enhance mechanical  
 142 properties and self-healing abilities. Adding different proportions of the fibre into concrete is  
 143 carried out to identify the percentage that can perform the highest self-healing ability.

### 144 1.2.3 Self-healing Concrete

#### 145 1. Background of Self-healing Concrete

146 The mechanism of healing cracks is to produce calcium carbonate and then cracks can be  
 147 filled up with calcium carbonate. There are two ways to generate calcium carbonate during  
 148 self-healing procedures. The first one is that unreacted cement particles start hydration to  
 149 form  $CaCO_3$ . The second one is that  $CaCO_3$  is formed after dissolution of  $Ca(OH)_2$   
 150 [22]. Equation X.1 shows different ways for forming calcium carbonate in different pH values  
 151 of water [23].

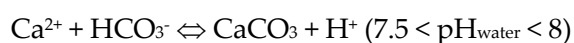
152



153



154



(EQUATION X.1 HERE)

155

#### 156 2. Influence Factors of Self-healing

157 Many factors which may influence self-healing abilities are concluded by previous  
 158 researchers. There are five main factors as follows:

- 159 • Moisture content: pilot specimens stored in water can heal by themselves more effectively.
- 160 • Crack width: width of cracks smaller than 0.3mm can be healed completely [24]. Cracks  
 161 which are wider than 0.3mm may not be healed. 0.1mm width cracks are completely  
 162 healed after around 200 hours. Moreover, 0.2mm and 0.3mm width cracks are mostly  
 163 healed within 30 days [25]. Cracks ranging in width from 0.15mm to 0.3 mm significantly  
 164 decrease in 7 days and are completely healed in 33 days [26].

- 165 • Time for hydration: hydration for a longer time can yield a better performance on  
166 self-healing [27].
- 167 • Pressure loaded on cracks: loading proper pressure on cracks can stimulate a better  
168 self-healing ability.
- 169 • Water cement ratio: a higher water cement ratio includes more unreacted cement particles  
170 that can be used for further hydration to boost generation of calcium carbonate.

171 Furthermore, time of cracking is also important. Earlier cracking concrete has more unreacted  
172 cement particles, thus it can perform a high self-healing ability with ongoing hydration [28].

### 173 1.2.4 Assessment of Self-healing Concrete

#### 174 1. Making Cracks

175 There are specimens with standardized cracks and natural cracks in this chapter.

176 For natural cracks, they were made by using a compressive test machine and controlled the  
177 width of cracks carefully by visual inspection learned from previous researchers [29, 30].  
178 However, it was almost impossible to make cracks on unreinforced specimens when just used a  
179 compressive machine according to tests conducted by the author. This is because of flexural  
180 strength of specimens is very low. Thus, specimens were completely broken into 2 pieces by  
181 only using compressive machine.

182 Standardized cracks were usually made by inserting plates. A thin cooper plate of 0.3mm  
183 was inserted in the middle of fresh concrete [31]. In this chapter, 0.25mm thickness plastic films  
184 are used to make standardized cracks.

#### 185 2. Methods of Measuring Self-healing Abilities

#### 186 3. Ultrasonic Pulse Velocity Values

187 UPV values are usually used to detect integrity of concrete and non-destructively measure  
188 damage degrees of concrete [24]. Moreover, researchers have proven that there is a connection  
189 between damage and decrease of UPV results [32, 33, 34]. If cracks are healed, UPV results of  
190 specimens with cracks will decrease to the values of unbroken specimens. This can be  
191 recognized as the mechanism of measuring self-healing abilities by applying UPV tests [30]. In  
192 this chapter, another aided method is to visually inspect whether cracks can be healed by  
193 themselves.

#### 194 • Natural Frequencies

195 Natural Frequencies are used to detect inside damage in construction industries, especially  
196 on road and bridge construction sites. Nature frequencies of concrete specimen will be changed,  
197 when hardness of the specimen is varied [35]. That is the reason why the natural frequency can  
198 be a potential property to identify self-healing abilities of specimens with different cracks in this  
199 chapter. Detecting natural frequencies to identify self-healing abilities of concrete is firstly  
200 applied in this chapter.

## 201 2. Materials and Methods

202 The methodology of this project can be divided into 4 main steps. The first step is to  
203 investigate behaviours of concrete with crumb rubber and fibre, using engineering test  
204 standards, reviewing self-healing concrete theories, developing evaluation methods of

205 self-healing effectiveness and natural frequencies. The second step is to design experiments.  
206 The third one is to test specimens. And the final step is to analyse and discuss results.

## 207 2.1 Materials

### 208 2.1.1 Cement

209 According to the British standard BS EN 197-1, Ordinary Portland Cement type 1 (CEM 1) with  
210 the strength of 42.5 MPa is used to make concrete.

### 211 2.1.2 Water

212 The water in the laboratory is used.

### 213 2.1.3 Fine Aggregate and Coarse Aggregate

214 According to BS EN 12620:2002, sand particles which are smaller than 5mm can be used as  
215 fine aggregate [40]. Gravel particles which are between 5mm and 10mm can be used as coarse  
216 aggregate. A vibrating sieve can screen out useable aggregates. Before making concrete,  
217 aggregate need to be dried by an oven at 100° for an hour and moved outside for cooling to  
218 reach indoor temperature.

219 Furthermore, moisture content needs to be calculated during each test. 100g wet sand and  
220 1000g wet gravel are weighed and burned with 10-minute mix until there is no free water on the  
221 surface of aggregates. Afterwards aggregates are weighed again. Then, moisture contents of  
222 aggregates can be calculated and is shown in Table X.1.

223 TABLE X.1 HERE Moisture Contents of Aggregates

No.	Mixes	Moisture content (%)	
		Sand	Gravel
MIX 1	Reference Concrete	5	1.5
MIX 2	5% 180&400 CRC	5	1.5
MIX 3	5% 180&400 CRC+0.1% fibre	4.6	1.2
MIX 4	5% 180&400 CRC+0.15% fibre	8	1.4
MIX 5	5% 180&400 CRC+0.2% fibre	5	1.5
MIX 6	5% 180&400 CRC+0.25% fibre	10	1

224

225

### 226 2.1.4 Crumb Rubber

227 Sizes of crumb rubber in this chapter are 180 microns and 400 microns in Figure X.1 which  
228 are free from Lehigh Technologies Incorporation. They are mixed at the ratio of 1:1.

229 Moreover, Chen and Xiang [36, 18] showed that 5% of sand replaced by crumb rubber  
 230 obtained the highest compressive strength than other proportions of crumb rubber. Thus, in  
 231 this chapter, 5% of sand will be substituted by crumb rubber from Mix 2 to Mix 6.

232 FIGURE X.1 HERE a) 180 microns crumb rubber; b) 400 microns crumb rubber

### 233 2.1.5 Fibre

234 High performance construction fibre called DURUS EasyFinish from the ADFIL Construction  
 235 Fibre Company, as shown in Figure X.2, is used in this chapter. The fibre can reduce embodied  
 236 carbon dioxide and create more durable structures. The properties of fibre are shown in Table  
 237 X.2.

238 FIGURE X.2 HERE Duras Easyfinish Fibre

239

240 TABLE X.2 HERE Properties of Duras Easyfinish Fibre

Fibre Length	40mm
Fibre Type	Macro Monofilament
Shape	Embossed Elongated Design
Absorption	None
Specific Gravity	0.92kg/dm <sup>3</sup>
Electrical Conductivity	None
Softening Point (Melt Point)	165°C
Colour	Grey
Tensile Strength	470Mpa
E-Modules	6000Mpa
Chloride Content	None
SO <sub>3</sub> Content	None

241

## 242 2.2 Methods

### 243 2.2.1 Design of Concrete

244 In this chapter, there are 6 mixes of concrete which are listed in Table X.3. The water  
 245 cement ratio of concrete is 0.44 and slump values are from 60mm to 180mm. Mix 1 is the  
 246 reference concrete (RFC) which does not contain crumb rubber or fibre. From Mix 2 to Mix 6, all  
 247 of them contain 5% crumb rubber of the mass of sand. Mix 3, Mix 4, Mix 5 and Mix 6 contain  
 248 0.1%, 0.15%, 0.2% and 0.25% fibre of the mass of gravels respectively. Concrete specimens are  
 249 not reinforced, because reinforcement may cause interference of self-healing performance of the  
 250 fibre.

251

252

253



254

TABLE X.3 HERE Concrete Design

	Design of Concrete Mixtures	Cement	Water	Gravel	Sand	rubber	fibre	
No	Mixes							
MIX 1	Reference Concrete	530	233	986	630	32		
MIX 2	5% 180&400 Crumb Rubber Concrete			986	598			
MIX 3	5% 180&400 Crumb Rubber Concrete+0.1% fibre			983.621	598			2.379
MIX 4	5% 180&400 Crumb Rubber Concrete+0.15% fibre			982.431	598			3.569
MIX 5	5% 180&400 Crumb Rubber Concrete+0.2% fibre			981.242	598			4.758
MIX 6	5% 180&400 Crumb Rubber Concrete+0.25% fibre			980.052	598			5.948
		Unit: kg/m <sup>3</sup>						

255

## 256 2.2.2 Mixing Concrete

257 Making concrete follows steps in the BS ISO 1920-3 [37]. Slump tests are shown in Figure  
258 X.3.

259

260 FIGURE X.3 HERE Slump Tests

## 261 2.2.3 Casting Concrete

## 262 2.2.4 Making Cracks

## 263 • Standardized Cracks

264 For making standardized cracks, there are three steps. Firstly, concrete is poured into  
265 moulds. Secondly, plastic films of 0.25mm thickness with 100mm length are inserted in the  
266 middle of concrete after plastic films are completely oiled. Moreover, depth of plastic films is  
267 10mm, 20mm and 30mm respectively. Finally, plastic films are pulled out after 24 hours. Thus,  
268 three types of standardized cracks are generated. The size of the first type of cracks which is  
269 called A is W0.25mm xD10mm x L100mm. Moreover, the size of the second type of cracks  
270 which is called B is W0.25mm xD20mm x L100mm. Furthermore, the size of the third type of  
271 cracks which is called C is W0.25mm xD30mm x L100mm. Figure X.4 shows types of  
272 standardized cracks.

273

274 FIGURE X.4 HERE Standardized Cracks

## 275 • Natural Cracks

276 For making natural cracks, a 4-point bending machine is used. 24 Prisms (W100mm x  
277 H100mm x L500mm) are brought out from a curing tank at 28-days. Then, loads pressed by a  
278 4-point bending machine gradually increased with the rate of 100N/s. Afterwards, loads should  
279 be kept until cracks are visualized.

## 280 2.2.5 Concrete tests

### 281 • Compressive Strength

282 Based on BS EN 12390-3, three 100mm cubic samples are used for compressive strength  
283 tests at 7 days, 14 days and 28 days respectively [38]. The brand of the compressive machine is  
284 called Avery-Dension Limited. The model of the machine is 7225 DT which is made in Leeds of  
285 the UK. During compressive tests, 3 aspects should be paid attention. Firstly, cubes need to be  
286 dried naturally before testing. Secondly, all surfaces of cubes should be cleaned. Next, cubes  
287 must be put in the centre of the compression plate [39].

### 288 • Splitting Tensile Strength

289 Based on BS EN 12390-6, three cylinders ( $\varnothing$ 100mm x L 200mm) are tested with a 4-point  
290 bending machine at 28 days [40]. The brand of the machine is named by Avery-Dension  
291 Limited. The model type of it is AD-T42 which is manufactured in Leeds of the UK. Before  
292 testing, the loading pad of the machine and all surfaces of cylinders need to be cleaned. During  
293 testing, the rate of loading is 100N/s. The loading pad needs to be lifted immediately when  
294 cylinders fail. Then, the maximum splitting tensile strength values showed on the machine  
295 need to be recorded.

### 296 • Flexural Strength

297 Based on BS EN 12390-5, three prisms (W100mm x H100mm x L500mm) will be tested  
298 using a bending machine at 28 days [41]. Specimens need to be cleaned and dried and then put  
299 in the centre of the machine. Afterwards, continuous loading is essential with a rate of 100N/s  
300 until prisms fail.

### 301 • Self-healing Evaluation

302 There are some methods for calculating self-healing rates which have been utilized by  
303 previous researchers, such as Scanning Electron Microscopy (SEM) [9]. By using SEM methods,  
304 it is possible to see deposition sites. However, it is impossible to distinguish compositions of  
305 precipitation.

306 The UPV test is an alternative measuring method of self-healing. Based on BS EN 12504-4,  
307 an UPV test is used to evaluate the speed of passing concrete [42]. Before UPV testing, prisms  
308 are brought from a curing tank and dried in an oven at 90° for 30 minutes to reduce negative  
309 effects from high moisture content. Then, prisms are taken out for cooling to reach at room  
310 temperature for eliminating errors from high temperature.

311 The UPV equipment in Figure X.5 needs to be calibrated before testing by referring to  
312 25.1us with a block whose traveling time is known and then zeroed. For every prism, it is  
313 essential to test 3 times from different dimensions to obtain more accurate data. Testing  
314 dimensions of each prism need to be recorded and orderly tested every time. Results of the UPV  
315 test should remain steady and then can be recorded.

316

317 FIGURE X.5 HERE UPV Tests

318 For natural and standardized cracks, the UPV test starts from 28 days after casting and they  
319 are tested every 2 days. Equation X.2 can be used to convert passing time to speed:

$$320 \quad V = \frac{L}{T} \quad \text{(EQUATION X.2)}$$

321

322 Where:

323 T refers to the time taken by the pulse to transverse specimens (us)

324 L refers to the length of specimens (500mm)

325 Moreover, qualities of concrete classified by speed is listed in Table X.4 [43]. According to  
326 UPV results presented in the Appendix A, it shows that qualities of concrete in this chapter is  
327 good.

328

329 TABLE X.4 HERE Speed Classifications of Qualities of Concrete

No	Pulse velocity cross probing (km/S)	Concrete quality grading
1	> 4.5	Excellent
2	3.5-4.5	Good
3	3.0-3.5	Medium
4	< 3.0	Doubtful

330

331 • Natural Frequencies Test

332 In the Natural Frequencies Test, the Prosig P8004 hammer equipment showed in Figure X.6  
333 is used. Firstly, rubber pads and wood blocks are used to support prisms so as to reduce  
334 influence from the earth. Secondly, the computer programmer is set. Thirdly, the receiver of the  
335 equipment is installed in the centre of prisms then the hammer is used to hit a point which is  
336 near the receiver for 5cm. Finally, the frequency at the highest amplitude is recorded.

337 FIGURE X.6 HERE (a) The Receiver of Prosig P8004 Equipment; (b) The Hammer of Prosig  
338 P8004 Equipment.

339

340

### 341 3. Results

#### 342 3.1 Slump Tests

343 Slump tests of every mix are listed in Table X.5.

344

345 TABLE X.5 HERE Slump Tests

Mix	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6
Slump value	65mm	60mm	67mm	82mm	86mm	80mm

346

347 According to Table X.5, slump values of Mixes 1, 2 and 3 are around 64mm. Furthermore,  
 348 values of Mixes 4, 5 and 6 are around 83mm. The reason of this increment in slump values is  
 349 that gravel has been replaced by fibres. Gravel is recognised as the skeleton of concrete.  
 350 However, fibres are not as strong as gravel. Thus, values of slump tests will go down when  
 351 gravel is substituted with fibre.

#### 352 3.2 Compressive Strength

353 FIGURE X.7 HERE Compressive Strength

354 As mentioned in the literature review section, adding rubber will induce a reduction of  
 355 compressive strength. In Figure X.7, there is a 17.4% reduction of compressive strength caused  
 356 by adding 5% rubber between Mix 1 and Mix 2. Then, compressive strength of Mix 3, Mix4 and  
 357 Mix 5 with the rates of 5.3%, 2.2% and 1.6% respectively. The compressive strength of Mix 5 is  
 358 the highest in all mixes. The reason of it is that fibre confines concrete and supports the concrete  
 359 to suffer higher loads. However, the compressive strength of Mix 6 drops with a rate of 1.2% to  
 360 53.14Mpa. This phenomenon can be attributed to the fact that too much fibre induces  
 361 reductions of compressive strength.

#### 362 3.3 Splitting Tensile Strength

363 FIGURE X.8 HERE Splitting Tensile Strength

364 According to Figure X.8, a significant decline of splitting tensile strength with the rate of  
 365 10% can be observed between Mix 1 and Mix 2. This comes about as a result of the additional  
 366 rubber. Afterwards, there is a noticeable increase of strength between Mix 2 and Mix 3 with a  
 367 rate of 3.9%, which is the highest. Then, two continuous increases in splitting tensile strength of  
 368 Mix 4 and Mix 5 with rates of 2.1% and 2.0% respectively. This can be explained in that the  
 369 strength increases by adding fibre into concrete. However, those increments stop at Mix 5 with  
 370 0.2% fibre. Finally, the strength of Mix 6 decreases to 2.97 MPa with a rate of 2.0%. According to  
 371 values in Figure X.8, it can be considered that splitting tensile strength is reduced when  
 372 excessive fiber is added in concrete.

#### 373 3.4 Flexural Strength

374 FIGURE X.9 HERE Flexural Strength

375 In Figure X.9, there is a considerable decline of flexural strength with a rate of 13.4% in Mix  
 376 2, compared with Mix 1 which is plain concrete. After that, strength of Mix 3, Mix 4 and Mix 5  
 377 increases constantly at rates of 0.3%, 0.5% and 0.2% respectively. Finally, the strength of Mix 6  
 378 remains at 5.92 MPa. It can be concluded that additional fibre can improve flexural strength,  
 379 because fibre can increase adhesion of concrete particles when they are broken. Nevertheless,  
 380 increments stop at Mix 5 with 0.2% fibre.

### 381 3.5 Self-healing Evaluation

382 From previous researches, there has been no researcher who calculated increase rates of  
 383 self-healing. In this chapter, a method of measuring self-healing increments is presented.  
 384 Firstly, four prisms are prepared in a same design of concrete with one of them named as a  
 385 reference concrete. Secondly, speed of UPV tests of other prisms is used to minus the speed of  
 386 reference. Then values calculated in the second step are divided by the speed of a reference  
 387 concrete to obtain decreased speed ratios in different cracks between two specimens.  
 388 Afterwards, the n day's decreased speed ratio is used to minus t day's decreased speed ratio so  
 389 as to gain the increased self-healing rate, which is shown in Equation X.3.

390

391

$$392 \quad D_t = (V_t - V_{rt}) / V_{rt}$$

$$393 \quad D_n = (V_n - V_{rn}) / V_{rn}$$

(EQUATION X.3)

$$394 \quad I_{n_t} = D_n - D_t$$

395 Where:

396  $V_t$  refers to speed of control samples at t day397  $V_{rt}$  refers to the speed of the reference sample at t day398  $V_{rn}$  refers to the speed of the reference sample at n day399  $V_n$  refers to speed of control samples at n day400  $D_t$  refers to decreased speed ratios by different cracks at t day401  $D_n$  refers to decreased speed ratios by different cracks at n day402  $I_{n_t}$  refers to increase rates of self-healing between t day and n day ( $n > t$ )

#### 403 3.5.1 Standardized Cracks

404 From Figure X.10, self-healing increments of every specimen can be observed. As regards  
 405 Mix 1, the self-healing increment rate of specimen B drops from 0.75% to 0.1% between 30 and  
 406 32-days, then it fluctuates from 0.1% to 0.4% up until 42 days. For A and C, self-healing rates  
 407 fluctuate from 0.2% to 0.45% and from 0.1% to 0.45% respectively. Moreover, the fluctuation  
 408 range of self-healing rates of specimens in Mix 2 is from 0.2% to 1.0%. Furthermore, self-healing

409 rates of specimens in Mix 3 fluctuate from 0.38% to 1.0%. Additionally, rates of specimens in  
 410 Mixes 4, 5 and 6 all fluctuate from 0.2% to 1.0%. According to results showed in Figure X.10, it  
 411 can be concluded that self-healing increments of specimens with standardized cracks all  
 412 fluctuate between 0.1% and 1%. During tests, the author has not found any healing  
 413 phenomenon on specimens with standardized cracks.

414 FIGURE X.10 HERE (a) self-healing rates of specimens A, B and C with standardized cracks of  
 415 Mix 1; (b) self-healing rates of specimens A, B and C with standardized cracks of Mix 2; (c)  
 416 self-healing rates of specimens A, B and C with standardized cracks of Mix 3; (d) self-healing  
 417 rates of specimens A, B and C with standardized cracks of Mix 4; (e) self-healing rates of  
 418 specimens A, B and C with standardized cracks of Mix 5; (f) self-healing rates of specimens A, B  
 419 and C with standardized cracks of Mix 6.

### 420 3.5.2 Natural Cracks

421 In this chapter, Mix 1 and Mix 2 with standardized cracks will be utilized to compare  
 422 self-healing rates with specimens which have natural cracks. Because non-reinforced concrete  
 423 specimens are easily broken by using bending machine. Other mixes except for Mix 1 and Mix 2  
 424 can be made for natural cracks because there is fibre inside of concrete which helps to bond  
 425 concrete particles. Theoretically, Mix 1 and Mix 2 with standardized cracks pre-cracked at an  
 426 early age are more likely to be healed than other mixes such as mix 3, 4, 5 and 6 which were  
 427 cracked at 28 days. It can be concluded that specimens with natural cracks are much harder to  
 428 be healed than specimens with standardized cracks. The difference between natural cracks and  
 429 standardized cracks is the presence of fibre between gaps.

430 FIGURE X.11 HERE (a) self-healing rates of specimens A, B and C with natural cracks of Mix 3;  
 431 (b) self-healing rates of specimens A, B and C with natural cracks of Mix 4; (c) self-healing rates  
 432 of specimens A, B and C with natural cracks of Mix 5; (d) self-healing rates of specimens A, B  
 433 and C with natural cracks of Mix 6.

434

435 FIGURE X.12 HERE Increase Rates on self-healing of Every Mix

436

437 As you can see in Figure X.11, self-healing rates of specimens with natural cracks are  
 438 illustrated. In Mix 3, self-healing rates of specimens all slightly increase between 30 days and 36  
 439 days, then they decline from 36 days to 42 days. The rate of specimen B of Mix 3 which is always  
 440 the highest goes up from 3.9% to 4.0%, then it decreases to 3.5%. For Mix 4, rates of specimen A  
 441 and C remain at 4.0% from 30 days to 36 days, afterwards they go down to around 3.0% up until  
 442 42 days. The self-healing rate of specimen B decreases from 3.0% to 2.8% from 30 days to 32  
 443 days, then it goes back to 3.0% within 2 days, finally it drops to 2.0% up until 42 days. In regard  
 444 to Mix 5, rates of specimens A and B slightly increase from 4.0% to 4.1%. In the meanwhile, the  
 445 rates of specimen C increase from 3.0% to 3.1%. In mix 6, rates of specimens A and C remain at  
 446 3.0% from 30 days to 38 days, then they decrease to 2.8% and 2.5% respectively up until 42 days.  
 447 The rate of specimen B fluctuates around 2.5% between 30 days and 38 days, then it drops to  
 448 2.4% in the last 4 days. According to results in Figure X.11, it can be concluded that self-healing  
 449 rates of specimens with natural cracks increase slightly or remain at a certain value from 28  
 450 days. Afterwards, increments of self-healing rates stop at around 36 days. Then, they start to  
 451 decrease. The drops of self-healing rates can be interpreted as that there is almost no unreacted  
 452 cement can be converted into calcium carbonate. Thus, UPV results are pretty much the same  
 453 across different days. Compared with UPV values in Figure X.11, they indicate a trend on

454 self-healing rates which can be concluded that self-healing rates increase to a highest speed then  
455 decrease to an actual value according to different proportions of fibres. Furthermore, 0.2% of  
456 fibre performs the highest self-healing rates of specimens with natural cracks in every mix of  
457 concrete.

458 The mechanism of identifying self-healing abilities involves comparing control samples  
459 with reference samples in the same mix at the same day. According to equation 3, self-healing  
460 rates can be calculated as shown in Figure X.11 and Figure X.12. As you can see in Table X.6,  
461 specimens with natural cracks of Mix 3 clearly show a self-healing ability. According to UPV  
462 results in the Appendix A, it can be observed that differences on speed of UPV tests between  
463 control samples and reference samples in the same mix at the same day is smaller day-by-day.  
464 It can be concluded that cracks are healed to improve speed of UPV tests.

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TABLE X.6 HERE Self-healing Increments Calculations of Specimens in Mix 3

	Time	Speed	Difference	Time	Speed	Difference	Increase Rate	Time	Speed	Difference	Increase Rate
	28-DAYS	/	/	30-DAYS	/	/	/	32-DAYS	/	/	/
Reference	100.4	4.9801	/	99.5	5.0251	/	/	99.2	5.0403	/	/
Specimen A	114.7	4.3592	12.467%	109.7	4.5579	9.298%	3.169%	109.3	4.5746	9.241%	3.227%
Specimen B	113.9	4.3898	11.853%	108.1	4.6253	7.956%	3.897%	107.7	4.6425	7.892%	3.960%
Specimen C	115.5	4.3290	13.074%	111.4	4.4883	10.682%	2.391%	111.0	4.5045	10.631%	2.443%

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Time refers to the time of passing through prisms.

Speed refers to speed of UPV tests.

Difference refers to percentages of the difference between control samples and reference samples in the same Mix at the same day.

Increase Rate refers to self-healing increments



480 Figure X.12 shows self-healing increase rates of specimens with natural cracks in Mix 3, 4, 5  
481 and 6. The self-healing rate of Mix 5 which is always the highest of all mixes increases from 3.5%  
482 to 3.8% between 30 and 40 days, then it slightly drops to 3.7% at 42 days. For mix 3 and 6,  
483 self-healing rates remain at 3.1% and 2.9% from 30 days to 38 days respectively, afterwards they  
484 drop to 3.0% and 2.7% respectively. In regard to Mix 4, the self-healing rate goes up from 3.5%  
485 to 3.7% between 30 days and 36 days, then it falls down to 2.8% within six days. In total,  
486 self-healing rates initially are around 3.25% at 30 days. Afterwards, they rise to around 3.5% up  
487 until 36 days. Finally, they start decreasing. Moreover, it can be observed that Mix 5 with 0.2%  
488 fibre performs better than other mixes on self-healing. The following are pictures showing  
489 healed cracks of Mix 3, 4, 5 and 6 in Figure X.13, X.14, X.15 and X.16.

490

491

492 FIGURE X.13 HERE (a) Existing cracks of specimens with natural cracks in Mix 3; (b)  
493 Self-healing phenomenon of specimens with natural cracks in Mix 3.

494

495 FIGURE X.14 HERE (a) Existing cracks of specimens with natural cracks in Mix 4; (b)  
496 Self-healing phenomenon of specimens with natural cracks in Mix 4.

497

498 FIGURE X.15 HERE (a) Existing cracks of specimens with natural cracks in Mix 5; (b)  
499 Self-healing phenomenon of specimens with natural cracks in Mix 5.

500

501 FIGURE X.16 HERE (a) Existing cracks of specimens with natural cracks in Mix 6; (b)  
502 Self-healing phenomenon of specimens with natural cracks in Mix 6.

503 *3.6 Natural Frequencies*

504 FIGURE X.17 HERE (a) Natural frequencies of specimens with standardized cracks in Mix 1; (b)  
505 Natural frequencies of specimens with standardized cracks in Mix 2; (c) Natural frequencies of  
506 specimens with standardized cracks in Mix 3; (d) Natural frequencies of specimens with  
507 standardized cracks in Mix 4; (e) Natural frequencies of specimens with standardized cracks in  
508 Mix 5; (f) Natural frequencies of specimens with standardized cracks in Mix 6.

509

510 The Natural Frequency Test is usually used for detecting cracks of building slabs or  
511 bridges. From the recorded data in Figure X.17, undulated lines can be noticed. With regard to  
512 lines in Figure X.17, it can be interpreted that natural frequencies of specimens in all mixes  
513 fluctuate randomly between 20 Hz and 23 Hz. However, there is no trend found in natural  
514 frequency tests.

515

## 516 **4. Discussion**

517 *4.1 Mechanical properties*

518 According to results in Figure X.7, Figure X.8 and Figure X.9, it can be concluded that  
519 mechanical properties all decrease when 5% of rubber is added to concrete. Subsequently,

520 mechanical properties increase when the fibre is put in concrete. This means that adding the  
521 fibre can improve mechanical properties of concrete. More of the fibre induces higher  
522 mechanical properties. Finally, mechanical properties stop increasing when 0.2% the fibre is  
523 added, then they start to drop when 0.25% of the fibre is added in concrete. It can be supposed  
524 that excessive fibre will induce reductions of mechanical properties.

#### 525 *4.2 self-healing abilities of specimens with standardized cracks*

526 According to Figure X.10, a fluctuation from 0.1% to 1% of self-healing abilities of  
527 specimens with standardized cracks can be observed. Self-healing rates of specimens with  
528 standardized cracks are very low and can be ignored. The phenomenon can be attributed to the  
529 fact that there is no bonding force between fibre and concrete, thus calcium carbonate cannot be  
530 formed to fill gaps. This is the reason why specimens with standardized cracks cannot be  
531 healed.

532 Results in Figure X.10 reveal that inserting plastic films is not practical for autogenous  
533 self-healing tests. This because plastic films will physically block fibre between gaps, and then  
534 fibre cannot bridge separated concrete to enhance self-healing abilities. Values in Figure X.10  
535 also show that additional fibre in specimens with standardized cracks have no function in  
536 stimulating self-healing ability when it is merely added in concrete instead of being put in gaps.

#### 537 *4.3 self-healing abilities of specimens with natural cracks*

538 According to Figure X.11, self-healing rates of specimens with natural cracks gradually  
539 increase, then they stop increasing at around 36 days, finally they decrease up until 42 days.  
540 Compared with control mixes which are Mix 1 and Mix 2, self-healing rates of Mix 3, 4, 5 and 6  
541 are much higher. Self-healing rates of Mix 3, 4, 5, and 6 are between 3% and 4%. Self-healing  
542 rates of Mix 1 and Mix 2 are between 0.1% and 1%. Furthermore, there is no crack healed found  
543 in Mix 1 and Mix 2. This can be attributed to the advantage of adding fibre. The fibre bridge  
544 cracks and be cores of calcium carbonate during hydration processes. Furthermore, self-healing  
545 values in Figure X.12 show that specimens of Mix 5 are healed the fastest. It can be considered  
546 as that 0.2% of the fibre in rubberized concrete has the best self-healing ability.

#### 547 *4.4 Review of Making Cracks*

548 According to tests carried out by the author in this chapter, the key factor of self-healing  
549 tests is to generate cracks. Because it is hard to control crack width of concrete specimens  
550 without reinforcement. A linear variable differential transformer (LVDT) was installed at the  
551 bottom of specimens to restrict the crack width [44]. In that case, width of cracks was  
552 successfully limited from 0.15mm to 0.17mm. Moreover, a clip gauge was used to control width  
553 of cracks [45]. As mentioned in the Literature Review section, cracks should be smaller than  
554 0.3mm or cracks cannot be healed [24] [25]. This shows that the use of LVDT or Clip Gauge can  
555 be available methods to limit crack width in future studies on self-healing concrete.

556 Moreover, it is easier to generate cracks in smaller specimens than in big prisms. Small  
557 cylinders or prisms can be wrapped by tape to prevent them from being separated into two  
558 parts. Thus, cracks can be easily generated.

#### 559 *4.5 Review of Test Methods*

560 The UPV test is very sensitive. Totally, Main factors influencing UPV results can be  
561 concluded as sizes of aggregate, ages of concrete, temperatures of tests, moisture content of  
562 specimens, types of cement, shapes and sizes of specimens and curing conditions [46].  
563 Furthermore, 1% more water content of concrete specimens increases by 160m/s of UPV results.

564 Results of UPV will increase by 34m/s on average when temperature increases by 10° [47]. In  
565 future studies, every parameter needs to be recorded before starting UPV tests. Hopefully, an  
566 equation for calibrating UPV values to evite negative influence can be provided. There are other  
567 methods utilized by previous researchers to identify self-healing abilities. These methods are  
568 listed as follows.

#### 569 Scanning Electron Microscope (SEM)

570 The SEM was applied to monitor detailing of cracks by zooming in at a high magnification  
571 rate [1]. Using the SEM, one can clearly see detailed images of gaps. It is thus easy to measure  
572 width of cracks. However, this method cannot analyse the composition of precipitation.

#### 573 X-Ray Diffraction (XRD)

574 It is commonly known that calcium carbonate is white substance. Researchers usually use  
575 this phenomenon to preliminarily identify whether there is a self-healing performance. If there  
576 is newly formed calcium carbonate between cracks, it means that cracks are healed. However, it  
577 is difficult to distinguish whether white substance is calcium carbonate. XRD can emit certain  
578 X-rays to distinguish calcium carbonate by irradiating specimens [1]. XRD can be combined  
579 with SEM to accurately identify self-healing phenomenon.

580 In future studies on self-healing concrete, XRD, SEM and UPV methods can be utilized  
581 together to precisely identify self-healing abilities.

#### 582 *4.6 Natural Frequencies*

583 Based on Figure X.17, natural frequencies of specimens all fluctuate between 20 Hz and 23  
584 Hz. Theoretically, frequencies will be different when variable cracks are obtained initially. It  
585 means that if cracks are healed, frequencies of specimens with cracks will change to be the same  
586 frequency with reference concrete. However, natural frequencies of those specimens in this  
587 chapter just randomly fluctuate. The reason may because specimens in this chapter are too  
588 small to cause changes in frequencies. Because measuring natural frequencies usually utilized  
589 on huge structures such as bridges and panels. Thus, it could be concluded that natural  
590 frequencies are not available for inspecting self-healing abilities.

### 591 **5. Conclusion**

592 An improved concrete which contains 5% of 180-microns and 400-microns rubber and  
593 different proportions of Duras Easyfinish fibre is measured for self-healing abilities in this  
594 chapter. The concrete helps to reduce negative influence of waste rubber. Furthermore, the  
595 concrete can be used in construction industries to reduce maintenance fees and enlarge  
596 durability.

597 Compressive strength, flexural strength and splitting tensile strength which can be  
598 concluded as mechanical properties are tested in this chapter. There are noticeable reductions of  
599 mechanical properties when the rubber is added in the concrete. It can be interpreted that  
600 adding the crumb rubber in concrete dramatically induces reductions on mechanical properties.  
601 Afterwards, each strength increases by adding more fibre. This means that adding Duras  
602 Easyfinish fibre can enhance mechanical properties of rubberized concrete to support higher  
603 loads and bond concrete together. However, these increments in mechanical properties stopped  
604 when 0.2% of the fibre is added. This can be recognised that mechanical properties increase to  
605 the highest value when 0.2% of the fibre is put to concrete.

606 For standardized cracks, self-healing rates fluctuated between 0.1% and 1% which are very  
607 low. Additionally, there is no self-healing phenomenon shown in standardized cracks. Thus, it  
608 can be interpreted that standardized cracks cannot be healed by adding the fibre in rubberized  
609 concrete. For natural cracks, self-healing rates go up to around 3.5% at 36 days. Then, rates  
610 starting dropping within next six days. According to the data in Table A4 and A5, it is obvious  
611 that the difference between control samples and the reference sample in the same Mix on the same  
612 day is smaller day-by-day which can be recognised as the evidence of self-healing. Disadvantages of  
613 UPV tests has been listed in the section 4.5. Moreover, the SEM and the XRD method have been  
614 analysed and suggested to be combined with the UPV test to improve self-healing abilities  
615 measurement.

616 In regard to the natural frequency test, results randomly fluctuated between 20Hz and 23  
617 Hz. Moreover, there is no change on natural frequencies between specimens with different  
618 depth of cracks. Thus, this method may not be available for inspecting self-healing ability. This  
619 may result from the smallness of the specimens.

620 In a summary, concrete with 5% crumb rubber which shows the best mechanical properties  
621 can be utilized to satisfy concrete requirements of standards and reduce negative influence of  
622 waste rubber. Moreover, it can be concluded that concrete with 0.2% of the fibre which has the  
623 best performance on self-healing can be applied in construction areas. In regard of making  
624 cracks, LVDT and Clip Gauge have been suggested to be used to limit cracks' width in future  
625 studies on self-healing. Moreover, the SEM and the XRD method have been suggested to assist  
626 the UPV method to measure self-healing abilities more accurate. Testing natural Frequencies  
627 has been discarded as a method of evaluating self-healing abilities because of no change on  
628 natural frequencies between specimens with different depth of cracks.

629

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636

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639

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648

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