

# Early-age dynamic moduli of crumbed rubber concrete for compliant railway structures

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Technical Paper

*“Eco-efficient high-strength concrete engineered by micro crumb rubber  
from recycled tires and plastics”*

(Title contains 7 words)

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# Eco-efficient high-strength concrete engineered by micro crumb rubber from recycled tires and plastics

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## Abstract

Crumb rubber concrete (CRC) is one of the new construction materials, which has been developed as a by-product from wasted rubber tires and plastics. Fundamentally, CRC has both advantages and disadvantages. Most previous research focuses on applications of low-strength CRC. This paper thus presents engineering characteristics of novel high-strength CRC and its benefits to the environment, as well as to investigate the ability of micro crumb rubbers to enhance CRC's mechanical properties. Independent experiments (compressive, splitting tensile and flexural strength) of CRC containing micro-crumb rubber were conducted. The results revealed that replacing fine aggregate with micro rubber particles caused the reduction in mechanical properties of concrete. However, due to the effect of micro size of rubber content and silica fume, the compressive strength of CRC achieved over 55 MPa, which will significantly benefit advanced construction of compliant structural systems. The tensile strength of CRC was higher than plain concrete by approximately 8.74% (splitting tensile strength) and 17.46% (flexural strength), but it was still lower than that of silica fume concrete. Moreover, CRCs also provided the ability to resist the crack of the concrete. Adding suitable amount of rubber particles to concrete can prevent the crack initiation and propagation, providing superior characteristics for high-strength CRC. The adoption of high-strength CRC in railway practices will significantly minimise wastes from used rubber tires and plastics, thus paving a robust pathway for environmental impact to societies.

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79 **Keywords:** Crumb rubber concrete; Micro engineering; Silica fume concrete; Mechanical  
80 properties of Crumb rubber concrete; Crack resistance; High performance concrete.

## 81 **1. Introduction**

82 Waste tyre is one of the significant problems affecting the world's environment. Each year over 1  
83 billion waste tyres are generated worldwide (Duangburong et al., 2015). As its nature, tyres are  
84 designed to be durable and hard-wearing. When they reach the end of their useful life, they are thus  
85 very difficult to dispose or decompose (Muzenda, 2014). Therefore, it is very important to find  
86 sustainable solutions to manage this problem. In the past, the cheapest way to decompose this kind  
87 of waste would be burning. However, this method is considered as a poor waste management  
88 because of its negative impacts to the environment such as air pollution, soil and water  
89 contamination (Pacheco et al., 2012). Thus, the burning method is unacceptable and it should be  
90 only used if there is no better alternative way to dispose the waste (Issa & Salem, 2013).

91 Other method used to manage waste tyres is called landfill. Generally, this method is quite useful  
92 because it can deal with enormous amount of wastes and also does not create air pollution.  
93 Nevertheless, it requires large area to contain the wastes which can negatively affect the landscape  
94 (Duangburong et al., 2015). In addition, toxic and soluble components in tyres could also spread to  
95 soil which reduce biodiversity in the collecting area (Pacheco et al., 2012). Therefore, recently this  
96 method has become not popular and dangerous for people living nearby.

97 Nowadays, recycling seems to be a famous method used to manage this waste. Rubber waste can be  
98 recycled into several things such as furniture, admixture in rubber manufacturing process,  
99 construction material (mixed with concrete), etc. In this study, the use of waste tyre mixing with  
100 concrete is focused. Waste tyres, after processing into small particles as crumb rubber, can be mixed  
101 into concrete as an aggregate. Most researches revealed that crumb rubber can help to increase the  
102 damping property of concrete, which is very important in absorbing impact energy (Najim & Hall,  
103 2012). However, this type of concrete can be utilised only for non-structural application such as

104 railway noise barrier (Lakusic et al., 2011). This is because its compressive strength and other  
105 mechanical properties (e.g. tensile strength, hardness, etc.) are relatively low compared to normal  
106 concrete (Issa & Salem, 2013; Aliabdo et al., 2015 and El-Gammal et al., 2010). Therefore, the  
107 crumb rubber concrete still requires further development, especially for achieving high compressive  
108 strength, in order to apply as structural material in the future. Therefore, this paper aims to study  
109 new mechanical properties of crumb rubber concrete (CRC) containing micro-crumb rubber. Two  
110 different sizes of crumb rubber are focused: 425 and 75 Micron. The use of silica fume to enhance  
111 the CRC properties are analysed, and the experimental results of compressive strength, splitting  
112 tensile strength, flexural strength, and failure patterns after compressive testing are presented in this  
113 study.

## 114 **2. Previous Researches on Mechanical Properties of CRC**

115 In this study, CRC are considered to be used as structural material. Therefore, it is highly important  
116 to understand the properties of CRC from the previous researches before conducting the  
117 experiments and finding the method to improve it. The properties of CRC (both in fresh and  
118 hardened condition) are clearly summarised below.

### 119 ***2.1 Properties of Fresh CRC***

#### 120 ***2.1.1 Fresh Density***

121 The fresh density of CRC was observed by Siddique & Naik (2004) and Su, H. et al. (2015). In  
122 these researches, fresh CRC had lower density than normal concrete, and an increase in the  
123 percentage of crumb rubber affected the reduction in the fresh density. This is because the crumb  
124 rubber has low specific gravity. In addition, the non-polar nature of rubber particles may repel water  
125 and attract air on rubber surface, which would cause air void increase.

#### 126 ***2.1.2 Workability***

127 Workability of CRC can be evaluated by measuring slump of fresh concrete. Various researches  
128 have stated that an increase in crumb rubber replacement reduces the workability of fresh CRC  
129 (Najim & Hall, 2011; cited in Pacheco et al., 2012 and Su, H. et al., 2015). In addition, the size of

130 crumb rubber also has an impact on the workability of concrete. Su, H. et al. (2015) found that there  
131 is a reduction of slump, once the size of rubber particle is decreased. However, this workability  
132 issue can be solved by adding optimum amount of plasticizer admixture (about 2-3%) into the  
133 concrete as reported by Topcu & Bilir, (2009) and Aiello & Leuzzi, (2010).

## 134 ***2.2 Properties of Hardened CRC***

### 135 *2.2.1 Compressive Strength*

136 As well known, one of concrete's main properties is compressive strength. For CRC, most of the  
137 previous researches have obviously illustrated that an increase in rubber content leads to reduction  
138 in compressive strength (Eldin & Senouci, 1993; Guneyisi et al., 2004; Aiello & Leuzzi, 2010; Issa  
139 & Salem, 2013; Su et al., 2015). However, it is not only the amount of rubber content that will  
140 affect the compressive strength, but there are also other factors. For example, Eldin and Senouci  
141 (1993) investigated the strength of concrete mixing with different amounts of crumb rubber  
142 replacing both fine and coarse aggregate (25, 50, 75 and 100% by volume). Consequently the  
143 results highlighted, there was significant reduction in strength when rubber content increases. In  
144 addition, a smaller reduction in compressive strength was observed when only fine aggregate was  
145 replaced by crumb rubber. Su et al. (2015) studied about the effect of different sizes of rubber  
146 particles (3, 0.5, 0.3 mm) added to the compressive strength of CRC. They revealed that at 28 days,  
147 cube compressive strength ( $100^3 \text{ mm}^3$ ) of concrete increased with a decrease in the rubber particle  
148 size due to a better void filling ability of finer crumb rubber. Moreover, the types of crumb rubber  
149 also had a significant impact to the compressive strength. Several researches mentioned the use of  
150 rubber waste treated with waste organic sulfur compounds (Chou, L.H. et al., 2010), sodium  
151 hydroxide solution (NaOH) (cited in Pacheco et al., 2012) or silane coupling agent (Su et al., 2014)  
152 would enhance adhesion between rubber and cement particles and improve the compressive strength  
153 significantly. Therefore, this factor can be also addressed as one of the development methods of CRC.

### 154 *2.2.2 Tensile Strength*

155 According to the reduction of compressive strength, tensile strength of CRC is also influenced on  
156 the amount of rubber content. Increasing in rubber content decreases both splitting and flexural  
157 strength (Guneyisi et al., 2004; Su et al., 2015; Gupta et al., 2016). However, reduction of tensile  
158 strength seems to be less impact than in the case of compressive strength, which is about 5 to 10% if  
159 fine aggregate is substituted (cited in Pacheco et al., 2012). The reduction of tensile strength also  
160 depends on the size of rubber particle. Greater rubber particle will negatively impact to the tensile  
161 strength (Ganjian et al., 2009; Su et al., 2015). Furthermore, the types of aggregate that is  
162 substituted also have an effect on tensile strength. Larger decrease in tensile strength occurred when  
163 coarse aggregate was replaced by rubber wastes rather than fine aggregate (Aiello & Leuzzi, 2010).

#### 164 2.2.3 Elastic Modulus

165 Elastic modulus is one of the concrete properties affected by rubber content. It tends to reduce when  
166 increasing the percentage replacement of coarse or fine aggregate with waste rubber (Guneyisi et  
167 al., 2004; Kumar et al., 2014). This result is very intelligible because replacing stiff aggregate with  
168 rubber (low stiffness) is a critical factor that influences the reduction in elastic modulus  
169 (Onuaguluchi & Panesar, 2014; Onuaguluchi, 2015; Thomas et al., 2016). Furthermore, bigger size  
170 of crumb rubber seemed to cause more reduction in elastic modulus than that of smaller size (Zheng  
171 et al., 2008; Guo et al., 2016). Therefore, it is necessary for future research to consider this  
172 particular parameter in order to develop a better CRC.

#### 173 2.2.4 Impact Resistance

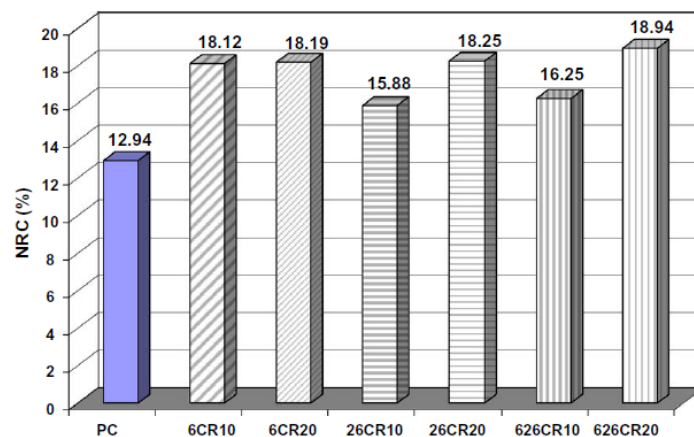
174 Even though the elastic modulus of CRC decreases, the strain rate increases considerably when  
175 increasing rubber content. This makes CRC have lower brittleness index (BI) than plain concrete,  
176 which causes CRC to have greater ductility performance (Zheng et al., 2008; Snelson et al., 2009;  
177 Thomas and Gupta, 2015; 2016). In addition, it was revealed by Li et al., (2004) that CRC also has  
178 higher toughness and better energy absorbing ability compared to normal concrete. This result is  
179 consistent with current report stated by Aliabdo et al. (2015) and Gupta et al. (2015). Therefore, this  
180 property of CRC would be advantageous for railway application, especially for concrete sleeper.

### 2.2.5 Electrical Resistivity

Resistivity describes the ability of material to resist the electrical current flow inside the material. Generally, this property depends on various factors such as microstructure, test age, moisture content, etc. Therefore, it is necessary to understand these factors before conducting the experiment. For CRC, several researches on this property, suggests that rubber content in concrete performs as an electrical insulator which influences the resistivity of CRC becoming higher than that of plain concrete (Issa & Salem, 2013; Onuaguluchi & Panesar, 2014).

### 2.2.6 Noise Absorption

Sukontasukkul (2009) conducted an experiment to investigate the noise absorption ability of CRC. Two size of crumb rubber were considered: passing sieve No. 6 (3.36 mm) and 26 (0.707 mm). These groups of crumb rubber were used to replace fine aggregate. The noise absorption ability of each concrete mix was compared by using noise absorption coefficient ( $\alpha$ ). As results, CRC seemed to have better noise absorption ability compared to reference concrete as presented in Figure 1. Even though temperatures were varied (low, normal and high), CRC still performed well in terms of sound absorption than plain concrete (Holmes et al., 2014).



**Figure 1** – Noise Reduction Coefficient of Each Mix of CRC (Sukontasukkul, 2009)

### 2.2.7 Thermal Resistance

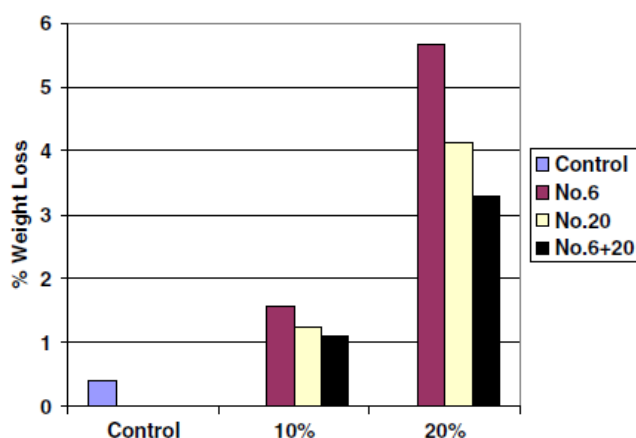
Thermal resistance of CRC has been studied by Kaloush et al. (2005). The result illustrated that coefficient of thermal expansion (CTE) of CRC will decrease when crumb rubber content is



increased in both heating (expansion) and cooling (contraction) cycles. This means CRC can be more resistant in thermal changing than normal concrete. In addition, Sukontasukkul (2009) also found the relationship between the size of crumb rubber and thermal resistivity. Smaller rubber particles provided a better thermal resistance to concrete.

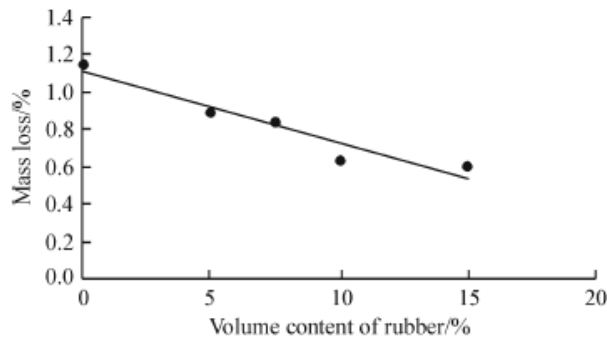
#### 2.2.8 Abrasion Resistance

Sukontasukkul & Chaikaew (2006) investigated the abrasion properties of concrete pedestrian block mixed with crumb rubber. Three categories of concrete mix were considered with different sizes of crumb rubber: No. 6 (3.36 mm), No. 20 (0.850 mm) and No.6+No.20. These rubbers were used to replace both fine and coarse aggregate at equal amount of 10 and 20% by weight respectively. The abrasion test was conducted following ASTM C944-95 method. As illustrated in Figure 2, an increase in the crumb rubber content caused the reduction in abrasion resistance of concrete (higher percent weight loss). In addition, Concrete with smaller rubber particles seemed to have less percent weight loss than concrete containing bigger rubber particles.



**Figure 2** – Abrasion Test Results (after Sukontasukkul & Chaikaew, 2006)

However, Kang et al. (2012) found the opposite results from previous research when only replacing same volume of fine aggregate with crumb rubber. They found that CRC seemed to have a better abrasion resistance than plain and silica fume concrete (lower percent mass loss). The abrasion resistance of CRC tended to increase as rubber content increase as presented in Figure 3. This may be because the CRC has excellent dynamic performances in terms of energy absorption, toughness and cracking resistance. Therefore, these parameters resulted in better abrasion resistance in CRC.



**Figure 3** – Relationship between Percent Mass Loss and Rubber Content in Concrete (after Kang et al., 2012)

### 2.2.9 Freeze Thaw Resistance

Freeze thaw resistance can be defined as a property of concrete to resist the deterioration caused by freezing of water inside the concrete (Cao & Chung, 2002). As theory, when the water freezes, its volume expands approximately 9% which leads to the change in internal stress of concrete and make the damage occur (Janssen & Snyder, 1994). According to literatures, the addition of crumb rubber can enhance a freeze thaw protection to the concrete. Richardson et al. (2012; 2016) stated that the use of 0.6% crumb rubber by weight of concrete significantly influenced the increase of freeze thaw resistance. However, it was found by Gesoglu et al. (2014) that the freeze thaw resistance of CRC improved clearly after passing 300 freeze-thaw cycles compared to normal concrete. Furthermore, finer rubber particles were likely to provide a better freeze-thaw performance than a bigger size. This was because small size of rubber has higher surface area which can increase the amount of micro scale pores, and theses pores can reduce the effect of internal stress once the water freezes (Gesoglu et al., 2014).

### 3. Remarkable Point from Literature review

CRC has a lot of advantages such as impact resistance, thermal resistance, sound absorption and electrical resistivity, abrasion resistance and freeze thaw resistance, which could be applied for strengthening concrete sleepers. However, there are still some points of mechanical properties that need to be improved which are compressive strength, tensile strength and elastic modulus. Thus, this research focuses on the development of these properties, especially to develop eco-efficient

high strength crumb rubber concrete for applications in aggressive environment such as railway, coast lines, or nuclear infrastructure.

As reviewed, it was remarkable that mixing a small size of rubber waste particles into the concrete could mitigate mechanical property's problems. The comprehensive review of over recent 100 relevant technical publications in open literature shows that previous work mostly focuses on moderate strength of concrete (Meesit, 2015). Therefore, this study is the first to investigate the static properties of high-strength crumb rubber concrete. The very small particles of rubber waste as micro scale (425 and 75 micron) were selected to use in the experiment. This technique is expected to improve Micro and Nano structures of concrete and to solve the drawbacks of CRC.

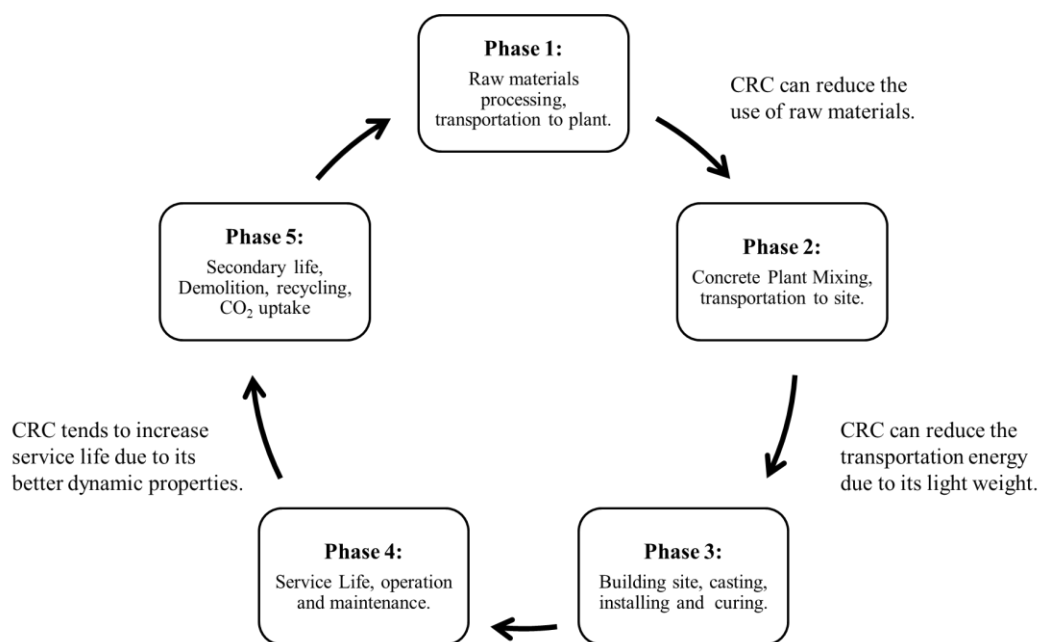
#### **4. Environmental Benefits of Crumb Rubber Concrete**

Besides the benefits to the dynamic properties, CRC can be also advantageous to the environment such as reducing landfill, reducing embodied carbon in construction projects and minimising noise and vibration to surrounding environment. Therefore, this section will discuss those issues and provide the encouragement to the use of CRC in the future.

The recycle of waste rubber by mixing with the concrete plays a significant role in the way to reduce landfill (Richardson et al., 2011). As well known, waste rubber is not simply biodegradable and it does take a long period of landfill treatment to dispose of it. Therefore, the application of rubber with concrete can positively minimise the waste rubber in landfill sites. The additional benefit could contribute to the reduction of landfill pollutions in terms of soil and water contamination from toxic and soluble components from waste tyres.

There is no doubt that concrete is one of the common construction material which is widely used around the world due to its high strength and durability. However, there is still concern about its embodied carbon, CO<sub>2</sub> (NRMCA, 2012). With the increasing trend of environmental awareness, rubber wastes have become the optional raw material of the concrete mix. The replacement of concrete aggregates with rubber particles can relatively reduce the carbon footprint of the concrete

269 (Talukdar et al., 2011). As shown from life cycle of concrete (see Figure 4), production of CRC  
 270 leads to the reduction in the use of natural materials, rubber wastes and transportation energy due to  
 271 its light weight, etc. (Allen, 2010). Moreover, the service life of CRC tends to be longer than normal  
 272 concrete due to its better dynamic properties. Therefore, using CRC in the construction can support  
 273 the project becoming more sustainable and reputation in terms of excellent environmental  
 274 management.



275  
 276 **Figure 4 – Life Cycle of Concrete with the Advantages of CRC in Terms of Carbon Footprint**  
 277 (Adapted from Nielsen, 2008)

278 As revealed by various researches, CRC also provides a better noise and vibration absorption ability  
 279 (Sukontasukkul, 2009; Holmes et al., 2014). Thus, applying CRC as a material in construction  
 280 projects where noise and vibration are the main concern such as railway, highway can be beneficial.  
 281 Recently, CRC is still used only for non-structural applications due to its low strength (Issa &  
 282 Salem, 2013; Aliabdo et al., 2015). Therefore, to enhance the environmental benefits of CRC, its  
 283 drawback needs to be eliminated.

284 In summary, CRC can provide substantial benefits to the environment. Using CRC in projects can  
 285 help reduce the pollutions generated from waste rubber tyres. In addition, the applications of CRC  
 286 will also increase the sustainability of the project. Therefore, if there is no limitation about its

287 strength, this type of concrete will surely become the main choice of construction material in the  
288 future.

289

## 290 **5. Concrete Mix Design and Preparation of Specimens**

### 291 **5.1 Materials**

292 In this study, the materials used to make concrete specimens can be separated into five main groups  
293 which are cement, clean water, fine and coarse aggregate, crumb rubber and silica fume. The  
294 properties of each material are clearly explained below.

#### 295 *5.1.1 Cement*

296 Ordinary Portland cement type I with characteristic strength of 52.5 MPa (Accordance with BS EN  
297 197-1) was used to prepare concretes in this study. It has grey colour, which is compatible with  
298 cement replacement admixtures such as silica fume, fly ash, etc. This cement was contained in the  
299 airtight package stored in room with dry condition before use.

#### 300 *5.1.2 Water*

301 Clean water supplied from the laboratory was used to make hydration reaction in the concrete  
302 mixtures.

#### 303 *5.1.3 Fine and Coarse Aggregate*

304 Natural sand and crushed gravel provided by civil engineering laboratory were used as fine and  
305 coarse aggregate. Sand has a maximum particle size of 5 mm, and crushed gravels have a maximum  
306 size of 10 mm. Before using in the mixture, moisture contents of these materials were investigated.  
307 The samples of sand and gravel (100g) were burned until there was no free water on the surface.  
308 This situation can be assumed to be under saturated surface dry condition. After that, these samples  
309 were weighed in order to use to calculate moisture content. The percentages of moisture content in  
310 each type of aggregate are presented in Table 1. It is noted that the moisture content of aggregate

311 was recalculated before mixing every time in order to adjust the proportion of concrete mix and  
 312 keep water cement ratio (w/c) constant following the design.

313

314

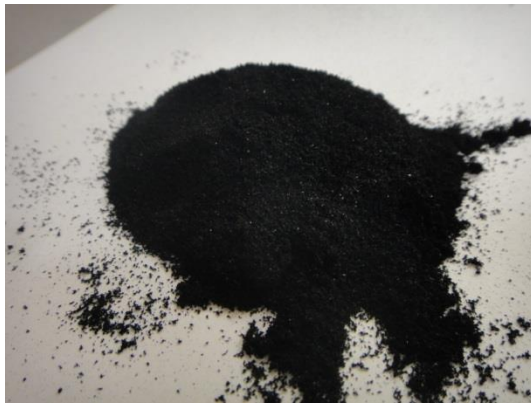
315

**Table 1 – Moisture Content of Aggregate**

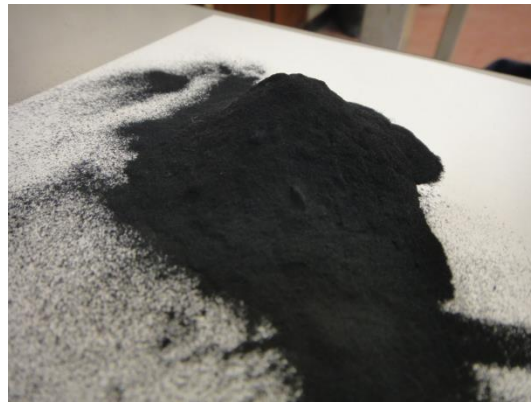
No.	Mixtures	Moisture Content (%)	
		Sand	Gravel
1.	Reference concrete (RFC )	1.0	0.3
2.	Concrete contained 10wt% of silica fume (SFC)	1.0	1.0
3.	SFC + 5wt% of 425 micro-crumb rubber (SFRC-425-5)	3.0	0.5
4.	SFC + 10wt% of 425 micro-crumb rubber (SFRC-425-10)	3.0	0.1
5.	SFC + 5wt% of 75 micro-crumb rubber (SFRC-75-5)	2.0	0.3
6.	SFC + 10wt% of 75 micro-crumb rubber (SFRC-75-10)	2.4	0.7

#### 316 5.1.4 Crumb Rubber

317 In this study, two different sizes of crumb rubber were focused: 425 and 75 Micron. The 425 micro-  
 318 crumb rubber was kindly provided by J. Allcock & Sons Ltd. (see Figure 5(a)). It is a common type  
 319 of crumb rubber made from the ambient grinding of truck tyre buffing. It has black colour with  
 320 specific gravity of  $1.14 \pm 0.02$  (Wellington Rubber Co Ltd, 2015). For the 75 micro-crumb rubber  
 321 (see Figure 5(b)), it was supplied by Lehigh Technologies Incorporation. This type of crumb rubber  
 322 was also produced from end-of-life tyres. It has also black colour with similar specific gravity of  
 323  $1.14 \pm 0.03$  (Lehigh Technologies Incorporation, 2015). This material has very small size of  
 324 particles. Thus, it can be also called as micronized rubber powder instead of crumb rubber. Before  
 325 use, these two crumb rubbers were packed in airtight package which was free from contaminations  
 326 such as metal, textile, dust, etc. Therefore, it could be ensured that there was no effect from other  
 327 factors to concrete mixtures.



(a) 425 micron



(b) 75 micron

**Figure 5** – Rubber Powder 425 micron (a) and 75 micron (b)

### 5.1.5 Silica Fume

Elkem silica fume, grade 940 was used for purpose of enhancing mechanical properties of CRC in this study. It is an Undensified silica fume which has grey colour. Before use, it was stored in the dry condition at civil engineering laboratory. The chemical and physical properties of this silica fume are presented in Table 2.

**Table 2** – Chemical and Physical Properties of Undensified Silica Fume (Elkem AS, 2015)

No.	Properties	Value
1.	SiO <sub>2</sub>	Minimum 90%
2.	Loss of Ignition	Maximum 3%
3.	Coarse Particles > 45µm	Maximum 1.5% (tested on undensified)
4.	Bulk Density (U)	200-350 kg/m <sup>3</sup>
5.	Bulk Density (D)	500-700 kg/m <sup>3</sup>

### 5.2 Design of Concrete Mixtures

Six concrete mixes were designed based on method explained in the Design of Normal Concrete Mixes (Teychenne et al.,1997). The reference concrete (RFC) was designed by using water-cement ratio of 0.44 and slump value of 60-180 mm, in order to achieve a target means strength of 63 MPa at 28 days. The second mix was the silica fume concrete which 10 weight percent (wt%) of cement was replaced by silica fume (SFC). For the remaining four concrete mixes, they were modified from the second mix by replacing 5 and 10wt% of fine aggregate with 425 and 75 micro rubber powders, respectively. All of mixture portions are presented in Table 3 in the unit of kg/m<sup>3</sup>.

**Table 3** – Mixture Proportions of Concrete, Unit in kg/m<sup>3</sup>

No.	Mixes	Cement	Water	Gravel	Sand	Silica Fume	425 micron rubber	75 micron rubber
1.	RFC	530	233	986	630	-	-	-
2.	SFC	477	233	986	630	53	-	-
3.	SFRC-425-5	477	233	986	598.5	53	31.5	-
4.	SFRC-425-10	477	233	986	567	53	63	-
5.	SFRC-75-5	477	233	986	598.5	53	-	31.5
6.	SFRC-75-10	477	233	986	567	53	-	63

### 344 5.3 Mixing of Concrete

345 After design stage, the mixing process was carefully carried out. All types of aggregates were  
 346 investigated the moisture contents are presented in Table 1. These data were used to calculate the  
 347 new quantities of aggregate required after deducing the amount of water content. The quantities of  
 348 each material were measured by using weighing scale and added in to the mechanical mixer as  
 349 following order: coarse aggregate, fine aggregate, cement and rubber powder. Then, these materials  
 350 were stirred by mechanical mixer for 3 minutes in order to prepare a dry mixture. After that, two  
 351 thirds of the required water was added in to the mixer, and all materials were blended again for  
 352 another 3 minutes. At the next step of the mixing process, silica fume and another one thirds of the  
 353 water were added in to the mixer, and all materials were thoroughly mixed until concrete had a  
 354 uniform consistency as presented in Figure 6.





(a) Fresh Normal Concrete



(b) Fresh CRC

**Figure 6** – Example of Fresh Normal Concrete (a) and CRC (b)

As illustrated in Figure 6(b), the workability of CRC seemed to reduce due to the effect of adding the small particles of rubber and silica fume into the concrete. However, it was not an obstacle in this study because the workability of CRC was still enough to cast the concrete sample. In reality, if there was an issue about the workability of CRC, by adding 2-3% of plasticizer admixture into the concrete could help to solve this issue.

#### 5.4 Casting and Preparing of Concrete Specimens

The concrete specimens of each mix were produced after the mixing process. The mould shapes used in this experiment were 100 mm cube, Ø100x L200 mm cylinder and W100 x H100 x L500 mm prism. Each type of mould was used to cast the concrete for compressive strength, splitting tensile strength, and flexural strength, respectively. Before pouring concrete, every concrete mould was prepared by cleaning and coating with release agent in order to prevent concrete bonding to the mould. After that, concrete was poured into the moulds by separating into two equal layers. In each layer, the concrete was compacted for 30 seconds by vibration table in order to eliminate air void within the concrete. Once all moulds were filled with concrete, they were covered with polythene sheeting to protect the moisture loss during the setting period of the concrete.

#### 5.5 Curing Specimens

373 After 24 hours, all the concrete specimens were removed from the moulds. Then, they were marked  
374 with the code and date in order to identify the mixture of each concrete. After that all of the samples  
375 were moved into the water tank where the temperature was controlled to be constant at 23°C. These  
376 concrete samples were cured for 7 and 28 days depending on the test requirement.

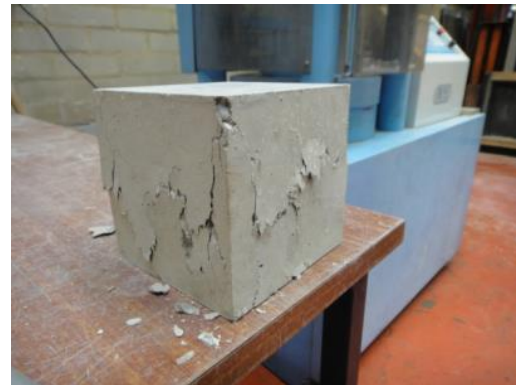
## 377 **6. Experimental Testing and Results**

### 378 **6.1 Compressive Strength**

379 The compressive strength testing was conducted according to BS EN 12390-3. Three 100 mm cube  
380 samples per mixture were used in the test. One was tested at 7 days and the other two samples were  
381 tested at 28 days. Before the test, the concrete samples were removed from the curing tank and then  
382 cleaned from surface water. After they became dry, the specimen was placed into Avery-Denison  
383 testing machine. Constant loading applied to the sample was set to 0.7 MPa/s. Once the test was  
384 started, the machine automatically carried out the test until the concrete sample failed. Then, an  
385 ultimate load was shown on the machine's monitor, and it was recorded into the logbook. The test  
386 procedures are presented in Figure 7.



(a) *Placing Specimen into Testing Machine*

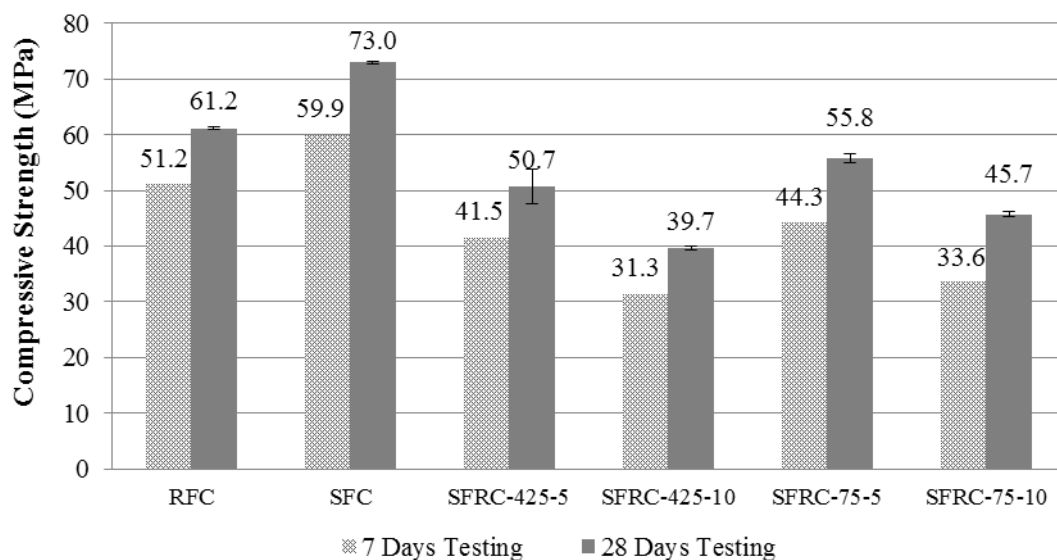


(b) *Failure of Specimen*

**Figure 7 – Compressive Strength Testing Procedure**

388 As explained, the 100 mm cube-compressive strength of all concrete mixes was tested at 7 and  
389 28 days. The results are presented in Figure 8; the compressive strengths of all mixes seemed to  
390 be in the same trend on both 7 and 28 days. The compressive strength of RFC was 51.2 MPa at 7  
391 days, and it improved 19.53% to be 61.2 MPa at 28 days. However, this strength was still lower

392 than the target mean strength around 2.94%. SFC was found as a mixture which has the highest  
 393 compressive strength of 59.9 and 73.0 MPa at both 7 and 28 days, respectively. This was  
 394 relatively higher than RFC about 19.28% for 28 days. Thus, it can be concluded that silica fume  
 395 has a positive impact to the concrete, which can improve compressive strength significantly.



396  
 397 **Figure 8 – 7 and 28 days-Compressive Strength of All Concrete Mixes**

398 As well-known from the literature reviews, replacing fine aggregate with crumb rubber causes  
 399 the reduction in compressive strength of the concrete, and an increase in rubber content also  
 400 leads to decrease in compressive strength. This can be confirmed by the results of this research.  
 401 Even though the 425 or 75 micro-crumb rubber was used in this study, the reduction of  
 402 compressive strength still appeared. However, it was not so much due to the effect of silica fume.  
 403 For example, in the case of SFRC-75-5 there was only 9.67% reduction compared to RFC. In  
 404 addition, it can be clearly seen that the compressive strength of concrete contained the bigger  
 405 size of rubber particles such as SFRC-425-5 and SFRC-425-10 has lower compressive strength  
 406 than that of smaller size (SFRC-75-5 and SFRC-75-10) for both 7 and 28 days. This is because  
 407 finer rubber particles provide a better void filling ability which causes higher compressive  
 408 strength (Su, H. et al., 2015). The SFRC-75-5 had the highest compressive strength compared to  
 409 the other CRCs.

## 410 **6.2 Splitting Tensile Strength**

411 The splitting tensile strength testing was conducted following BS EN 12390-6. In this test, three  
 412 samples of Ø100x L200 mm cylinder per mixture were used. After the samples were cured for  
 413 28 days, they were removed from the water tank, and their surface water was wiped. Once they  
 414 were dry, each cylinder sample was horizontally positioned into special metal jig for splitting  
 415 tensile strength testing as presented in Figure 9(a). Then, it was carefully placed on Denison  
 416 testing machine. After that, the compression load of 0.05 MPa/s was applied dimensionally and  
 417 uniformly along the length of cylinder sample until the sample failed (see Figure 9(b)), then an  
 418 ultimate load was recorded into the logbook.



(a) Specimen on Metal Jig



(b) Failure of Specimen

419 **Figure 9 – Splitting Tensile Strength Testing**

420 The ultimate load data obtained from the test at 28 days was calculated by using the formula  
 421 provided in BS EN 12390-6 (see Equation 1).

$$f_{ct} = \frac{2 \times F}{\pi \times L \times D} \quad (1)$$

422 where:

- 423  $f_{ct}$  is the splitting tensile strength of concrete specimen (MPa);  
 424 F is the ultimate load obtained from the testing machine (N);  
 425 L is the length of specimen (mm);  
 426 D is the cross-sectional diameter of specimen (mm).

427 The calculations of the splitting tensile strength of all concrete mixes are presented in Table 4.  
 428 From results, SFC seemed to have the highest average splitting tensile strength (3.97 MPa) over

all of concrete mixes, and it was higher than RFC approximately 38.81%. Thus, it can be interpreted that silica fume does not only improve compressive strength of concrete but it also enhances the tensile strength.

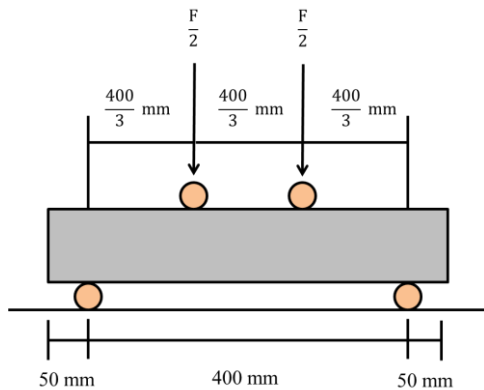
**Table 4 – Splitting Tensile Strength of All Mixes**

Mixes	Sample 1		Sample 2		Sample 3		Average (MPa)	S.D.
	Load (N)	$f_{ct}$ (MPa)	Load (N)	$f_{ct}$ (MPa)	Load (N)	$f_{ct}$ (MPa)		
RFC	88,800	2.83	89,300	2.84	91,000	2.89	2.86	0.0367
SFC	125,400	3.99	123,900	3.95	125,000	3.98	3.97	0.0247
SFRC-425-5	8,2100	2.62	85,400	2.72	87,500	2.79	2.71	0.0867
SFRC-425-10	86,800	2.76	76,300	2.43	70,800	2.26	2.48	0.2589
SFRC-75-5	98,900	3.15	92,100	2.93	102,300	3.26	3.11	0.1654
SFRC-75-10	104,000	3.31	103,400	3.29	105,400	3.35	3.32	0.0327

According to the literature review, increase in rubber content causes the reduction in tensile strength of concrete (Guneyisi et al., 2004; Su, H. et al., 2015). The results of this study tend to be in the same way of this concept for concrete contained 425 micro-crumb rubber. For example, replacing fine aggregate with 425 micro-crumb rubber for 5wt% and 10wt% reduced the splitting tensile strength to 2.71 and 2.48 MPa, which were lower than RFC about 5.53% and 15.32%. However, the very interesting results of this study were in the group of concrete mixed with 75 micro-crumb rubber. As can be seen in Table 4, the splitting tensile strengths of these concretes were relatively high (3.11 and 3.32 MPa for SFRC-75-5 and SFRC-75-10, respectively). Moreover, increase in 75 micron-rubber content can significantly improve the tensile strength of concrete. Therefore, it can be summarised that mixing concrete with proper amount of silica fume and 75 micro-crumb rubber can enhance the splitting tensile strengths of CRC.

### 6.3 Flexural Strength

Flexural strength testing is one of the methods for investigating the tensile strength of the concrete. The test is normally based on bending moment concept and it can be carried out conforming to BS EN 12390-5. In this study, this test was used to confirm the result of splitting tensile strength testing. Therefore, only one W100 x H100 x L500 mm sample of each concrete mix was tested at 28 days. The test procedure was started from removing the specimen from the curing tank and then the specimen was cleaned and dried. After that, it was marked the position for setting the experiment. At the next step of the process, the beam specimen was placed onto the roller supports (see Figure 10(a)). The continuous load was applied at the constant rate of 0.05 MPa/s from two upper rollers. When the beam failed (the crack occurred within the middle one thirds of the sample), the ultimate load shown on the monitor of testing machine was recorded into the logbook.



(a) Loading Position



(b) Failure of Specimen

**Figure 10** – Arrangement of Flexural Strength Testing

As described, this flexural strength test was conducted to confirm the results of the tensile strength test. The ultimate load data obtained from the test at 28 days was calculated by using the formula provided in BS EN 12390-5 (see Equation 2).

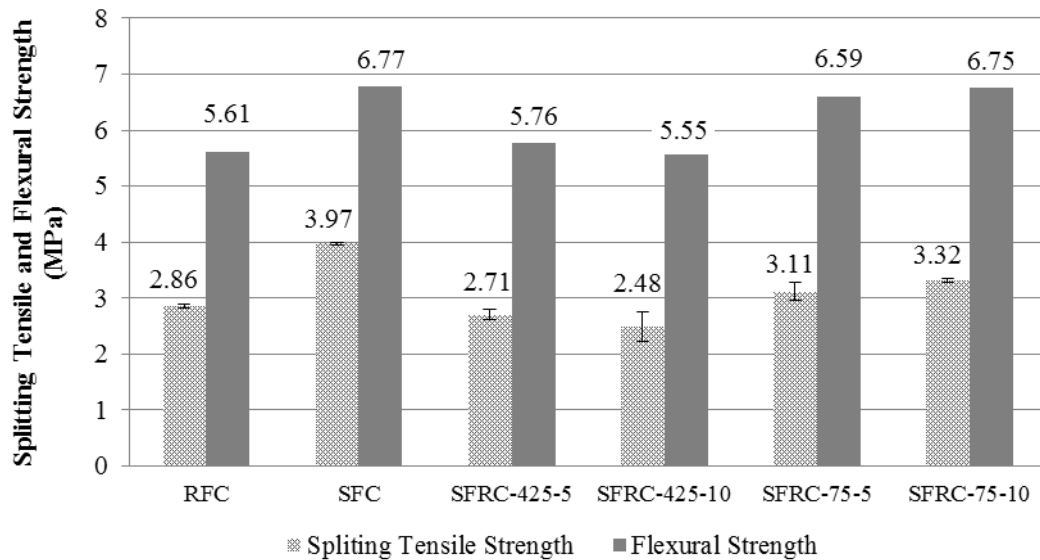
$$f_{cf} = \frac{F \times I}{d_1 \times d_2^2} \quad (2)$$

where:



467  $f_{cf}$  is the flexural strength (MPa);  
 468  $F$  is the ultimate load applied on concrete specimen (N);  
 469  $I$  is the distance between roller supports (mm);  
 470  $d_1$  and  $d_2$  are the cross-sectional dimension of concrete specimen (mm).

471 The testing results showed that the flexural strengths of all concrete mixes appeared in the  
 472 similar trend to splitting tensile strengths (see Figure 11). The SFC was still the mixture that had  
 473 the highest flexural strength (5.77 MPa), which was higher than RFC about 20.67%. In addition,  
 474 it was observed that smaller size of rubber particles mixed into concrete caused lower negative  
 475 effect to the flexural strength. For example, the flexural strengths of SFRC-75-5 and SFRC-75-  
 476 10 were greater than that of SFRC-425-5 and SFRC-425-10 by 14.40 and 21.62%, respectively.  
 477 This is because smaller size of crumb rubber can act as filler and can maintain its strength.  
 478 Furthermore, due to the ability of silica fume, SFRC-75-5 and SFRC-75-10 also had the flexural  
 479 strength much higher than RFC. Therefore, there is no concern for using these types of CRC  
 480 instead of RFC in terms of tensile strength application.



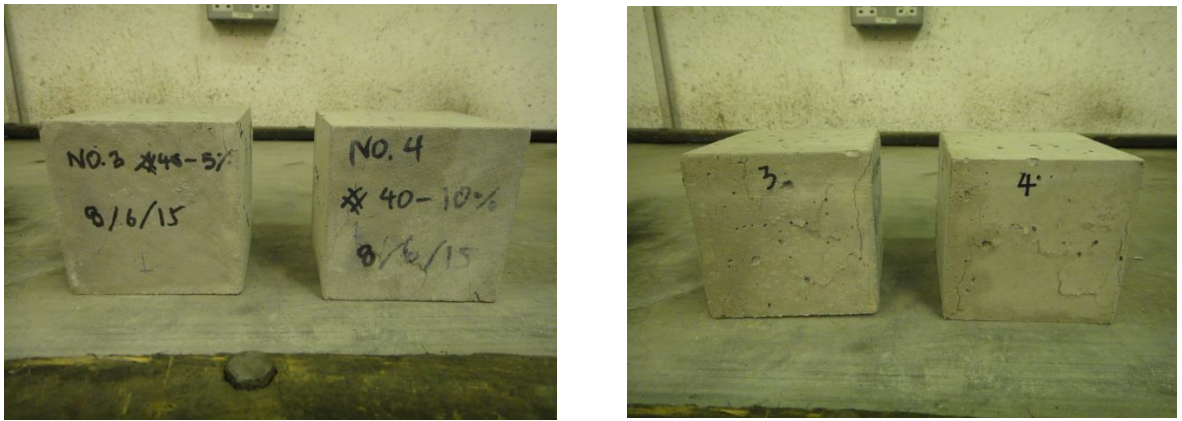
481  
 482 **Figure 11** – Comparison of Splitting Tensile and Flexural Strength

483 **6.4 Failure Patterns of Crumb Rubber Concrete**

484 After the compressive strength testing at 28 days, the failures of each concrete mix were visually  
485 inspected by considering at the crack pattern of the 100 mm cube-concrete samples as presented  
486 in Figure 12.



(a) Failure of FRC (1) and SFC (2)



(b) Failure of SFRC-425-5 (3) and SFRC-425-10 (4)



(c) Failure of SFRC-75-5 (5) and SFRC-75-10 (6)

487 **Figure 12** – The Failure Patterns of Each Concrete Mix (Author, 2015)



488 As observed from Figure 12, the failure patterns of six concrete mixes were moderately different.  
489 The RFC was a normal concrete which seemed to have the highest damage from the load applied  
490 by the testing machine. The cracks made some pieces of the concrete break off from the concrete  
491 sample as shown in Figure 12(a). The failure pattern of SFC appeared to be quite similar to RFC,  
492 but its damage was relatively lower. However, for SFRC-425-5 and SFRC-425-10, all of the four  
493 exposed faces were crack equally. The cracks propagated slightly on the specimen's surface and  
494 occurred parallel to the direction of the load. In the case of SFRC-75-5 and SFRC-75-10, the  
495 cracks were clearer than SFRC-425-5 and SFRC-425-10, but they were still following the  
496 previous pattern.

497 From the results explained above, it can be concluded that CRC tended to have a better crack  
498 resistance than the normal concrete (Sohrabi & Karbalaie, 2011). Adding accurate amount of  
499 rubber particles to concrete can control the crack initiation and propagation of concrete (Kaloush  
500 et al., 2005). This is because once the crack happens, the rubber particles inside the concrete  
501 perform as a crack arrester. They attempt to absorb the stress of the crack (Turatsinze et al.,  
502 2005). That is the reason why the CRC exhibited good characteristic in terms of crack resistance.

## 503 **7. Conclusion**

504 This study focused on the review and the development of the environment-friendly concrete  
505 using micro waste rubber (425 and 75 micron) as Micro-filler. Six different types of concrete  
506 were designed and produced in accordance to British standard. They consisted of RFC, SFC,  
507 SFRC-425-5, SFRC-425-10, SFRC-75-5 and SFRC-75-10. Three experiments were conducted:  
508 compressive strength, splitting tensile strength and flexural tensile strength. From the results,  
509 replacing fine aggregate with rubber particles caused the reduction in mechanical properties of  
510 concrete such as compressive and tensile strength. Increase in rubber content resulted in more  
511 strength reduction. However, due to the effect of micro size of rubber content (5wt% of 75  
512 micron) and silica fume, the compressive strength of CRC achieved over 55 MPa, which reduced  
513 by only 9.67% compared to RFC. The tensile strength of CRC was higher than RFC by

514 approximately 8.74% (splitting tensile strength) and 17.46% (flexural strength), but it was still  
515 lower than that of SFC. In addition, CRC tended to have a better crack resistance than the normal  
516 concrete. Adding accurate amount of rubber particles to concrete can control the crack initiation  
517 and propagation. When the crack occurs, the rubber particles inside the concrete perform as a  
518 crack arrester, which attempt to absorb the stress of the crack (Turatsinze et al., 2005).  
519 Therefore, the micro-crumb rubber concrete exhibited great mechanical properties in this study.  
520 However, it still needs further development in order to eliminate all weaknesses of CRC. Further  
521 research should investigate the influence of mixing smaller rubber particles such as Nano scale  
522 into the concrete. The chemical effect of waste rubber on the Micro and Nano structure of  
523 concrete should also be studied in order to ensure that waste rubber will not be hazardous to  
524 concrete after usage over a long life period.

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