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

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

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1. Introduction

1.1 Background

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

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

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

1.2 Literature Review

1.2.1 Crumb Rubber Concrete (CRC)

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

Different views have been put forward on mechanical properties of rubberized concrete. There was a kind of concrete with rubber has lower compressive strength than plain concrete [14, 15]. Nevertheless, Faraz, Jain and Singh [16] obtained a different result that the compressive strength of 5% rubberized concrete was higher than that of plain concrete. The reason of this special case is that rubber in concrete generated voids which may reduce bonding strength between cement and rubber [17]. Splitting tensile strength and flexural strength will also decrease by adding rubber in concrete [18, 19]. Thus, it is significant to find other materials to offset influence of adding rubber.

1.2.2 Fibre in Concrete

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

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

1.2.3 Self-healing Concrete

1. Background of Self-healing Concrete

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

$$H_2O + CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \Leftrightarrow 2H^+ + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \Leftrightarrow CaCO_3 \ (pH_{water} > 8)$$

$$Ca^{2+} + HCO_3^- \Leftrightarrow CaCO_3 + H^+ \ (7.5 < pH_{water} < 8)$$

(EQUATION X.1 HERE)

2. Influence Factors of Self-healing

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

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

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

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

1.2.4 Assessment of Self-healing Concrete

1. Making Cracks

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

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

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

2. Methods of Measuring Self-healing Abilities

3. Ultrasonic Pulse Velocity Values

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

- Natural Frequencies

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

2. Materials and Methods

The methodology of this project can be divided into 4 main steps. The first step is to investigate behaviours of concrete with crumb rubber and fibre, using engineering test standards, reviewing self-healing concrete theories, developing evaluation methods of self-healing effectiveness and natural frequencies. The second step is to design experiments. The third one is to test specimens. And the final step is to analyse and discuss results.

2.1 Materials

2.1.1 Cement

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

2.1.2 Water

The water in the laboratory is used.

2.1.3 Fine Aggregate and Coarse Aggregate

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

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

TABLE X.1 HERE Moisture Contents of Aggregates

No.	Mixes	Moisture content (%)	
		Sand	Gravel
MIX 1	Reference Conrete	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
MXI 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

2.1.4 Crumb Rubber

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

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

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

2.1.5 Fibre

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

FIGURE X.2 HERE Duras Easyfinish Fibre

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/dm³
Electrical Conductivity	None
Softening Point (Melt Point)	165°C
Colour	Grey
Tensile Strength	470Mpa
E-Modules	6000Mpa
Chloride Content	None
SO_3 Content	None

2.2 Methods

2.2.1 Design of Concrete

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

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		
MIX 2	5% 180&400 Crumb Rubber Concrete			986	598	32	
MIX 3	5% 180&400 Crumb Rubber Concrete+0.1% fibre			983.621	598		2.379
MXI 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/m³					

2.2.2 Mixing Concrete

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

FIGURE X.3 HERE Slump Tests

2.2.3 Casting Concrete

2.2.4 Making Cracks

- Standardized Cracks

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

FIGURE X.4 HERE Standardized Cracks

- Natural Cracks

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

2.2.5 Concrete tests

- Compressive Strength

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

- Splitting Tensile Strength

Based on BS EN 12390-6, three cylinders (Ø100mm x L 200mm) are tested with a 4-point bending machine at 28 days [40]. The brand of the machine is named by Avery-Dension Limited. The model type of it is AD-T42 which is manufactured in Leeds of the UK. Before testing, the loading pad of the machine and all surfaces of cylinders need to be cleaned. During testing, the rate of loading is 100N/s. The loading pad needs to be lifted immediately when cylinders fail. Then, the maximum splitting tensile strength values showed on the machine need to be recorded.

- Flexural Strength

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

- Self-healing Evaluation

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

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

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

FIGURE X.5 HERE UPV Tests

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

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

Where:

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

L refers to the length of specimens (500mm)

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

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

- Natural Frequencies Test

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

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

3. Results

3.1 Slump Tests

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

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

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

3.2 Compressive Strength

FIGURE X.7 HERE Compressive Strength

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

3.3 Splitting Tensile Strength

FIGURE X.8 HERE Splitting Tensile Strength

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

3.4 Flexural Strength

FIGURE X.9 HERE Flexural Strength

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

3.5 Self-healing Evaluation

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

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

$$D_n = {(V_n - V_{rn})}/{V_{rn}} \qquad \text{(EQUATION X.3)}$$

$$In_t = D_n - D_t$$

Where:

Vt refers to speed of control samples at t day

V_{rt} refers to the speed of the reference sample at t day

V_{rn} refers to the speed of the reference sample at n day

V_n refers to speed of control samples at n day

D_t refers to decreased speed ratios by different cracks at t day

D_n refers to decreased speed ratios by different cracks at n day

I_{n_t} refers to increase rates of self-healing between t day and n day ($n > t$)

3.5.1 Standardized Cracks

From Figure X.10, self-healing increments of every specimen can be observed. As regards Mix 1, the self-healing increment rate of specimen B drops from 0.75% to 0.1% between 30 and 32-days, then it fluctuates from 0.1% to 0.4% up until 42 days. For A and C, self-healing rates fluctuate from 0.2% to 0.45% and from 0.1% to 0.45% respectively. Moreover, the fluctuation range of self-healing rates of specimens in Mix 2 is from 0.2% to 1.0%. Furthermore, self-healing rates of specimens in Mix 3 fluctuate from 0.38% to 1.0%. Additionally, rates of specimens in Mixes 4, 5 and 6 all fluctuate from 0.2% to 1.0%. According to results showed in Figure X.10, it can be concluded that self-healing increments of specimens with standardized cracks all fluctuate between 0.1% and 1%. During tests, the author has not found any healing phenomenon on specimens with standardized cracks.

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

3.5.2 Natural Cracks

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

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

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

As you can see in Figure X.11, self-healing rates of specimens with natural cracks are illustrated. In Mix 3, self-healing rates of specimens all slightly increase between 30 days and 36 days, then they decline from 36 days to 42 days. The rate of specimen B of Mix 3 which is always the highest goes up from 3.9% to 4.0%, then it decreases to 3.5%. For Mix 4, rates of specimen A and C remain at 4.0% from 30 days to 36 days, afterwards they go down to around 3.0% up until 42 days. The self-healing rate of specimen B decreases from 3.0% to 2.8% from 30 days to 32 days, then it goes back to 3.0% within 2 days, finally it drops to 2.0% up until 42 days. In regard to Mix 5, rates of specimens A and B slightly increase from 4.0% to 4.1%. In the meanwhile, the rates of specimen C increase from 3.0% to 3.1%. In mix 6, rates of specimens A and C remain at 3.0% from 30 days to 38 days, then they decrease to 2.8% and 2.5% respectively up until 42 days. The rate of specimen B fluctuates around 2.5% between 30 days and 38 days, then it drops to 2.4% in the last 4 days. According to results in Figure X.11, it can be concluded that self-healing rates of specimens with natural cracks increase slightly or remain at a certain value from 28 days. Afterwards, increments of self-healing rates stop at around 36 days. Then, they start to decrease. The drops of self-healing rates can be interpreted as that there is almost no unreacted cement can be converted into calcium carbonate. Thus, UPV results are pretty much the same across different days. Compared with UPV values in Figure X.11, they indicate a trend on self-healing rates which can be concluded that self-healing rates increase to a highest speed then decrease to an actual value according to different proportions of fibres. Furthermore, 0.2% of fibre performs the highest self-healing rates of specimens with natural cracks in every mix of concrete.

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

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

	Ti me	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%

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

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

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

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

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

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

3.6 Natural Frequencies

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

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

4. Discussion

4.1 Mechanical properties

According to results in Figure X.7, Figure X.8 and Figure X.9, it can be concluded that mechanical properties all decrease when 5% of rubber is added to concrete. Subsequently, mechanical properties increase when the fibre is put in concrete. This means that adding the fibre can improve mechanical properties of concrete. More of the fibre induces higher mechanical properties. Finally, mechanical properties stop increasing when 0.2% the fibre is added, then they start to drop when 0.25% of the fibre is added in concrete. It can be supposed that excessive fibre will induce reductions of mechanical properties.

4.2 self-healing abilities of specimens with standardized cracks

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

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

4.3 self-healing abilities of specimens with natural cracks

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

4.4 Review of Making Cracks

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

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

4.5 Review of Test Methods

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

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

Scanning Electron Microscope (SEM)

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

X-Ray Diffraction (XRD)

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

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

4.6 Natural Frequencies

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

5. Conclusion

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

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

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

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

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

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