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Eco-friendly High-Strength Concrete Engineered by Micro Crumb Rubber from Recycled Tires and Plastics for Railway Components

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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. Most previous research focuses on applications of low-strength CRC that cannot linearly predict the high-strength counterpart. This paper thus presents a study into engineering characteristics of higher-strength CRC and its benefits to the environment, as well as investigates the ability of micro crumb rubbers to enhance CRC's mechanical properties. The results revealed that replacing fine aggregate with micro rubber particles caused a reduction in mechanical properties of concrete. However, because of the micro size of rubber content and silica fume (SFC), the compressive strength of CRC achieved over 55 MPa, which will significantly benefit the 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 SFC concrete. Moreover, CRCs also provided the ability to resist cracking of the concrete. It is found that a suitable amount of rubber particles should not be more than 10 % of the weight for novel and sustainable high-strength CRC in railway applications. The outcome of this study will help improve the database for materials in civil constructions. The adoption of sustainable high-strength CRC in railway practices will significantly minimize wastes from used rubber tires and plastics, thus paving a robust pathway for environmental impact to societies.

Keywords

concrete, polymer, flexural strength, tensile strength, mechanical properties, precast

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Introduction

Waste tires are one of the significant problems affecting the world's environment. Each year over 1 billion waste tires are generated worldwide.[1] As its nature, tires are designed to be durable and hard-wearing. When they reach the end of their useful life, they are thus very difficult to discard or decompose.[2] Therefore, it is very important to find sustainable solutions to manage this problem. In the past, the cheapest way to decompose this kind of waste would be burning. However, this method is considered poor waste management because of its negative impacts to the environment, such as air pollution and soil and water contamination.[3] Thus, the burning method is unacceptable and it should be only used if there is no better alternative way to dispose of the waste.[4]

Another method used to manage waste tires is called landfill. Generally, this method is quite useful because it can deal with an enormous amount of waste and also does not create air pollution. Nevertheless, it requires a large area to contain the wastes, which can negatively affect the landscape.[1] Additionally, toxic and soluble components in tires could also spread to soil, which reduces biodiversity in the collecting area.[3] Therefore, recently this method has become unpopular and dangerous for people living nearby.

Nowadays, recycling seems to be a famous method used to manage this waste. Rubber waste can be recycled into several things such as furniture, admixture in the rubber manufacturing process, construction material (mixed with concrete), etc. This study focuses on the use of waste tire mixed with concrete in order to supplement more data that could lead to a better prediction. A recent comprehensive review indeed shows large deviations of prediction errors, and more research to identify fundamental characteristics is still necessary.[5–9] Waste tires, after processing into small particles as crumb rubber, can be mixed into concrete as an aggregate. Most research reveals that crumb rubber can help to increase the damping property of concrete, which is very important in absorbing impact energy.[10] However, this type of concrete can be utilized only for nonstructural applications such as railway noise barriers.[11] This is because its compressive strength and other mechanical properties (e.g., tensile strength, hardness, etc.) are relatively low compared to normal concrete.[4,12,13] Therefore, crumb rubber concrete (CRC) still requires further development, especially for achieving high compressive strength, in order to apply as structural materials in the future. Therefore, this paper aims to study new mechanical properties of high-strength CRC containing micro crumb rubber. Two different sizes of crumb rubber are used: 425 and 75 micrometers. The use of silica fume (SFC) to enhance the CRC properties are analyzed, and the experimental results of compressive strength, splitting tensile strength, flexural strength, and failure patterns after compressive testing are presented in this study.

Literature Review

A critical detailed review of literature has been conducted from nearly 200 relevant publications. Most of them focus on nonstructural applications and on low- to moderate-strength concrete. In this study, CRCs are considered to be used as structural material in railway built environments, which requires higher strength and defines the novelty of this research. However, it is highly important to understand the fundamental properties of CRC and lessons learned from the previous research before conducting the experiments and finding the method to improve them. The properties of CRC (both in fresh and hardened condition) are clearly summarized in the following.

PROPERTIES OF FRESH CONCRETE

Cement

The fresh density of CRC was observed by Siddique and Naik[14] and Su et al.[15] In these studies, fresh CRC had lower density than normal concrete, and an increase in the percentage of crumb rubber affected the reduction in the fresh density. This is because the crumb rubber has low specific gravity. In addition, the nonpolar nature of rubber particles may repel water and attract air on the rubber surface, which would cause air void increase.

Workability

Workability of CRC can be evaluated by measuring slump of fresh concrete. Various researches have stated that an increase in crumb rubber replacement reduces the workability of fresh CRC.[10,14,15] In addition, the size of crumb rubber also has an impact on the workability of concrete. Su et al.[15] found that there is a reduction of slump once the size of rubber particles is decreased. However, this workability issue can be solved by adding the optimum amount of plasticizer admixture (about 2–3 %) into the concrete, as reported by Topçu and Bilir[16] and Aiello and Leuzzi.[17]

PROPERTIES OF HARDENED CONCRETE

Compressive Strength

As well known, one of concrete's main properties is compressive strength. For CRC, most of the previous researches have obviously illustrated that an increase in rubber content leads to a reduction in compressive strength.[4,15–19] However, it is not only the amount of rubber content that will affect the compressive strength, but there are also other factors. For example, Eldin and Senouci[18] investigated the strength of concrete mixed with different amounts of crumb rubber, replacing both fine and coarse aggregate (25, 50, 75 and 100 % by volume). Consequently, the results highlighted, there was significant reduction in strength when rubber content increased. In addition, a smaller reduction in compressive strength was observed when only fine aggregate was replaced by crumb rubber. Su et al.[15] studied the effect of different sizes of rubber particles (3, 0.5, and 0.3 mm) added to the compressive strength of CRC. They revealed that at 28 days, the cube compressive strength (1,003 mm^3) of concrete increased with a decrease in the rubber particle size due to a better void-filling ability of finer crumb rubber. Moreover, the type of crumb rubber also had a significant impact on the compressive strength. Several researches mentioned the use of rubber waste treated with waste organic sulfur compounds,[20] sodium hydroxide solution,[3] or silane coupling agent[21] would enhance adhesion between rubber and cement particles and improve the compressive strength significantly. Therefore, this factor can be also addressed as one of the development methods of CRC.

Tensile Strength

According to the reduction of compressive strength, tensile strength of CRC is also influenced by the amount of rubber content. An increase in rubber content decreases both splitting and flexural strength.[15,19,22] However, the reduction of tensile strength seems to have less impact than in the case of compressive strength, which is about 5 to 10 % if fine aggregate is substituted.[3] The reduction of tensile strength also depends on the size of the rubber particle. A larger rubber particle will negatively impact the tensile strength.[15] Furthermore, the type of aggregate that is substituted also has an effect on tensile strength. A larger decrease in tensile strength occurred when coarse aggregate was replaced by rubber wastes rather than fine aggregate.[17]

Elastic Modulus

Elastic modulus is one of the concrete properties affected by rubber content. It tends to reduce when increasing the percentage replacement of coarse or fine aggregate with waste rubber.[19,23] This result is very intelligible because replacing stiff aggregate with rubber (low stiffness) is a critical factor that influences the reduction in elastic modulus.[24–26] Furthermore, a larger size of crumb rubber seemed to cause more reduction in elastic modulus than did a smaller size.[27,28] Therefore, it is necessary for future research to consider this particular parameter in order to develop a better CRC.

Impact Resistance

Even though the elastic modulus of CRC decreases, the strain rate increases considerably when increasing rubber content. This makes CRC have a lower brittleness index than plain concrete, which causes CRC to have greater ductility performance.[29–32] In addition, it was revealed by Li et al.[33] that CRC also has higher toughness and better energy absorbing ability compared to normal concrete. This result is consistent with current reports stated by Aliabdo, Elbaset, and AbdElbaset[12] and Gupta, Sharma, and Chaudhary.[34] Therefore, this property of CRC would be advantageous for railway applications, especially for concrete sleepers.

Electrical Resistance

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 suggest that rubber content in concrete performs as an electrical insulator, which influences the resistivity of CRC to become higher than that of plain concrete.[4,24]

Noise Absorption

Sukontasukkul[35] conducted an experiment to investigate the noise absorption ability of CRC. Two sizes of crumb rubber were considered: passing sieve Nos. 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 the noise absorption coefficient (α). As a result, CRC seemed to have better noise absorption ability compared to the reference concrete (RFC), 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.[36]

Thermal Resistance

Thermal resistance of CRC has been studied by Kaloush, Way, and Zhu.[37] The result illustrated that the coefficient of thermal expansion 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 to thermal changing than normal concrete. In addition, Sukontasukkul[35] also found a relationship between the size of crumb rubber and thermal resistivity. Smaller rubber particles provided better thermal resistance to concrete.

Abrasion Resistance

Sukontasukkul and Chaikaew[38] 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 amounts of 10 and 20 % by weight, respectively. The abrasion test was conducted following ASTM C944-99, *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*. As illustrated in **figure 2**, an increase in the crumb rubber content caused a reduction in the 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 larger rubber particles.

FIG. 1

Noise reduction coefficient of each mix of CRC, based on the data from Sukontasukkul.[35]

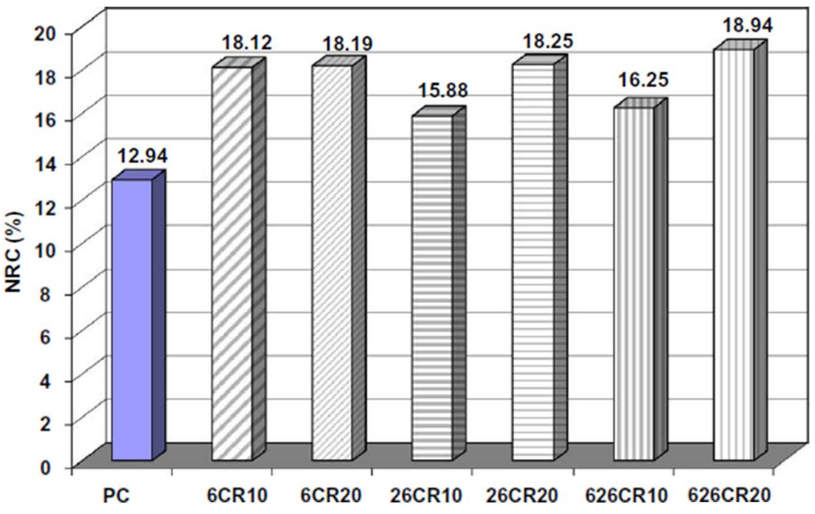


FIG. 2

Abrasion test results (based on the data from Sukontasukkul and Chaikaew[38]).

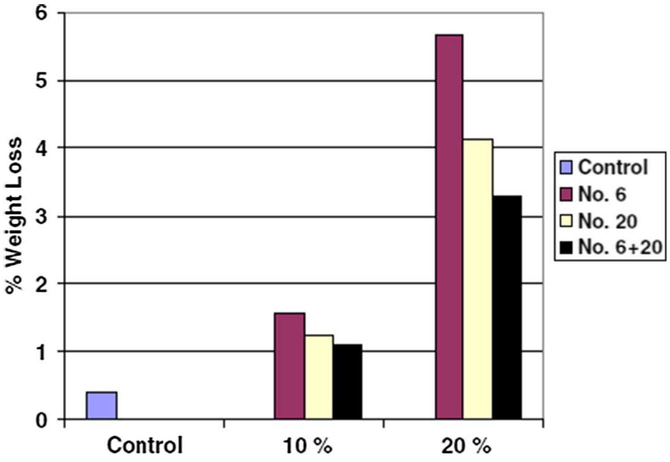
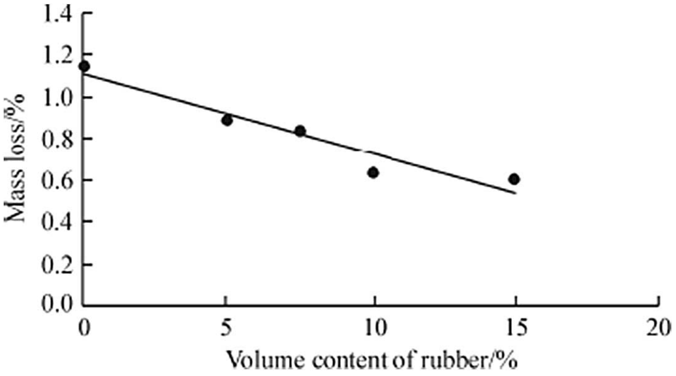


FIG. 3

Relationship between percent mass loss and rubber content in concrete (based on the data from Kang, Zhang, and Li[39]).



However, Kang, Zhang, and Li[39] found the opposite results of previous research when only replacing the same volume of fine aggregate with crumb rubber. They found that CRC seemed to have a better abrasion resistance than plain and SFC concrete (lower percent mass loss). The abrasion resistance of CRC tended to increase as rubber content increased, as presented in **figure 3**. This may be because the CRC has excellent dynamic performance in terms of energy absorption, toughness, and cracking resistance. Therefore, these parameters resulted in better abrasion resistance in CRC.

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.[40] In theory, when the water freezes, its volume expands approximately 9 %, which leads to a change in internal stress of the concrete and makes the damage occur.[41] According to the literature, the addition of crumb rubber can enhance freeze-thaw protection of the concrete. Richardson et al.[42,43] 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 Gesoğlu et al.[44] 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 larger size. This was because a small size of rubber has higher surface area, which can increase the amount of microscale pores, and these pores can reduce the effect of internal stress once the water freezes.[44]

Remarks 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, including compressive strength, tensile strength, and elastic modulus. Thus, this research focuses on the development of these properties, especially to develop eco-efficient high-strength CRC for applications in aggressive environments 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 the mechanical property problems. The comprehensive review of nearly 200 relevant technical publications in open literature shows that previous work mostly focuses on low- to moderate-strength concrete.[45–49] The moderate-strength concrete cannot meet the serviceability and ultimate limit states requirements for industrial applications in railway environments.[50,51] Therefore, this study is the first to investigate the engineering properties of high-strength CRC (>50 MPa). The very small particles of rubber waste as microscale (425 and 75 micrometers) were selected to use in the experiment. This technique is expected to improve microstructures of concrete and to solve the drawbacks of CRC. It is clear that the strength and serviceability of CRC cannot be directly or linearly predicted from previous studies. Thus, the development of novel and sustainable high-strength CRC still requires further research.

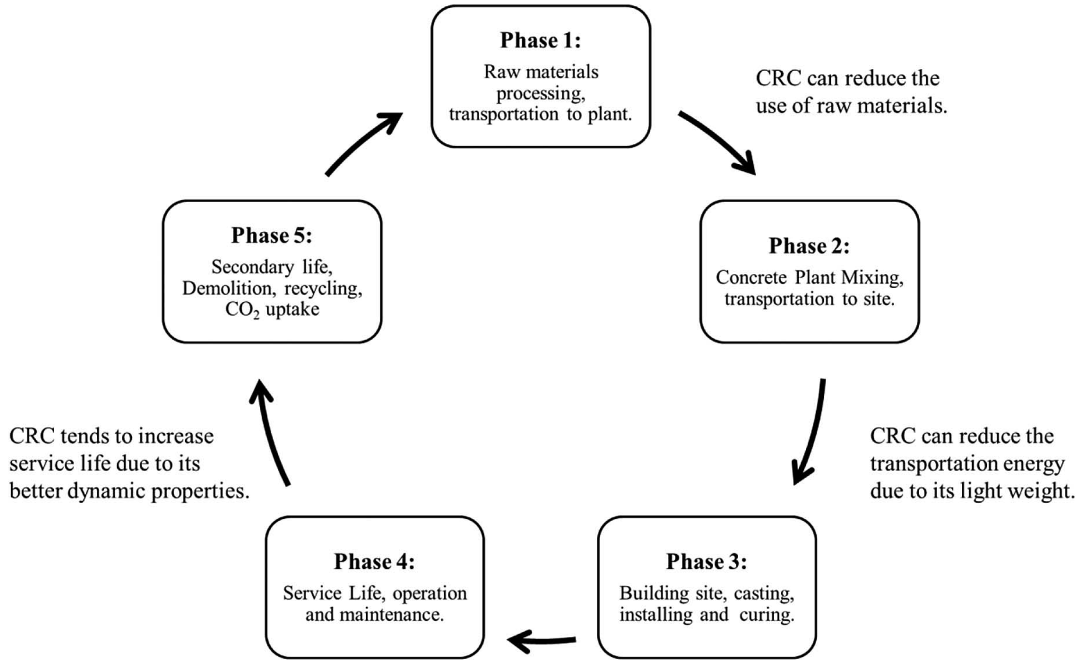
Environmental Benefits

Besides the benefits to the dynamic properties, CRC can be also advantageous to the environment in various ways, such as reducing landfill, reducing embodied carbon in construction projects, and minimizing noise and vibration to the surrounding environment. Therefore, this section will discuss those issues and provide the encouragement to the use of CRC in the future. The recycling of waste rubber by mixing it with concrete plays a significant role in reducing landfill.[52] As is 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 minimize the waste rubber in landfill sites. The additional benefit could contribute to the reduction of landfill pollution in terms of soil and water contamination from toxic and soluble components from waste tires.

There is no doubt that concrete is one of the more common construction materials and is widely used around the world because of its high strength and durability. However, there is still concern about its embodied carbon, carbon dioxide.[53] With the increasing trend of environmental awareness, rubber wastes have become the optimal raw material of the concrete mix. The replacement of concrete aggregates with rubber particles could potentially reduce the carbon footprint of the concrete.[54] As shown from the life cycle of concrete (see **fig. 4**), production of CRC leads to a reduction in the use of natural materials, rubber wastes, and transportation energy due to its light weight, etc.[55,56] Moreover, the service life of CRC tends to be longer than normal concrete due to its better dynamic properties. Therefore, using CRC in construction can support the project to become more sustainable and improve its reputation in terms of excellent environmental management.

As revealed by various researches, CRC also provides a better noise and vibration absorption ability.[35,36] Thus, applying CRC as a material in construction projects where noise and vibration are the main concern, such as railway and highway, can be beneficial. Recently, CRC is still used only for nonstructural applications due to its low strength.[4,12] Therefore, to enhance the environmental benefits of CRC, its drawbacks need to be eliminated. In summary, CRC can provide substantial benefits to the environment. Just 5 % of crumb usage in concrete globally can actually reduce plastic wastes by more than 1 billion tons. Using CRC in projects can help reduce the pollutions generated from waste rubber tires. In addition, the applications of CRC will also increase the sustainability of the project. Therefore, if there is no limitation to its strength, this type of concrete will surely become the main choice of construction material in the future.

FIG. 4 Life cycle of concrete with the advantages of CRC in terms of carbon footprint, based on the data from Nielsen.[56]



Concrete Mix Design and Specimens

MATERIALS

In this study, the materials used to make concrete specimens can be separated into five main groups: cement, clean water, fine and coarse aggregate, crumb rubber, and SFC. The properties of each material are clearly explained in the following.

Cement

Ordinary Portland cement type I with a characteristic strength of 52.5 MPa (in accordance with BS EN 197-1, *Cement. Composition, Specifications and Conformity Criteria for Common Cements*[57]) was used to prepare concretes in this study. It has a gray color that is compatible to cement replacement admixtures such as SFC, fly ash, etc. This cement was contained in an airtight package and stored in a room with dry conditions before use.

Water

Clean water supplied from the laboratory was used to make a hydration reaction in the concrete mixtures. In this study, plasticizer has not been used because this is a study to determine the actual characteristics of crumb rubbers and their interaction with cement binders.

Fine and Coarse Aggregates

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

TABLE 1

Moisture content of aggregate

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

Note: [a] Target for high-strength concrete for railway applications.

content of the aggregate was recalculated before mixing every time in order to adjust the proportion of concrete mix and keep the water-cement ratio constant following the design.

Crumb Rubber

This study focused on two different sizes of crumb rubber: 425 and 75 micrometers. The 425-micron crumb rubber was kindly provided by J. Allcock & Sons Ltd. (see fig. 5*A*). It is a common type of crumb rubber made from the ambient grinding of truck tire buffing. It has black color with specific gravity of 1.14 ± 0.02. The 75-micron crumb rubber (see fig. 5*B*) was supplied by Lehigh Technologies Inc. This type of crumb rubber was also produced from end-of-life tires. It has also black color with a similar specific gravity of 1.14 ± 0.03. This material has very small-sized particles. Thus, it can be also called micronized rubber powder instead of crumb rubber. Before use, these two crumb rubbers were packed in airtight packaging that was free from contaminants such as metal, textile, dust, etc. Therefore, it could be ensured that there was no effect of other factors on the concrete mixtures.

SFC

Elkem SFC, grade 940 was used for the purpose of enhancing mechanical properties of CRC in this study. It is an undensified SFC and has a gray color. Before use, it was stored in dry conditions at a civil engineering laboratory. The chemical and physical properties of this SFC are presented in Table 2.[58]

DESIGN OF CONCRETE MIXTURES

Six concrete mixes were designed based on the method explained in *Design of Normal Concrete Mixes*.[59] The RFC was designed by using a water-cement ratio of 0.44 and slump value of 60–180 mm in order to achieve a target

FIG. 5 Rubber powder, (*A*) 425 micrometers and (*B*) 75 micrometers.

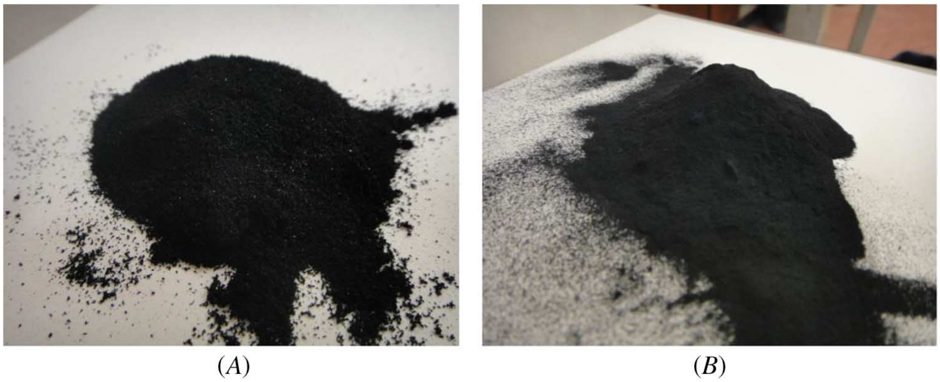

(*A*) (*B*)

TABLE 2

Chemical and physical properties of undensified SFC[58]

No.	Properties	Value
1	SiO_2	Minimum, 90 %
2	Loss of ignition	Maximum, 3 %
3	Coarse particles > 45 µm	Maximum, 1.5 % (tested on undensified)
4	Bulk density (*U*)	200–350 kg/m^3
5	Bulk density (*D*)	500–700 kg/m^3

TABLE 3

Mixture proportions of concrete, kg/m^3

No.	Mixes	Cement	Water	Gravel	Sand	SFC	425-Micrometer Rubber	75-Micrometer 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

mean strength of 63 MPa at 28 days. The second mix was the SFC concrete, of which 10 weight percent (wt%) of the cement was replaced by SFC. For the remaining four concrete mixes, they were modified from the second mix by replacing 5 and 10 wt% of fine aggregate with 425- and 75-micron rubber powders, respectively. All of mixture proportions are presented in **Table 3** in the unit of kg/m^3.

MIXING OF CONCRETE

After the design stage, the mixing process was carefully carried out. All types of aggregates were investigated; the moisture contents are presented in **Table 1**. These data were used to calculate the new quantities of aggregate required after deducing the amount of water content. The quantities of each material were measured by using a weighing scale and added into the mechanical mixer in the following order: coarse aggregate, fine aggregate, cement, and rubber powder. Then, these materials were stirred by mechanical mixer for 3 minutes in order to prepare a dry mixture. After that, two thirds of the required water was added into the mixer, and all materials were blended again for another 3 minutes. At the next step of the mixing process, SFC and another one third of the water were added into the mixer, and all materials were thoroughly mixed until the concrete had a uniform consistency. The workability of CRC seemed to reduce because of adding the small particles of rubber and SFC 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 concerning the workability of CRC, adding 2–3 % of plasticizer admixture into the concrete could help solve this issue.

CASTING OF CONCRETE SPECIMENS

The concrete specimens of each mix were produced after the mixing process. The mold shapes used in this experiment were a 100-mm cube, Ø100 × L200 mm cylinder, and W100 × H100 × L500 mm prism. Each type of mold was used to cast the concrete for compressive strength, splitting tensile strength, and flexural strength, respectively. Before pouring concrete, every concrete mold was prepared by cleaning and coating with release agent in order to prevent the concrete from bonding to the mold. After that, concrete was poured into the molds by separating into two equal layers. In each layer, the concrete was compacted for 30 seconds by vibration table in order to eliminate the air void within the concrete. Once all molds were filled with concrete, they were covered with polythene sheeting to protect the moisture loss during the setting period of the concrete.

CURING OF CONCRETE SPECIMENS

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

Experiments

COMPRESSIVE STRENGTH

The compressive strength testing was conducted according to BS EN 12390-3, *Testing Hardened Concrete Part 3: Compressive Strength of Test Specimens.*[60] Three 100-mm cube samples per mixture were used in the test. Indicatively, one was tested at 7 days and the other two were tested at 28 days. Note that a set of three samples was tested for each engineering properties to confirm the outcomes separately.[53] Prior to the test, the concrete samples were removed from the curing tank and then cleaned from surface water. After they dried, the specimens were placed into the Avery-Denison testing machine. Constant loading applied to the sample was set to 0.7 MPa/s. Once the test was started, the machine automatically carried out the test until the concrete sample failed. Then, an ultimate load was shown on the machine's monitor, and it was recorded into the logbook. As explained, the 100-mm cube compressive strength of all concrete mixes was tested at 7 and 28 days. The results are presented in **figure 6**; the compressive strengths of all mixes seemed to be in the same trend at both 7 and 28 days. The compressive strength of RFC was 51.2 MPa at 7 days, and it improved 19.53 % to be 61.2 MPa at 28 days. However, this strength was still lower than the target mean strength around 2.94 %. SFC was found as a mixture, which has the highest compressive strength of 59.9 and 73.0 MPa at both 7 and 28 days, respectively. This was relatively higher than RFC, about 19.28 %, for 28 days. Thus, it can be concluded that SFC has a positive impact to the concrete, which can improve compressive strength significantly.

As is well known from literature reviews, replacing fine aggregate with crumb rubber causes the reduction in compressive strength of the concrete, and an increase in rubber content also leads to decrease in compressive strength. This can be confirmed by the results of this research. Even though the 425- or 75-micron crumb rubber was used in this study, the reduction of compressive strength still appeared. However, it was not so much because of SFC. For example, in the case of SFRC-75-5, there was only 9.67 % reduction compared to RFC. In addition, it can be clearly seen that the compressive strength of concrete containing the larger size of rubber particles such as SFRC-425-5 and SFRC-425-10 is lower than that containing smaller size (SFRC-75-5 and SFRC-75-10) at both 7 and 28 days. This is because finer rubber particles provide a better void-filling ability, which causes higher compressive strength.[15] The SFRC-75-5 had the highest compressive strength compared to the other CRCs.

FIG. 6 Compressive strength at 7 and 28 days for all concrete mixes.

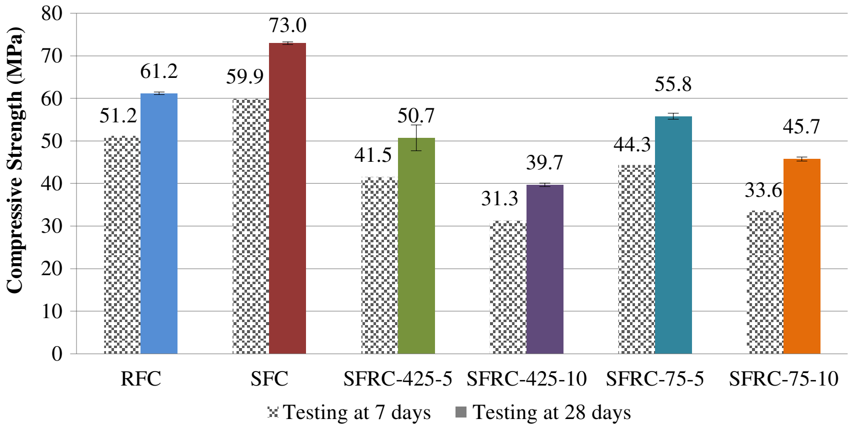


TABLE 4

Splitting tensile strength of all mixes

	Sample 1		Sample 2		Sample 3		Average	
Mixes	Load, kN	f_{ct}, MPa	Load, kN	f_{ct}, MPa	Load, kN	f_{ct}, MPa	f_{ct}, MPa	*SD*
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	82,100	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

SPLITTING TENSILE STRENGTH

The splitting tensile strength testing was conducted following BS EN 12390-6, *Testing Hardened Concrete Part 6: Tensile Splitting Strength of Test Specimens*.[61] In this test, three samples of Ø100 × L200 mm cylinder, per mixture, were used. After the samples were cured for 28 days, they were removed from the water tank, and their surface water was wiped. Once they were dry, each cylinder sample was horizontally positioned into a special metal jig for splitting tensile strength testing. Then, it was carefully placed on the Denison testing machine. After that, the compression load of 0.05 MPa/s was applied dimensionally and uniformly along the length of the cylinder sample until the sample failed, and then an ultimate load was recorded into the logbook. The ultimate load data obtained from the test at 28 days were calculated by using the formula provided in BS EN 12390-6 (see equation (1)).

$$f_{ct} = \frac{2 \times F}{\pi \times L \times D} \tag{1}$$

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

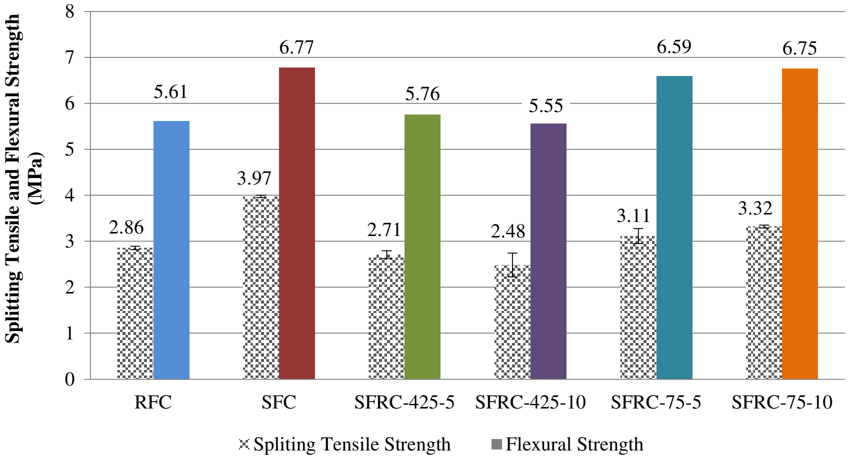
The calculations of the splitting tensile strength of all concrete mixes are presented in **Table 4**. From the results, SFC seemed to have the highest average splitting tensile strength (3.97 MPa) over all concrete mixes, and it was higher than RFC by approximately 38.81 %. Thus, it can be interpreted that SFC does not only improve the compressive strength of concrete but it also enhances the tensile strength.

According to the literature review, an increase in rubber content causes a reduction in the tensile strength of concrete.[15,19] The results of this study tend to agree with this concept for concrete containing 425-micron crumb rubber. For example, replacing fine aggregate with 425-micron crumb rubber for 5 wt% and 10 wt% 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, an increase in 75-micrometer rubber content can significantly improve the tensile strength of concrete. Therefore, it can be summarized that mixing concrete with the proper amount of SFC and 75-micro crumb rubber can enhance the splitting tensile strength of CRC.

FLEXTURAL STRENGTH

Flexural strength testing is one of the methods for investigating the tensile strength of the concrete. The test is normally based on the bending moment concept and it can be carried out conforming to BS EN 12390-5, *Testing Hardened Concrete Part 5: Flexural Strength of Test Specimens*.[62] In this study, this test was used to confirm the result of splitting tensile strength testing. Therefore, only one W100 × H100 × L500 mm sample of each concrete mix was tested at 28 days. The test procedure was started by removing the specimen from the curing tank, and then the specimen was cleaned and dried. After that, the position for setting the experiment was marked. At the next step of the process, the beam specimen was placed onto the roller supports. The continuous load was applied at the

FIG. 7 Comparison of splitting tensile and flexural strengths.



constant rate of 0.05 MPa/s from two upper rollers. When the beam failed (the crack occurred within the middle one third of the sample), the ultimate load shown on the monitor of testing machine was recorded into the logbook.

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 were calculated by using the formula provided in BS EN 12390-5[62] (see equation (2)).

$$f_{cf} = \frac{F \times I}{d_1 \times d_2^2} \tag{2}$$

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

The testing results showed that the flexural strengths of all concrete mixes appeared in a similar trend to splitting tensile strengths (see **fig. 7**). The SFC was still the mixture that had the highest flexural strength (5.77 MPa), which was higher than RFC, about 20.67 %. In addition, it was observed that the smaller size of rubber particles mixed into concrete caused a lower negative effect to the flexural strength. For example, the flexural strengths of SFRC-75-5 and SFRC-75-10 were greater than those of SFRC-425-5 and SFRC-425-10 by 14.40 and 21.62 %, respectively. This is because the smaller size of crumb rubber can act as filler and can maintain its strength. Furthermore, due to the ability of SFC, SFRC-75-5 and SFRC-75-10 also had flexural strengths much higher than RFC. Therefore, there is no concern for using these types of CRC instead of RFC in terms of tensile strength application.

FAILURE MODES

After the compressive strength testing at 28 days, the failures of each concrete mix were visually inspected by considering the crack pattern of the 100-mm cube concrete samples, as presented in **figure 8**.

As observed from **figure 8**, the failure patterns of six concrete mixes were moderately different. The RFC was a normal concrete, which seemed to have the highest damage from the load applied by the testing machine. The cracks made some pieces of the concrete break off from the concrete sample, as shown in **figure 8*A***. The failure pattern of SFC appeared to be quite similar to RFC, but its damage was relatively lower. However, for SFRC-425-5 and SFRC-425-10, all four exposed faces were cracked equally. The cracks propagated slightly on the specimen's surface and occurred parallel to the direction of the load. In the case of SFRC-75-5 and SFRC-75-10, the cracks were clearer than SFRC-425-5 and SFRC-425-10, but they still followed the previous pattern. From the results explained previously, it can be concluded that CRC tended to have a better crack resistance than the normal

FIG. 8 The failure patterns of each concrete mix. (*A*) Failure of FRC (1) and SFC (2); (*B*) failure of SFRC-425-5 (3) and SFRC-425-10 (4); and (*C*) failure of SFRC-75-5 (5) and SFRC-75-10 (6)

(*A*)

(*B*)

(*C*)

concrete.[63] Adding an accurate amount of rubber particles to concrete can control the crack initiation and propagation of concrete.[37] This is because once the crack happens, the rubber particles inside the concrete perform as a crack arrester. They attempt to absorb the stress of the crack.[64–70] That is the reason why the CRC exhibited good characteristics in terms of crack resistance.

Conclusions

This study focused on the review and development of the environment-friendly concrete using micro waste rubber (425 and 75 micrometers) as micro-filler. This study into high-strength CRC at the particle size is uncommon, and this study highlights the new development of high-strength concrete using micro crumb rubbers (>50 MPa). Six different types of concrete were designed and produced high-strength products in accordance to British standards. Variation of SFC has been established to enable strength compensation of concrete mixes. They consisted of RFC, SFC, SFRC-425-5, SFRC-425-10, SFRC-75-5, and SFRC-75-10. Three experiments were conducted: compressive strength, splitting tensile strength, and flexural tensile strength. From the results, replacing fine aggregate with rubber particles caused reduction in mechanical properties of concrete, such as compressive and tensile strength. An increase in rubber content resulted in more strength reduction. However, due to the effect of the micro size of rubber content (5 wt % of 75 micrometers) and SFC, the compressive strength of CRC achieved over 55 MPa, which reduced by only 9.67 % compared to RFC. The tensile strength of CRC was higher than that of RFC by approximately 8.74 % (splitting tensile strength) and 17.46 % (flexural strength), but it was still lower than that of SFC. These results are original and define untraditional trends in the mechanical behaviors of high-strength CRC, which are different from those of traditional CRCs. In addition, CRC tended to have a better crack resistance than the normal concrete. Adding an accurate amount of rubber particles to concrete can control crack initiation and propagation. When the crack occurs, the rubber particles inside the concrete perform as a crack arrester and attempt to absorb the stress of the crack. Therefore, the micro crumb rubber concrete exhibited great mechanical properties and implied the feasible use as a waste management strategy in this study. However, further development is needed in order to eliminate all weaknesses of CRC. Further research should investigate the influence of mixing smaller rubber particles such as nanoscale into the concrete. The chemical effect of waste rubber on the micro- and nanostructure of concrete should also be studied in order to ensure that waste rubber will not be hazardous to concrete after usage over a long life period.

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