Effects of Long Shredded Rubber Particles Recycled from Waste Tires on Mechanical Properties of Concrete

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ABSTRACT:

The goal of this research is to study the mechanical properties of recycled rubber particles extracted from scrap tires in concrete to introduce a sustainable waste management system and subsequently to reduce the use of non-renewable resources in concrete. In this paper, fine aggregates of concrete are partially replaced (up to 50% by volume of fine aggregate) with recycled long shredded rubber particles mainly smaller than sieve #4 in size. Concrete cylinders with different proportion of rubber are prepared and tested under compression. Also, specimens without rubber are prepared and tested as control specimens. The compressive strength, elastic modulus, and stress-strain curves of the specimens are analyzed to characterize the behaviour of concrete with recycled long shredded rubber particles. The results showed that the rubber weakened the compressive strength and elastic modulus of concrete. Empirical equations are also proposed to account the effect of rubber content on the mechanical properties.

KEYWORDS: Recycled tire, crumb rubber, long shredded rubber, concrete, strength, modulus.

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1. INTRODUCTION

Use of recycled tire particles as a construction material helps to reduce the use of natural resources and promote more environmentally friendly practices. On the other hand, if waste tire recycling process is not managed in a proper manner, it will affect to the health of people and animals. As a method of recycling of waste tires, rubber particles obtained from waste tires can be used in concrete [1] and it has motivated a significant body of research in the field of concrete technology [2]. Three deferent sizes of recycled tires can be normally taken in to research including rubber powder (partially replacing cement and/or filler materials), crumb rubber less than 5 mm in size (partially replacing fine aggregates or sand) and rubber chips larger than 5 mm in size (partially replacing course aggregates or gravel) in concrete. Several studies [3][4][5][6] have shown that rubber particles lower the strength of concrete due to the lack of bonding between rubber particles and cement paste and coarser rubber particles lower the strength more than finer rubber particles.

Majority of studies on the applications of rubber particles recycled from waste tires in concrete have been focused on crumb rubber particles with almost round-shape geometry. For example, Mendis et al. [7] partially replaced fine aggregate in concrete with crumb rubber ranging from about 5 to 21% of the total volume of fine aggregates. Li et al. [8] studied the mechanical properties of concrete with low volume of crumb rubber particles in concrete mixture replacing of fine aggregates rubber content ranging from 2 to 12%. Recently, Youssf et al. [9] studied the mechanical performances of a 20% crumb rubber content in concrete mixes. The rubber content was selected as Khatib et al. [10] suggested that using more than 20% rubber in concrete may magnify the adverse effects on concrete characteristic.

Multiple other researchers [11][12][13] also studied the use of crumb rubber as fine aggregate replacement in concrete. Overall, it is believed that due to a low elastic modulus of crumb rubber with respect to conventional stone aggregates, rubber aggregates act as large pores and do not significantly contribute to the strength of concrete [2]. As increasing the rubber content decreases concrete strength, it has been concluded that up to 25% replacement by volume of fine aggregate with crumb rubber in concrete mixes, does not significantly reduce the compressive strength [12]. However, most of the previous studies have been based on crumb rubber with almost round particles and the effect of long rubber particles such as long shredded rubber (also known as rubber mulch) on concrete has not been investigated. The geometry of long shredded rubber might help bridging cracks rather that acting only as pores in concrete. Hence, the focus of this paper is to study the effect of long shredded rubber particle on strength, elastic modulus, and stress-strain behavior of concrete.

2. RESEARCH SIGNIFICANCE

There are many researches on the effects of rubber particles on mechanical properties of concrete. Majority of research activities have been concentrated on the use of round rubber particles known as crumb rubber partially replacing fine and/or coarse aggregates in concrete. There are also a few researches on large size rubber particles partially replaced coarse aggregates. Moreover, very fine rubber particles in the form of powder have been used as filler in concrete. However, there has been no research on long shredded rubber particles known as mulch in concrete. As these particles are long, they might be able to work similar to short fibers in concrete bridging cracks. This paper focusses on long shredded rubber particles recycled from tiers on mechanical properties of concrete.

3. EXPERIMENTAL PROGRAM

3.1. Specimen Layout

A total of 24 concrete cylinders (100 mm diameter and 200 mm height) was prepared and tested under compression loading. The replacement of fine aggregates from shredded rubber by volume was used to prepare concrete mix at different percentages of 0, 10, 20, 30, 40, and 50% (by volume of fine aggregates) as shown in Table 1 and other all ingredients were constant. Four identical specimens were prepared in each group. The specimens without shredded rubber were designed as control specimens.

3.2.Material Properties

General use Portland cement was used for this study. Fine aggregate (natural sand) with bulk density 1791 kg/m^3 and coarse aggregate having a maximum size of 12.5 mm with bulk density 1666 kg/m^3 were used. Shredded rubber particles were used for this study with bulk density 535 kg/m^3. Figure 1 shows the shredded rubber particles used in this experimental program and Figure 2 shows the particle size distribution of shredded rubber, fine aggregates (sand), and coarse aggregates (gravel). The average particle size remained on the Sieve No. 04 was approximately 28 mm long. The figure shows that the shredded rubber used in this study had a gradation curve in between the fine and coarse aggregates. Each specimen was prepared with 656.8 kg/m^3 cement, 221.1kg/m^3 water and 949.8kg/m^3 course aggregates. A constant water cement ratio of 0.33 was considered for this experiment and the dosage of superplasticizer (PLASTOL 6400) 2 ml per 1 kg of cement was added to achieve the required workability for the mixture. The mix proportions of six groups are shown in Table 1.

3.3. Specimen Preparation

As shown in Figure 3, cylindrical plastic molds with a size of 100 mm diameter and height of 200mm were used to cast all specimens. Since the two number of control specimens, 3.357 Kg coarse aggregates and 1.805 Kg fine aggregates (sand) added to the mortar mixing machine as shown in figure 3 and mixed around 2 minutes in dry condition. After that, 2.232 kg cement also added to the mixture and mixed another 1 to 2 minutes as required. Then, measured water 785ml added to the mixture regularly during operation of the mixing machine and 5 ml superplasticizer also add to each mixture and continue another 2 to 3 minutes. The same procedure was followed for the all other mixtures with adding shredded rubber to the finer aggregate as specified in section 2.1 specimen layout. All concrete mixes were placed in cylinders which were already cleaned and applied mould oil, with three equal layers and compacted using 10 mm tamping rod each layer 25 times. Four specimens in each group were prepared. The samples were kept at curing room for 28 days. The density of each specimen was calculated by taken weight of each sample after 28 days dividing the volume of the specimen. specimens were weighed under dry condition after 28 days. Calculated densities are tabulated in Table 2. Capping of the samples were done using sulfur mortar to give a smooth leveled surface to concrete cylinder faces to apply the compressive load evenly through the specimen. With reference to the results taken from the average density, it could be clearly identified that the increase of shredded rubber in concrete mix had decreased the density of the concrete. The increase of the shredded rubber from 0% to 20% decreased the density 2530.73 kg/m^3 to 2441.76 kg/m^3 (3.52% decrease) also, the increase of the shredded rubber from 0% to 50% decreased the density 2530.73 kg/m^3 to 2343.11 kg/m^3 (7.41% decrease). In addition to that, the results show, the density reduction rate has increased at 1.51%, 2.01% and 2.6% from R0 to R10, R10 to R20 and R20 to R30 respectively and from R30 to R50, the increasing rate has decreased except the average density results of the R40 concrete. This error might be appeared during the calculation of density due to the volume of specimens were taken as same for the all samples and there might be a slight difference of the interior dimensions of the plastic moulds.

3.4. Test Setup and Instrumentation

The instrumentation setup for compression test was arranged as shown in figure 4. LP1 and LP 2 were fixed straight in the Centre of the cylinder to measure the lateral stain during the test and LP3 and LP4 were fixed into the steel rings to measure the axial strain as displayed in figure 4. These LPs were used to measure axial and lateral displacement during the test. The axial deformation referred to in this paper is the average value of the LP3 and LP4. The 100 mm gap between the two ring's center to center was maintained for each test. The bottom steel cylinder was used to achieve the enough room for LP no. 03 and 04 during the test. The compressive strength test was done by carefully placing the load to the center of the specimen to maintain the zero eccentricity and the computer programmed to deform the specimens at a rate of 0.4 mm per minute. The specimens were compressed until it did not seem safe to deform the specimen any further.

4. RESULTS AND DISCUSSION

4.1.Failure Modes

Figure 5 shows the specimens failure modes after the tests. It was noted that, the R0 cylinder (control) was failed as more brittle compared to the other specimens and behaviour of brittle failure was decreased with an increment of shredded rubber. The failure cracks were generated approximately in vertical direction for all the specimens except R50 specimen. R50 specimen were generated cracks in both directions approximately in horizontally and vertically. Overall, increasing the shredded rubber content changed the mode of failure from typical diagonal cracks to a combination of longitudinal and transverse cracks.

4.2.Effect of Shredded Rubber on Concrete Strength

Figure 6 illustrates the effect of shredded rubber content on concrete strength in compression. Each dot shows the average compressive strength of each group and the error bars show a standard deviation above and below the average value. Overall, by increasing the rubber content to 10, 20, 30, 40, and 50% of the fine aggregates by volume, the average compressive strength of each group was reduced by 21, 23, 33, 32, and 47 % with respect to the average strength of the control specimens, respectively. The results generally show that the increasing of shredded rubber content in concrete decreased the compressive strength. As shown in the figure, there is an exponential trend for the reduction as follows:

$$f_c'(R) = f_{co}' e^{-1.2R/100} \tag{1}$$

where f'_c is the compressive strength of concrete with a shredded rubber content of R in percent and f'_{co} is the compressive strength of control concrete without rubber. The empirical equation has an R-squared value of 89% indicating a relatively good correlation between the model prediction and the test results.

4.3. Effect of Shredded Rubber on Concrete Elastic Modulus

The elastic modulus also has decreased due to the increase of the shredded rubber in concrete. The results in Figure 7 show the average elastic modulus of each group of test specimens. Elastic modulus of each test was obtained from the slope of the trend line to the stress-strain curves up to 45% of peak stress. Overall, by adding 10, 20, 30, 40, and 50% shredded rubber, the elastic modulus decreased by 6, 16, 28, 27, and 36% compared to the control specimen, respectively. The results indicate that the elastic modulus of concrete is less sensitive to the shredded rubber content than compressive strength. This shows that after the initial micro cracking of concrete beyond the elastic region, micro cracks propagated faster in concrete with high rubber content than that of in low rubber content. As shown in Figure 7, there is an exponential trend between the elastic modulus and shredded rubber content in concrete as follows:

$$E_c(R) = E_{co} e^{-0.9R/100} \tag{2}$$

where E_c is the elastic modulus of concrete with a shredded rubber content of R in percent and E_{co} is the elastic modulus of control concrete without rubber. The empirical equation has an R-squared value of 96% indicating a very good correlation between the model prediction and the test results. This means that the model of elastic modulus has a better agreement with the test data in comparison with the model of compressive strength.

4.4. Effect of Shredded Rubber on Concrete Stress-Strain Curve

Figure 8 shows the stress-strain curves of the test specimens. Each curve is the average of all specimens with the same rubber content. The right side of the diagram shows the axial strain and the left side shows the lateral strain. The results show that the increasing of the shredded rubber content from 0 to 50% gives a lower slope (modulus) to the stress-strain curve with reducing the peak axial stress (i.e. compressive strength). The figure also shows that the axial strain at the peak stress does not change significantly and stay at the normal range of conventional concrete, i.e. about 0.002 mm/mm. However, the specimens with shredded rubber showed a significant post peak behavior, indication the potential for higher energy absorption and less brittle failure. This is compatible with failure observed during the tests and failure modes presented in Figure 5. The lateral strain curves presented in Figure 8 also show similar trend to the axial strain, however with longer post peak behavior. For the future, concrete containing large quantity of shredded rubber can be considered for cases under lateral confining pressure where the confinement [14][15]can compensate the lack of strength due to shredded rubber. It has been shown that confinement is more effective on low strength concrete in comparison with high strength concrete [16][17]. Also, mixing the shredded rubber with large rubber aggregates known as tire-derived aggregate [18][19] is recommended to be considered for future studies.

4.5. Parameters Affecting Strength and Elastic Modulus

As it was discussed in the previous sections, the compressive strength of the concrete specimens contained shredded rubber is decreased with the increase of the rubber content in the mixture. The elastic modulus shows the similar behaviour as compressive strength. Multiple researchers [20][21][22] have tried to give explanation why strength and elastic modulus are decreased. The fact is that replacing stone aggregates with rubber particles in concrete reduces the volume of stone aggregates. As rubber has lower stiffness (E) than stone aggregates, with increasing rubber content, the area (A) of softer material at any given cross-section of concrete increases. This in return, decreases the overall axial stiffness (EA) of the concrete member proportionally. As a result, the overall elastic modulus of the concrete member is reduced as follows:

$$E_c = \frac{\sum E_i A_i}{\sum A_i} \tag{3}$$

The same concept can be applied to compressive strength of the concrete member. Replacing stone aggregates with shredded rubber particles in concrete reduces the volume of stone aggregates, which acts as the backbone of concrete along with cement paste. As rubber has much lower strength than stone aggregates, with increasing rubber content, the area of weaker material at any given cross-section of concrete increases. This in return, decreases the overall strength of the concrete member. In addition, the lack of proper bond between the aggregates and cement paste when introducing the rubber particles into the mixture can cause development of micro-cracks accelerating the breakdown of the internal structure of concrete.

4.6. Parametric Study

In this section, a parametric study is performed on the effect of shredded rubber content using the proposed empirical models. As shown in Figure 9(a), the rubber content ranges from zero to 100% of fine aggregates (by volume) and the compressive strength of plain concrete ranges from 40 to 70 MPa. In Figure 9(b), the rubber content also ranges from zero to 100% to see the behavior of the proposed model on concrete with low and high elastic modulus ranging from 20 to 40 GPa. Both figures indicate that the proposed model is able to predict the effect of high rubber. Further research is needed to validate the performance of the models on different concrete strength and modulus with high content of shredded rubber content.

5. FUTURE RESEARCH

Recently, multiple review papers [23][24][25] have been published on the use of rubber particles recycled from tires in concrete. There is a consensus that adding rubber in concrete can reduce compressive strength and elastic modulus of concrete, and the reduction is magnified by increasing the size and content of rubber particles. The reduction is associated to the lower strength and modulus of rubber than stone aggregates producing a pseudo porous concrete. However, the reduction in tensile and flexural properties can be lower than the reduction in compressive properties. As the shredded rubber particles used in this study are long in comparison with almost round crumb rubber particles, they might be more effective in bridging tensile and flexural cracks. Thus, it is recommended extending this study to beam specimens to examine the effectiveness of the long, shredded particles in concrete under bending.

In addition, it has been reported that the bond interfacial between rubber particles and cement paste can be improved by the pre-treatment of rubber particles using different physical and chemical methods. Physical methods can be washing with water and pre-coating with cementitious materials. Chemical methods can be soaking in sodium hydroxide, silane coupling agent, acids, acetone, etc. even exposing to ultra-violent radiation has been considered in the literature. There are many advantages and disadvantages of using these treatment methods. It is recommended extending this study and apply selected physical and chemical treatment methods on the long, shredded rubber particles to evaluate the effects of the treatment methods on improving the mechanical properties and durability of concrete.

6. CONCLUSIONS

In this paper, the behaviour of concrete containing recycled shredded rubber particles was studied. Concrete cylinders (100 mm diameter and 200 mm height) were prepared by replacing of fine aggregates with shredded rubber at different percentages of 0, 10, 20, 30, 40, and 50% (by volume of fine aggregates) and tested under compression load. The results showed that the rubber weaken the compressive strength and elastic modulus of concrete. For example, the cylinders with 50% shredded rubber content lost 47% of compressive strength and 36% of elastic modulus, whereas the density decreased only 7%. It was observed during the tests that the brittle failure of control specimen was changed to less brittle failure with increasing the rubber content. Also, the failure patterns of the concrete from typical diagonal cracks was changed to a combination of longitudinal and transverse cracks. Empirical models were proposed to predict the effect of shredded rubber content on both compressive strength and elastic modulus of concrete. However, future research on different level of concrete strength and high rubber content is needed to validate the models for practical applications. Considering the long, shredded rubber particles for concrete under bending is also suggested to be studied. Moreover, the physical and chemical treatment of the long, shredded rubber particles is recommended to possibly enhance the bond between the rubber particles and cement paste.

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Table 1: Test matrix and mix proportions of concrete specimens

Group #	Specimen group ID	Shredded rubber content (%)	Fine aggregate (kg/m^3)	Shredded rubber (kg/m^3)
1	R0	0	567.5	0.0
2	R10	10	510.7	16.9
3	R20	20	454.0	33.9
4	R30	30	397.2	50.8
5	R40	40	340.5	67.8
6	R50	50	283.7	84.7

Table 2: Density of concrete specimens containing shredded rubber

Specimen ID	Average Density (kg/m^3)	Standard Deviation (kg/m^3)	Coefficient of Variation (%)	Density Reduction (%)
R0	2530.73	24.64	0.97	0.00
R10	2492.52	16.36	0.66	1.51
R20	2441.76	18.41	0.75	3.52
R30	2375.88	58.48	2.46	6.12
R40	2403.71	16.17	0.67	5.02
R50	2343.11	11.53	0.49	7.41

Sieve No. 04 (4.70 mm)

Sieve No. 08 (2.36 mm)

Sieve No. 16 (1.18 mm)

Sieve No. 30 (600 µm)

Sieve No. 50 (300 µm)

Sieve No. 100 (150 µm)

Sieve No. 200 (75 µm)

Pan (< 75 µm)

Figure 1: Various sizes shredded rubber particles remained on sieve#4, #8, #16, #30, #50, #100, #200, and Pan

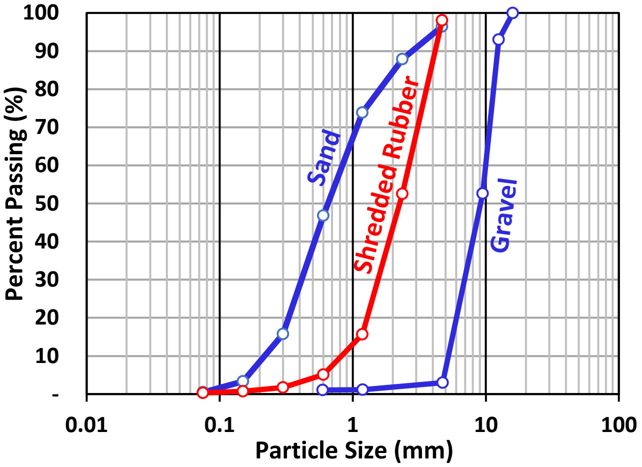


Figure 2: Particle size distribution of shredded rubber, fine aggregates, and coarse aggregates

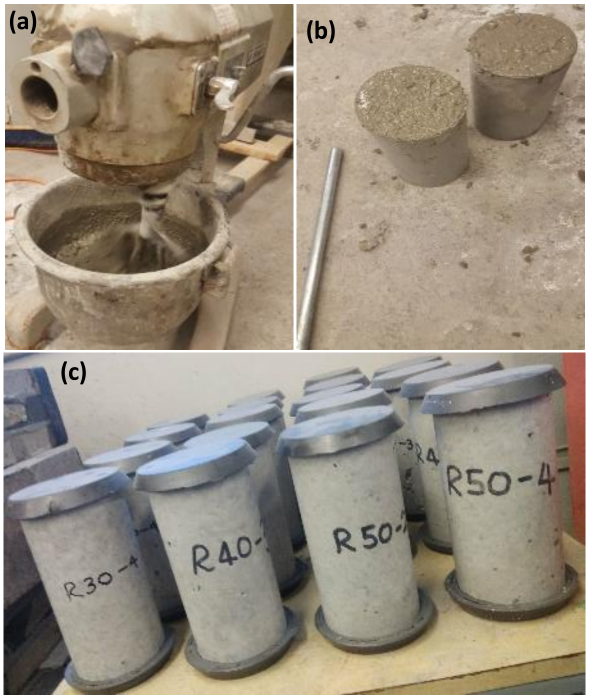
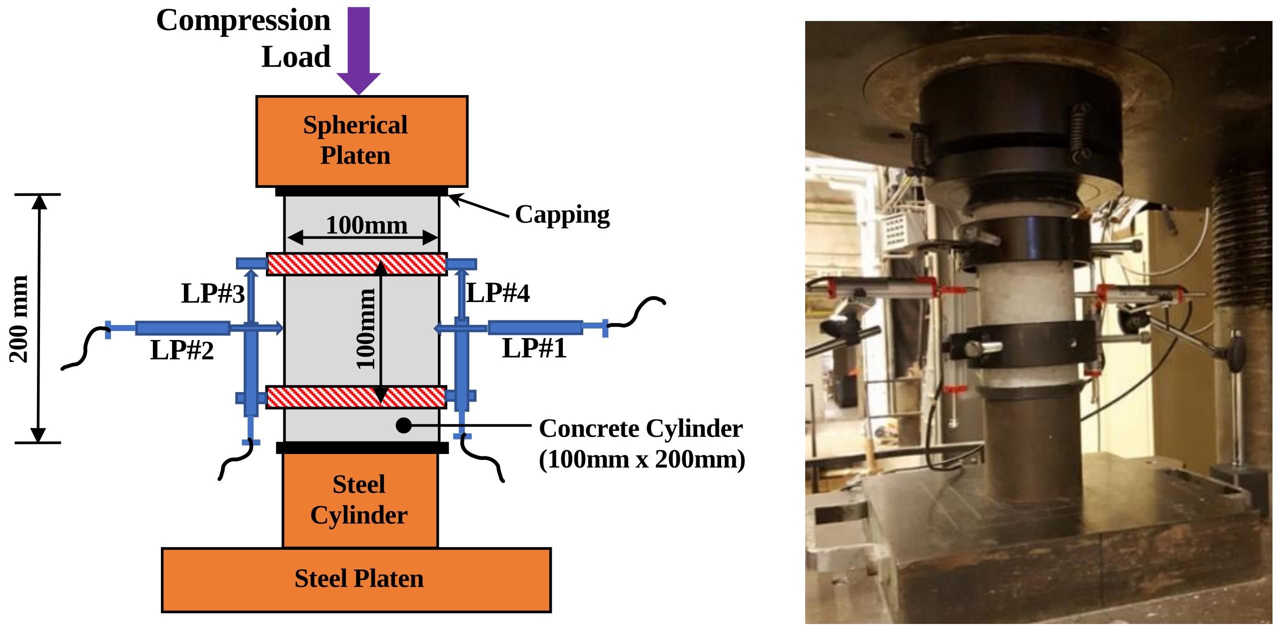


Figure 3: Specimen preparation: (a) mixing of concrete; (b) casting by hand compaction; and (c) prepared specimens prior to test



(a) (b)

Figure 4: Test setup and instrumentation: (a) schematic of test setup and (b) photo of setup

Figure 5: Failure mode of specimens: (a) R0; (b) R10; (c) R20; (d) R30; (e) R40; and (f) R50

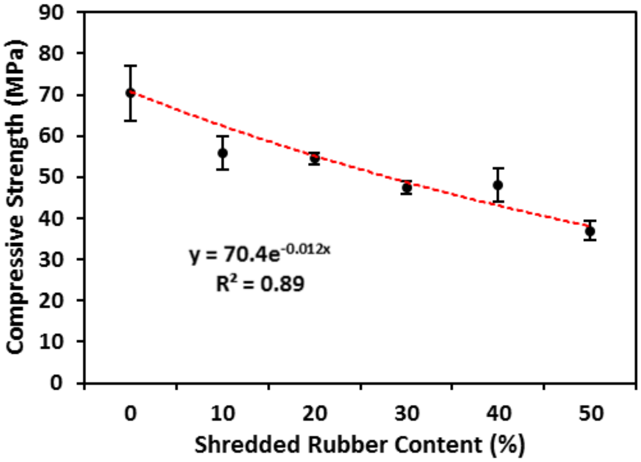


Figure 6: Effect of shredded rubber content on concrete strength in compression

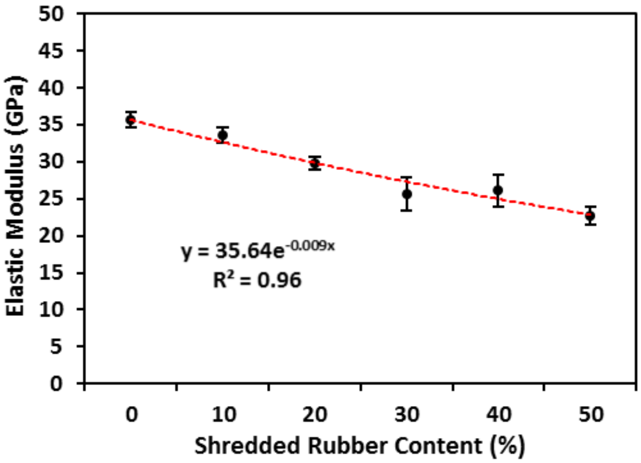


Figure 7: Effect of shredded rubber content on concrete elastic modulus in compression

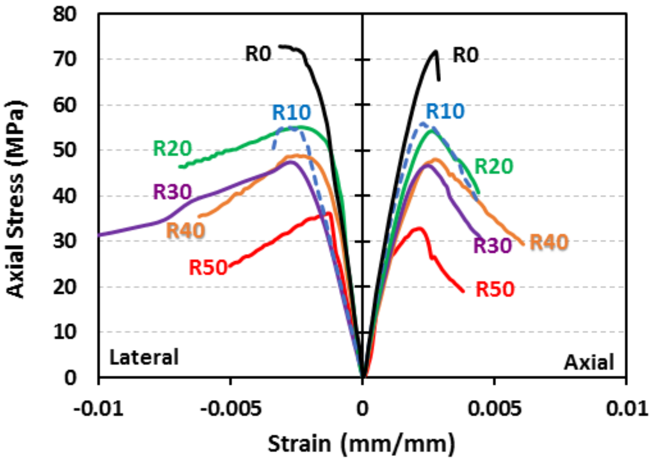


Figure 8: Stress-strain behaviour of test specimens (Note: each curve typically represents the average of four identical specimens)

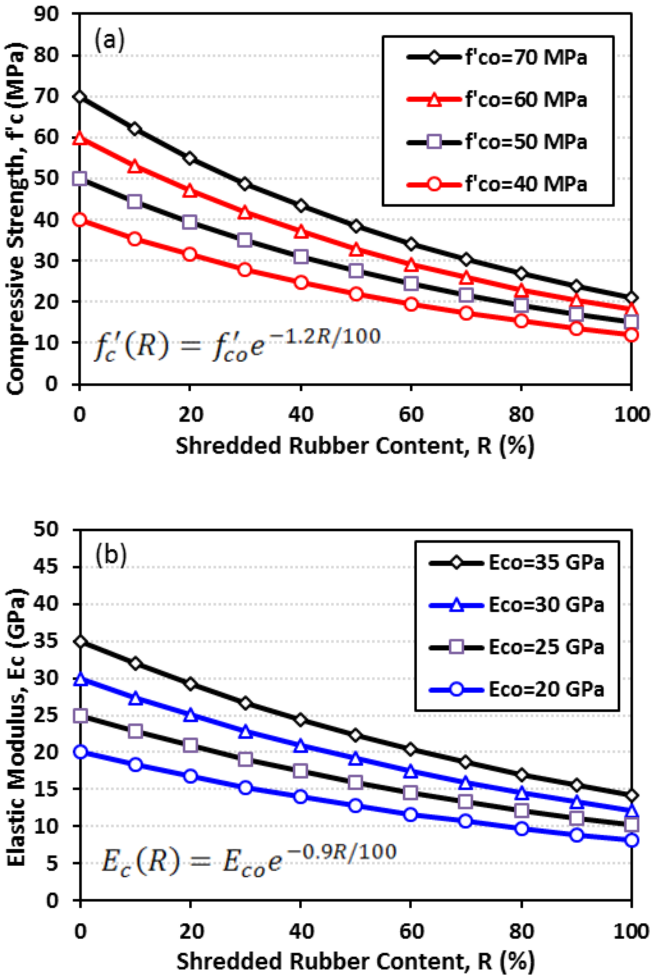


Figure 9: Parametric study using propose empirical models on the effect of shredded rubber content: (a) compressive strength and (b) elastic modulus