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# UTILIZATION OF RECYCLED CRUMB RUBBER IN STRUCTURAL SELF-CONSOLIDATING CONCRETE

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**ABSTRACT**

The present work evaluates the impact of using recycled crumb rubber (CR) as a partial replacement of fine aggregate on the fresh and mechanical properties of concrete composite, especially when self-consolidating concrete is used. In this study, seven mixtures containing various amounts of fine CR (0-30% by volume of sand) were tested. The fresh properties tests included flowability, passing ability, and segregation resistance. On the other hand, the mechanical properties tests included compressive strength, modulus of elasticity, splitting tensile strength, and flexural strength. The results indicated that although increasing the CR replacement decreased the fresh and mechanical properties of concrete, all the developed mixtures achieved adequate fresh and mechanical properties required for structural applications. The rigidity of concrete composite was also decreased effectively, exhibiting more ductile failure behaviour at ultimate loadings. In addition, using recycled rubber as a partial replacement for fine aggregate promotes the development of eco-friendly concrete with a reduced self-weight, which is receiving greater attention nowadays.

Keywords: Self-consolidating concrete, crumb rubber, fresh properties, mechanical properties.

## 1. INTRODUCTION

Accumulation of huge volumes of scrap tyres annually, is one of the most challenging problems worldwide, especially with the rapid expansion of the automobile industry. For example, in the United States more than 275 million scrap tyres are produced per year (Papakonstantinou and Tobolski 2006). As this number increases, hazardous techniques are being used to dispose of these tyres such as piling in landfills to remain stockpiled or to burn down. Burning of these tyres is difficult to ignite and is also difficult to extinguish. In addition, tyre burning releases a dense black smoke which pollutes the air with toxic gas, harming the surrounding soil and groundwater. Also, storing scrap tyre in landfills provides an area for rodents or mosquito larvae to develop which leads to the spread of disease. Tyres are not naturally biodegradable, thus remaining an environmental hazard (Cairns et al. 2004).

Reutilization of scrap tyres in civil engineering applications, for example concrete production, can help prevent environmental issues as well as develop economically-friendly designs (Najim and Hall 2010). Recently potential research has been involved in replacing coarse and/or fine aggregate with waste rubber (from the scrap tyres). Recycling scrap tyres to produce green concrete not only decreases the environmental hazards, but also contributes to the development of semi-lightweight concrete due to the low density of rubber particles compared to conventional aggregates. Significant studies investigated the use of crumb rubber (CR) as a partial replacement for fine aggregate in vibrated rubberized concrete (VRC). Most of these studies have concluded that using CR decreased compressive strength, tensile strength, and modulus of elasticity of concrete (Eldin and Senouci, 1993); however, the damping ratio, impact resistance, ductility and toughness of concrete increased as the CR contents increased (Najim and Hall 2010).

Comparing to VRC, self-consolidating rubberized concrete (SCRC) can combine the beneficial effects of the addition of CR and the desirable properties of self-consolidating concrete such as spreading and filling the formwork under its own weight without applying vibration. Recently, researchers investigated the effect of adding crumb rubber on the fresh performance of self-consolidating concrete (SCC). (Güneyisi 2010) stated that increasing the rubber content caused an increase in $T_{50}$, V-funnel flow times, and viscosity, but using rubber and fly ash together reduced the viscosity of the mixture. (Topçu and Bilir 2009) observed that increasing the rubber content increased the fluidity, but with an increased risk of segregation. They also found that the optimum amount of crumb rubber (< 4 mm) for fresh and mechanical properties of self-consolidating rubberized concrete (SCRC) was 8% replacement of total aggregate weight. (Turatsinze and Garros 2008) developed SCRC using chipped rubber as a coarse aggregate, but the strength reduction reached 33 and 73% at 10 and 25% replacements of sand by rubber, respectively.
The main objective of this research was to develop SCRC mixtures with high contents of CR and with acceptable mechanical properties for structural applications. The percentage of CR varied from 0% to 30% replacements by fine aggregate volume. The fresh properties tests included slump flow, V-funnel, L-box, J-ring, sieve segregation resistance, and air content tests while the mechanical properties tests included compressive strength, splitting tensile strength (STS), flexural strength (FS), and modulus of elasticity (ME). Also, the stability of the tested mixtures was evaluated by using.

## 2. EXPERIMENTAL DESIGN

### 2.1 Materials

General use Portland cement, MK, fly ash (FA) conforming to ASTM C150 Type I, ASTM C618 Class N and ASTM C618 Type F, respectively, were used in the production of the developed mixtures. Natural crushed stone with a maximum size of 10 mm and natural sand were used for the coarse and fine aggregates, respectively. Each aggregate type had a specific gravity of 2.6 and absorption of 1%. A crumb rubber aggregates with a maximum size of 4.75 mm, specific gravity of 0.95, and negligible absorption was used as a partial replacement of the fine aggregate in the SCRC mixtures. The aggregate gradations of the crushed stone, natural sand, and CR are presented in Figure 1. Glenium 7700 high-range water-reducer admixture (HRWRA), similar to ASTM Type F (ASTM C494) (2013), was used to achieve the required slump flow of developed mixtures.

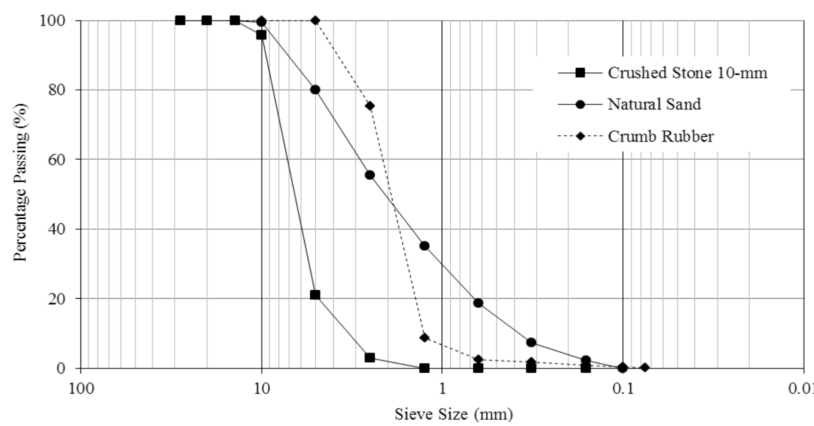

Figure 1: Gradation curve of fine and coarse aggregates and crumb rubber

### 2.2 Mixture Design

The development of SCRC required a balanced viscosity to improve the rubber particle suspension and reduce the risk of segregation. This also provided a good workability for achieving the acceptable fresh properties of SCC. Therefore, a preliminary trial mixes stage was carried out to determine the minimum water-to-binder (w/b) ratio, the total binder content, the coarse-to-fine (C/F) aggregate ratio, and the SCMs that can achieve acceptable SCC fresh properties without overdosing the HRWRA. The results of the trial mixes stage indicated that a w/b ratio of at least 0.4 and 550 kg/m$^3$ binder content should be used to obtain SCC having 700 ± 50 mm slump flow with no visual sign of segregation. FA was also used to increase the flow-ability of mixtures to avoid using high dosages of HRWRA to compensate for the reduction in the workability resulting from the addition of CR. The consistency of SCRC was adjusted by incorporating MK into the mixture to improve its viscosity, resulting in higher stability for CR particles. Moreover, to obtain SCRC with adequate mechanical properties, MK was used to compensate for the reduction in the concrete strengths resulting from using high percentages of CR. The MK and FA were used with replacement levels of 20% and 30% (by weight of the binder content), respectively. These percentages were chosen based on optimal values obtained from previous research carried out with these SCMs. (Güneyisi, E.2010, and Hassan A. A. A.; and Mayo, J. R., 2014) All mixtures were developed using a 10 mm crushed stone aggregate. A constant coarse-to-fine aggregate (C/F) ratio of 0.7 was chosen for all tested mixtures based on previous research carried out on SCC with different C/F ratios (Hassan et al., 2015). The amount of HRWRA was varied in all tested mixtures to obtain a slump flow diameter of 700 ± 50 mm. The mixture proportions and designations of the seven VRC and SCRC mixtures tested are presented in Table 1.

Table 1: Mix design for tested mixtures

| Mix # | Mixture | Cement (kg/m$^3$) | SCM (Type) | SCM (kg/m$^3$) | C. A. (kg/m$^3$) | F. A. (kg/m$^3$) | CR (kg/m$^3$) | HRWRA (L/m$^3$) | Density (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 550C-0CR | 275 | MK+FA | 110+165 | 620.3 | 886.1 | 0.0 | 3.43 | 2246 |
| 2 | 550C-5CR | 275 | MK+FA | 110+165 | 620.3 | 841.8 | 16.2 | 3.43 | 2207 |
| 3 | 550C-10CR | 275 | MK+FA | 110+165 | 620.3 | 797.5 | 32.4 | 3.75 | 2163 |
| 4 | 550C-15CR | 275 | MK+FA | 110+165 | 620.3 | 753.2 | 48.6 | 3.75 | 2128 |
| 5 | 550C-20CR | 275 | MK+FA | 110+165 | 620.3 | 708.9 | 64.8 | 3.75 | 2094 |
| 6 | 550C-25CR | 275 | MK+FA | 110+165 | 620.3 | 664.6 | 80.9 | 3.75 | 2041 |
| 7 | 550C-30CR | 275 | MK+FA | 110+165 | 620.3 | 620.3 | 97.1 | 4.38 | 2006 |

Note: All mixtures have a 0.4 w/b ratio; C. A. = Coarse Aggregates; F. A. = Fine Aggregates; CR = Crumb Rubber; MK = Metakaolin; FA = Fly Ash.

### 2.3 Testing Procedures

The fresh properties of all tested mixture were conducted as per The European Guidelines for Self-Compacting Concrete (2005). The fresh properties tests included slump flow, V-funnel, and L-box tests. Also, the segregation resistance (SR) of SCRC mixtures was assessed using a sieve segregation resistance test. The percentage of the entrained air in the fresh SCC mixtures was measured by following a procedure given in ASTM C231. The compressive strength and splitting tensile strength (STS) were conducted using 100 mm diameter x 200 mm height concrete cylinders, according to ASTM C39 and C496. The flexure strength (FS) of 100 mm x 100 mm x 400 mm prisms was measured for all SCRC mixtures according to ASTM C293. 100 mm diameter by 200 mm length cylinders with an attached 25 mm strain gauge was used to test the modulus of elasticity (ME) of all mixtures. The mechanical properties tests were implemented after the sample had been moist cured for 28 days.

## 3. DISCUSSION OF TEST RESULTS

### 3.1 Density and Air Content

Figure 2a and Table 2 show the effect of the addition of CR on the unit weight of SCRC mixtures. From the figure, it can be observed that increasing the CR content generally reduced the unit weight of the tested mixtures. Varying the percentage of CR from 0% to 30% linearly decreased the self-weight of SCRC by 10.7%. This reduction is directly attributed to two reasons: i) the lower density of CR compared to that of natural sand; and ii) the increased air content due to the addition of CR. As also shown in Figure 2a, increasing the percentage of CR from 0% to 30% raised the measured air content from 1.5% to 5%. This increase may be related to the capability of rubber particles to entrap air in their jagged surface texture. Another assumption suggested by (Naito et al. 2014) reported that the increase in the measured air content may come from the high compressibility of rubber particles, which may result in an artificial amount of air measured by the standard (ASTM C231 2014) test method.

### 3.2 HRWRA Demand

Table 1 presents the HRWRA demands required to achieve the target slump flow of 700 ± 50 mm for tested SCRC mixtures. Inclusion of CR content up to 25% showed a slight increase in the HRWRA demand, reaching up to 9.3% compared to the control mixture (percentage of CR = 0%). Further increases in CR content led to increases in the HRWRA demand required to obtain the target flow-ability. With the addition of 30% CR in mixture 500C-30CR, the HRWRA dosage was increased by 27.7% compared to the control mixture with no CR. This result is similar to that reported by other researchers, (Güneyisi, E., 2010 and Topçu, I.B.; and Bilir, T. 2009) who have also observed an increase in the HRWRA demand of SCRC mixtures with high percentages of CR content.

### 3.3 Flowability

The flowability of SCRC mixtures were evaluated using $T_{50}$ (time to reach 500 mm slump flow diameter), $T_{50J}$ (time to reach 500 mm J-ring diameter), and V-funnel time. In general, increasing the CR content showed an increase in the mixture viscosity or a reduction in its flow-ability. As shown in Table 2 and Figure 2b, increasing the percentage of CR from 0% to 30% raised the $T_{50}$ from 1.95 seconds to 3.76 seconds. The J-ring and V-funnel tests also showed a similar behaviour: i.e., for the same increase in the percentage of CR, the $T_{50J}$ and the V-funnel time recorded an increase reaching up to 1.81 and 2.46 times, respectively (see Figure 2b). Based on the $T_{50}$ and V-funnel time, the (EFNARC, 2005) proposed a classification for the viscosity of SCC mixtures. The first class is named VS1/VF1, which includes mixtures with a $T_{50}$ of less than 2 seconds and V-funnel flow time of less than 8 seconds. This class of mixtures is characterized by having good filling and self-levelling ability but is more likely to suffer from bleeding and segregation. The second class is named VS2/VF2, which includes mixtures with a $T_{50}$ of more than 2 seconds and V-funnel flow time ranging from 9 to 25 seconds. VS2/VF2 mixtures are more likely to exhibit thixotropic effects, which may help to improve segregation resistance and limit the formwork pressure. According to these categories, the control mixture (550C-0CR) can be classified as VS1/VF1, while the SCRC mixtures with up to 30% CR meet the limits of VS2/VF2. Both categories (VS1/VF1 and VS2/VF2) have good potential uses in different structural applications such as slabs, columns, piles, walls, and ramps, especially with a relatively high slump flow of 700 ± 50 mm found in mixtures with up to 30% CR.

### 3.4 Passing-ability

The passing-ability of all tested mixtures was assessed by measuring the L-box (H2/H1) ratio and the difference between the slump flow and J-ring diameters. Table 2 and Figure 2c, illustrate that adding CR had a negative impact on the passing ability of SCC. Varying the percentage of CR from 0% to 30% reduced the L-box ratio from 0.91 to 0.75. Similarly, the difference between the slump flow and J-ring diameters increased from 10 mm to 70 mm as the percentage of CR increased from 0% to 30%. The reduction of the passing ability with the increased percentage of CR could be attributed to the high friction and blocking between crushed stone aggregate and rubber particles. According to the (EFNARC, 2005) and the (Pre-stressed Concrete Institute 2003) the recommended value of H2/H1 in the L-box test is 0.75 or greater. The results of this stage indicated that all tested SCRC mixtures with up to 30% CR replacement showed an acceptable passing ability.

### 3.5 Segregation Resistance

The sieve segregation resistance (SR) values were used to evaluate the coarse aggregate segregation of all tested mixtures. As shown in Table 2 and Figure 2d, increasing the CR content reduced the stability of mixtures. This finding matches what other researchers have reported (Topçu, I.B.; and Bilir, T. 2009) Adding 30% CR increased the SR value up to four times as much as mixtures with no CR. However, all mixtures with up to 30% CR did not exceed the acceptable limit (SR ≤ 15%) for SCC mixtures, as recommended by (EFNARC 2005). In addition to the SR test, this study visually evaluated the stability of rubber particles by investigating the distribution of CR particles along hardened, split cylinders. As mentioned earlier, the low density of the rubber (0.95) may decrease the stability of mixtures and make it easy for the rubber to float toward the concrete surface during mixing. From Figure 3, it can be seen that mixtures with up to 30% CR appeared to have a good distribution of CR particles, indicating the effect of the mixture's viscosity on improving particle suspension.

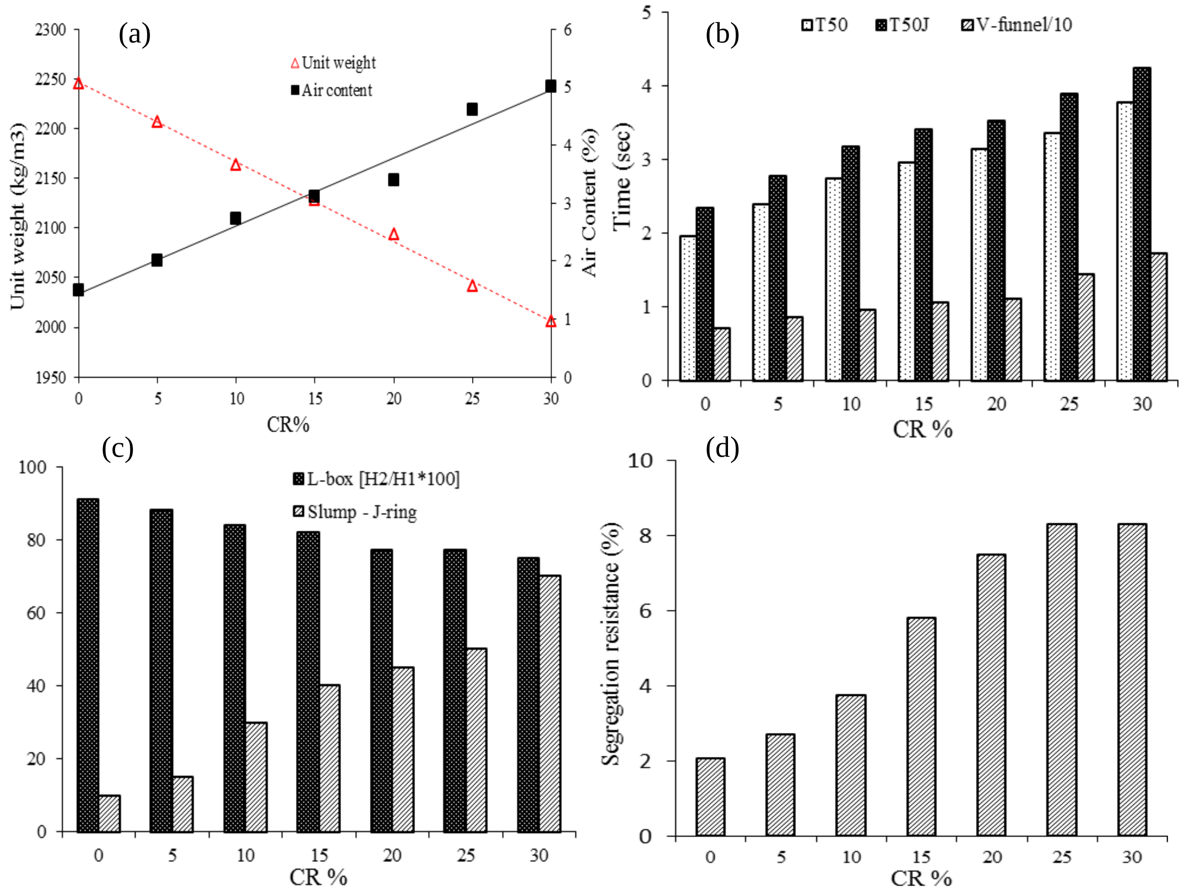


Figure 2: Effect of CR replacement on the properties of the tested SCRC mixtures: (a) unit weight and air content, (b) $T_{50}$, $T_{50J}$, and V-funnel, (c) passing ability, (d) segregation resistance.

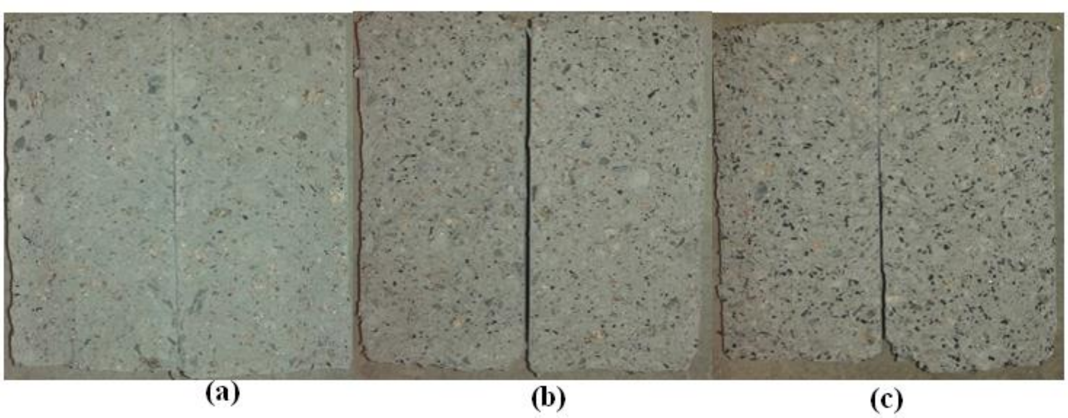


Figure 3: Distribution of CR particles: (a) 5% CR, (b) 15% CR, and (c) 30% CR

Table 2: Fresh properties of tested mixtures

| Mix # | Mixture designation | Slump/Slump flow | | J-ring | | Slump–J-ring (mm) | L-box H2/H1 | V-funnel | SR % | Air % |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $D_s$ (mm) | $T_{50}$ (sec) | $D_J$ (mm) | $T_{50J}$ (sec) | | | $T_0$ (sec) | | |
| 1 | 550C-0CR | 725 | 1.95 | 715 | 2.34 | 10 | 0.91 | 7.01 | 2.08 | 1.5 |
| 2 | 550C-5CR | 720 | 2.39 | 705 | 2.77 | 15 | 0.88 | 8.50 | 2.71 | 2.0 |
| 3 | 550C-10CR | 720 | 2.74 | 690 | 3.17 | 30 | 0.84 | 9.51 | 3.75 | 2.7 |
| 4 | 550C-15CR | 715 | 2.96 | 675 | 3.40 | 40 | 0.82 | 10.59 | 5.83 | 3.1 |
| 5 | 550C-20CR | 710 | 3.14 | 665 | 3.51 | 45 | 0.77 | 10.97 | 7.50 | 3.4 |
| 6 | 550C-25CR | 700 | 3.35 | 650 | 3.88 | 50 | 0.77 | 14.30 | 8.33 | 4.6 |
| 7 | 550C-30CR | 670 | 3.76 | 600 | 4.23 | 70 | 0.75 | 17.25 | 8.33 | 5.0 |

### 3.6 Mechanical Properties

The 28-day compressive strengths of the tested mixtures are shown in Table 3 and Figure 4. As seen from mixtures, increasing the percentage of CR decreased the 28-day compressive strengths. Varying the CR from 0% to 30% reduced the 28-day compressive strength by around 57.88%. This reduction in the mechanical properties with higher percentages of CR may be attributed to (i) the lower modulus of elasticity for rubber particles compared to hardened cement paste, which may encourage precocious cracking around the rubber particles under loading, (Reda-Taha, M. M. et. al. 2008 and Naito, C. et. al. 2014) (ii) the poor strength of the interface between the rubber particles and surrounding mortar, as observed by other researchers, (Najim, K. B.; and Hall, M. 2012 and Emiroglu, M. et. al. 2007), and (iii) the increase in the mixtures' porosity due to the effect of rubber particles on heightening air entrainment (see Table 2). It is worth noting that although the addition of CR decayed the mechanical properties, mixtures with up to 15% CR could be developed with a compressive strength of almost 45 MPa. In addition, mixtures with up to 30% CR achieved adequate strengths for multiple structural applications.
The STS, FS, and ME results for the tested mixtures are presented in Table 3 and Figure 4. It can be observed that the STS, FS, and ME decreased as a function of the increase in the CR replacement. Increasing the percentage of CR from 0% to 30% reduced the STS, FS, and ME by 40.3%, 31.7%, and 36.3%, respectively. These reductions may be attributed to the same reasons for the reduction of compressive strength with increased percentage of CR. As shown in Figures 5, the reduction in the mechanical properties could be fitted in a linear relationship with a good accuracy, as follows:

[1] Reduction in $f'_c$= 2.1849*CR% ($R^2$= 0.92)
[2] Reduction in STS= 1.256*CR% ($R^2$= 0.97)
[3] Reduction in FS= 1.0419*CR% ($R^2$= 0.99)
[4] Reduction in ME= 1.2246*CR% ($R^2$= 0.99)

Table 3: Mechanical properties of tested mixtures

| Mixture # | Mixture designation | 28-day $f'_c$ | 28-day STS | 28-day FS | ME |
|---|---|---|---|---|---|
| | | MPa | MPa | MPa | GPa |
| 1 | 550C-0CR | 75.65 | 4.49 | 5.74 | 29.37 |
| 2 | 550C-5CR | 66.72 | 4.29 | 5.48 | 27.54 |
| 3 | 550C-10CR | 53.48 | 4.08 | 5.12 | 25.71 |
| 4 | 550C-15CR | 44.77 | 3.82 | 4.82 | 24.66 |
| 5 | 550C-20CR | 38.40 | 3.41 | 4.57 | 21.97 |
| 6 | 550C-25CR | 36.77 | 3.00 | 4.27 | 20.02 |
| 7 | 550C-30CR | 31.86 | 2.68 | 3.92 | 18.70 |

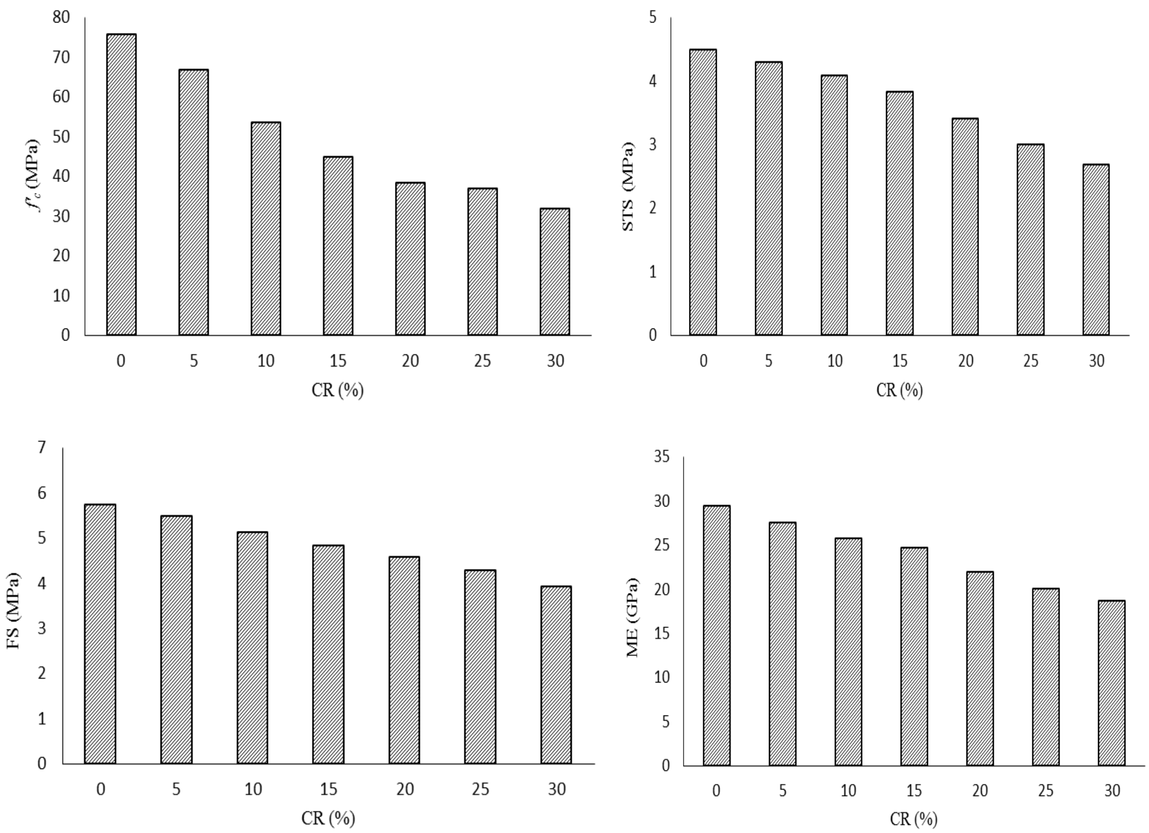


Figure 4: Effect of CR replacement on the mechanical properties of the tested SCRC mixtures

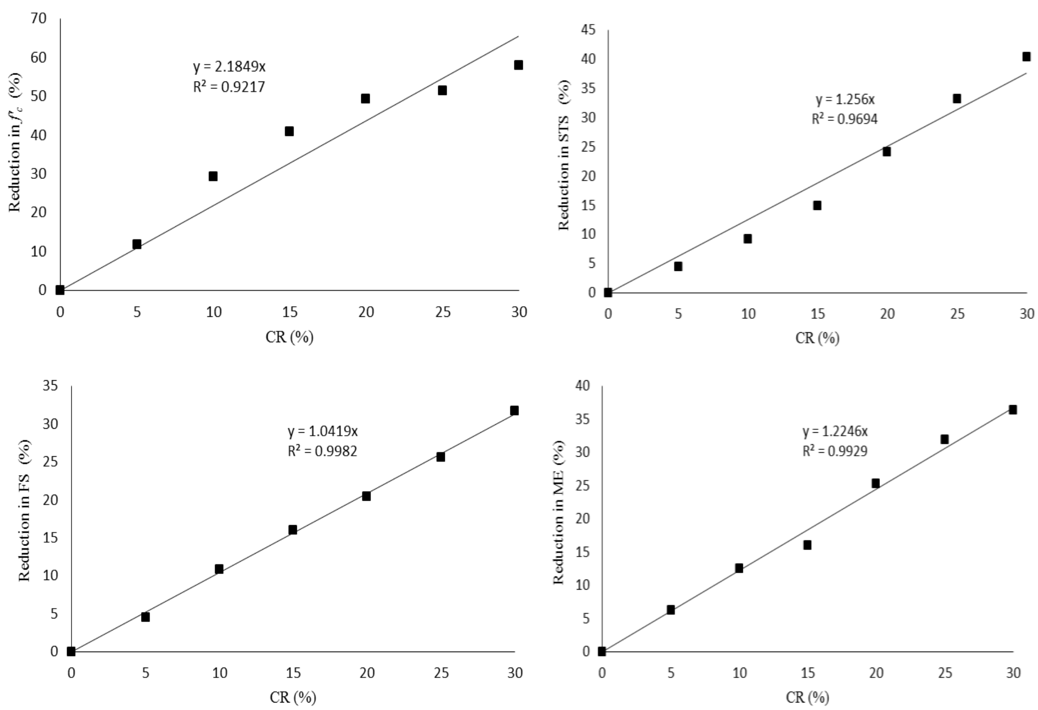


Figure 5: (%) Reductions in the the mechanical properties of the tested SCRC mixtures

### 3.7 Failure Mode

All tested samples showed more ductile failure as the percentage of CR increased in the mixture. Increasing the percentage of CR raised the ductility of SCRC mixtures, which changed the common behaviour of concrete at ultimate loading to non-brittle failure. In addition, CR particles made the failed samples appear to be more cohesive without a noticeable distortion compared to the control mixture (CR% = 0) (see Figure 6). From Figure 6, it can be observed that the compressive strength samples of the control mixture were destroyed with a significant spalling. The splitting tensile strength samples of this mixture were also completely splintered into two halves at the ultimate splitting load. On the other hand, cylinders with a high percentage of CR showed a better geometrical shape with insignificant spalling, very fine cracks, and no splintering/spalling at the ultimate compressive and/or tensile loading. The reason for this behaviour may be related to the low stiffness of the CR particles that provide a relatively higher ductility for concrete composite, improving the energy absorption capacity of samples than obtained by conventional concrete. This effect was also observed in flexure samples with a high percentage of CR; the failed prisms were not completely broken, but they had a major flexural crack with an average width of 0.5 mm (see Fig. 6d) and the crack width decreased as the CR replacement increased.

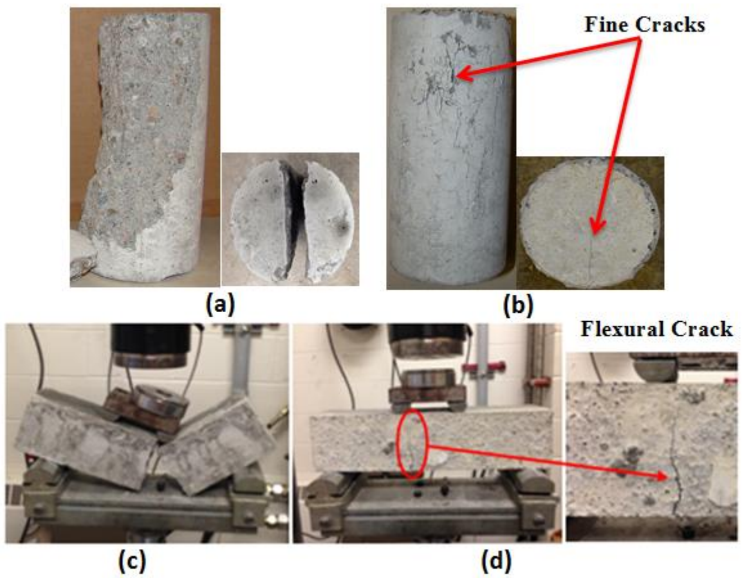


Figure 6: Failure pattern of tested samples: (a) control mixture (0% CR) in compressive and STS tests, (b) typical failure mode for mixtures with high percentage of CR in compressive and STS tests, (c) control mixture (0% CR) in FS test, (d) typical failure mode for mixtures with high percentage of CR in FS test

## 4. CONCLUSION

This study investigated the fresh and mechanical properties of SCRC mixtures. The percentage of CR replacement varied from 0% to 30% of fine aggregate volume. The following conclusions can be drawn based on the results described in this paper:

1. Using 550 kg/m$^3$ binder content for mixtures containing 20% MK and 30% FA helped to obtain SCRC mixtures with balanced viscosity. This allowed mixtures with up to 30% CR replacement that satisfy the criteria of self-compatibility to be developed.
2. Increasing the percentage of CR in SCRC mixtures showed a reduction in the flowability, passing ability, stability, and unit weight, while the air content and HRWRA demand increased.
3. Increasing the percentage of CR in SCRC mixture has a direct impact on the mechanical properties of the mixture. Increasing the CR from 0% to 30% reduced the 28-day compressive strength, STS, FS, and ME by

57.88%, 40.3%, 31.7%, and 36.3%, respectively. However, mixtures up to 30% CR could be achieved with adequate strengths for multiple structural applications (> 30 MPa).

4. SCRC mixtures showed more ductile failure behaviour compared to mixtures with no CR. Samples with higher percentages of CR showed insignificant spalling, very fine cracks, and no splintering or spalling at the ultimate compressive and/or tensile failure compared to samples with no CR. Moreover, high percentages of CR contribute to the development of semi-lightweight mixtures with a density of less than 2006 kg/m$^3$.


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