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Performance of Full-Scale Self-Consolidating Rubberized Concrete Beams in Flexure

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This research investigated the performance of full-scale self-consolidating rubberized concrete (SCRC) and vibrated rubberized concrete (VRC) beams in flexure. The beam mixtures were developed with a maximum possible percentage of crumb rubber (CR) (0 to 50% by volume of sand) while maintaining acceptable fresh properties and minimum strength reduction. The mixture variables included different binder contents, the addition of metakaolin, and the use of air entrainment. The performance of the tested beams was evaluated based on load-deflection response, concrete strain/stiffness, cracking behavior, first crack load, ultimate load, ductility, and toughness. In general, increasing the CR content decreased the mechanical properties, first crack load, stiffness, and self-weight of all SCRC and VRC beams. However, using up to 10% CR enhanced the deformation capacity, ductility, and toughness of tested beams without affecting the flexural capacity. This improvement in the deformation capacity, ductility, and toughness appeared to continue up to 20% CR (but with a slight reduction of the flexural capacity) and then reduced with further increases in the CR content. The results also indicated that although it was possible to produce VRC beams with higher percentages of CR (50% compared to 40% in SCRC), this increased percentage only gave VRC beams an advantage in terms of self-weight reduction, while it had a limited contribution in enhancing the structural performance of the beams.

Keywords: beam(s); cracking behavior; crumb rubber; deflection characteristics; flexure capacity; reinforced concrete; self-consolidating concrete.

INTRODUCTION

Over the last two decades, waste rubber in concrete has received greater attention due to its availability in large volumes. For example, the applications of waste rubber in concrete in 2011 were estimated to be 1 billion tires produced worldwide.[1] The review of literature showed that many studies have been conducted to investigate the performance of concrete with different levels of rubber replacement. Researchers have found that substituting fine and/or coarse aggregates with crumb or shredded rubber particles in concrete enhances its strain capacity (ductility), energy dissipation, damping ratio, impact resistance, and toughness compared to normal concrete using conventional aggregate.[1-4] Using rubber can significantly contribute to the development of semi-lightweight and lightweight concrete due to the low density of rubber aggregate compared to conventional aggregate. In addition, involving waste rubber in construction promotes the development of eco-friendly buildings and encourages the concept of sustainable production.[5] However, increasing the rubber content has a negative effect on the compressive strength, tensile strength, flexural strength, and modulus of elasticity.[6,7] This can be related to the weak bonding between the rubber particles and surrounding mortar.[8]

Najim and Hall[1] presented a simple investigation for intermediate-scale reinforced concrete beams containing crumb rubber (CR). Eight reinforced concrete beams, two for each mixture—vibrated concrete, vibrated rubberized concrete (VRC), self-consolidating concrete (SCC), and self-consolidating rubberized concrete (SCRC)—were cast with dimensions of 1700 x 200 x 100 mm (66.93 x 7.87 x 3.94 in). The CR replacement reached up to 14% and 18% of the total aggregate volume for VRC and SCRC, respectively. The authors reported that adding CR decreased the flexural capacity and stiffness of beams. Meanwhile, the deformation capacity and energy absorption were increased with increased percentages of CR. Ganesan et al.[5] also studied the behavior of SCRC beam-column joints under monotonic and cyclic load. Shredded rubber aggregates were used to replace 15% of the fine aggregate by volume. Their results indicated that the addition of shredded rubber improves the beam-column joint behavior in terms of the energy absorption capacity, crack resistance, and ductility. Meanwhile, SCRC specimens showed a slight reduction in load-carrying capacity. The same behavior was observed in the study conducted by Sadek and El-Attar,[9] in which the structural behavior of masonry walls made from rubber-cement bricks was tested. In the production of the bricks, two sizes of rubber were used to replace the coarse and fine aggregates with replacements ranging from 0 to 100% and from 0 to 50% (by volume), respectively.

The development of SCRC offers many advantages such as increasing the productivity rate and decreasing the required labor (as it can spread and fill the formwork under its own weight without applying vibration). SCRC also has enough flowability and filling ability to fix the problems of concrete flowing through congested reinforcements. The mixture proportions and components can have some effects on the properties of SCRC. The amount of fine materials (binder) and the percentage of air entrainment in the mixture can affect the mechanical properties of SCRC mixtures. The use of air entrainment can improve the fresh properties[10] of the mixture, but will negatively impact mechanical properties. On the other hand, increasing the binder content has

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shown to improve the fresh and mechanical properties of the mixture.[11] Using supplementary cementitious materials (SCMs) is one of the ways of potentially enhancing the fresh and mechanical properties of SCRC. Metakaolin (MK) is one of the most effective SCMs that can be used in SCRC and is proven to enhance the mechanical and durability performance of SCRC. Madandoust and Mousavi[12] reported that the compressive strength and tensile strength of SCC containing MK were significantly improved (by 27% and 11.1%, respectively) compared to the control mixtures of SCC. Hassan and Mayo[13] also observed that the inclusion of 20% MK increased the 28-day compressive strength by 30%.

The review of literature indicates that small-scale specimens such as cubes, cylinders, and prisms were used extensively to investigate the performance of rubberized concrete. On the other hand, full-scale testing to study the applicability of this type of concrete for structural applications is significantly lacking, especially when SCRC is used. The main objective of this research was to study the structural performance of full-scale reinforced SCRC and VRC beams under flexural load. A number of SCRC mixtures containing maximum percentages of CR (by volume of fine aggregate) and acceptable fresh properties were developed to cast SCRC beams. Also, additional beams made with VRC mixtures containing maximized percentages of CR were tested for comparison. The investigation included evaluations of the effect of CR on the flexural capacity, cracking behavior, load-deflection response, concrete strain/stiffness, ductility, and toughness of the tested beams. The beams' mixtures were developed with variable percentages of CR (0 to 50%) using different binder content, the addition of MK, and/or using air entrainment. The investigation also discussed the performance of some code-based equations in predicting the ultimate flexural capacity of the tested beams.

RESEARCH SIGNIFICANCE

Waste rubber is used in concrete to enhance the ductility, toughness, and impact resistance, and reduce the unit weight, of the structural members. In addition, using waste rubber in construction promotes the development of eco-friendly concrete and encourages the concept of sustainable production, which is receiving greater attention nowadays. Although there is a growing need to use waste rubber in structural concrete applications, there is a lack of data available regarding the performance of full-scale rubberized concrete elements, especially when SCRC is used. Therefore, this study was conducted to investigate the structural performance of SCRC in full-scale beams. The paper provides information regarding stiffness, ductility, toughness, and cracking behavior of SCRC and VRC beams under flexural load. The authors believe that this investigation will strongly contribute to evaluating the effectiveness of SCRC in structural applications.

EXPERIMENTAL PROGRAM

Materials properties

MK was delivered from the eastern United States, conforming to ASTM C618 Class N.[14] The cement used (Type GU) was similar to that of ASTM C618 Type F.[14] The chemical and physical properties of cement and MK are shown in Table 1. Natural crushed stone, with a 10 mm (0.394 in.) maximum size, 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 aggregate (with no steel wires) had a maximum size of 4.75 mm (0.187 in.), a specific gravity of 0.95, and negligible absorption was used as a partial replacement of the fine aggregate in SCRC and VRC mixtures. The aggregate gradations of the 10 mm (0.394 in.) crushed stone, natural sand, and CR are presented in Fig. 1. A polycarboxylate-based high-range water-reducer admixture (HRWRA) similar to ASTM C494/C494M[15] Type F was used to achieve the required slump flow of SCRC mixtures. An air-entrainment admixture similar to ASTM C260/C260M[16] was used to improve the workability of SCRC mixtures.

Table 1—Chemical and physical properties of all SCMs used

Chemical properties, %	Cement	MK
SiO_2	19.64	51 to 53
Al_2O_3	5.48	42 to 44
Fe_2O_3	2.38	<2.2
FeO	—	—
TiO_2	—	<3.0
C	—	—
Cr_2O_3	—	—
MnO	—	—
P_2O_5	—	<0.2
SrO	—	—
BaO	—	—
SO_4	—	<0.5
CaO	62.44	<0.2
MgO	2.48	<0.1
Na_2O	—	<0.05
C_3S	52.34	—
C_2S	16.83	—
C_3A	10.50	—
C_4AF	7.24	—
K_2O	—	<0.40
L.O.I	2.05	<0.50
Specific gravity	3.15	2.5
Blaine fineness (m^2/kg)	410	19,000

Note: 1 m^2/kg = 4.8824 ft^2/lb.

Concrete mixtures

A total of 12 concrete mixtures were developed to cast 12 reinforced concrete beams. In general, the experimental investigation aimed to develop a number of SCRC mixtures having maximum percentages of CR (by volume of fine aggregate) and a minimum reduction in strength and stability. To achieve acceptable mixture flowability with no sign of segregation in all tested mixtures, a preliminary trial mixtures stage was performed to determine the minimum water-binder ratio (w/b) and the minimum total binder content that can achieve acceptable SCRC flowability without overdosing the HRWRA. The results of the trial mixture stage indicated that at least 0.4 w/b and 500 kg/m^3 (31.215 lb/ft^3) as a total binder content should be used to obtain SCRC having acceptable slump flow with no visual sign of segregation. Therefore, 0.4 w/b and a minimum of 500 kg/m^3 (31.215 lb/ft^3) total binder content were used in all tested mixtures (Table 2). Also, a constant coarse-to-fine aggregate ratio (C/F) of 0.7 was chosen for all tested mixtures in this investigation. This ratio was chosen based on previous research[13] carried out on SCC with different C/F.

During the trial mixtures stage, it was found that the mixtures with 500 kg/m^3 (31.215 lb/ft^3) binder content and no SCMs (Mixtures 1 to 4) can have a maximum of 15% CR to maintain acceptable SCC fresh properties. Increasing this percentage to 20% resulted in a significant reduction in the passing ability (H2/H1 of L-Box) for all mixtures with 500 (31.215 lb/ft^3) binder content. However, when increasing the total binder content from 500 kg/m^3 to 550 kg/m^3 (31.215 to 34.335 lb/ft^3), the maximum percentage of CR that maintains acceptable SCC fresh properties increased to 20%. The results of the trial mixtures also indicated that using MK enhanced the viscosity of tested mixtures and had a direct impact on improving the particle suspension and passing ability, which allowed a higher percentage (up to 30%) of CR to be used safely in SCRC mixtures. Further increasing the percentage of CR in SCRC mixtures with MK from 30% to 40% required the use of air-entraining admixture (Mixtures 9 and 10) to improve the flowability and passing ability of mixtures. Considering the type of materials used in this investigation, the authors found it very difficult to develop SCRC mixtures with acceptable SCC fresh properties using more than 40% CR. The trial mixtures of this investigation also included developing VRC (Mixtures 11 and 12) to compare its performance with that of SCRC. Because the passing ability and segregation are not factors in VRC mixtures, it was possible to reach a maximum percentage of CR of 50%. Using more than 50% CR in VRC mixtures resulted in a very low compressive strength.

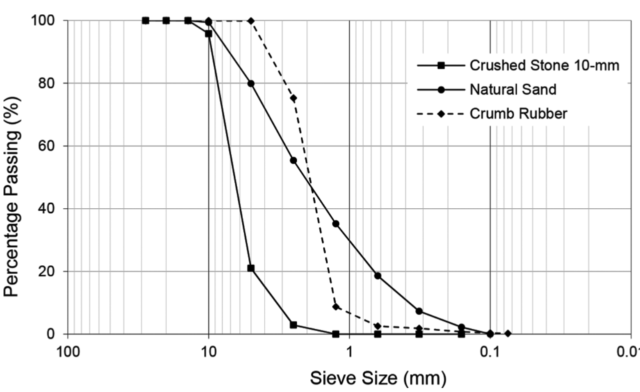

Fig. 1—Grading curves for both fine, coarse, and crumb rubber aggregates. (Note: 1 mm = 0.0394 in.)

The experimental program was divided in two stages. The first stage included four SCRC mixtures with CR percentages varying from 0% to 15% and a binder content of 500 kg/m^3 (31.215 lb/ft^3). The second stage involved using higher binder content, adding MK and air entrainment, and testing VRC mixtures. The second stage included: 1) two SCRC mixtures with higher binder content of 550 kg/m^3 (34.335 lb/ft^3) having 15% and 20% CR; 2) two SCRC mixtures with MK having 20% and 30% CR; 3) two SCRC mixtures with MK and air entrainment (0.2205 kg/m^3 [0.0138 lb/ft^3]) with 30% and 40% CR; and 4) two VRC mixtures with 40% and 50% CR (refer to Table 2). All tested beams were designated by the total binder content, percentage of CR, SCM used, and either the inclusion of micro air (MA) or VRC. For example, a

Table 2—Mixture design for tested mixtures

Beam no.	Mixture	Cement, kg/m^3	SCM (Type)	SCM, kg/m^3	CA, kg/m^3	FA, kg/m^3	CR, kg/m^3	HRWRA, kg/m^3	Density, kg/m^3
Stage 1									
1	500C-0CR	500	—	—	686.5	980.8	0.0	2.37	2367.3
2	500C-5CR	500	—	—	686.5	931.7	17.9	2.37	2336.2
3	500C-10CR	500	—	—	686.5	882.7	35.8	2.37	2305.1
4	500C-15CR	500	—	—	686.5	833.7	53.8	2.37	2273.9
Stage 2									
5	550C-15CR	550	—	—	648.1	787.0	50.7	1.84	2255.9
6	550C-20CR	550	—	—	648.1	740.7	67.7	1.84	2226.5
7	550C-20CR-MK	440	MK	110	638.4	729.6	66.7	5.26	2204.7
8	550C-30CR-MK	440	MK	110	638.4	638.4	100.0	5.26	2146.8
9	550C-30CR-MK-MA	440	MK	110	638.4	638.4	100.0	5.26	2146.8
10	550C-40CR-MK-MA	440	MK	110	638.4	547.2	133.3	5.53	2088.9
11	550C-40CR-MK-VRC	440	MK	110	638.4	547.2	133.3	3.50	2088.9
12	550C-50CR-MK-VRC	440	MK	110	638.4	456.0	166.6	4.00	2031.0

Note: All mixtures have a 0.4 w/b; CA is coarse aggregates; FA is fine aggregates; CR is crumb rubber; 1 kg/m^3 = 0.06243 lb/ft^3.

Table 3—Fresh and mechanical properties for tested mixtures

Mixture no.	Mixture	Slump flow		L-box H2/H1	V-funnel	Air, %	28-day f_c'	28-day STS
		D_s, mm	T_{50}, s		T_0, s			
Stage 1								
1	500C-0CR	700	1.20	0.89	6.39	1.5	50.2	3.87
2	500C-5CR	690	1.55	0.83	6.95	2.00	43.0	3.23
3	500C-10CR	687	1.74	0.79	7.57	2.3	41.8	2.94
4	500C-15CR	675	2.00	0.75	8.75	4.3	35.3	2.67
Stage 2								
5	550C-15CR	710	1.32	0.76	5.97	3.5	37.6	2.73
6	550C-20CR	700	1.54	0.75	6.65	3.2	32.8	2.49
7	550C-20CR-MK	680	2.57	0.86	8.25	3.4	40.8	2.69
8	550C-30CR-MK	620	2.86	0.75	13.5	4.20	34.8	2.36
9	550C-30CR-MK-MA	705	1.53	0.93	5.89	7.5	30.2	2.27
10	550C-40CR-MK-MA	700	1.74	0.84	9.79	8	26.4	1.84
11	550C-40CR-MK-VRC	95	—	—	—	4.5	28.9	2.22
12	550C-50CR-MK-VRC	80	—	—	—	6.1	22.4	1.74

Note: 1 mm = 0.0394 in.

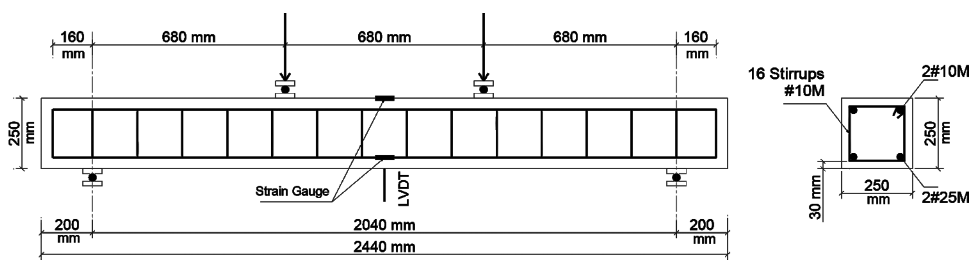

Fig. 2—Dimensions and reinforcement of tested beams. (Note: 1 mm = 0.0394 in.)

beam containing 550 kg/m^3 (34.335 lb/ft^3) binder, 40% CR, MK, and MA would be labeled 550C-40CR-MK-MA, and a beam using 550 kg/m^3 (34.335 lb/ft^3) binder, 50% CR, MK, and VRC would be labelled 550C-50CR- MK-VRC.

Casting of beam specimens

Twelve full-scale concrete beams were prepared using the 12 developed mixtures. Immediately after mixing, tests on the fresh properties of the concrete mixtures, as well as casting of beams in preassembled wooden forms, were carried out. All SCRC beams were cast without consolidation; the concrete was poured from one side until it flowed and reached the other side. Visual observation showed that the SCRC properly filled the forms with ease of movement around reinforcing bars. On the other hand, VRC beams were consolidated using electrical vibrators and trowel-finished for smooth top surfaces. Formwork was removed after 24 hours of casting, and the beams were moist-cured for 4 days and then air-cured until the date of testing.

Fresh and hardened concrete property tests

The fresh properties of all tested mixtures were conducted as per the European Guidelines for Self-Compacting Concrete.[17] The fresh properties tests included slump flow, V-funnel, and L-box tests. The percentage of air entrainment in the fresh SCC mixtures was measured by following a procedure given in ASTM C231/C231M.[18] The compressive strength and splitting tensile strength (STS) tests were conducted using 100 mm (3.94 in.) diameter x 200 mm (7.87 in.) height concrete cylinders, according to ASTM C39/C39M[19] and C496/C496M,[20] respectively. The compressive strength and STS tests were implemented after the sample had been exposed to condition of curing similar to that of the tested beams. The results of the fresh and mechanical properties of the tested mixtures are presented in Table 3.

Flexure test setup, instrumentation, and loading procedure

All beams contained shear and flexural reinforcement and were designed to fail in flexure with a ductile behavior. Figure 2 shows the test setup used for all 12 concrete beams during testing. The load was applied through a hydraulic jack (with capacity of 500 kN [112.4 kip]) at a single point and then distributed into two-point loads acting on the beam surface. A linear variable differential transformer (LVDT) and two strain gauges were used to measure the midspan deflection and reinforcement strain, respectively. The strain gauges were installed at the bottom of the longitudinal reinforcement at midspan (maximum flexural moment location). The beams were loaded gradually, with a constant loading rate through four stages until failure (first crack load, and 50%, 75%, and 100% of the theoretically calculated failure load). After each stage of loading, the cracks were marked and their widths recorded and plotted on each crack pattern. The overall behavior of the beams, including the development of cracks, crack patterns, crack widths, crack heights, and failure modes, was observed and sketched for all beams (Fig. 3). The results obtained from the flexure testing of the 12 tested beams are presented in Tables 4 and 5.

DISCUSSION OF TEST RESULTS

Fresh properties of SCRC mixtures

Table 3 presents the fresh properties of all tested mixtures. In general, as the percentage of CR increased, the fresh properties of SCRC mixtures decreased. The T_{50} results (the time it takes a mixture to reach 500 mm [19.7 in.] diameter in the slump flow test) and V-funnel time were used to evaluate the viscosity and flowability of SCRC mixtures. The results of Mixtures 1 to 4, which present mixtures with 500 kg/m^3 (31.215 lb/ft^3) binder and no SCMs, showed that increasing the percentage of CR appeared to increase the mixture viscosity and reduce its flowability. As shown in Table 3, the T_{50} and V-funnel increased by 66.7% and 36.9%, respectively, as the percentage of CR increased from 0% to 15%. This effect was also found in mixtures with 550 kg/m^3 (34.335 lb/ft^3) binder content and no SCMs (Mixtures 5 and 6) and mixtures with MK (Mixture 8 compared to Mixture 7, and Mixture 10 compared to Mixture 9), in which the mixture flowability decreased as the CR increased. On the other hand, by comparing Mixture 4 to Mixture 5, it can be observed that increasing the binder content improved the flowability of SCRC and also reduced the dosage of the HRWRA. Meanwhile, by looking at Mixture 6 versus Mixture 7, using MK greatly improved the passing ability (H2/H1 of L-box) of the mixture and caused a reduction in the flowability and a significant increase in HRWRA demand. It should be noted that despite the reduction of the flowability and the increased HRWRA demand of MK mixtures, MK was used in Mixtures 7 to 12 to improve the H2/H1 of L-box to obtain successful SCC passing ability (that is, reach values above 0.75) as per the European Guidelines for Self-Compacting Concrete.[17] The result of using higher binder content and/or adding MK matched other researchers' results in concrete mixtures without CR.[21-23] The results also indicated that adding air entrainment greatly enhanced the mixture flowability (T_{50} and V-funnel of Mixture 9 compared to Mixture 8). This result also matched other researchers' results[24] where the entrained air in SCC mixtures had a significant effect on improving the mixture flowability.

The results of H2/H1 L-box ratio showed that the addition of CR reduced the passing ability of the mixtures. Mixtures 1 to 4 show that increasing the percentage of CR from 0% to 15% reduced the H2/H1 L-box ratio by 15.7%. Using higher binder content (550 kg/m^3 [34.335 lb/ft^3] instead of 500 kg/m^3 [31.215 lb/ft^3]) showed a slight enhancement in the passing ability while adding MK increased the L-box ratio significantly, as expected.[25] The increase of the passing ability in MK mixtures could be attributed to the fact that the addition of MK improves the mixture viscosity,

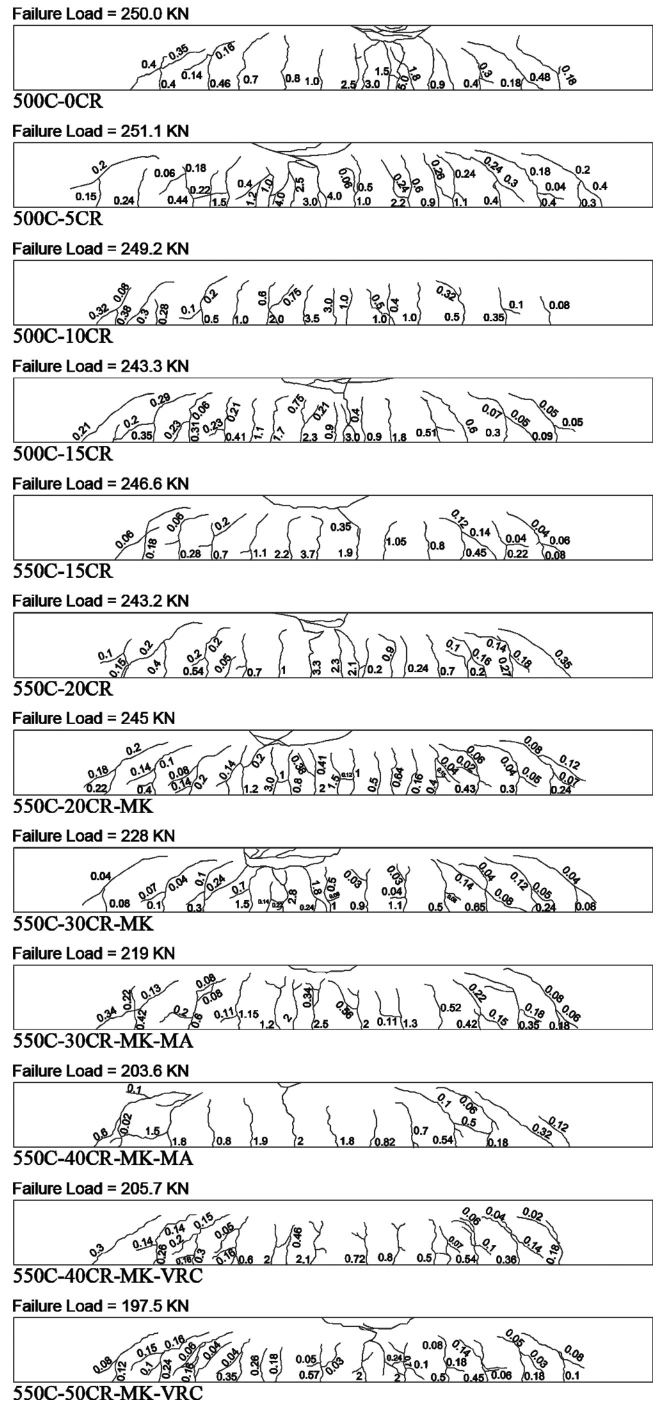

Fig. 3—Crack patterns of tested beams at failure (crack width in mm). (Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.)

which contributed to enhancing the distribution and suspension of aggregate particles, and this had a direct impact on improving the passing ability. The addition of air entrainment also showed a significant improvement in the passing ability (Mixture 9 compared to Mixture 8) and secured a higher H2/H1 value, which facilitated developing mixtures with higher CR contents and acceptable passing ability range (above 0.75). This improvement is related to the fact that the air bubbles in concrete mixtures act as a fine aggregate with low surface friction and considerable elasticity, reducing the particle collision/friction and, thus, improving the passing ability.[26] The reduction of the passing ability with

Table 4—Results of flexure test

Beam no.	Beam ID	First crack load, kN	Failure crack load, kN	Failure type	At failure	
					Number of cracks	Maximum crack width, mm
Stage 1						
B1	500C-0CR	32.8	250.0	Flexure	16	5.0
B2	500C-5CR	25.3	251.1	Flexure	18	4.0
B3	500C-10CR	22.8	249.2	Flexure	17	3.5
B4	500C-15CR	21.4	243.3	Flexure	19	3.0
Stage 2						
B5	550C-15CR	22.0	246.6	Flexure	14	3.7
B6	550C-20CR	18.2	243.2	Flexure	17	3.3
B7	550C-20CR-MK	20.8	245.0	Flexure	17	3.0
B8	550C-30CR-MK	17.2	228.0	Flexure	16	2.8
B9	550C-30CR-MK-MA	16.5	219.0	Flexure	14	2.5
B10	550C-40CR-MK-MA	13.9	203.6	Flexure	13	2.0
B11	550C-40CR-MK-VRC	14.8	205.7	Flexure	14	2.1
B12	550C-50CR-MK-VRC	14.0	197.5	Flexure	13	2.0

Note: 1 mm = 0.0394 in; and 1 kN = 0.225 kip.

Table 5—Midspan deflection, ductility, and toughness of tested beams

Beam no.	Beam ID	Concrete strain at service load (10^{-6})	Deflection at yield, δ_y, mm	Deflection at failure, δ_u, mm	Ductility ratio (δ_u/δ_y)	Toughness, kN.m
Stage 1						
B1	500C-0CR	337.0	10.3	27.0	2.62	4.7
B2	500C-5CR	532.0	9.3	28.5	3.07	5.3
B3	500C-10CR	714.0	8.8	28.2	3.21	5.1
B4	500C-15CR	783.6	9.1	30.8	3.39	5.4
Stage 2						
B5	550C-15CR	747.0	8.8	25.9	2.94	4.7
B6	550C-20CR	866.7	8.9	26.8	3.01	5.0
B7	550C-20CR-MK	699.0	9.0	21.9	2.43	3.7
B8	550C-30CR-MK	722.4	9.2	21.3	2.32	3.2
B9	550C-30CR-MK-MA	831.1	8.1	17.9	2.21	2.5
B10	550C-40CR-MK-MA	933.4	9.2	15.7	1.71	1.9
B11	550C-40CR-MK-VRC	980.1	9.0	16.2	1.80	2.0
B12	550C-50CR-MK-VRC	1051.2	9.3	15.9	1.71	1.8

Note: 1 mm = 0.0394 in.; and 1 kN.m = 0.0088 kip.in.

the increased percentage of CR could be attributed to the high friction and blocking between crushed stone aggregate and rubber particles. However, all tested mixtures agreed with the limitations given by the European Guidelines for Self-Compacting Concrete[17] and the recommended value by the Interim Guidelines for the Use of Self-Consolidating Concrete,[27] in which the H2/H1 L-box ratio did not decrease below 0.75.

Compressive and splitting tensile strength

The 28-day compressive strength and STS of the tested mixtures are shown in Table 3. As seen from Mixtures 1 to 4, increasing the percentage of CR showed a general reduction in both compressive strength and STS. Varying the CR from 0% to 15% reduced the 28-day compressive strength and STS by 29.6% and 31%, respectively. In Mixtures 5 and 6 (mixtures with 550 kg/m^3 [34.335 lb/ft^3] binder content), the reduction in the 28-day compressive strength and STS was 12.8% and 13.8%, respectively, as the percentage of CR increased from 15% to 20%. Similar behavior was also noticed in MK mixtures (Mixtures 7 to 12), in which the compressive strength and the STS reduced as the percentage of CR increased. The reduction of the mechanical properties with increased percentages of CR may be attributed to the poor strength of the interfacial transition zone between the rubber particles and surrounding mortar, as reported by many researchers.[28,29] In addition, the significant difference between the modulus of elasticity of the rubber aggregate and the surrounding mortar can contribute to decreasing the mechanical properties as the CR increased. Moreover, increasing the percentage of CR increased the air content (Table 3), which may also have had a negative effect on the mechanical properties of the mixtures.

Increasing the binder content from 500 to 550 kg/m^3 (31.215 to 34.335 lb/ft^3) raised the compressive strength and STS by 6.5% and 2.25%, respectively, as shown in Mixture 4 compared to Mixture 5. Also, by comparing Mixture 7 to Mixture 6, it can be seen that the addition of MK showed an enhancement in the mechanical properties; the compressive strength and STS increased by 24.4% and 8%, respectively. Meanwhile, from Table 3, using air entrainment helped to develop SCRC with up to 40% CR; however, the 28-day compressive strength and the STS had a reduction of 13.2% and 3.8%, respectively, with the use of air entrainment, as shown in Mixture 8 compared to Mixture 9. The results also indicated that the 28-day compressive strength and STS showed some improvement when using VRC compared to SCRC (Mixture 11 compared to Mixture 10). This can be attributed to the reduction in the air content, as shown in Table 3. It should be noted that the use of VRC (Mixtures 11 and 12) could benefit from using up to 50% CR, in which a further decrease of the mixtures' self-weight was obtained.

Load-deflection characteristics and failure behavior

Figure 4 presents the load-central deflection responses of the tested beams. The load and deflection were recorded at the first flexural crack and at various load levels (50, 75, and 100% of failure load). The first flexural cracking load was detected visually and confirmed by the first step or slope change in the load-central deflection response (Fig. 4) and by the load-longitudinal bar strain curves at midspan. Looking closely at Fig. 4, it can be observed that up to the first crack load, the curves appear to be linear with higher stiffness, and then the curves deviate from linearity, showing a reduction in their slopes that indicates lower stiffness due to formation of microcracks. After additional application of load, the longitudinal steels started to yield. During the lifetime between the first crack load and the load that caused steel yielding, the slope of the load-deflection curves changed many times due to multiple cracking. Further increasing the applied load finally caused the concrete crushed in the compression zone and beams to fail. All plots present a typical ductile mode of failure, normally called tension failure, in which the steel bars in tension side yielded before the failure occurrence (as confirmed from the steel strain gauges). The load-deflection curves show that the flexural stiffness (the slope of the load-central deflection curve) of the tested beams decreased as the CR content increased. However, this decrease was not clear in Stage 1 beams (0% to 15% CR) and was more pronounced in beams with higher percentages of CR (more than 20%). This decrease in flexural stiffness is most likely attributed to decreased modulus of elasticity of the SCRC as

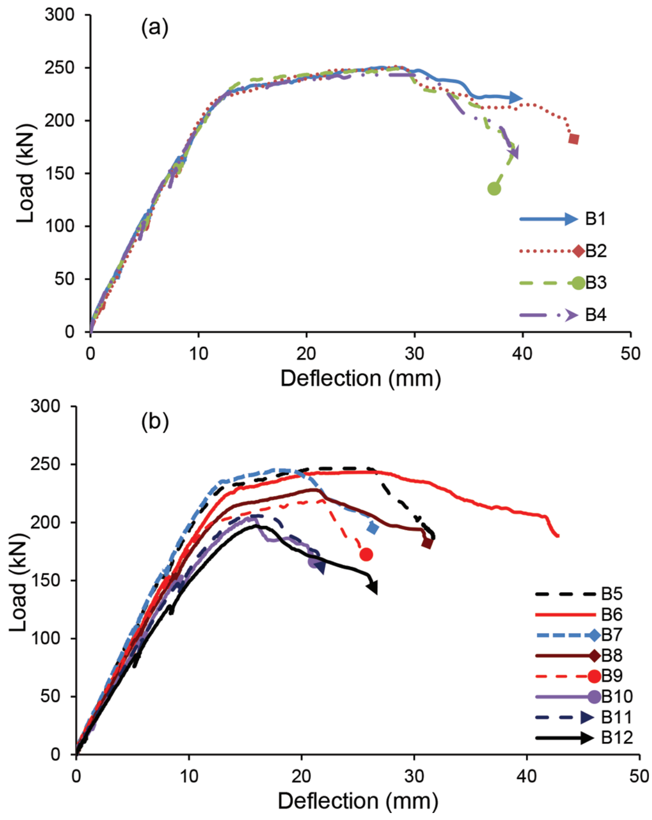

Fig. 4—Experimental load-midspan deflection responses: (a) Stage 1; and (b) Stage 2. (Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.)

the CR content increased.[1] From Table 5 and Fig. 4, it can be observed that increasing the CR content from 0% to 15%, in the first stage, improved the deformation capacity of the tested beams; the maximum deflection increased from 27 to 30.8 mm (1.06 to 1.21 in.). This effect was also noticed up to 20%, as shown in B6 compared to B5 of the second stage. Meanwhile, at high levels of CR replacement (30 to 50%), the rubber-cement composite became weak, which limits the material's ability to absorb energy and thus exhibits lower deformation capacity. Such behavior proves that using CR up to 20% can enhance the deformation capacity of conventional concrete. Comparing VRC to SCRC (B11 compared to B10) shows that both beams had comparable stiffness and deformation capacity.

Concrete strain

As mentioned previously, two strain gauges were attached on the top surface of the concrete beams at the midspan. These strain gauges monitored the concrete strain along the history of the beam's loading (Fig. 5). During the final stage of loading, and before reaching the ultimate failure load, the top surface of the concrete beams was cracked and crushed near the glued strain gauges. Therefore, it was not possible to obtain reliable results from the concrete strain gauges at the ultimate failure load. For this reason, the concrete strain readings in Fig. 5 were recorded up to approximately 95% of the failure load, and therefore the ultimate strain values were higher than the values presented in the figure. It can be generally observed that the slope of the load-strain curve

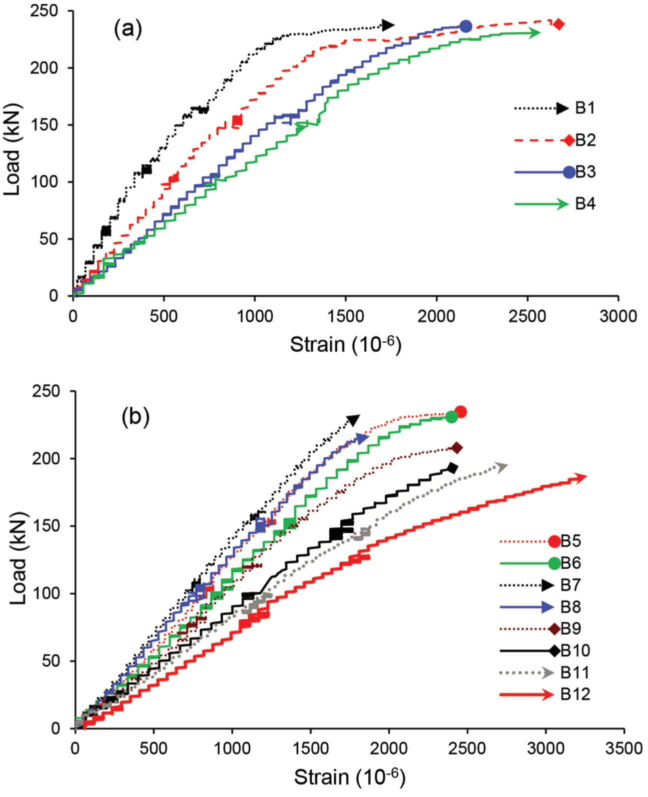

Fig. 5—Experimental load-strain curve of concrete: (a) Stage 1; and (b) Stage 2. (Note: 1 kN = 0.225 kip.)

decreased as the percentage of CR increased (in both Stage 1 and Stage 2). This result indicates that the concrete stiffness decreased as the percentage of CR increased from 0% to 50%.

To focus on the effect of CR specifically at service condition, the values of the concrete strain were recorded at 40% of the ultimate failure load as the customary level service load.[30] Table 5 presents the results of the concrete strain at service load for all tested beams. The results showed that varying the percentage of CR from 0% to 15% (Stage 1) raised the strain at service load from 337×10^{-6} to 783.6×10^{-6}, respectively. A similar trend of results was noticed in the tested beams of Stage 2. The concrete strain at service load continued to increase with increased CR content. The maximum value of the strain at service load occurred with 50% CR and was 1051.2×10^{-6}. Such findings could be attributed to the reduction in the stiffness of rubber-cement composite, which resulted from the ability of the rubber particles to undergo large elastic deformation under loading. The results of Fig. 5 and Table 5 also indicated that slight differences in concrete stiffness and strain at service load were noted between VRC and SCRC (B11 compared to B10).

Ductility and toughness

Displacement ductility was also investigated in this study. Table 5 and Fig. 6 present the ductility ratio μ of the tested beams, which was expressed in terms of $\mu = \delta_u/\delta_y$, where δ_u is the experimental deflection value at peak failure load, and δ_y is the experimental deflection at steel yielding. In general, increasing the ductility ratio of the structural member indicates its ability to experience large deflections before failure and, thus, provide ample warning to the occurrence of failure. The results of Stage 1 showed that increasing the CR content improved the ductility of concrete; as the percentage of CR increased from 0% to 15% (B1 compared to B4), μ increased by 29.4%. Replacing the conventional aggregate with rubber aggregate, which has lower stiffness, can greatly enhance the flexibility and energy absorption of rubber-cement composite and, thus, increase the ductility of beams. Stage 2 showed that the ductility enhancement continued up to 20% (B5 compared to B6) replacement level. Further increasing the CR content, however, reduced the ductility of the beams. This reduction may be related to the weakened concrete at the compression zone at higher CR percentages due to the poor bonding between the CR and the surrounding mortar, which limited the beams' ability to experience higher loading beyond the yielding point. It should be noted that Beams B2 to B4 (Stage 1) and B6 (Stage 2) showed a ductility ratio of 3.07 to 3.39 and 3.01, respectively, which indicate a potential ductility for structural members subjected to large displacements, such as sudden forces caused by earthquake.[31,32]

Because the use of CR contributed to enhancing the ductility of the tested beams, it was expected that this improvement can directly affect the beam's toughness. Toughness is the property that can express the capacity of a material to absorb energy up to failure. To compare the toughness of tested beams, the ultimate deformation energy was determined by measuring the area under the load-deflection curve up to the failure load. Table 5 and Fig. 7 show the calculated toughness for all tested beams. Examining the load-deflection curves of the first set of beams (B1 to B4), it can be seen that the area enclosed by the load-deflection curve increased as the CR increased, which indicates an improved toughness of rubberized concrete. For example, increasing the percentage of CR from 0% to 15% raised the toughness by 14.9%. The reason for this increase could be attributed to low stiffness of the CR particles that impart relatively high flexibility and, hence, absorb considerably more energy than could be absorbed by conventional concrete. As shown from the results of Stage 2, the toughness of the tested beams continued to improve up to 20% replacement level (B5 versus B6) and started to drop with higher CR replacement levels (30% to 50%). Toughness is a combination of strength and ductility; the results showed a reduction of the beam's ductility with a CR percentage higher than 20%. In the meantime, the flexure strength started to drop with increasing the percentages of CR. Therefore, the significant deterioration in the strength and ductility of rubberized concrete at higher levels of CR reduced the ability of concrete to absorb more energy before failure. However, it is worth noting that the possibility of producing SCRC and VRC with higher CR replacement (30% to 50%) contributed to the development of structural members with reduced self-weight. By comparing VRC and SCRC (B10 versus B11), it can be observed that both beams have comparable ductility ratios and toughness, with a slight increase in VRC beams.

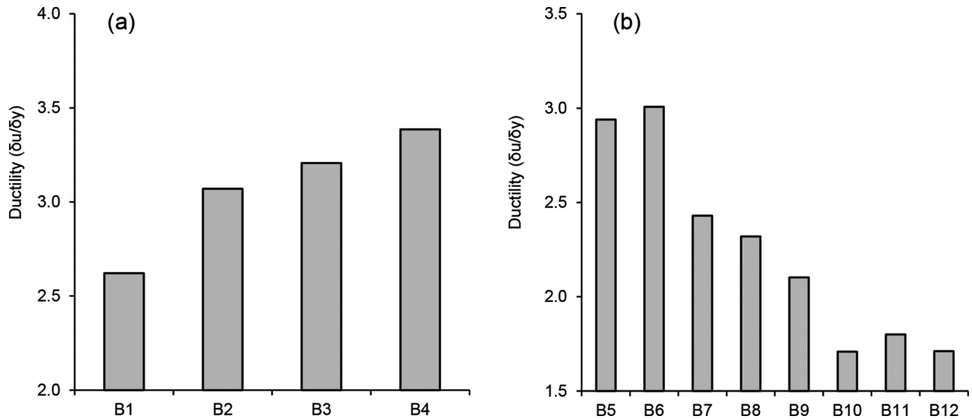

Fig. 6—Effect of CR content on ductility: (a) Stage 1; and (b) Stage 2.

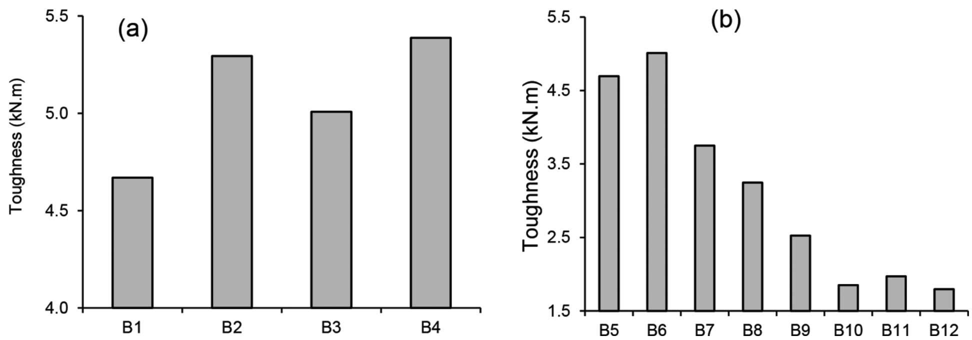

Fig. 7—Effect of CR content on toughness: (a) Stage 1; and (b) Stage 2. (Note: 1 kN.m = 0.0088 kip.in.)

General cracking and failure behavior

As mentioned, the cracks were outlined with a black felt-tipped marker and the crack width was determined and labeled at each loading stage. Figure 3 shows the crack patterns of all tested beams at the failure stage. During early stages of loading, fine vertical flexural cracks appeared around the midspan of all beams, as expected. With the increase in load, these flexural cracks extended and other new flexural cracks were formed along the loaded span. With a further increase in load (exceeding 50% of theoretical failure load), the flexural cracks that were formed away from the midspan started to propagate diagonally toward the loading points, and other new diagonal cracks began to form separately in locations farther away from the midspan along the beam (Fig. 3).

Figure 3 and Table 4 show the crack pattern and crack widths/numbers of all tested beams, respectively. Regarding Stage 1, the beam without CR (B1) appeared to have a larger crack width at failure compared to rubberized concrete beams (B2 to B4). This may be attributed to the higher energy absorption capacity of rubber particles. On the other hand, the failure pattern of rubberized concrete beams (B2 to B4) was characterized by having slightly more cracks than B1. Such results could be related to increasing the midspan deflection (beam's curvature) as the CR content increased (Table 5), which resulted in the development of more cracks before failure. Increasing the CR content in the second-stage beams also followed the same behavior in terms of higher number of cracks and reduction of the crack width at failure. Table 4 and Fig. 3 also indicated a similar cracking behavior with insignificant differences in terms of crack widths/numbers for both VRC and SCRC beams (B10 compared to B11).

First crack load and ultimate load

The first flexural crack load was visually observed and then compared/verified with values associated with the change in slope of the load-deflection and load-longitudinal steel strain curves obtained from the test. Table 4 presents the loads at first flexural crack and failure loads of all tested beams. The results showed that increasing the CR content generally reduced the first crack load and the ultimate failure load in both Stages 1 and 2. Regarding the results of Stage 1, the first crack load appeared to be more affected by increasing the CR content compared to the ultimate failure load, which showed a slight decrease with higher percentages of CR. Increasing the CR content from 0 to 15% reduced the first crack load by 34.76% while the ultimate failure load showed a reduction of 2.67%. The reduction in first crack load could be attributed to the significant deterioration in the tensile strength of the concrete as the CR content increased, as explained previously (results of STS test).

Similar behavior was noticed in Stage 2, in which increasing the CR content exhibited a lower first cracking load and lower ultimate failure load. However, the reduction of the ultimate failure load was relatively higher when the percentage of CR exceeded 20%. For example, by comparing B7 to B8, it can be observed that the ultimate failure load reduced by 6.94%. This higher reduction may be due to the decline in the ductility and toughness properties that were noticed at the higher replacement levels (from 30 to 50%). It should be noted that up to 10% CR (Stage 1), the ultimate failure load did not reduce and it only started to drop with higher percentages of CR. This result indicates that using up to 10% CR can help improving the beam's ductility and toughness (as proved earlier) without affecting the ultimate flexural capacity of the beam. Although using higher percentage of CR (30% to 50%) reduced the ultimate failure capacity of the beams, it contributed to developing semi-lightweight concrete with density varied from 2031 to 2146.8 kg/m^3 (126.791 to 134.02 lb/ft^3).[33] By comparing VRC to SCRC (B10 to B11), it can be observed that both beams showed a comparable ultimate failure load while the first crack load showed a slight increase in VRC beams. This slight increase in the first crack load may be attributed to the improvement of the tensile strength of the VRC mixtures compared to SCRC mixtures.

Experimental and theoretical bending moment capacity

A comparison between the experimental ultimate moments ($M_{exp.}$) and the theoretical design moments ($M_{theo.}$) is shown in Table 6 and Fig. 8. The theoretical design moment of the beams was predicted using the rectangular stress block analysis, as recommended by CSA-04[33] and ACI 318-08.[34] The comparison showed that the ultimate moments obtained from the experiments were approximately 5 to 23% higher than the predicted values of both CSA-04[33] and ACI 318-08.[34] Increasing the CR content from 0 to 15% (B1 to B4 in Stage 1) and from 15% to 20% (B5 to B6 in Stage 2) showed a slight increase of the value of M_{exp}/M_{theo}, indicating improvement of the flexural capacity of the beams compared to the predicted values. However, increasing the CR content more than 20% showed a general decrease of the value of $M_{exp.}/M_{theo}$. This finding may be related to the noticeable reduction of the ductility and toughness of the tested beams that occurred at high levels of CR replacement. However, CSA-04[33] and ACI 318-08[34] can be used to obtain a conservative estimate of the ultimate moment capacity as well as provide an adequate load factor against failure for CR content up to 50%.

Table 6—Predictions of ultimate moment capacity

	Ultimate moment capacity, kN.m			Margin of safety ($M_{exp}/M_{theo.}$)	
Beam no.	Experi-mental	CSA-04	ACI 318-08	CSA-04	ACI 318-08
B1	85.0	70.7	71.4	1.20	1.19
B2	85.4	69.6	70.2	1.23	1.22
B3	84.7	69.3	69.9	1.22	1.21
B4	82.7	67.9	68.5	1.22	1.21
B5	83.8	68.5	69.1	1.22	1.21
B6	82.6	67.3	67.9	1.23	1.22
B7	83.3	69.1	69.8	1.20	1.19
B8	77.5	67.8	68.4	1.14	1.13
B9	74.5	66.6	67.1	1.12	1.11
B10	69.2	65.4	65.8	1.06	1.05
B11	70.0	66.2	66.7	1.06	1.05
B12	67.2	63.7	64.1	1.05	1.05

Note: 1 kN.m = 0.0088 kip.in.

CONCLUSIONS

The structural performance of full-scale reinforced SCRC and VRC beams under flexural load was investigated. The beam mixtures were developed with variable percentages of CR using different binder content, the addition of MK, and/or using air entrainment. The flexural capacity, cracking behavior, load-deflection response, concrete strain/stiffness, ductility, and toughness were studied for all beams. From the results described in this paper, the following conclusions can be drawn:

1. Using CR had an adverse impact on the fresh and mechanical properties of both SCRC and VRC. In SCRC mixtures, the flowability (T_{50} and V-funnel time), passing ability (H2/H1 of L-box), unit weight, compressive strength, and STS decreased as CR increased while the air content increased.

2. As the percentage of CR increased from 0 to 50%, the first crack load, concrete's stiffness and beams' flexural stiffness decreased. On the other hand, the deformation capacity, ductility, and toughness of the tested beams appeared to improve with increases in the CR replacement from 0 to 20% and started to drop with further increases (20 to 50%).

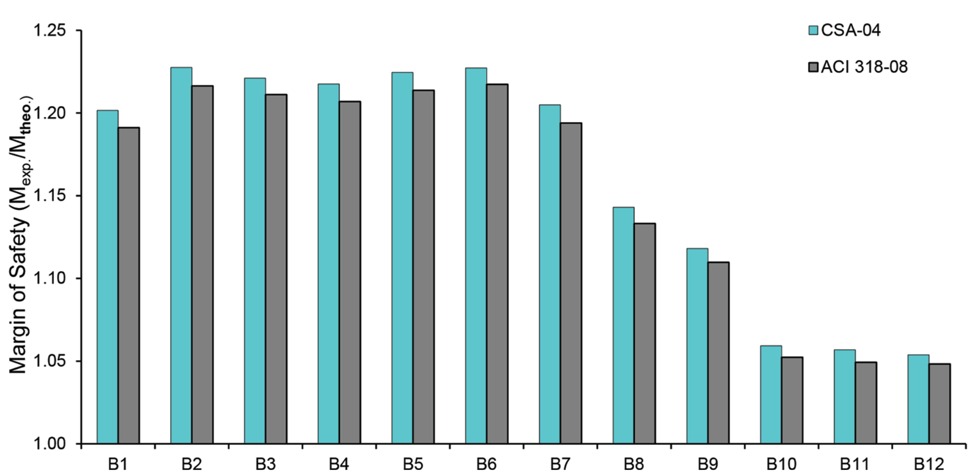

Fig. 8—Effect of CR content on predictions of ultimate moment capacity.

3. No significant difference was noticed between VRC and SCRC beams in terms of their behavior under flexural load. However, at 40% CR, the development of SCRC needed the use of air entrainment to obtain successful SCRC mixtures with acceptable passing ability. This essential use of air entrainment in SCRC mixtures resulted in a slight reduction in the compressive strength and STS of SCRC compared to VRC.

4. Using up to 10% CR can improve the beam's deformation capacity, ductility, and toughness without affecting the ultimate flexural load. However, 10 to 20% CR replacement may continue to improve the beam's deformation capacity, ductility, and toughness but with a slight reduction in the ultimate flexural load.

5. In this investigation, it was possible to develop SCRC with a maximum CR percentage of 40%. This percentage could be increased to 50% with VRC. However, the 10% increase of CR gave VRC the advantage over SCRC in terms of reducing self-weight while it had a limited advantage in terms of the overall structural behavior of the tested beams.

6. Increasing the percentage of CR more than 20% appeared to affect the conservative estimation for the beams' moment capacity based on the current ACI 318-08 and CSA-04 design codes. However, ACI 318-08 and CSA-04 can be used to obtain a conservative estimate of the ultimate moment capacity as well as to provide adequate load factor against failure.

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NOTATION

CR	=	crumb rubber
SCC	=	self-consolidating concrete
SCRC	=	self-consolidating rubberized concrete
VRC	=	vibrated rubberized concrete
SCM	=	supplementary cementitious material
C/F	=	coarse-to-fine aggregate
w/b	=	water-to-binder ratio
MK	=	metakaolin
MA	=	micro air
HRWRA	=	high-range water-reducer admixture
STS	=	splitting tensile strength

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