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An experimental study on flexural strength of reinforced concrete beams with 100% recycled concrete aggregate

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ABSTRACT

The following paper presents the results of an experimental investigation of the flexural strength of full-scale reinforced concrete beams constructed with both 100% recycled concrete aggregate (RCA) as well as conventional concrete (CC). This experimental program consisted of eight beams (four for each concrete type). The test parameters for this study include longitudinal reinforcement ratio and concrete type. The beams were tested under a simply supported four-point loading condition. The experimental cracking, yielding, and ultimate moment of the beams were compared with the ACI 318-11 and Eurocode 2-05 provisions and the modified compression field theory (MCFT) method. Furthermore, the experimental flexural strengths of the beams were compared with both flexural test databases of CC and RCA specimens. Results of this study show that the RCA beams have comparable ultimate flexural strength and approximately 13% higher deflection corresponding to the ultimate flexural strength of the CC beams.

1. Introduction and research significance

Sustainability is at the forefront of our society. Unfortunately, concrete, our most common construction material uses a significant amount of non-renewable resources. Consequently, many researchers have investigated the use of recycled materials in the production of concrete such as fly ash [1–7] and recycled aggregate [8–17].

Unfortunately global data on concrete waste generation is not available, but construction and demolition waste accounts for around 900 million tones every year just in Europe, the US, and Japan [18]. Recycling concrete not only reduces using virgin aggregate but also decreases landfills.

Comprehensive research [19–25] has been done on both the fresh and hardened properties of recycled concrete aggregate (RCA), recycled aggregate resulting from crushed concrete, but very little research has been performed on the structural behavior of RCA. The early research on structural performance of RCA was published in Japan [9]. Mukai and Kikuchi [8] tested 150×150 mm cross section and 1.8-m long beams with both 15% and 30% RCA replacement and reported no significant difference in ultimate moment, but lower cracking moment for RCA beams. Yagashita et al. [9] used three types of recycled aggregate with 100% replacement as follows: low grade RCA, using only impact crusher (R3); medium grade RCA, impacting R3 with roll crusher (R2); and high grade RCA, crushing R2 once again with roll crusher (R1). Their results showed using high grade RCA slightly decrease (around 10%) the flexural capacity of RCA beams. Ajdukiewicz and Kliszczewicz [10] used partial or full recycle aggregate. All the beams were rectangle 200×300 mm and 2600 mm long with two longitudinal reinforcement ratios (0.90% and 1.60%). They reported that the RCA beams had slightly (3.5% in average) lower moment capacity and higher deflection compared with the CC beams. Sato et al. [11] tested 37 beams with three different longitudinal reinforcement ratio (0.59%, 1.06%, and 1.65%). They used 100% recycled aggregate for their mix designs. Results of their study showed that the RCA beams had larger deflection compared with the CC beams. In terms of crack spacing no significant difference observed between the RCA and CC beams; however, the RCA beams had wider cracks compared with the CC beams. They also reported almost the same ultimate moment for the RCA and CC beams. Maruyama et al. [12] tested beams with 1% longitudinal reinforcement ratio and reported that the RCA beams cracks were

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wider and spaced closer compared with the CC beams. The RCA beams had larger deflection, but no significant difference between the flexural capacity of the RCA and CC beams. Fathifazl et al. [13] used equivalent mortar volume (EMV) method for their mix designs. They used both limestone (63.5% recycled aggregate) and river gravel (74.3% recycled aggregate) as a coarse aggregate for their mix designs. Their beams had three different longitudinal reinforcement ratio ranged between 0.49% and 3.31%. They reported comparable and even superior flexural behavior for RCA beams at both service and ultimate states. They concluded that current codes flexural provisions can be used for RCA beams. Bai and Sun [14] used 8–10 years old RCA with different replacement levels (50%, 70%, and 100%). They observed similar crack pattern, but deflection and crack width increased with the increment of RCA replacement level. They also concluded that RCA replacement level does not significantly affect the cracking ultimate moment of beams. Ignjatovic et al. [15] studied nine full scale beams with 0%, 50%, and 100% recycled coarse aggregate and 0.28%, 1.46%, and 2.54% longitudinal reinforcement ratio. They reported no noticeable difference between load–deflection behavior, service load deflection, and ultimate flexural strength of RCA and CC beams. But they observed that the beams with higher range of recycled aggregate showed higher level of concrete destruction at failure. Kang et al. [16] used beams with longitudinal reinforcement ratio ranged between 0.5% and 1.8% with RCA replacement level up to 50% for both normal and high strength concrete. They observed greater number of cracks and lower cracking moment for RCA beams. They also reported no significant decrease in flexural capacity up to 30% RCA replacement level. Knaack and Kurama [17] tested 150 × 230 mm cross section and 2000 mm long beams. They used RCA from late 1920s foundation and with both 50% and 100% replacement level. They reported higher deflection for the RCA beams, but they concluded that the existing analytical models and code provisions can be used for the RCA beams.

In summary, only using EMV method by Fathifazl et al. [13] resulted in superior flexural strength performance of RCA beams compared with CC beams, otherwise using RCA instead of virgin aggregate showed either lower flexural strength or almost the same flexural strength for RCA beams compared with CC beams.

Based on a review of the existing literature, there is a lack of full-scale flexural testing of RCA specimens, particularly with 100% replacement of virgin aggregate and also some conflicting results. Consequently, the authors, in conjunction with the Missouri Department of Transportation (MoDOT), developed a testing plan to evaluate flexural strength of RCA specimens with local materials. The mix designs, based on standard mixes currently used by MoDOT, was on the lower end of cement content in order to develop a relatively harsh mix to investigate constructability issues common to RCA concrete. The experimental program, test results, and analyses for this study are presented in the following discussion.

2. Experimental program

2.1. Specimen design

A total of eight beams were constructed (four CC and four RCA). Beams have two different longitudinal reinforcement ratios (0.47% and 0.64%) with shear reinforcements to preclude shear failure and satisfy the minimum and maximum longitudinal reinforcement requirements of ACI 318-11 [26]. All beams had a rectangular cross section with a width of 300 mm, a height of 460 mm (see Fig. 1). The beam designation included a combination of letters and numbers: F stands for flexural beams and numbers 6 (19 mm diameter) and 7 (22 mm diameter) indicate the size of longitudinal reinforcement bars within the tension area of the beam section. For example, F-6 indicates a beam with 2#6 (19 mm diameter) within the bottom of the beam.

2.2. Materials and mixture proportions

For the CC mix, ASTM Type I Portland cement, crushed limestone with a maximum nominal aggregate size of 25 mm from the Potosi quarry (Potosi, MO) were used. The fine aggregate was natural sand from Missouri River Sand (Jefferson City, MO).

This mix design was used to construct control specimens to serve as baseline comparisons to the RCA mix and will also serve as parent material for the RCA source. The resulting concrete was ground into aggregate with a maximum nominal aggregate size of 25 mm. Test results for the coarse aggregate used in the CC mix design as well as the resulting RCA are shown in Table 1. As expected, the RCA had lower specific gravity and unit weight and considerably higher absorption. The Los Angeles abrasion test results were virtually identical. For the RCA mix, all the ingredients were the same except the coarse aggregate was 100% recycled coarse aggregate (by volume) that contained 46.1% residual mortar (by weight). The residual mortar content of RCA was determined based on a method developed by Abbas et al. [27] which involved immersion of RCA in sodium sulfate solution and its subjection to three freeze-and-thaw cycles. Both the CC and RCA had a similar gradation.

The longitudinal and shear reinforcement steel consisted of ASTM A615 [28], Grade 60, (414 MPa) material. All of the reinforcing bars were from the same heat of steel, used the same deformation pattern, and met the requirements of ASTM A615. Table 2 shows the tested mechanical properties of the reinforcing steel.

The concrete mixtures with a target compressive strength of 35 MPa were delivered by a local ready-mix concrete supplier (Rolla, MO). The purpose of using the ready-mix supplier was to validate the RCA concept in actual concrete production runs. The mixture proportions, fresh and hardened properties of both the CC and RCA mixes are given in Tables 3 and 4, respectively.

2.3. Fabrication and curing of test specimens

Specimens were constructed, cured, and tested in the Structural Engineering High-Bay Research Laboratory (SERL) at Missouri University of Science and Technology. After casting, the beam specimens and the quality control/quality assurance companion cylinders (ASTM C39 [29], C469 [30], and C496 [31]) and beams (ASTM C78 [32]) were covered with both wet burlap and plastic sheeting. All of the beams and companion cylinders were moist cured for seven days and, after formwork removal, were stored in a semi-controlled environment with a temperature range of 18–24 °C and a relative humidity range of 30–50% until they were tested at an age of 28 days.

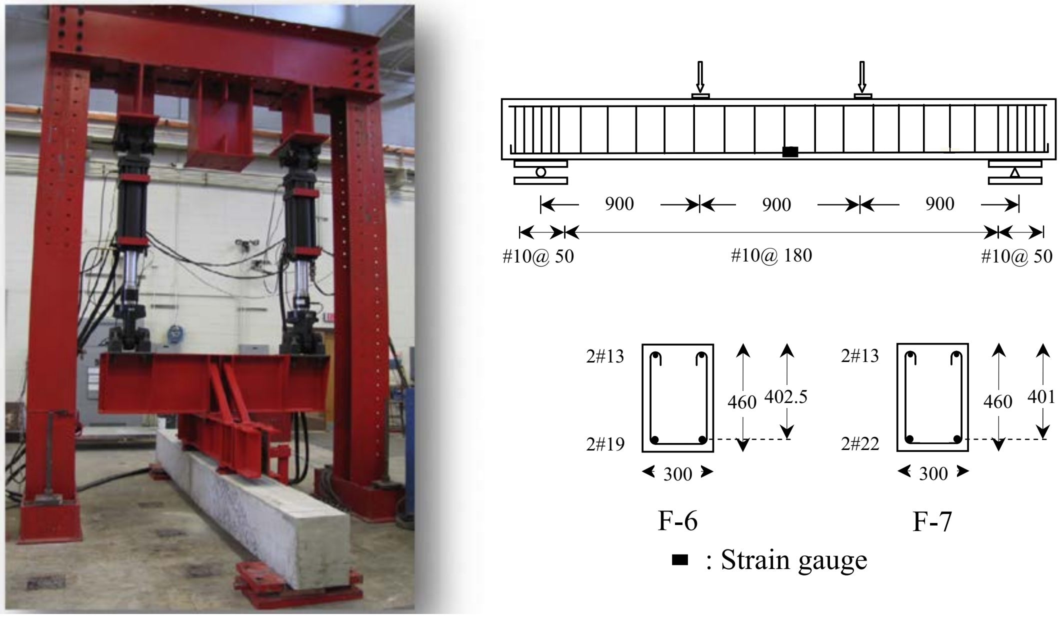
2.4. Flexural test setup and procedure

2.4.1. Testing facilities

A load frame was assembled and equipped with two 490-kN (980-kN in total), servo-hydraulic actuators intended to apply the two point loads to the beams (Fig. 1). The load was applied in a displacement control method at a rate of 0.50 mm/min. The flexural beams were supported on a roller and a pin support, 300 mm from each end of the beam, creating a four-point loading situation with the two actuators.

2.4.2. Instrumentations

A Linear variable differential transformer (LVDT) and strain gauges were used to measure the deflection at the beam center



(a) Test set up and load pattern (b) Cross sections and reinforcement layout

All dimensions are in mm

Fig. 1. Test set up, load pattern, cross sections, reinforcement layout, and location of strain gauges on the test beams.

Table 1
Aggregate physical properties.[a]

Property	CC	RCA
Bulk Specific Gravity, Oven-Dry	2.72 (4.1)[b]	2.35 (5.2)[b]
Dry-Rodded Unit Weight, (kg/m^3)	1600 (5.3)[b]	1440 (4.3)[b]
Absorption (%)	0.98 (4.8)[b]	4.56 (5.7)[b]
Los Angeles Abrasion (% Loss)	43 (5.1)[b]	41 (5.9)[b]

[a] Values represent the average of three tests.
[b] Coefficient of variation (%).

and strain in the reinforcement. Two strain gauges were installed on the lower layer of the bottom longitudinal reinforcement at midspan (maximum flexural moment location). Fig. 1 shows both the beam loading pattern and the location of the strain gauges. During the test, any cracks that formed on the surface of the beam were marked at load increments of approximately 22 kN, and both the deformation and strains were monitored until the beam reached failure.

3. Flexural test results and discussion

3.1. General behavior (cracking and failure mode)

In terms of crack morphology and crack progression, the behavior of the both CC and RCA beams was similar except for cracking space (the RCA beams cracks were closer to each other compared with the CC beams cracks). All of the beams failed in flexure. In all of the beams, the longitudinal tension steel yielded first (Figs. 2 and 3), followed by the concrete crushing, which is a ductile mode of failure, normally called tension failure.

Fig. 2 shows the load–deflection behavior for the beams (the deflection was measured at midspan). Before the first flexural cracks occurred (point A), all of the beams displayed a steep lin-

Table 2
Mechanical properties of reinforcing steel.[a]

Bar No.	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity (MPa)	Elongation (%)
10	494 (1.0)[b]	746 (1.0)[b]	206,890 (3.9)[b]	11.7 (8.7)[b]
19	568 (0.4)[b]	811 (0.7)[b]	196,570 (6.7)[b]	13.7 (4.2)[b]
22	517 (1.0)[b]	791 (0.1)[b]	193,140 (7.7)[b]	16.3 (3.5)[b]

[a] Values represent the average of three specimens.
[b] Coefficient of variation (%).

Table 3
Mixture proportions of concrete.

Material	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Recycled coarse aggregate (kg/m^3)	AE[a] (l/m^3)	HRWR[b] (l/m^3)
CC	117	315	725	1135	–	0.62	1.65
RCA	126	315	800	–	880	0.21	1.25

[a] Air entraining admixture.
[b] High range water reducer admixture.

Table 4
Fresh and hardened concrete properties.

Property	CC-1	CC-2	RCA-1	RCA-2
Fresh				
Slump (mm)	140	205	205	190
Air content (%)	8.5	9.0	6.5	6.0
Unit weight (kg/m^3)	2330	2340	2280	2240
Hardened				
Compressive strength[a] (MPa)	37.2(3.1)[c]	34.2(4.1)[c]	30.5(5.2)[c]	31.3(4.8)[c]
Split tensile strength[a] (MPa)	3.48(5.0)[c]	2.97(6.1)[c]	2.10(3.2)[c]	2.15(4.5)[c]
Flexural tensile strength[b] (MPa)	3.45(7.1)[c]	2.90(4.1)[c]	2.70(6.2)[c]	2.33(5.3)[c]
Modulus of elasticity[a] (GPa)	34.5(8.1)[c]	33.1(5.1)[c]	26.3(7.3)[c]	26.5(9.0)[c]
Fracture Energy[d] (N/m)	143.6(9.3)[d]	136.6(7.8)[d]	99.8(8.7)[d]	105.1(9.2)[d]

[a] Values represent the average of three cylinders (ASTM C39 (2012), C496 (2011), and C469 (2010)).
[b] Values represent the average of three beams (ASTM C78 (2010)).
[c] Coefficient of variation (%).
[d] Values represent the average of four notched beams (the beams measured 150 × 150 × 600 mm with a span length of 450 mm and notch with a depth of 40 mm and a thickness of 6 mm).

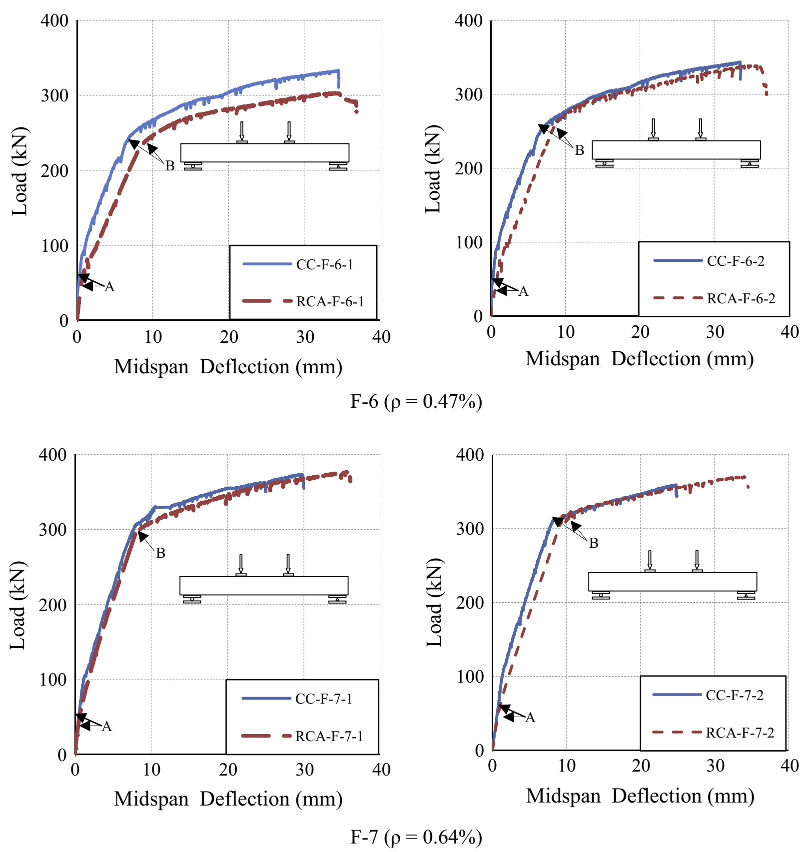


Fig. 2. Load–deflection plots of the full-scale test beams.

ear elastic behavior. After additional application of load, the longitudinal steel yielded (point B). Upon further increasing the applied load, finally concrete crushed in compression zone and beams failed. As it can be seen from Fig. 2, the RCA beams showed lower cracking moment that maybe ascribed to the existence of two types of interfacial transition zones (ITZ) in the RCA beams (ITZ between virgin aggregate and residual mortar in RCA and also ITZ between residual mortar and fresh mortar) compared with only one ITZ (between virgin aggregate and fresh mortar) in the CC beams. Fig. 3 shows load–strain behavior of the reinforcing steels and as expected all of reinforcing steels yielded (the majority of strain gauges failed before reaching the ultimate loads).

Furthermore, the RCA beams showed lower stiffness after the cracking moments that can be attributed to lower modulus of elasticity of the RCA mix compared with the CC mix (see Table 4).

Crack progression in the beams began with the appearance of flexural cracks in the maximum moment region, followed by additional flexural cracks forming between the load and support regions as the load was increased. Upon further increasing the applied load, the majority of the flexural cracks developed vertically and, after that, inclined flexure-shear cracks began to appear. Fig. 4 offers a direct visual comparison of the crack shape and distribution at failure for the beams of both CC and RCA mixes, which are different in term of crack spacing that has been reported by other research.

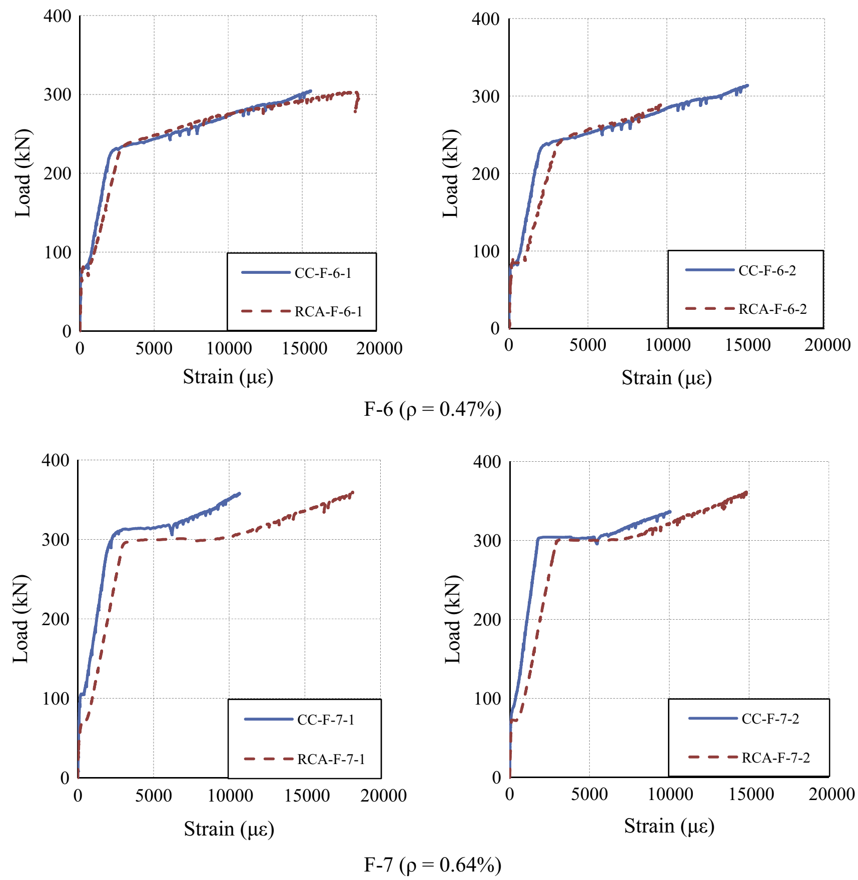


Fig. 3. Load–strain (steel reinforcement) plots of the full-scale test beams.

Table 5 summarizes the compressive strength of both the CC and RCA beams at time of testing, cracking moment, M_{cr} (Eq. (1)), yielding moment, M_y (Eq. (2)), nominal flexural strength, M_n (Eq. (3) can be used since for all the beams reinforcing steels yielded), yielding deflection, δ_y, and ultimate deflection, δ_u.

$$M_{cr} = \frac{fr \times I_g}{y_t} \quad (1)$$

$$M_y = A_s f_y d\left(1 - \frac{k}{3}\right) \quad (2)$$

$$M_n = \rho f_y b d^2\left(1 - .59\rho\frac{f_y}{f'_c}\right) \quad (3)$$

where:

A_s: area of nonprestressed tension reinforcement
b: width of compression face of member
d: distance from extreme compression fiber to centroid of longitudinal tension reinforcement
E_s: modulus of elasticity of steel
E_c: modulus of elasticity of concrete
f_c': specified compressive strength of concrete for use in design
f_y: specified minimum yield strength of reinforcing bars
I: moment of inertia of cracked concrete section about centroidal axis
I_g: moment of inertia of gross concrete section about centroidal axis

$$k = \sqrt{((\rho n)^2 + 2\rho n)} - \rho n$$

M_{cr}: cracking moment
M_n: nominal flexural strength at section
M_{cr}: yielding moment
n: E_s/E_c
y: distance from centroidal axis of cracked section
y_t: distance from centroidal axis of gross section
ρ: ratio of A_s to $b * d$

The ACI 318-11 Eq. (9) (shown as Eq. (1) here) underestimates on average the cracking moment for both the CC (13%) and RCA beams (5%); however, it overestimates for the RCA-F-6 beams around 5%. Similar results observed when the cracking moments compared to Eurocode 2-05 [28], Eurocode 2-05 provision under predicts the cracking moment around 14% and 7% for the CC and RCA beams, respectively. There was a good agreement (less than 2% on average) between the analytical and experimental results of yielding moments for both the CC and RCA beams. In terms of ultimate moment, the experimental moments for both the CC and RCA beams are 18% and 21% greater than the ACI 318-11 provision and also 22% and 23% greater than the Eurocode 2-05 provision, respectively.

To compare the service deflection, δ_s, this study considered 40% of the ultimate load as the customary level for service load (δ_s was obtained from the load–deflection curve). Both the ACI 318-11 and Eurocode 2-05 provisions overestimated the service load deflection on average 18% and 16% for the CC, but underestimated around 7% and 16% for the RCA beams.

The RCA beams showed higher ultimate deflection compared with the CC beams around 5% for F-6 and 22% for F-7 beams. This phenomena has been reported by previous researchers that can be

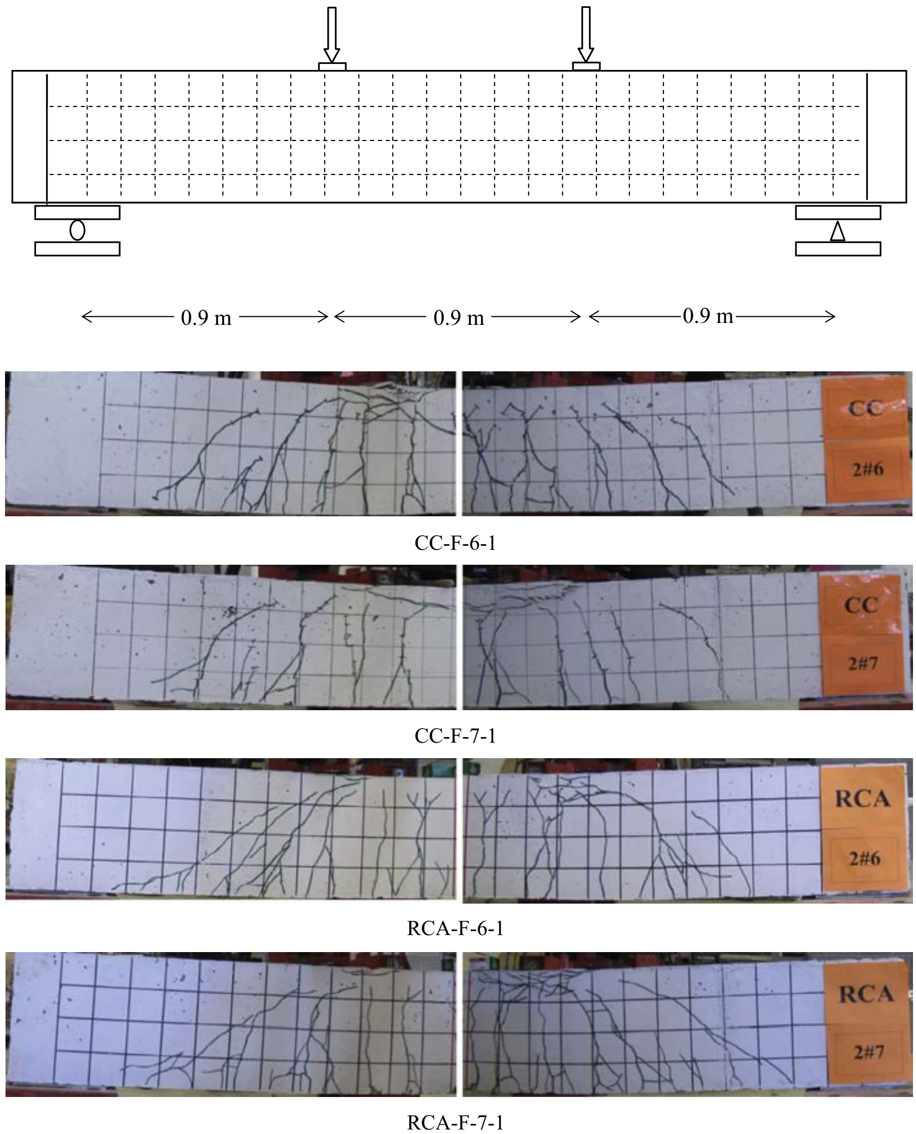


Fig. 4. Crack pattern of the test beams at flexural failure.

attributed to lower modulus of elasticity and also lower effective moment inertia (more cracks) of the RCA beams compared with the CC beams.

In terms of crack spacing, for the CC beams the F-6 and F-7 sections cracks spaced 120 and 155 mm on average, respectively; however, they decreased to 105 and 110 mm for the RCA beams. The crack spacing for both the CC and RCA beams were less than Eurocode 2-05 provision (204 and 206 mm for the F-6 and F-7 sections, respectively).

3.2. Material properties test results and comparison with flexural behavior

The following section compares the mechanical properties for both the CC and RCA mixes studied in this investigation. To compare the mechanical properties of the CC and RCA beams, the test results must be adjusted to reflect the different compressive strengths. The ACI 318-11 provisions use the square root of the compressive strength of concrete to determine the splitting tensile strength (Eq. (4)), flexural strength (Eq. (5)), and modulus of elasticity (Eq. (6)) of beams. In terms of fracture energy, Bazant [33], JSCE-07 [34], and CEB-FIP Model Code 2010 equations [35] (Eq. (7) through Eq. (9)) use 0.46, 0.33, and 0.18 as a power of the compressive strength of concrete, respectively, to calculate the fracture energy of concrete. Therefore, to normalize the data for comparison, the splitting tensile strengths, flexural strengths, and modulus of elasticity were divided by the square root of the compressive strengths of the respective concretes; however, fracture energies were divided by the compressive strengths to the corresponding powers of the Bazant, JSCE-07, and CEB-FIP Model Code 2010 equations.

$$f_{ct} = 6.7\sqrt{f'_c} \tag{4}$$

$$f_r = 7.5\sqrt{f'_c} \tag{5}$$

$$E_c = 4700\sqrt{f'_c} \tag{6}$$

$$G_F = 2.5\alpha_o\left(\frac{fc'}{0.051}\right)^{0.46}\left(1+\frac{d_a}{11.27}\right)^{0.22}\left(\frac{w}{c}\right)^{-0.30} \tag{7}$$

Table 5
Test results summary and comparison with ACI 318 and EC 2 codes.

Section		f'_c (MPa)	M_{cr} (KN m)	M_y (KN m)	M_n (KN m)	δ_y (mm)	δ_u (mm)	δ_u/δ_y
(a) Test results summary								
CC								
F-6	1	37.2	43.4	123.4	154.1	7.1	34.0	4.8
	2	34.2	42.7	121.4	157.3	6.6	33.0	5.0
F-7	1	37.2	46.8	147.8	170.7	8.1	29.5	3.6
	2	34.2	45.4	146.7	164.2	8.1	27.2	3.4
RCA								
F-6	1	30.5	34.6	119.3	149.6	9.1	34.3	3.8
	2	31.3	35.9	125.4	154.9	8.9	35.8	4.0
F-7	1	30.5	42.0	147.4	172.6	7.9	35.6	4.5
	2	31.3	42.7	148.2	169.3	7.9	33.8	4.3

Section		Test/ACI 318			Test/EC 2			Test/MCFT		
		M_{cr}	M_n	δ_s	M_{cr}	M_n	δ_s	M_y	M_n	δ_u
(b) Comparison with ACI 318 and EC 2 codes										
CC										
F-6	1	1.07	1.24	0.76	1.10	1.27	0.75	1.02	1.18	1.50
	2	1.10	1.27	0.66	1.13	1.30	0.68	1.01	1.22	1.45
F-7	1	1.16	1.13	0.94	1.15	1.18	0.98	1.01	1.11	1.65
	2	1.17	1.09	0.90	1.16	1.14	0.96	1.00	1.07	1.52
Ave.		1.13	1.18	0.82	1.14	1.22	0.84	1.01	1.15	1.53
RCA										
F-6	1	0.95	1.00	1.14	0.94	1.25	1.20	1.00	1.16	1.22
	2	0.96	1.03	1.06	0.96	1.29	1.13	1.05	1.20	1.27
F-7	1	1.15	1.41	1.03	1.19	1.21	1.15	1.01	1.13	1.98
	2	1.14	1.38	1.04	1.18	1.18	1.15	1.01	1.11	1.90
Ave.		1.05	1.21	1.07	1.07	1.23	1.16	1.02	1.15	1.59

$$G_F = 10d_{\max}^{0.33}f_{ck}^{0.33} \tag{8}$$

$$G_F = 73f_{cm}^{0.18} \tag{9}$$

Fig. 5 offers a comparison of the splitting tensile strength, flexural strength, modulus of elasticity, and fracture energy for both the CC and RCA mixes tested in this study. The splitting tensile strength, flexural strength, modulus of elasticity, and fracture energy of RCA decreased 15%, 7%, 15%, 23%, 24%, and 25% compared to the CC, respectively. These results showed that even mechanical properties of the RCA mix decreased up to 25%, but the flexural strength slightly increased.

3.3. Comparison of test results with MCFT method

The modified compression field theory (MCFT) is a sectional analysis method that was developed by researchers at the University of Toronto [36]. It calculates the strength and ductility of a reinforced concrete cross-section subjected to shear, moment, and axial load. All three loads are considered simultaneously to find the full load–deformation response.

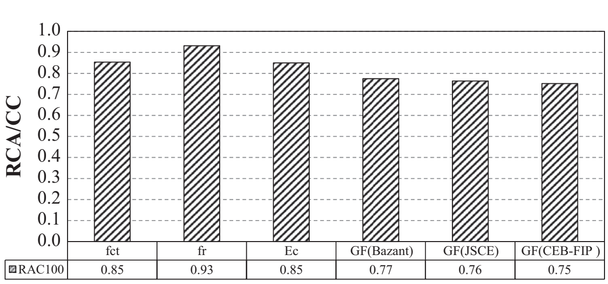


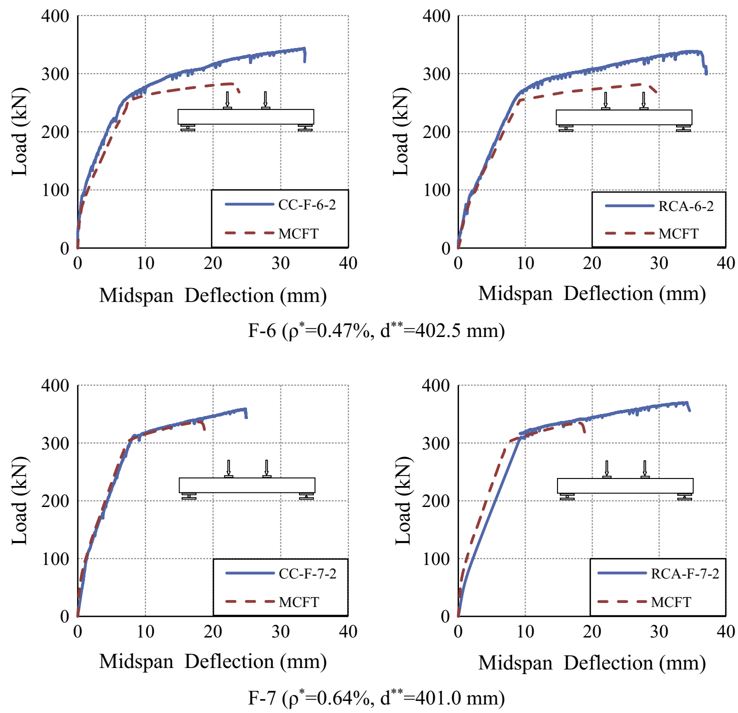
Fig. 5. Comparison of mechanical properties of the CC and RCA beams.

Fig. 6 compares the load–deflection behavior between the experiments with those predicted by the MCFT method using Response 2000 software [37,38]. As shown in the figure, plot based on the MCFT method shows good agreement with the experimental results except for the maximum deflection values, those are lower than the test results for both the CC and RCA beams. Table 5 presents the ratio of moments from experiment to predicted values from the MCFT method for cracking moment. As it can be seen in Table 5, the MCFT method (Response 2000) underestimates the ultimate moment around 15% for both the CC and RCA beams. However, in terms of ultimate deflection, the MCFT method (Response 2000) underestimates around 53% and 59% for the CC and RCA beams, respectively.

3.4. Comparison of test results with a flexural test database and previous research

As discussed previously, based on a review of the existing literature, there is a lack of full-scale flexural testing of RCA specimens. Consequently, in this section, the test results are first compared with studies performed on conventional Portland cement concrete. Following this discussion, the results are then compared with the limited amount of testing completed on RCA specimens.

Fig. 7 presents the normalized flexural strength versus normalized longitudinal reinforcement ratio for the beams of this study as well as the wealth of flexural test data available in the literature for CC [39]. Fig. 7 seems to indicate that the RCA and CC test results fall within the upper bound and central portion of the data. Furthermore, statistical analysis (regression analysis) of the data indicates that the RCA and CC test results fall within a 95% confidence interval of a nonlinear regression curve fit of the database. This result indicates that the test values are very consistent with the wealth of flexural test data available in the literature. Furthermore,



*: Longitudinal reinforcement ratio

**: The distance from the extreme fiber in compression to the centroid of the longitudinal reinforcement on the tension side

Fig. 6. Load–deflection plots of the test beams (Test vs. MCFT).

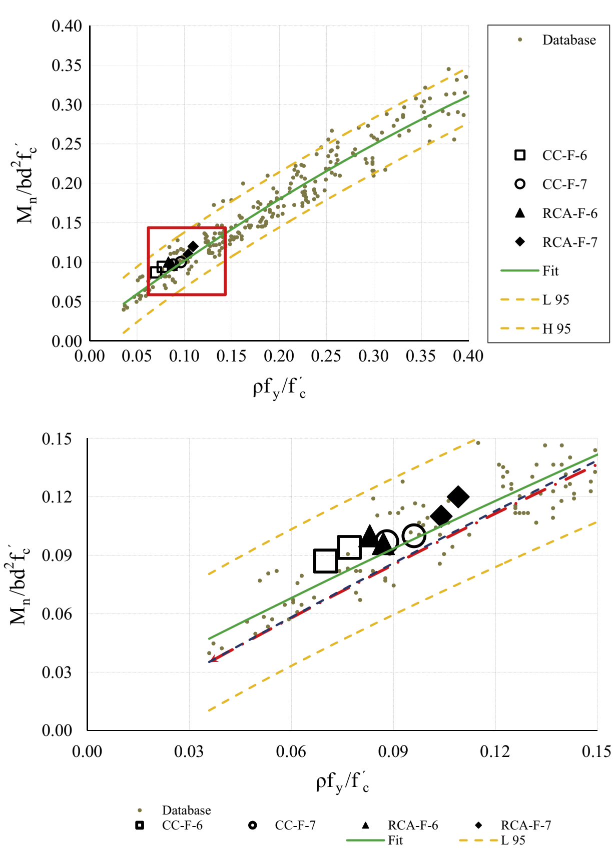


Fig. 7. Normalized flexural strength vs. normalized longitudinal reinforcement ratio; results from [34] and test results of this study.

Fig. 7 shows that both the RCA and CC test results are higher than both the ACI 318-11 and Eurocode 2-05 provisions values.

Fig. 8 compares the test results of this study with the results of different studies with 100% RCA replacement that shows they follow the same trend and all of them are higher than both the ACI 318-11 and Eurocode 2-05 provisions values.

In terms of cracks spacing, results of this study had a good agreement with previous research that shows the RCA beams cracks spaced closer compared with the CC beams. Results of this study also revealed that the RCA beams had higher ultimate deflection compared with the CC beams that has been reported by Ajdukiewicz and Kliszczewicz [10], Sato et al. [11], and Maruyama et al. [12]. Furthermore, the RCA beams of this study showed comparable and even slightly higher ultimate flexural strength compared with the CC beams that are similar to finding of Sato et al. [11], Maruyama et al. [12], Fathifazl et al. [13], and Ignjatovic et al. [15]. Finally, findings of this study confirm that the existing flexural provisions can be used for RCA beams as well.

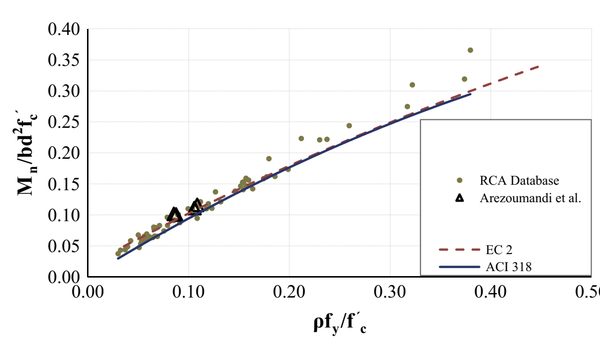


Fig. 8. Normalized flexural strength vs. normalized longitudinal reinforcement ratio; results from the previous RCA tests and test results of this study.

4. Conclusions

The following conclusions are presented with regard to flexural behavior of the CC and RCA mixes:

- In terms of crack morphology and crack progression, the RCA beams cracks spaced closer compared to the CC beams.
- The RCA beams showed lower cracking moment (around 7%) compared to the CC beams, but no significant difference observed between yielding moments of the RCA and CC beams.
- In terms of load deflection behavior, the RCA beams showed lower stiffness after the cracking moments compared with the CC beams as a consequence the RCA beams showed higher ultimate deflection compared with the CC beams.
- The RCA beams showed comparable flexural capacity with the CC beams that means existing design standards conservatively predicted the flexural capacity of the RCA beams.
- The MCFT method (Response 2000) under predicted flexural strength of both the CC and RCA beams around 15%, but it underestimated the deflection of both the CC and RCA beams around 35%.
- Both the CC and RCA mixes test results fall within a 95% confidence interval of a nonlinear regression curve fit of the CC flexural test database.

As a result, the RCA beams showed very promising results in terms of flexural strength and existing codes can be used to design the RCA beams. It means RCA (sustainable and environmentally friendly concrete) can be used instead of CC that uses significant amount of non-renewable resources.

However, due to the limited nature of the data set regarding mix designs, aggregate type and content, aspect ratio of the beams, etc., investigated, the researchers recommend further testing to increase the database of test results for RCA.

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