Mechanical Properties and Structural Performance of Recycled Aggregate Concrete: An Overview

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Abstract

Using Recycled Concrete Aggregate (RCA) in concrete has been the subject of many studies for years. A comprehensive literature review on mechanical properties of Recycled Aggregate Concrete (RAC) including splitting tensile strength, modulus of elasticity, flexural strength, and fracture mechanic is presented. Furthermore, this paper summarizes previous studies on structural behavior (shear, flexural, and bond) of RAC. In addition, databases are created for both mechanical properties and structural performances of RAC in order to lead to changes or acceptance in design codes and standards' provisions. Additionally, mechanical properties and structural strengths of RAC were compared with both the U.S. and European standards. Results of this study show that existing code provisions are not conservative for both mechanical properties and structural strengths of RAC.

Keywords: Mechanical Properties; Structural performance; Recycled Concrete Aggregate

Introduction

Around 25 billion tons of concrete is used each year globally that means over 3.8 tons per person in the world each year [1]. Occupying about 60% to 70% of the volume, aggregate is a main ingredient of concrete. Nowadays, there is an increasing trend toward using sustainable concrete and reusing of aggregates from demolished concrete is one way to achieve this aim. Although using recycled concrete aggregate (RCA) does not lead to significant reduction of CO₂ emission, but it reduces using natural resources (virgin aggregate) as well as helping to reduce dumping construction and demolition wastes in landfills. More than 900 million tons of construction and demolition waste is produced each year only in Europe, the U.S., and Japan [1]. The use of RCA to make a new concrete began in Europe after World War II. Also the building contractors' society of Japan started research on RCA after the 1973 oil crisis [2]. Although comprehensive research has been done on fresh and hardened properties of recycled aggregate concrete (RAC), relatively limited studies have been performed on structural behavior of RAC. This paper compiles around 60 published studies (from 1977 to 2015) that studied mechanical properties (splitting tensile strength, modulus of elasticity, flexural strength, and fracture mechanic) as well as structural performance (shear, flexural, and bond) of RAC. The work presented here summarized only those studies

that used RCA as a coarse aggregate replacement. Given the fact that incorporation of fine RCA is typically reported to result in inferior fresh and hardened properties, the present study summarizes the properties of RCA incorporating coarse RCA [3].

Mechanical Properties

The following section compares splitting tensile strength and flexural strength as well as modulus of elasticity and fracture energy of RAC with the ACI 318, CEB-FIP, Eurocode 2 and JSCE provisions [4,7].

Splitting tensile strength

Table 1(a,c) summarizes the compressive strength (f_c') splitting tensile strength (f_{ct}) and ratio of the experimental-to-code values for splitting tensile strength based on the ACI 318 [5] and Eurocode 2 [7] provisions for previous studies [8-28]. The average values of experimental-to-code ratio are 0.90 and 0.92 for the ACI 318 [5] and Eurocode 2 [7] provisions, respectively. Both provisions are conservative for about 22% of the data points. In other words, the investigated codes overestimate the splitting tensile strength for RAC (Figure 1) based on measured compressive strength values. Furthermore, Regression analysis was conducted to draw the best fit and 95% confidence intervals for the investigated data points. The lower and upper 95%

confidence intervals (L95 and U95) are established. Results of the statistical data analysis reveal the fact that even in the case of the mixtures made with 100% RCA replacement (RAC-100),

test results fall within a 95% confidence interval of a nonlinear regression curve fit of the conventional concrete (CC) database (Figure 1).

Table 1 (a-c): Summary of splitting tensile strength test results.

Author	Year	RCA (%)	f'c	fct	Test/ACI	Test/EC2	Author	Year	RCA	f'c	fct	Test/ACI	Test/EC2
Sagoe et al. [8]	2001	100	27	3.2	1.1	1.18	Ajdukiewicz & Kliszczewicz (9)	2002	100	52.1	3.8	0.94	0.9
			31	3.7	1.19	1.25				24.3	2	0.72	0.77
			29	2.7	0.9	0.95				35.9	2.9	0.86	0.91
Ajdukiewicz & Kliszczewicz [9]	2002	100	18.2	1.9	0.8	0.95				41.8	3.3	0.91	0.92
			29.7	2.9	0.95	1				46	3.6	0.95	0.95
			37.1	3.3	0.97	0.98				49.6	3.8	0.96	0.93
			41.3	3.7	1.03	1.04				53.8	4.1	1	0.98
			44.5	4	1.07	1.05				55.4	4.3	1.03	1.02
			47.1	4.3	1.12	1.1				13	1.4	0.69	0.82
			49.3	4.5	1.14	1.1				31.7	2.3	0.73	0.77
			23.9	2.3	0.84	0.92				42.3	2.9	0.8	0.81
			35.4	2.7	0.81	0.84				48.2	3.6	0.93	0.9
			39.3	3	0.85	0.86				54.4	4	0.97	0.95
			42.3	3.2	0.88	0.89				58.7	4.4	1.03	1
			46.1	3.4	0.89	0.87	Ettxeberria et al. (10)	2007	25	38.8	3.01	0.86	0.89
			49.6	3.6	0.91	0.88				46.3	3.88	1.02	0.99
			53.1	3.8	0.93	0.9			50	39.4	3.36	0.96	0.96
			24.6	2.3	0.83	0.82				44.4	3.65	0.98	0.96
			38.2	3	0.87	0.88			100	38.3	2.79	0.81	0.82
			44.3	3.4	0.91	0.89	Ajdukiewicz & Kliszczewicz (11)	2007	100	38.7	3.28	0.94	0.96
			48.5	3.7	0.95	0.93				34.6	2.6	0.79	0.81
			52.5	4	0.99	0.95				56.4	3.3	0.78	0.79
			55.4	4.2	1.01	1				40.1	2.9	0.82	0.83
			56.1	4.3	1.03	1.02				60.2	4.3	0.99	0.98
			14.2	1.8	0.85	1				85.3	5.3	1.02	1.08
			30.4	2.7	0.87	0.93				35.3	3	0.9	0.94
			36.8	3	0.88	0.91				57.6	3.7	0.87	0.86
			41.3	3.3	0.92	0.92				36.6	2.9	0.86	0.88
			45.2	3.5	0.93	0.92				35.8	3.2	0.96	0.97
			48.8	3.7	0.95	0.93							

Author	Year	RCA (%)	f'c	fct	Test/ACI	Test/EC2	Author	Year	RCA (%)	f'c	fct	Test/ACI	Test/EC2
Sato et al. [12]	2007	100	30.4	2.6	0.84	0.9	Kou et al. [18]	2013	50	34.3	2.21	0.67	0.69
			28.4	2.4	0.8	0.86				48.8	3.12	0.8	0.76
			34.5	2.8	0.85	0.88				55.4	3.64	0.87	0.87
			31.8	3.3	1.04	1.1				35.6	2.26	0.68	0.71
Belén & Fernando [3]	2007	50	39.7	3.4	0.96	0.97			100	49.2	3.07	0.78	0.75
			39.2	3.3	0.94	0.94				54.1	3.52	0.85	0.84
			41.5	3.4	0.94	0.94				21	1.65	0.64	0.75
			40.5	3.4	0.95	0.97				26.7	2.18	0.75	0.81
Yang et al. [13]	2008	30	36.7	4.03	1.19	1.22			25	28.1	2.35	0.79	0.84
			32.6	3.21	1	1.07				32.2	2.98	0.94	0.96
		50	38	3.65	1.06	1.07				38.3	3.24	0.93	0.95
			30.4	2.85	0.92	0.98				41.7	3.83	1.06	1.06
		100	36	3.49	1.04	1.09				20.2	1.97	0.78	0.9
			29.5	2.56	0.84	0.88				27.4	2.31	0.79	0.83
Tabsh & Abdelfatah [14]	2009	100	36	4	1.19	1.25	Abd Elhakam et al. [19]	2012	75	31.1	2.88	0.92	0.96
			25	2.9	1.04	1.12				32.3	2.65	0.83	0.85
			23	2.8	1.04	1.17				38.6	2.94	0.85	0.86
			36	4	1.19	1.25				41.5	3.83	1.06	1.06
			52	4.7	1.16	1.12				20	0.98	0.39	0.45
			50	4.8	1.21	1.17				21.5	1.41	0.54	0.61
			48	4.2	1.08	1.05				22.7	1.78	0.67	0.74
			47	4	1.04	1.03				27.2	1.59	0.54	0.59
Fathifazl et al. [15]	2009	63.5	41.6	3.4	0.94	0.94				34.9	2.53	0.76	0.79
		74.3	49.1	3.7	0.94	0.9				35.4	2.82	0.85	0.88
Choi et al. [16]	2010	30	24.7	2.4	0.86	0.92				20.7	1.47	0.58	0.77
		50	24.2	2.3	0.83	0.88				25.9	2.18	0.76	0.99
		100	22.6	2.3	0.86	0.96				30.1	2.35	0.76	0.81
Butler et al. [17]	2011	100	30.9	2.8	0.9	0.93				27.4	2.18	0.74	0.78
			47.9	3.4	0.88	0.92				35.7	2.88	0.86	0.9
			31.3	2.3	0.73	0.77				37.5	3.59	1.05	1.06
			49.4	3.1	0.79	0.76							

Author	Year	RCA (%)	f'_c	f_{ct}	Test/ACI	Test/EC2	Author	Year	RCA (%)	f'_c	f_{ct}	Test/ACI	Test/EC2
Ignjatovic et al. [20]	2013	50	44.2	2.7	0.73	0.71	Kou & Poon [23]	2013	100	62.7	4.83	1.09	1.1
		100	42.5	3.2	0.88	0.86				52.2	4.41	1.09	1.08
Butler et al. [21]	2013	100	38.6	3.51	1.01	1.03	Arezoumandi et al. [24]	2014	100	30	2.55	0.83	0.88
			38.1	3.11	0.9	0.91				34.1	2.65	0.81	0.83
			39.3	3.3	0.94	0.94	Kang et al. [25]	2014	15	59.4	3.5	0.81	0.8
			60.1	3.84	0.88	0.87			30	48.8	3.4	0.87	0.85
			60.2	3.7	0.85	0.84			15	32.7	3	0.94	0.97
			62.8	3.72	0.84	0.85			30	31.7	2.7	0.86	0.9
									50	29	2.7	0.9	0.93
									30	39.2	3.87	1.1	1.11
									60	30.4	3.9	1.26	1.34
									100	29.1	3.32	1.1	1.14
Kim & Yun [22]	2013	30	33.8	2.5	0.77	0.81	Folino & Xargay [26]	2014	100	36.5	2.5	0.74	0.76
		60	32.4	2.7	0.85	0.87			50	50.6	3.2	0.8	0.78
		100	29.3	2.7	0.89	0.93			100	45.1	4.1	1.09	1.08
		30	31.5	2.7	0.86	0.9							
		60	30.7	2.1	0.68	0.72							
		100	29.5	1.8	0.59	0.62							
Kou & Poon [23]	2013	50	42.5	3.16	0.87	0.85	Butler et al. [27]	2014	100	30.7	2.8	0.9	0.97
			41.3	3.9	1.08	1.08				38.6	3.5	1.01	1.03
			51.2	3.51	0.88	0.86				48.2	3.4	0.87	0.85
			47.1	3.41	0.89	0.85				60.1	3.9	0.9	0.89
			55.6	3.92	0.94	0.93				31.1	2.3	0.74	0.77
			50.6	3.62	0.91	0.88				49.4	3.1	0.79	0.76
			61.4	4.41	1.01	1				39.3	3.3	0.94	0.94
			55.1	4.14	1	0.99				62.8	3.7	0.83	0.84
			65.3	4.71	1.04	1.07							
			57.5	4.32	1.02	1	Steele [28]	2014	50	24.5	2.2	0.79	0.85
		100	38.1	3.06	0.89	0.9			100	33.4	2.2	0.68	0.73
			36.5	2.98	0.88	0.9							
			46.6	3.56	0.93	0.91	Ave.					0.9	0.92
			43.1	3.44	0.94	0.93							
			51.1	4.12	1.03	1							
			46.2	3.78	0.99	0.97							
			56.3	4.45	1.06	1.06

Figure 1: Database for splitting tensile strength of RAC.

Figure 2: Database for flexural strength of RAC.

Table 2 (a): Summary of flexural strength test results.

Author	Year	RCA (%)	f _c '	f _r	Test/ACI	Test/EC	Author	Year	RCA (%)	f _c '	f _r	Test/ACI	Test/EC
Katz [29]	2003	100	24.1	4.7	1.54	1.25	Butler et al. [21]	2013	100	46	5.26	1.25	0.96
			30.5	5.3	1.55	1.26				42.8	5.2	1.28	0.98
			29.1	4.6	1.38	1.11				39.7	5.77	1.48	1.14
Yang et al. [13]	2008	30	36.7	4.21	1.12	0.88				39.7	4.62	1.18	0.91
			32.6	3.59	1.01	0.8				40.3	5.16	1.31	1.02
		50	38	4.01	1.05	0.81				41.2	5.18	1.3	1.01
			30.4	3.4	0.99	0.81				54.7	5.8	1.26	0.95
		100	36	3.84	1.03	0.82				56.8	4.95	1.06	0.8
			29.5	3.2	0.95	0.76				56.8	5.11	1.09	0.83
		Schubert et al. [30]	2012	100	34.7	4.9				1.34	1.06	56.4	4.43
38.4	5.5				1.43	1.12				59	4.36	0.92	0.68
34.1	4.5				1.24	0.97				20	88.5	7.4	1.27
50	31.7			5.2	1.49	1.2				50	94.8	7.7	1.28
	30.7			5.3	1.54	1.26	100	93.4	6.8	1.13	0.92		
	30.6			4.7	1.37	1.12	20	102.1	8	1.28	1		
	31			4.6	1.33	1.08	50	98.8	6.8	1.1	0.9		
100	25.1			4.3	1.38	1.14	100	100.1	6.3	1.02	0.82		
	24.9			4.2	1.36	1.12	20	91.7	6.7	1.13	0.93		
	26.2			4.2	1.32	1.09	50	84.4	6.8	1.19	0.96		
26.8	4.1	1.28	1.07	100	79.9	6.5	1.17	0.94					

Table 2 (b): Summary of flexural strength test results.

Author	Year	RCA (%)	f'_c	f_r	Test/ACI	Test/EC	Author	Year	RCA (%)	f'_c	f_r	Test/ACI	Test/EC
Arezoumandi et al. [24]	2014	100	30	2.81	0.82	0.68	Knaack & Kurama [32]	2014	50	40	3.5	0.89	0.69
			34.1	2.76	0.77	0.62			50	39.3	4.1	1.05	0.81
Butler et al. [27]	2014	100	30.7	4.6	1.34	1.1			100	43.8	3.4	0.83	0.62
			38.6	5.2	1.35	1.04			100	38.5	2.8	0.73	0.57
			48.2	4.5	1.05	0.78			50	43.6	4.4	1.07	0.81
			60.1	5.8	1.21	0.91			50	40.2	4.3	1.09	0.85
			31.1	4.5	1.3	1.07			100	41.4	3.9	0.98	0.76

			49.4	4.7	1.08	0.79			100	35.7	3.5	0.94	0.76
			39.3	5.2	1.34	1.03			50	36.7	3.4	0.91	0.71
			62.8	4.4	0.9	0.68			50	37.6	4	1.05	0.82
									100	42	3.4	0.85	0.64
									100	37.5	2.8	0.74	0.58
									50	41.8	4.3	1.07	0.83
									50	37.4	4.2	1.11	0.87
									100	39.1	3.8	0.98	0.75
									100	39.2	3.7	0.95	0.73
								Ave.				1.15	0.91

Flexural strength

Figure 2 presents the flexural strength database of RAC mixtures compared to the provisions of both ACI 318 [5] and Eurocode 2 [6]. Based on the observed trends, it may be concluded that both provisions over predict flexural strength of RAC. However, the ACI 318 [4] is unconservative for 24% of the data points compared to overestimations observed for about 65% of the data points in the case of the EC 2 [6]. Table 2 (a,b) summarizes the compressive strength, f_c , flexural strength, f_r , and the experimental-to-code ratios for flexural strength based on the ACI 318 [4] and EC 2 [6] provisions for previous studies from 2003 to 2014. The average values of the experimental-to-code ratios are 1.15 for the ACI 318 [4] and 0.92 for the EC 2 [6] provision. This reveals the fact that the ACI 318 underestimates the flexural strength of RAC by 15%, proposing ACI 318 as a reliable source for predicting the flexural strength of the RCA. Contrary to the ACI 318, the EC2 seems to overestimate the average flexural strength by about 8%. In addition, regression

analysis of the CC data indicates that part of the RAC-100 test results don't fall within a 95% confidence interval of a nonlinear regression curve fit of the CC database. This result indicates that the RAC-100 flexural strength is lower than the CC for mixes with compressive strength around 35MPa and higher.

Modulus of elasticity

Figure 3: Database for modulus of elasticity of RAC.

Table 3 (a): Summary of modulus of elasticity test results.

Author	Year	RCA (%)	f'_c	E_c	Test/ACI	Test/EC	Author	Year	RCA (%)	f'_c	E_c	Test/ACI	Test/EC
Katz [29]	2003	100	24.1	11.4	0.49	0.4	Fathifazl et al. [15]	2009	63.5	24.1	11.4	0.98	0.88
			30.5	13.7	0.53	0.45							
			29.1	11.5	0.45	0.38	Berndt [34]	2009	100	29.1	11.5	1.38	1.22
Ajdukiewicz & Kliszczewicz [11]	2007	100	34.6	25.9	0.94	0.81	Debieb et al. [35]	2010	100	34.6	25.9	0.85	0.68
			56.4	31.8	0.9	0.86	Bai & Sun [36]	2010	50	56.4	31.8	0.91	0.82
			40.1	24.3	0.82	0.73			70	40.1	24.3	0.87	0.79
			60.2	28.5	0.78	0.76			100	60.2	28.5	0.87	0.79
			85.3	35.3	0.81	0.84	Choi et al. [16]	2010	30	85.3	35.3	1.18	0.96
			35.3	31.7	1.14	0.99			50	35.3	31.7	1.1	0.89
			57.6	35.9	1.01	0.97			100	57.6	35.9	1.01	0.8
			105.3	43.5	0.9	0.98	Zega & Di Maio [37]	2010	25	105.3	43.5	1.17	0.9
			36.6	28.1	0.99	0.87				36.6	28.1	1.19	1.02
			35.8	33.4	1.19	1.04			50	35.8	33.4	1.15	0.88

Etzeberria et al. [10]	2007	100	38.3	28.64	0.98	0.87				38.3	28.6	1.13	0.98
Yang et al. [13]	2008	100	36	29.22	1.04	0.9			75	36	29.2	1.12	0.83
			29.5	23.72	0.93	0.78				29.5	23.7	1.09	0.94
Casuccio et al. [33]	2008	100	18	23.4	1.17	0.89	Butler et al. [21]	2013	100	18	23.4	0.93	0.86
			15.4	22.6	1.23	0.9				15.4	22.6	0.93	0.83
			36.4	28.8	1.02	0.89				36.4	28.8	0.88	0.8
			35.7	28.3	1.01	0.88				35.7	28.3	0.82	0.8
			44.4	34.3	1.1	1				44.4	34.3	0.77	0.76
			43.8	32.7	1.05	0.95				43.8	32.7	0.76	0.74

Table 3 (b): Summary of modulus of elasticity test results.

Author	Year	RCA (%)	f'c	Ec	Test/ACI	Test/EC	Author	Year	RCA (%)	f'c	Ec	Test/ACI	Test/EC
Kou et al. [38]	2011	100	38.1	22.5	0.78	0.68	Knaack & Kurama [32]	2014	50	40	28.8	0.97	0.86
			36.5	21.6	0.76	0.67			50	39.3	28.3	0.96	0.85
			46.6	24.1	0.75	0.69			100	43.8	23.3	0.75	0.68
			43.1	22.8	0.74	0.67			100	38.5	21.6	0.74	0.66
			51.1	25.4	0.76	0.71			50	43.6	29.4	0.95	0.86
			46.2	24.9	0.78	0.72			50	40.2	31	1.04	0.93
			56.3	27.8	0.79	0.75			100	41.4	23.3	0.77	0.69
			50.8	26.3	0.79	0.73			100	35.7	22.3	0.79	0.69
			62.7	29.5	0.79	0.77			50	36.7	26	0.91	0.8
			52.2	27.4	0.81	0.76			50	37.6	24.6	0.85	0.75
Ignjatovic et al. [20]	2013	50	44.2	26.2	0.84	0.76			100	42	21.9	0.72	0.65
		100											
		100	42.5	25.4	0.83	0.75			100	37.5	22.5	0.78	0.69
Folino & Xargay [26]	2014	100	29.1	20.75	0.82	0.68			50	41.8	27.6	0.91	0.82
Cui et al. [39]	2014	100	49	22	0.67	0.62			50	37.4	25.2	0.88	0.77
			56	27.8	0.79	0.75			100	39.1	20.9	0.71	0.63
			54	25.9	0.75	0.71			100	39.2	22.7	0.77	0.68
Kang et al. [25]	2014	15	59.4	36.2	1	0.96	Steele [28]	2014	50	24.5	25.9	1.11	0.9
		30	48.8	32.8	1	0.93			100	33.4	27.6	1.02	0.87
		15	32.7	29.2	1.09	0.93							
		30	31.7	26.5	1	0.85							
		50	29	25.3	1	0.84	Ave.					0.91	0.81

Table 3 (a,b) presents the test results for modulus of elasticity from literature on RAC with replacement level from 25% to 100%. Comparison of test results with the ACI 318 [4] and EC 2 [6] provisions showed only 34% and 5% of results is higher than the codes predictions, respectively (Figure 3). Almost all the previous studies reported lower modulus of elasticity for RAC compared to CC and it may be attributed to the lower stiffness and rigidity of the RCA particles which in turn decrease the rigidity and modulus of elasticity of the RAC [8].

Fracture energy

Limited literature is available in the case of the fracture energy of RAC. Results presented in [21,24,27,33] suggest decrease in fracture energy as a function of increases in RCA replacement ratio. Table 4 shows that the CEB-FIP [5] code provision is conservative only for 7% of the investigated data points The Japan's code [7] underestimates the fracture energy

for 17% of the experimental results (Table 4). Likewise splitting tensile strength, statistical analysis of the data shows that the RAC-100 test results fall within a 95% confidence interval of a nonlinear regression curve fit of the CC database. That means the RAC-100 fracture energy is similar to the CC (Figure 4).

Figure 4: Comparison of database for flexural strength of RAC and CC [51].

Table 4: Summary of fracture energy test results.

Author	Year	RCA (%)	f'_c	GF	Test/CEB-FIP	Test/JSCE	Author	Year	RCA (%)	f'_c	E_c	Test/CEB-FIP	Test/JSCE
Casuccio et al. [33]	2008	100	18	90	0.73	1.13	Butler et al. [27]	2014	100	30.7	112	0.83	1.37
			15.4	99	0.83	1.31				38.6	114.7	0.81	1.3
			36.4	147	1.05	1.46				48.2	73.8	0.5	0.78
			35.7	107	0.77	1.07				60.1	111.1	0.73	1.09
			44.4	113	0.78	1.05				31.1	102	0.75	1.24
			43.8	106	0.74	0.99				49.4	113.8	0.77	1.19
Butler et al. [21]	2013	100	46	106.3	0.73	1.14	Arezoumandi et al. [24]	2014	30	44.5	148.9	1.03	1.47
			42.8	123.1	0.86	1.35				45.5	143.5	0.99	1.41
			39.7	126.7	0.89	1.42				35.2	123	0.89	1.31
			39.7	104.2	0.74	1.17				34.1	105.9	0.77	1.14
			40.3	119.1	0.84	1.33							
			41.2	84.2	0.59	0.93							
			54.7	111.1	0.74	1.12							
			56.8	103.8	0.69	1.04							
			56.8	82.3	0.54	0.82							
			56.4	120.7	0.8	1.21							
Ave.			59	86.7	0.57	0.85						0.77	1.17

Structural Performance

The following sections compare structural test results of RAC including bond, flexural, and shear strength with both codes provisions and CC databases.

Bond Strength

Three most common methods to measure bond strength between reinforcing steel and concrete are pull-out, beam-end, and splice specimens. Although pull-out test method is the most commonly used due to the ease of sample fabrication, but this method has the least realistic bond strength measurements. The reason is the bar at pull-out specimen is loaded in tension

and the surrounding concrete is in compression, but in most practical applications, both the bar and surrounding concrete experience tensile stresses. For beam-end and splice specimens test methods, both the bar and surrounding concrete are in tension and provide a more realistic response [40]. The following section discusses the results of each test method separately.

Pull-out

Table 5(a-e) summarizes the results of pull-out tests from previous studies including RCA replacement level, compressive strength, f'_c and maximum aggregate size (d_{max}), rebar size, yielding strength of reinforcing steel (f_y), average bond stress, τ ,

and normalized bond strength, $\tau/\sqrt{f'_c}$ and $\tau/4\sqrt{f'_c}$. The bond strength provision is a function of the inverse square root of the compressive strength of concrete for most of design standards

[4,7,14-16], but the ACI 408 [13] recommends the fourth root of the compressive strength of concrete instead of the square root. For this reason, Table 5(a-e) presents normalized bond strength of previous studies for both methods.

Table 5 (a): Summary of pull-out test results.

Author	Year	Specimen	RCA (%)	d_{max} (mm)	Rebar Size (mm)	f_y	f'_c (MPa)	τ (MPa)	$\tau/\sqrt{f'_c}$	$\tau/4\sqrt{f'_c}$
Ajdukiewicz & Kliszczewicz [9]	2002	R 5.1	0	16	14	410	48.4	29.1	4.2	11
		R 8.1	0	16	14	410	48.9	29.1	4.2	11
		R 9.1	0	16	14	410	48.9	29.1	4.2	11
		R 11.1	0	16	14	410	52.3	26	3.6	9.7
		Ave.							4	10.7
		R 5.2	100	16	14	410	44.5	27.3	4.1	10.6
		R 8.2	100	16	14	410	45.2	26.8	4	10.3
		R 9.2	100	16	14	410	49.6	26.4	3.7	9.9
		R 11.2	100	16	14	410	54.4	24.4	3.3	9
		Ave.							3.8	10
Xiao & Falkner [43]	2007	RAC-II-0	0	13	10	420	43.5	17.4	2.6	6.8
		RAC-II-50	50	13	10	420	39.3	17.2	2.8	6.9
		RAC-II-100	100	13	10	420	34.6	17.4	3	7.2
Brecolotti & Materazzi [44]	2013	C0-0-1	0	24	14	NR*	55.8	25.2	3.4	9.2
		C25-50-1	50	24	14	NR*	47.2	20.1	2.9	7.7
		C25-100-1	100	24	14	NR*	36.5	22.7	3.8	9.2
		C0-0-2	0	24	14	NR*	53.1	25.5	3.5	9.4
		C25-50-2	50	24	14	NR*	50.6	25.9	3.6	9.7
		C25-100-2	100	24	14	NR*	45.1	24	3.6	9.3
Kim & Yun [22]	2013	RCA-10V-28	0	20	16	383	37	27.6	4.5	11.2
		RCA-130V-28	30	20	16	383	33.8	26.5	4.6	11
		RCA-160V-28	60	20	16	383	32.4	28.3	5	11.9
		RCA-1100V-28	100	20	16	383	29.2	26.9	5	11.6
		RCA-10V-365	0	20	16	383	50.6	29.9	4.2	11.2

Table 5 (b): Summary of pull-out test results.

Author	Year	Specimen	RCA (%)	d_{max}	Rebar Size	f_y	f'_c	τ	$\tau/\sqrt{f'_c}$	$\tau/4\sqrt{f'_c}$
Kim & Yun [22]	2013	RCA-130V-365	30	20	16	383	46.9	30	4.4	11.5
		RCA-160V-365	60	20	16	383	47.2	30.6	4.5	11.7
		RCA-1100V-365	100	20	16	383	42.7	29.9	4.6	11.7
		RCA-10V-730	0	20	16	383	47.7	23.6	3.4	9
		RCA-130V-730	30	20	16	383	43.1	23.1	3.5	9
		RCA-160V-730	60	20	16	383	45.8	23.9	3.5	9.2

		RCA-I100V-730	100	20	16	383	37	21.7	3.6	8.8
		RCA-I0V	0	20	16	383	27.6	21.8	4.2	9.5
		RCA-I30V	30	20	16	383	26.5	22.8	4.4	10.1
		RCA-I60V	60	20	16	383	28.3	23.8	4.5	10.3
		RCA-I100V	100	20	16	383	26.9	24.8	4.8	10.9
		RCA-II0V	0	25	16	383	25.3	25.8	5.1	11.5
		RCA-II30V	30	25	16	383	21.9	26.8	5.7	12.4
		RCA-II60V	60	25	16	383	21.6	27.8	6	12.9
		RCA-II100V	100	25	16	383	20.8	28.8	6.3	13.5
		RCA-I0HB-28	0	20	16	383	37	16.8	2.8	6.8
		RCA-I0HT-28	0	20	16	383	37	11.6	1.9	4.7
		RCA-I30HB-28	30	20	16	383	33.8	22.6	3.9	9.4
		RCA-I30HT-28	30	20	16	383	33.8	13	2.2	5.4
		RCA-I60HB-28	60	20	16	383	32.4	24.4	4.3	10.2
		RCA-I60HT-28	60	20	16	383	32.4	13.8	2.4	5.8
		RCA-I100HB-28	100	20	16	383	29.2	24.7	4.6	10.6
		RCA-I100HT-28	100	20	16	383	29.2	6.8	1.3	2.9
		RCA-I0HB-365	0	20	16	383	50.6	20.3	2.9	7.6
		RCA-I0HT-365	0	20	16	383	50.6	12.2	1.7	4.6
		RCA-I30HB-365	30	20	16	383	46.9	26.4	3.9	10.1
		RCA-I30HT-365	30	20	16	383	46.9	19.8	2.9	7.6

Table 5 (c): Summary of pull-out test results.

Author	Year	Specimen	RCA (%)	d _{max}	Rebar Size	f _y	f _c	τ	τ/√f _c	τ/4√f _c
Kim & Yun [22]	2013	RCA-I60HB-365	60	20	16	383	47.2	24.2	3.5	9.2
		RCA-I60HT-365	60	20	16	383	47.2	18.6	2.7	7.1
		RCA-I100HB-365	100	20	16	383	42.7	20.8	3.2	8.1
		RCA-I100HT-365	100	20	16	383	42.7	12	1.8	4.7
		RCA-I0HB-730	0	20	16	383	47.7	14.2	2.1	5.4
		RCA-I0HT-730	0	20	16	383	47.7	13	1.9	4.9
		RCA-I30HB-730	30	20	16	383	43.1	15.8	2.4	6.2
		RCA-I30HT-730	30	20	16	383	43.1	13	2	5.1
		RCA-I60HB-730	60	20	16	383	45.8	21.9	3.2	8.4
		RCA-I60HT-730	60	20	16	383	45.8	13.3	2	5.1
		RCA-I100HB-730	100	20	16	383	37	22.1	3.6	9
		RCA-I100HT-730	100	20	16	383	37	8.4	1.4	3.4
		RCA-II0HB	0	25	16	383	33.4	21.5	3.7	8.9

		RCA-I0HT	0	25	16	383	33.4	13	2.2	5.4
		RCA-II30HB	30	25	16	383	31.5	17.2	3.1	7.3
		RCA-II30HT	30	25	16	383	31.5	11.2	2	4.7
		RCA-II60HB	60	25	16	383	30.7	19.8	3.6	8.4
		RCA-II60HT	60	25	16	383	30.7	9.8	1.8	4.2
		RCA-II100HB	100	25	16	383	29.5	17.4	3.2	7.5
		RCA-II100HT	100	25	16	383	29.5	9.1	1.7	3.9
Steele [29]	2014	VAC-PO4-1	0	19	13	510	27.6	18.1	3.4	7.9
		VAC-PO4-2	0	19	13	510	27.6	18.3	3.5	8
		VAC-PO4-3	0	19	13	510	27.6	20	3.8	8.7
		Ave.							3.6	8.2
		VAC-PO6-1	0	19	19	516	27.6	21.2	4	9.2
		VAC-PO6-2	0	19	19	516	27.6	20.2	3.8	8.8
		VAC-PO6-3	0	19	19	516	27.6	19.9	3.8	8.7

Table 5 (d): Summary of pull-out test results.

Author	Year	Specimen	RCA (%)	d_{max}	Rebar Size	f_y	f_c	τ	$\tau/\sqrt{f_c}$	$\tau/\sqrt[4]{f_c}$
Steele [29]	2014	Ave.							3.9	8.9
		RAC50-PO4-1	50	19	13	510	37.6	22.4	3.7	9
		RAC50-PO4-2	50	19	13	510	37.6	23	3.8	9.3
		RAC50-PO4-3	50	19	13	510	37.6	20.4	3.3	8.2
		Ave.							3.6	8.9
		RAC50-PO6-1	50	19	19	516	37.6	24.3	4	9.8
		RAC50-PO6-2	50	19	19	516	37.6	22.2	3.6	9
		RAC50-PO6-3	50	19	19	516	37.6	24.5	4	9.9
		Ave.							3.9	9.6
		RAC100-PO4-1	100	19	13	510	35.5	24.5	4.1	10
		RAC100-PO4-2	100	19	13	510	35.5	21.5	3.6	8.8
		RAC100-PO4-3	100	19	13	510	35.5	21.8	3.7	8.9
		Ave.							3.8	9.3
		RAC100-PO6-1	100	19	19	516	35.5	23.6	4	9.7
		RAC100-PO6-2	100	19	19	516	35.5	23.1	3.9	9.5
		RAC100-PO6-3	100	19	19	516	35.5	23.2	3.9	9.5
		Ave.							3.9	9.5
Prince & Singh [46]	2014	A8R0-1	0	13	8	500	36.9	25.1	4.1	10.2
		A8R0-2	0	13	8	500	36.9	22.7	3.7	9.2
		A8R0-3	0	13	8	500	36.9	22.2	3.7	9
		Ave.							3.8	9.5
		A8R25-1	25	13	8	500	28.9	15.2	2.8	6.6
		A8R25-2	25	13	8	500	28.9	13.7	2.5	5.9
		A8R25-3	25	13	8	500	28.9	13	2.4	5.6
		Ave.							2.6	6
		A8R50-1	50	13	8	500	24	20.9	4.3	9.4
		A8R50-2	50	13	8	500	24	20	4.1	9
		A8R50-3	50	13	8	500	24	22.6	4.6	10.2

Table 5 (e): Summary of pull-out test results.

Author	Year	Specimen	RCA (%)	d_{max}	Rebar Size	f_y	f_c	τ	$\tau/\sqrt{f_c}$	$\tau/4\sqrt{f_c}$
Prince & Singh [46]	2014	Ave.							4.3	9.6
		A8R75-1	75	13	8	500	26.2	16.7	3.3	7.4
		A8R75-3	75	13	8	500	26.2	16.6	3.2	7.3
		Ave.							3.3	7.5
		A8R100-1	100	13	8	500	24.7	21.7	4.4	9.7
		A8R100-2	100	13	8	500	24.7	24	4.8	10.8
		A8R100-3	100	13	8	500	24.7	22.5	4.5	10.1
		Ave.							4.6	10.2
		A10R0-1	0	13	10	500	36.9	18.1	3	7.3
		A10R0-2	0	13	10	500	36.9	17.6	2.9	7.1
		A10R0-3	0	13	10	500	36.9	18.3	3	7.4
		Ave.							3	7.3
		A10R25-1	25	13	10	500	28.9	18.5	3.4	8
		A10R25-2	25	13	10	500	28.9	20	3.7	8.6
		A10R25-3	25	13	10	500	28.9	19.3	3.6	8.3
		Ave.							3.6	8.3
		A10R50-1	50	13	10	500	24	15.6	3.2	7
		A10R50-2	50	13	10	500	24	18.6	3.8	8.4
		A10R50-3	50	13	10	500	24	17.7	3.6	8
		Ave.							3.5	7.8
		A10R75-1	75	13	10	500	26.2	15.7	3.1	6.9
		A10R75-2	75	13	10	500	26.2	18.4	3.6	8.1
		A10R75-3	75	13	10	500	26.2	18.7	3.7	8.3
		Ave.							3.4	7.8
		A10R100-1	100	13	10	500	24.7	18.4	3.7	8.3
		A10R100-2	100	13	10	500	24.7	19.2	3.9	8.6
		A10R100-3	100	13	10	500	24.7	17.3	3.5	7.8
		Ave.							3.7	8.2
		A8R75-3	75	13	8	500	26.2	16.6	3.2	7.3
		Ave.							3.3	7.5

Mukai & Kikuchi [41] used both 15% and 30 % RCA replacement in their specimens and reported no reduction in bond between reinforcing steel and RAC. Ajdukiewicz & Kliszczewicz [11] replaced 100% RCA from seven years old structures for pull-out specimens based on RILEM 7-II-128 [42]. Their results showed that the RAC specimens possess 7% lower bond strength compared to the Xiao & Falkner [43] tested 36 pull-out specimens with 0, 50%, and 100% RCA replacement and reported similar load-slip curve for RAC specimens. However, 4% and 12% increase on bond strength of RAC was reported for the 50% and 100% replacements, respectively compared to the Breccolotti & Materazzi [44] used pull-out specimens with 0,

50%, and 100% RCA replacement and observed no significant difference between bond strength of the RAC and CC specimens.

Kim & Yun [22] used RCA with the replacement ratios of 30%, 60%, and 100% to make 144 direct pull-out tests. Authors reported that the RAC specimens with the smaller aggregate size had a greater bond strength compared to the specimen with the larger aggregate size, while the CC specimen showed similar bond strength for both aggregate sizes. Furthermore, authors reported that the current ACI 318 [5] and CSA [45] codes provisions can be applied to RAC specimens. Steele [28] results showed that replacing both 50% and 100% RCA slightly improved the bond strength of reinforcing steel and RAC compared to the CC

specimens. Prince and Singh [46] tested 30 pull-out specimens with 0, 25%, 50%, 75%, and 100 % RCA replacement ratios and reported identical load-slip relationships for the RAC and CC

specimens. However, the bond strengths for 10mm diameter deformed bars in the RAC were higher than the CC specimens.

Splice Beam

Table 6: presents dimensions and mechanical properties of materials used to test splice beams.

Author	Year	Specimen	RCA (%)	Rebar Size	f_c	f_y	f_s	$f_s/\sqrt{f_c}$	$f_s/4\sqrt{f_c}$
Steele [29]	2014	VAC-1	0	19	27.6	516	434.4	82.7	189.5
		VAC-2	0	19	27.6	516	488.2	92.9	213
		VAC-3	0	19	27.6	516	424.7	80.8	185.3
		Ave.						85.5	195.9
		RAC50-1	50	19	24.5	516	389.6	78.7	175.1
		RAC50-2	50	19	24.5	516	380.6	76.9	171.1
		RAC50-3	50	19	24.5	516	377.8	76.3	169.8
		Ave.						77.3	172
		RAC100-1	100	19	33.4	516	326.1	56.4	135.6
		RAC100-2	100	19	33.4	516	344.1	59.5	143.1
		RAC100-3	100	19	33.4	516	379.9	65.7	158
		Ave.						60.6	145.6
Author	Year	Specimen	RCA (%)	Rebar Size	f_c	f_y	f_s	$f_s/\sqrt{f_c}$	$f_s/4\sqrt{f_c}$
Steele [29]	2014	VAC-1	0	19	27.6	516	434.4	82.7	189.5
		VAC-2	0	19	27.6	516	488.2	92.9	213
		VAC-3	0	19	27.6	516	424.7	80.8	185.3
		Ave.						85.5	195.9
		RAC50-1	50	19	24.5	516	389.6	78.7	175.1
		RAC50-2	50	19	24.5	516	380.6	76.9	171.1
		RAC50-3	50	19	24.5	516	377.8	76.3	169.8
		Ave.						77.3	172
		RAC100-1	100	19	33.4	516	326.1	56.4	135.6
		RAC100-2	100	19	33.4	516	344.1	59.5	143.1
		RAC100-3	100	19	33.4	516	379.9	65.7	158
		Ave.						60.6	145.6

Table 6 presents dimensions and mechanical properties of materials used to test splice beams. The only difference is that Table 6 includes reinforcing steel stress at failure, f_s , instead of average bond stress based on ACI 408 [40] recommendation. Steele [28] tested full scale beams with cross section of 300×460mm for both 50% and 100% RCA replacement levels and reported that the bond strength decreased around 10% for 50% and 20% for 100% RCA replacement.

End beam

Fathifazl et al. [47] used both conventional method (replaced 100% RCA) as well as the equivalent mortar volume (EMV)

method for proportioning RAC. They reported 24% lower bond strength for the conventional method, while the EMV method bond strength was comparable (only 6% reduction) with the CC specimens. Butler et al. [17] tested 48 beam-end specimens with 100% RCA replacement from different resources, including regional sidewalk, curb, and gutter infrastructure, apron and terminal structures from Pearson International Airport in Toronto, Canada, and a concrete ready-mix plant. Their results showed 3% to 20% reduction in bond strength between reinforcing steel and the RAC compared to the CC beams. A summary of details for end beam tests can be found in Table 7 (a,b).

Table 7(a): Summary of end beam test results.

Author	Year	Specimen	RCA (%)	d_{max}	Rebar Size	f_y	f_c	τ_b	$\tau/\sqrt{f_c}$	$\tau/4\sqrt{f_c}$
Fathifazl [47]	2008	CM-30	100	19	30	449	48.5	6.01	0.9	2.3
		CL-30	0	19	30	449	38	6.95	1.1	2.8
		CM-15	100	19	15	407	48.5	8.1	1.2	3.1
		CV-30	100	19	30	449	49	6.29	0.9	2.4
		EV-30	74.3	19	30	449	43.5	7.36	1.1	2.9
		CG-30	0	19	30	449	35.9	7.13	1.2	2.9
Butler et al. [27]	2014	BE-NAC-30-125A	0	19	25	467	34.5	6.66	1.1	2.7
		BE-NAC-30-125B	0	19	25	467	34.5	7.55	1.3	3.1
		BE-NAC-40-125A	0	19	25	467	40.5	6.21	1	2.5
		BE-NAC-40-125B	0	19	25	467	39.4	6.92	1.1	2.8
		BE-NAC-50-125A	0	19	25	467	49	6.81	1	2.6
		BE-NAC-50-125B	0	19	25	467	49	6.91	1	2.6
		BE-NAC-60-125A	0	19	25	467	53.8	6.84	0.9	2.5
		BE-NAC-60-125B	0	19	25	467	53.8	7.27	1	2.7
		BE-RAC1-30-125A	100	19	25	467	30.9	5.72	1	2.4
		BE-RAC1-30-125B	100	19	25	467	30.9	5.78	1	2.4
		BE-RAC1-40-125A	100	19	25	467	43.7	6.17	0.9	2.4
		BE-RAC1-40-125B	100	19	25	467	42.6	7.01	1.1	2.7
		BE-RAC1-50-125A	100	19	25	467	47.9	6.25	0.9	2.4
		BE-RAC1-50-125B	100	19	25	467	47.9	5.89	0.9	2.2
		BE-RAC1-60-125A	100	19	25	467	53.8	6.4	0.9	2.4
		BE-RAC1-60-125B	100	19	25	467	49.9	6.96	1	2.6
		BE-RAC2-30-125A	100	19	25	467	31.3	5.15	0.9	2.2

		BE-RAC2-30-125B	100	19	25	467	31.3	6.02	1.1	2.5
		BE-RAC2-50-125A	100	19	25	467	49.4	5.88	0.8	2.2

Table 7 (b): Summary of end beam test results.

Author	Year	Specimen	RCA (%)	d_{max}	Rebar Size	f_y	f_c	τ_b	$\tau/\sqrt{f_c}$	$\tau/4\sqrt{f_c}$
Butler et al. [27]	2014	BE-RAC2-50-125B	100	19	25	467	49.4	6.03	0.9	2.3
		BE-RAC3-40-125A	100	19	25	467	41.4	6.5	1	2.6
		BE-RAC3-40-125B	100	19	25	467	41.5	5.62	0.9	2.2
		BE-RAC3-60-125A	100	19	25	467	56.2	6.71	0.9	2.5
		BE-RAC3-60-125B	100	19	25	467	57	6.51	0.9	2.4
		BE-NAC-30-375A	0	19	25	467	30	5.77	1.1	2.5
		BE-NAC-30-375B	0	19	25	467	30	5.79	1.1	2.5
		BE-NAC-50-375A	0	19	25	467	29	6.09	1.1	2.6
		BE-NAC-50-375B	0	19	25	467	29	5.8	1.1	2.5
		BE-RAC1-30-375A	100	19	25	467	30	5.12	0.9	2.2
		BE-RAC1-30-375B	100	19	25	467	30	5.13	0.9	2.2
		BE-RAC1-50-375A	100	19	25	467	31	5.5	1	2.3
		BE-RAC1-40-375B	100	19	25	467	31	5.18	0.9	2.2
		BE-RAC2-30-375A	100	19	25	467	33	5.05	0.9	2.1
		BE-RAC2-30-375B	100	19	25	467	33	5.11	0.9	2.1
		BE-RAC2-50-375A	100	19	25	467	33	5.59	1	2.3
		BE-RAC2-40-375B	100	19	25	467	33	5.21	0.9	2.2
		BE-NAC-40-450A	0	19	25	467	29	5.81	1.1	2.5
		BE-NAC-40-450B	0	19	25	467	29	5.11	0.9	2.2
		BE-NAC-60-450A	0	19	25	467	29	5.64	1	2.4
		BE-NAC-60-450B	0	19	25	467	30	5.86	1.1	2.5
		BE-RAC1-40-450A	100	19	25	467	35	5.39	0.9	2.2
		BE-RAC1-40-450B	100	19	25	467	35	5.36	0.9	2.2

		BE-RAC1-60-450A	100	19	25	467	37	5.16	0.8	2.1
		BE-RAC1-60-450B	100	19	25	467	37	5.41	0.9	2.2
		BE-RAC3-40-450A	100	19	25	467	45	5.29	0.8	2
		BE-RAC3-40-450B	100	19	25	467	45	5.25	0.8	2
		BE-RAC3-60-450A	100	19	25	467	46	5.13	0.8	2
		BE-RAC3-60-450B	100	19	25	467	46	5.07	0.7	1.9

Flexural Strength

Table 8: Summary of flexural beam test results.

Author	Year	Specimen	RCA (%)	b	h	d	ρ	fc	fy
Yagishita et al. [48]	1994	BR1	100	120	180	150	1.47	30.9	330
		BR2	100	120	180	150	1.47	32	330
		BR3	100	120	180	150	1.47	33.2	330
Maruyama et al. [49]	2004	CRC30	100	150	200	160	1.11	69	331
		CRC45	100	150	200	160	1.11	46.5	331
		CRC60	100	150	200	160	1.11	32.9	331
Sato et al. [12]	2007	CR45-01-10WB	100	150	200	160	0.59	30.4	332
		CR45-01-10DB	100	150	200	160	0.59	28.4	332
		CR60-01-10WB	100	150	200	160	0.59	34.5	332
		CR60-01-10DB	100	150	200	160	0.59	31.8	332
		CR45-01-13WB	100	150	200	160	1.06	30.4	353
		CR45-01-13DB	100	150	200	160	1.06	28.4	353
		CR60-01-13WB	100	150	200	160	1.06	34.5	353
		CR60-01-13DB	100	150	200	160	1.06	31.8	353
		CR45-01-16WB	100	150	200	160	1.65	30.4	342
		CR45-01-16DB	100	150	200	160	1.65	28.4	342
		CR60-01-16WB	100	150	200	160	1.65	34.5	342
		CR60-01-16DB	100	150	200	160	1.65	31.8	342
		CR30-03-DB	100	150	200	160	1.06	69	331
		CR45-03-DB	100	150	200	160	1.06	46.5	331
		CR60-03-DB	100	150	200	160	1.06	32.9	331

Table 8 (a): Summary of flexural beam test results.

Author	Year	Specimen	RCA (%)	b	h	d	ρ	f_c	f_y
Ajdukiewicz & Kliszczewicz [11]	2007	ORNI-b1	100	200	300	291	0.77	34.6	410
		ORNm-b1	100	200	300	291	0.77	56.4	410
		GRNI-b1	100	200	300	291	0.77	40.1	410
		GRNm-b1	100	200	300	291	0.77	60.2	410
		GRNh-b1	100	200	300	291	0.77	85.3	410
		BRNI-b1	100	200	300	291	0.77	35.3	410
		BRNm-b1	100	200	300	291	0.77	57.6	410
		BRNh-b1	100	200	300	291	0.77	105.3	410
		ORNI-b2	100	200	300	291	1.37	36.6	410
		BRNI-b2	100	200	300	291	1.37	35.8	410
Bai & Sun [36]	2010	RAC-2	50	150	300	260	0.68	42.3	420
		RAC-3	70	150	300	260	0.68	43.7	420
		RAC-4	100	150	300	260	0.68	43.5	420
		RAC-5	100	150	300	260	0.89	43.5	420
		RAC-6	100	150	300	260	1.03	43.5	420
Fathifazl et al. [15]	2009	EM-Min	63.5	200	350	304	0.39	36.9	473
		EM-Av	63.5	200	350	301	1.92	36.9	407
		EM-Max	63.5	200	390	307	3.2	36.9	431
		EM-CMP	63.5	200	350	302	3.25	36.9	431
		EV-Min	74.3	200	350	304	0.39	43.5	473
		EV-Av	74.3	200	350	301	1.92	43.5	407
		EV-Max	74.3	200	390	307	3.2	43.5	431
		EV-CMP	74.3	200	350	302	3.25	43.5	431
Arezoumandi et al. [50]	2015	F-6-1	100	305	460	400	0.47	30.5	568
		F-6-2	100	305	460	400	0.47	31.3	568
		F-7-1	100	305	460	400	0.64	30.5	517
		F-7-2	100	305	460	400	0.64	31.3	517

Table 8 (b): Summary of flexural beam test results.

Author	Year	Specimen	RCA (%)	b	h	d	ρ	f_c	f_y
Kang et al. [25]	2014	H15-0.5	15	135	270	230	0.51	59.4	377
		H15-1.0	15	135	270	230	0.85	59.4	408
		H15-1.5	15	135	270	230	1.3	59.4	389
		H15-1.8	15	135	270	230	1.83	59.4	411
		H30-0.5	30	135	270	230	0.51	48.8	377
		H30-1.0	30	135	270	230	0.85	48.8	408
		H30-1.5	30	135	270	230	1.3	48.8	389
		H30-1.8	30	135	270	230	1.83	48.8	411
		N15-0.5	15	135	270	230	0.51	32.7	377
		N15-1.0	15	135	270	230	0.85	32.7	408
		N15-1.5	15	135	270	230	1.3	32.7	389
		N15-1.8	15	135	270	230	1.83	32.7	411
		N30-0.5	30	135	270	230	0.51	31.7	377

		N30-1.0	30	135	270	230	0.85	31.7	408
		N30-1.5	30	135	270	230	1.3	31.7	389
		N30-1.8	30	135	270	230	1.83	31.7	411
		N50-0.5	50	135	270	230	0.51	29	377
		N50-1.0	50	135	270	230	0.85	29	408
		N50-1.5	50	135	270	230	1.3	29	389
		N50-1.8	50	135	270	230	1.83	29	411

Table 8 (a,b) presents details of flexural test specimens from previous research. Table 9 (a,b) compares cracking moment (M_{cr}), yielding moment (M_y), and ultimate moment (M_u), of the RAC beams with both the ACI 318 [5] and EC 2 [7] provisions. Mukai & Kikuchi [41] tested beams measuring 150×150mm in cross section and 1.8-m in length with both 15% and 30 % RCA replacement ratios and reported no significant difference in ultimate moment. However, authors reported lower cracking moment for RAC beams. Yagashita et al. [48] used low grade, medium grade, and high grade types of recycled aggregate with 100% replacement for determining the flexural strength of reinforced concrete beams. Their results showed using high grade RCA slightly decrease (around 10%) the flexural capacity of RAC beams. Ajdukiewicz and Kliszczewicz [11] used partial or full recycle aggregate. All the beams were fabricated with rectangular sections measuring 200×300mm and 2600mm in length with two longitudinal reinforcement ratios of 0.90% and 1.60%.

They reported that the RAC beams had slightly (3.5% in average) lower moment capacity and higher deflection compared with the CC beams. Sato et al. [12] tested 37 beams with three different longitudinal reinforcement ratios of 0.59%, 1.06%, and 1.65%. They used 100% recycled aggregate for their mix designs. Results of their study showed that the RAC beams had larger deflection compared to the CC beams. In terms of crack spacing no significant difference observed between the RAC and CC beams. However, the RAC beams had wider crack openings compared to the CC ones. They also reported almost the same ultimate moment for the RAC and CC beams.

Maruyama et al. [49] tested beams with 1% longitudinal reinforcement ratio and reported that the cracks propagated on the RAC beams were wider and spaced closer compared to those of the CC beams. The RAC beams had larger deflection, but authors reported no significant difference between the flexural capacity of the RAC and CC beams. Fathifazl et al. [15] incorporated the EMV method for their mix designs. They used both 64% and 74% RCA as a partial replacement of the coarse aggregate for their RAC mixtures. Their beams were cast with three different longitudinal reinforcement ratios ranging between 0.49% and 3.31%. Authors reported comparable and even superior flexural behavior for RAC beams at both service and ultimate states. They concluded that the flexural strength

provisions of the current codes can be used for RAC beams. Bai & Sun [36] used 8-10 years old RCA with different replacement levels of 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 doesn't significantly affect the cracking ultimate moment of beams. Ignjatovic et al. [20] 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 RAC 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. [25] 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 RAC beams. They also reported no significant decrease in flexural capacity up to 30% RCA replacement level. Knaack & Kurama [32] tested 150×230mm cross section and 2000mm long beams. They used RCA from late 1920s foundation and with both 50% and 100% replacement level. They reported higher deflection for the RAC beams, but they concluded that the existing analytical models and code provisions can be used for the RAC beams. Arezoumandi et al. [50] replaced 100% RCA in full scale beams (cross section 300×450mm and 3050mm long) and reported similar crack pattern and flexural capacity, but lower cracking moment for the RAC beams.

As it can be seen from Table 9 (a,b), in terms of ultimate moment, when 100% RCA used as a coarse aggregate, the ACI 318 [5] and EC 2 [7] provisions are conservative for 82% and 92% of beams, while only 83% of the RAC beams showed yielding moment higher than the predicted values. Furthermore, 53% of the RAC beams showed cracking moment less than the ACI 318 [5] provision; however, it was 39% when it compared to the EC 2 [7] provision. The ACI 318 [5] and EC 2 [7] ultimate moment provisions are conservative for the beams used less than 30% RCA as a coarse aggregate, but in terms of cracking and yielding moment 30% and 60% of beams showed values less than code predictions, respectively.

Table 9: Comparison of flexural beam test results with codes.

Author	Year	Specimen	M_{cr}	Test/ACI	Test/EC	M_y	Test/ predicted	M_n	Test/ACI	Test/EC
Yagishita et al. [48]	1994	BR1	12.25	1.03	0.98	NR*	NR*	12.25	1.03	0.98
		BR2	12.65	1.06	1.02	NR*	NR*	12.65	1.06	1.02
		BR3	12.4	1.04	1	NR*	NR*	12.4	1.04	1
Maruyama et al. [49]	2004	CRC30	15.3	1.12	1.14	12.5	0.98	15.3	1.12	1.14
		CRC45	14.8	1.1	1.11	13.2	1.04	14.8	1.1	1.11
		CRC60	15.3	1.16	1.2	12.8	1.02	15.3	1.16	1.2
Sato et al. [12]	2007	CR45-01-10WB	7.4	1.02	1.04	7.4	1.08	7.4	1.02	1.04
		CR45-01-10DB	7.1	0.98	1	7.1	1.03	7.1	0.98	1
		CR60-01-10WB	7.7	1.06	1.08	7.7	1.12	7.7	1.06	1.08
		CR60-01-10DB	7.8	1.08	1.1	7.8	1.13	7.8	1.08	1.1
		CR45-01-13WB	12.9	0.97	1.01	12.9	1.01	12.9	0.97	1.01
		CR45-01-13DB	13.2	1	1.03	13.2	1.03	13.2	1	1.03
		CR60-01-13WB	12.5	0.93	0.98	12.5	0.97	12.5	0.93	0.98
		CR60-01-13DB	13.4	1	1.05	13.4	1.05	13.4	1	1.05
		CR45-01-16WB	18.9	0.98	1.04	18.9	1	18.9	0.98	1.04
		CR45-01-16DB	18.9	0.99	1.05	18.9	1.01	18.9	0.99	1.05
		CR60-01-16WB	18.8	0.96	1.02	18.8	0.99	18.8	0.96	1.02
		CR60-01-16DB	19.7	1.02	1.1	19.7	1.04	19.7	1.02	1.1
		CR30-03-DB	12.5	0.96	0.98	12.5	1.02	12.5	0.96	0.98
		CR45-03-DB	13.2	1.03	1.04	13.2	1.09	13.2	1.03	1.04
		CR60-03-DB	12.8	1.01	1.06	12.8	1.07	12.8	1.01	1.06

Table 9 (a): Comparison of flexural beam test results with codes.

Author	Year	Specimen	M_{cr}	Test / ACI	Test/EC	M_y	Test / predicted	M_n	Test/ACI	Test/EC
Ajdukiewicz & Kliszczewicz [11]	2007	ORNI-b1	16	1.46	1.67	46.8	0.97	51.2	1.01	1.04
		ORNm-b1	12	0.86	1	50.4	1.03	62.4	1.21	1.23
		GRNI-b1	12	1.02	1.14	54	1.11	65.2	1.28	1.31
		GRNm-b1	16	1.11	1.29	50.8	1.04	54.4	1.05	1.07
		GRNh-b1	16	0.93	1.12	52	1.05	63.2	1.21	1.24
		BRNI-b1	16	1.45	1.65	52.8	1.09	60	1.18	1.21
		BRNm-b1	16	1.13	1.19	49.6	1.01	57.2	1.11	1.13
		BRNh-b1	20	1.05	1.29	56	1.13	66.4	1.26	1.31

Bai & Sun [36]		ORNI-b2	12	1.07	1.21	85.6	1.02	94.4	1.09	1.14
		BRNI-b2	18	1.62	1.84	85.6	1.02	96.4	1.12	1.18
	2010	RAC-2	10	1.1	1.22	28	1.06	34	1.22	1.24
		RAC-3	11.2	1.21	1.34	28	1.06	35.5	1.27	1.3
		RAC-4	10	1.09	1.2	26.5	1	34	1.22	1.24
		RAC-5	10.6	1.15	1.27	32.5	0.95	40.4	1.12	1.16
Fathifazl et al. [15]		RAC-6	10.6	1.15	1.27	40	1.01	48.4	1.17	1.21
	2009	EM-Min	13	0.85	0.96	38.4	1.21	46	1.39	1.42
		EM-Av	13.8	0.9	1.02	123.4	1.01	149.2	1.2	1.3
		EM-Max	21.1	1.11	1.25	210.6	0.97	221.9	1.1	1.22
		EM-CMP	24.7	1.61	1.82	193	0.9	246.1	1.24	1.38
		EV-Min	16.2	0.97	1.07	39.9	1.25	46.7	1.4	1.44
		EV-Av	15.2	0.91	1	136.6	1.11	150.2	1.19	1.25
		EV-Max	13.4	0.65	0.71	207.5	0.95	225.2	1.07	1.17
Arezoumandi et al. [50]		EV-CMP	29.1	1.74	1.92	220.2	1.02	245.7	1.19	1.3
	2015	F-6-1	34.6	0.94	1.1	119.3	0.99	149.6	1.21	1.25
		F-6-2	35.9	0.96	1.12	125.4	1.04	154.9	1.25	1.29
		F-7-1	42	1.14	1.33	147.4	1	172.6	1.14	1.19
		F-7-2	42.7	1.14	1.33	148.2	1.01	169.3	1.12	1.16

Table 9 (b): Comparison of flexural beam test results with codes.

Author	Year	Specimen	Mcr	Test/ACI	Test/EC	My	Test/ predicted	Mn	Test/ACI	Test/EC
Kang et al. [25]	2014	H15-0.5	5.8	0.73	0.86	13	1.02	18.2	1.35	1.4
		H15-1.0	6.6	0.84	0.98	21.7	0.96	29.3	1.23	1.25
		H15-1.5	7.9	1.01	1.18	30.2	0.94	38.6	1.13	1.15
		H15-1.8	9.1	1.16	1.35	45.2	0.96	58.1	1.17	1.23
		H30-0.5	5.3	0.74	0.8	11.2	0.88	16.9	1.26	1.3
		H30-1.0	6.2	0.87	0.95	21.9	0.97	28.8	1.21	1.24
		H30-1.5	7	0.99	1.07	31.1	0.96	38.4	1.13	1.17
		H30-1.8	7.9	1.11	1.21	46.9	1	49	1	1.05
		N15-0.5	6.6	1.14	1.31	10.9	0.86	14.8	1.12	1.14
		N15-1.0	8	1.37	1.58	22.6	1.01	27.2	1.17	1.22
		N15-1.5	8.7	1.5	1.73	30.6	0.96	35.8	1.09	1.14
		N15-1.8	12.4	2.13	2.46	47.3	1.02	51.6	1.11	1.2
		N30-0.5	5.7	1	1.16	12.5	0.99	14.7	1.11	1.13
		N30-1.0	8	1.39	1.62	23.5	1.05	26.3	1.14	1.18
		N30-1.5	8.4	1.46	1.7	32.4	1.02	35.3	1.08	1.15
		N30-1.8	12.4	2.16	2.51	44	0.95	50.2	1.09	1.2
		N50-0.5	6.6	1.21	1.42	11.1	0.88	13.6	1.03	1.04
		N50-1.0	8	1.45	1.71	22.6	1.02	24.4	1.06	1.09
		N50-1.5	8.8	1.61	1.9	32.3	1.02	32.8	1.01	1.07
		N50-1.8	11	2.01	2.37	48.8	1.05	50.5	1.11	1.18

Figure 4 presents the normalized flexural strength versus normalized longitudinal reinforcement ratio for the RAC beams as well as the wealth of flexural test data available in the literature for CC [51]. Figure 4 seems to indicate that the RAC and CC test results fall within the central portion of the data. Furthermore, statistical analysis (regression analysis) of the data indicates that the RAC and CC test results fall within a 95% confidence interval of a nonlinear regression curve fit of the database. This result indicates that the RAC flexural test values are very consistent with the wealth of flexural test data available in the literature.

Shear Strength

Mukai & Kikuchi [41] replaced both 15% and 30 % RCA instead of virgin aggregate and reported slightly inferior shear strength for the RAC compared with the CC beams. Han et al. [52] tested beams with different shear span to depth ($a/d=1.5$ to 4.0) and both washed and unwashed RCA and observed no significant difference in failure mode and shear capacity between the RAC and CC beams; however, the ACI 318 [5] shear provision was unconservative for beams with a/d greater than 3.0 . Yagashita et al. [48] used low, medium, and high grade RCA with 100% replacement level. They reported 8% lower shear stress at failure for the RAC beams (with high grade RCA) compared to the CC. Sogo et al. [53] used RCA (10 to 40-year-old concrete foundation) for casting the beams and reported 20% lower shear strength for the RAC beams compared to the CC beams. Gonza'lez-Fontboa et al. [54] tested beams with 50% RCA replacement and observed no significant difference on shear capacity between the RAC and CC beams. Etxeberria & Va'zquez [55] used different percentages of RCA (25%, 50%, and 100%)

for casting specimens and concluded that a substitution of less than 25% RCA, scarcely affects the shear capacity of RC beams. Ji et al. [56] tested beams with a cross section of 170×270 mm and a shear span-to-depth of 2 and 100% RCA replacement. Results of their study showed that existing codes can be used to predict shear strength of the RAC beams. Choi et al. [16] tested beams with different span-to-depth ratios (1.50, 2.50 and 3.25) and different RCA replacement ratios (30%, 50%, and 100%). They reported the lower shear strength for the RAC beams. Fathifazl et al. [57] used the EMV method with both 63.5% and 74.3% recycled aggregate replacement as a coarse aggregate for their mix designs. They tested beams with four different shear span-to-depth ratios ranging between 1.5 and 4. They reported superior shear strength for the RAC beams. They also concluded that current code provisions for shear conservatively predicted the capacities of the RAC beams. Schubert et al. [30] tested slabs with 100% RCA replacement and concluded that existing codes provision can be used to calculate shear strength of the RAC slabs. Xiao et al. [58] tested push-off specimens with different percentages of recycled coarse aggregate replacement. They observed similar shear stress-slip curves and crack propagation path between the RAC and CC specimens. They also reported that more than 30% RCA replacement decrease the ultimate shear capacity. Arezoumandi et al. [59] replaced 100% RCA in full scale beams with different longitudinal reinforcement ratios and reported 12% lower shear strength for the RAC beams compared to the CC beams. Knaack & Kurama [32] replaced both 50% and 100% of RCA (from 90 years old building) to cast beams with cross section of $150 \text{ mm} \times 230 \text{ mm}$. Their results showed small reduction on shear strength of the RAC beams, but still existing codes can be used to predict shear strength of the RAC beams.

Table 10: Summary of shear beam test results

Author	year	RCA (%)	b (mm)	d (mm)	h (mm)	a/d	d_{max} (mm)	ρ (%)	f_c Mpa	V kN	Test/ACI	Test/EC
	2001	100	170	270	300	1.5	25	1.1	39.6	83.5	1.7	2.32
			170	270	300	2	25	1.1	30.6	65.2	1.51	1.97
			170	270	300	2	25	1.1	32.6	60.6	1.36	1.79
			170	270	300	3	25	1.1	31.2	42.7	0.98	1.28
			170	270	300	4	25	1.1	31.9	31.7	0.72	0.94
Belén & Fernando [3]	2007	50	200	303	350	3.3	25	3	39.7	90.6	1.4	1.6
Etxeberria & Va'zquez [10]	2007	25	200	303	350	3.3	25	2.9	42.4	104	1.55	1.8
		50	200	303	350	3.3	25	2.9	41.3	89	1.34	1.55
		100	200	303	350	3.3	25	2.9	39.8	84	1.29	1.48
Ji et al. [56]	2008	100	170	270	300	2.2	NR*	1.1	39.7	60	1.22	1.66
Choi et al. [16]	2010	30	200	360	400	1.5	25	1.6	24.6	161.7	2.66	3.15
			200	360	400	2.5	25	1.6	24.6	81.4	1.34	1.59
			200	360	400	3.25	25	1.6	24.6	80.9	1.33	1.58
		50	200	360	400	1.5	25	1.6	24.2	152.9	2.54	3
			200	360	400	2.5	25	1.6	24.2	87.9	1.46	1.72

			200	360	400	3.25	25	1.6	24.2	71.6	1.19	1.4
		100	200	360	400	1.5	25	1.6	22.6	107.8	1.85	2.16
			200	360	400	2.5	25	1.6	22.6	84.8	1.46	1.7
			200	360	400	3.25	25	1.6	22.6	57.8	0.99	1.16
		30	200	360	400	2.5	25	0.53	24.6	56.7	0.93	1.6
			200	360	400	2.5	25	0.83	24.6	78.4	1.29	1.9
			200	360	400	2.5	25	1.61	24.6	81.4	1.34	1.58
		50	200	360	400	2.5	25	0.53	24.2	57.8	0.96	1.64
			200	360	400	2.5	25	0.83	24.2	67.2	1.12	1.64
			200	360	400	2.5	25	1.61	24.2	87.7	1.46	1.72
		100	200	360	400	2.5	25	0.53	22.6	59.8	1.03	1.73
			200	360	400	2.5	25	0.83	22.6	70.1	1.2	1.75
			200	360	400	2.5	25	1.61	22.6	84.8	1.46	1.7

Table 10 (a): Summary of shear beam test results

Author	year	RCA (%)	b (mm)	d (mm)	h (mm)	a/d	dmax (mm)	ρ (%)	fc Mpa	V kN	Test/ACI	Test/EC
Fathifazl et al. [57]	2011	63.5	200	300	375	1.5	19	1	41.6	186.7	2.84	4.12
			200	300	375	2	19	1.5	41.6	169.5	2.58	3.27
			200	309	375	2.7	19	1.62	41.6	103.9	1.53	1.91
			200	305	375	4	19	2.46	41.6	83.2	1.24	1.44
		74.3	200	300	375	1.5	19	1	49.1	195.3	2.73	4.08
			200	300	375	2	19	1.5	49.1	179	2.5	3.27
			200	305	375	4	19	2.46	49.1	105.6	1.45	1.73
		63.5	200	201	250	2.7	19	2	41.6	89.3	2.03	2.12
			200	309	375	2.6	19	1.6	41.6	103.9	1.53	1.92
			200	381	450	2.7	19	1.8	41.6	99.5	1.19	1.5
			200	476	550	2.7	19	1.7	41.6	104.6	1	1.34
		74.3	200	201	250	2.7	19	2	49.1	122.6	2.56	2.76
			200	381	450	2.7	19	1.8	49.1	111.7	1.23	1.59
			200	476	550	2.7	19	1.7	49.1	119.6	1.05	1.45
Knaack & Kurama [32]	2014	50	150	200	230	3.8	19	1.3	41.8	44	1.33	1.61
			150	200	230	3.8	19	1.3	41.8	39.1	1.19	1.43
			150	200	230	3.8	19	1.3	37.4	43.7	1.4	1.66
			150	200	230	3.8	19	1.3	37.4	41.2	1.32	1.57
		100	150	200	230	3.8	19	1.3	39.1	36.4	1.14	1.36
			150	200	230	3.8	19	1.3	39.1	38	1.19	1.42
			150	200	230	3.8	19	1.3	39.2	39.9	1.25	1.49
			150	200	230	3.8	19	1.3	39.2	36.1	1.13	1.35
Arezoumandi et al. [59]	2014	100	305	400	460	3.1	25	1.27	30	114.8	1.01	1.37
			305	375	460	3.25	25	1.27	30	143.2	1.34	1.79
			305	375	460	3.25	25	2.03	30	131.4	1.23	1.41
			305	400	460	3.1	25	2.03	34.1	113	0.93	1.11
			305	375	460	3.25	25	2.71	34.1	124.1	1.09	1.28
			305	375	460	3.25	25	2.71	34.1	140.3	1.24	1.45

Table 10 summarizes details of shear beams test including width, b , height, h , depth, d , shear span to depth, a/d , maximum aggregate size, d_{max} , longitudinal reinforcement ratio, ρ , compressive strength, f'_c , and shear at failure, V . Furthermore, test results compared with shear provisions of both ACI 318 [5] and EC 2 [7]. Table 10 (a) shows that both ACI 318 [5] and EC 2 [7] shear provisions are conservative for more than 90% of data, even though for the majority of tests the RAC beams showed lower shear strength compared to the CC beams.

The four key parameters that affect concrete contribution to shear strength include depth of member or size effect (d), shear span to depth ratio (a/d), compressive strength of concrete (f'_c), and longitudinal reinforcement ratio (ρ). To evaluate the effect of the aforementioned parameters on shear strength of the beams, the results of RAC beams are compared with the wealth of shear test data available in the literature for CC [60].

Figure 5 presents the shear stress versus f'_c , ρ , d and a/d , respectively. Given the significant scatter of the database of previous shear test results, it is somewhat difficult to draw definitive conclusions on the current test values. Nonetheless, visually, Figure 5 seems to indicate that the RAC test results fall within the lower portion of the data -except results of Fathifazl et al. [56] - and follow the same general trend of the database. Furthermore, statistical analysis (using regression analysis to draw the best fit and 95% confidence intervals) of the data indicates that the test results fall within a 95% confidence interval of a nonlinear regression curve fit of the database. This result indicates that the RAC beams shear strength is lower than the shear strength of the CC.

Conclusion

The following conclusions can be drawn from literature review of mechanical properties and structural behavior of RAC specimens:

- a. The existing codes provisions are unconservative for splitting tensile strength of RAC around 10%.

- b. The ACI 318 [4] and EC 2 [7] provisions overestimate flexural strength of RAC about 24% and 65%, respectively.
- c. Moduli of elasticity of RAC are around 10% to 20% lower than the predicted values of the ACI 318 [4] and EC 2 [7] codes provisions.
- d. Moduli of elasticity of RAC are around 10% to 20% lower than the predicted values of the ACI 318 [4] and EC 2 [7] codes provisions.
- e. The CEB-FIP [5] and Japan's code fracture energy provisions are unconservative for 90% and 20% of RAC, respectively.
- f. Pull-out specimens with different RCA replacement levels showed almost identical load-slip behavior with no significant difference in bond strength between RAC and CC specimens.
- g. Both splice beam and end beam results showed up to 20% reduction in bond strength of RAC with 100% RCA replacement.
- h. In terms of flexural strength, RAC beams showed wider cracks, lower cracking moment, larger deflection, but similar ultimate moment with CC.
- i. The RAC beams test results fall within a central portion of 95% confidence interval of a nonlinear regression curve fit of a CC flexural test database.
- j. Similar load-deflection for shear behavior observed between RAC and CC beams, but the majority of previous studies reported lower shear strength for RAC beams (up to 20% when 100% RCA used instead of virgin aggregate) compared to CC.
- k. The RAC beams test results fall within a lower portion of 95% confidence interval of a nonlinear regression curve fit of a CC shear test database.
- l. Using the EMV method avoids inferior mechanical and structural performance of RAC.

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