FINAL Report E

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Project Title: Recycled Concrete Aggregate (RCA) for Infrastructure Elements

Report E: Flexural Behavior of RCA Concrete

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ABSTRACT

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 recycled aggregate.

Most research to date has consisted only of the evaluation of the material strength and durability of recycled aggregate concrete (RAC) mixtures, while only a limited number of studies have implemented full-scale testing of specimens constructed with RAC to determine its potential use in the industry. For this research, a laboratory testing program was developed to investigate the flexural performance of reinforced concrete (RC) beams constructed with RAC. The experimental program consisted of eight tests performed on full-scale RC beams. The principal parameters investigated were: (1) concrete type (RAC or conventional concrete (CC)) and (2) amount of longitudinal (flexural) reinforcement. The cracking, yielding, and ultimate capacities of the beams were compared with existing design code provisions. Furthermore, the experimental flexural strengths of the beams were compared with a flexural test database of CC specimens.

Results of this study indicate that the RAC beams have comparable ultimate flexural strengths and approximately 13% higher deflections compared to CC.

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NOMENCLATURE

Symbol	Description
A_s	Area of longitudinal reinforcement
b	Width of cross-section
b_v	Effective width of cross-section
b_w	Width of cross-section
d	Effective depth of cross-section
E_c	Modulus of elasticity of the concrete
E_s	Modulus of elasticity of the steel
F_c	Concrete compressive force
F_s	Longitudinal reinforcement force
f'_c	Compressive strength of the concrete
f_{ci}	Compressive stress on crack surface
f_{cr}	Concrete stress at cracking
f_{ct}	Tensile strength of the concrete
f_t	Splitting tensile strength of the concrete
f'_t	Tensile strength of the concrete
f_v	Tensile stress in the stirrups
f_y	Yield stress of steel
h	Height of cross-section
I_g	Moment of inertia of gross concrete section about centroidal axis

jd	Distance between resultants of internal compressive and tensile forces on a cross-section
L	Length of the beam
M_{cr}	Cracking moment
M_{exp}	Experimentally determined total moment applied to specimen
M_n	Nominal moment capacity
MOR	Modulus of rupture of the concrete
P_{max}	Measured peak load
$^{w}/_{cm}$	Water-to-cementitious material ratio
$\overline{x}$	Arithmetic average
y_t	Distance from centroidal axis of gross section
z	Inner level arm
ε_0	Concrete strain at peak stress
ε_c	Compressive strain in the concrete
ε_s	Strain in the tension reinforcement
ρ_l	Longitudinal reinforcement ratio

1. INTRODUCTION

1.1. BACKGROUND

The construction of buildings, bridges, and roadways continues to increase in the twenty-first century, especially in areas with ever-growing populations. Existing structures and highways require repair or replacement as they reach the end of their service life or simply no longer satisfy their intended purpose due to the growing population. As modern construction continues, two pressing issues will become more apparent to societies: an increasing demand for construction materials, especially concrete and asphalt aggregates, and an increasing production of construction and demolition waste. Already, the Federal Highway Administration (FHWA 2004) estimates that two billion tons of new aggregate are produced each year in the United States. This demand is anticipated to increase to two and a half billion tons each year by 2020. With such a high demand for new aggregates, the concern arises of the depletion of the current sources of natural aggregates and the availability of new sources. Similarly, the construction waste produced in the United States is expected to increase. From building demolition alone, the annual production of construction waste is estimated to be 123 million tons (FHWA, 2004). Currently, this waste is most commonly disposed of in landfills.

To address both the concern of increasing demand for new aggregates and increasing production of waste, many states have begun to recognize that a more sustainable solution exists in recycling waste concrete for use as aggregate in new concrete, or recycled concrete aggregates (RCA). The solution helps address the question of how to sustain modern construction demands for aggregates as well as helps to reduce the amount of waste that enters already over-burdened landfills.

Based on a survey by FHWA in 2002, many states had begun to implement recycled concrete aggregates in some ways in new construction. As shown in **Figure 1.1**, most states had recognized the many uses of RCA as a raw material, such as for rip-rap, soil stabilization, pipe bedding, and even landscape materials. As shown in **Figure 1.2**, many states had gone a step further in integrating RCA into roadway systems for use as aggregate base course material. However, as shown in **Figure 1.3**, only a small number of states had begun using RCA in Portland cement concrete for pavement construction. However, over the intervening 12 years, the use of RCA has increased significantly, particularly within the last 5 years, and the Missouri Department of Transportation (MoDOT) has instituted a very aggressive program to increase the use of recycled materials in transportation-related construction. However, there are currently no acceptable standards or guidelines in the U.S. for utilizing RCA in structural concrete.

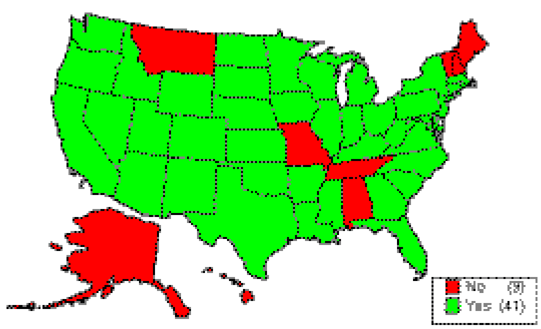


Figure 1.1: States using RCA as Aggregate

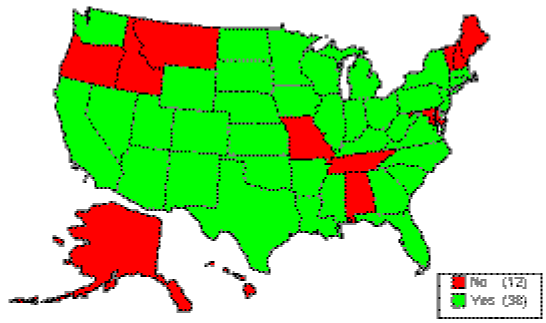


Figure 1.2: States using RCA as Base Aggregate

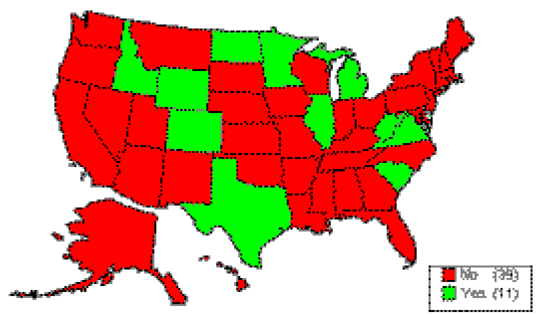


Figure 1.3: States using RCA in PC Concrete

1.2. CONCERNS WITH RECYCLED AGGREGATE CONCRETE

RCAs are composed of both the original, or virgin, aggregate, as well as mortar which remains adhered to the surface of the aggregate. In the production of RCA, the removal of all this residual mortar would prove costly and detrimental to the integrity of the virgin aggregates within the concrete. Therefore, residual mortar is inevitable. Research has shown that this residual mortar causes high water absorption, low density, low specific gravity, and high porosity in RCAs compared to natural aggregates. These effects in the recycled aggregate can decrease hardened concrete properties of recycled aggregate concrete (RAC). According to Abbas et al. (2008), the amount of residual mortar on the RCA can significantly affect the mechanical and durability properties of RAC. To reduce the negative impacts of this residual mortar, new mix design methods such as the equivalent mortar volume method can be used.

Due to the variety of sources of RCA and the various functions, environment, and wear of the concrete structures and pavements from which the RCA can be obtained, characterizing this aggregate can be very difficult. Controlled studies must be performed to account for each of these variables on a regional basis, such as for each state's Department of Transportation, so that the aggregates within the area can be adequately characterized.

1.3. OBJECTIVE AND SCOPE OF WORK

The main ***objective*** of this research study was to evaluate the flexural behavior and response of RCA through material, component, and full-scale testing. This objective included a study and evaluation of current analytical models used to predict the flexural response of conventional Portland-cement concrete as applied to RCA, including recommended modifications.

The following ***scope of work*** was implemented in order to achieve the objective of the research study:

- Perform a literature review;
- Develop a research plan;
- Develop mix designs for both conventional and RAC;
- Evaluate the fresh and hardened properties of several RAC and CC mixes;
- Design and construct small and full-scale specimens;

- Test specimens to failure;
- Record and analyze data from tests;
- Compare test results to current guidelines and previous research findings;
- Develop conclusions and recommendations; and
- Prepare this report to document the details, results, findings, conclusions, and recommendations of this study.

1.4. RESEARCH METHODOLOGY

The proposed research methodology included six (6) tasks necessary to successfully complete the study. They are as follows:

Task #1: Perform a literature review. The goal of the literature review was to become familiarized with testing methods and results from previous studies. This knowledge was used for a better understanding of the behavior of the specimens, to avoid mistakes, as well as to provide support for comparisons.

Task #2: Develop RAC and CC mix designs. The purpose of this task was to develop RAC mix designs that maximized the percentage of recycled concrete aggregate, but that still fulfilled typical construction needs, such as early strength development. Conventional concrete mix designs served as controls during this study. ACI 211.1-91 formed the basis for developing the mix designs.

Task #3: Perform material and component testing. A number of hardened concrete property tests were completed to evaluate the performance of the RAC mix and determine the validity of using these tests to predict the performance of concretes containing recycled concrete aggregate.

Task #4: Perform full-scale testing. This task involved the construction and testing of full-scale specimens to confirm the potential of RAC. The full-scale specimens included beam specimens for flexural testing only. These specimens were constructed with materials from the local ready mix concrete plant to validate the ability of transferring the mix designs from the laboratory to the field. In order to compare the flexural strength of conventional and RAC, full-scale beams were tested in a third point loading configuration. These beams were designed to fail in flexure. Different longitudinal reinforcement ratios were also considered. Strain gauges were applied to the flexural reinforcement, and the maximum load applied to the beam was also recorded and used to calculate the strength of the beams.

Task #5: Analyze test data. The material, component, and full-scale test results were analyzed to evaluate the flexural behavior and response of RAC compared to conventional Portland-cement concrete. The test data included: concrete compressive and tensile strength, modulus of rupture (MOR), flexural force-deflection plots, crack formation and propagation, and reinforcement strains.

Task #6: Develop findings, conclusions, and recommendations. This task synthesized the results of the previous tasks into findings, conclusions, and recommendations on the flexural behavior and response of RAC.

1.5. REPORT OUTLINE

This report includes six chapters. This section will discuss the information that will be presented in more detail throughout this document.

Chapter 1 acts as an introduction to the report. This introduction contains a brief background of recycled aggregate. It also discusses the research objective, scope of work, and research plan.

Chapter 2 includes information from previous research performed on the characterization of recycled aggregate and its applications as a coarse aggregate in concrete.

Chapter 3 includes information about the experimental program. The experimental program consisted of eight tests performed on full-scale reinforced concrete beams as well as material and component testing to determine hardened concrete properties such as compressive strength, splitting tensile strength, and flexural strength. This chapter also describes the fabrication process, test set-up, and instrumentation for the full-scale testing.

Chapter 4 presents the test results and the different analyses used to investigate the flexural resistance mechanisms. The overall behavior of the specimens is described first, with a focus on crack patterns, failure modes, and flexural strength.

Chapter 5 concludes this document, summarizing the findings and conclusions of this study and proposing recommendations and future research.

2. LITERATURE REVIEW ON RECYCLED AGGREGATE

2.1. GENERAL

Conventional Portland-cement concrete is produced more than any other material in the world. It is used in every civil engineering field for applications such as pavements, dams, bridges, and buildings because of its versatility, strength, and durability. In this chapter, a brief review is presented of the research performed on concrete mixtures containing recycled aggregate as coarse aggregate.

Concrete with recycled aggregate can be produced to achieve desired strengths at various ages, with a given water-cementitious ratio, aggregate size, air content, and slump as it is done for conventional concrete.

2.2. USE OF RECYCLED AGGREGATE AS COARSE AGGREGATE

Recently, there has been an increasing trend toward the use of sustainable materials. Sustainability helps the environment by reducing the consumption of non-renewable natural resources. Concrete – the second most consumed material in the world after water – uses a significant amount of non-renewable resources. As a result, numerous researchers have investigated the use of recycled materials in the production of concrete such as fly ash and recycled aggregate.

Unfortunately, global data on concrete waste generation is not available, but construction and demolition waste accounts for around 900 million tonnes every year just in Europe, the US, and Japan (WBCSD, 2012). Recycling concrete not only reduces using virgin aggregate but also decreases the amount of waste in landfills.

In general, RCA has lower specific gravity and unit weight and considerably higher absorption and porosity compared to natural aggregates. These factors need to be taken into account when designing concrete mixes containing RCA.

2.3. PREVIOUS STUDIES RELATED TO RAC

Comprehensive research has been done on both the fresh and hardened properties of recycled aggregate concrete (RAC), but limited research has been performed on the structural behavior of RAC. The early research on structural performance of RAC was published in Japan (Kikuchi et al., 1988). Maruyama et al. (2004) tested beams with 1.06% longitudinal reinforcement ratio and three different water-to-cement (w/c) ratios (0.30, 0.45, and 0.60). They reported that flexural cracks in the RCA beams were wider and spaced closer compared with the conventional concrete (CC) beams. The RCA beams also had larger deflections than the CC beams because of a lower modulus of elasticity. They also observed no significance difference between the flexural capacity of the RCA and CC beams.

Sato et al. (2007) tested 37 beams with three different longitudinal reinforcement ratios (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 deflections compared with the CC beams. In terms of crack spacing, no significant difference was 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.

Ajdukiewicz et al. (2007) summarized the test results of flexural tests from the period of 1998-2006 in Poland. Their mixtures used partial or full recycled aggregate. All the beams were rectangular, measuring 200 x 300 mm in cross section and 2600 mm in length with two longitudinal reinforcement ratios (0.90% and 1.60%). They reported that the RCA beams had slightly lower moment capacity (3.5% on average) and larger deflections compared with the CC beams.

Fathifazl et al. (2009) used the 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 ratios ranging 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 the flexural provisions in current codes can be used for RCA beams.

Ignjatovic et al. (2012) studied nine full scale beams with 0%, 50%, and 100% recycled coarse aggregate and 0.28%, 1.46%, and 2.54% longitudinal reinforcement ratios. 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 a higher range of recycled aggregate showed higher levels of concrete destruction at failure.

2.4. CONCLUDING REMARKS

The literature review reported no significance difference in terms of crack morphology, crack patterns, and also failure modes between CC and RAC beams: however, they reported higher deflection for RAC beams compared with CC beams.

3. EXPERIMENTAL PROGRAM

3.1. GENERAL

The objective of this study was to investigate the flexural performance of reinforced concrete (RC) beams composed of RCA. The experimental program consisted of eight tests performed on full-scale RC beams. The principal parameters investigated were:

(1) concrete type – recycled aggregate concrete (RAC) or conventional concrete (CC), and

(2) amount of longitudinal reinforcement.

Also, as part of this study, small scale testing was performed to determine hardened concrete properties such as compressive strength, flexural strength, and splitting tensile strength.

3.2. TEST BEAMS

The reinforcement for the beams was designed in accordance with the AASHTO LRFD Bridge Design Specifications (AASHTO LRFD, 2010). The beams measured 10 ft. in length, had a cross section of 12 in. x 18 in., and were constructed with two different longitudinal reinforcement ratios – 0.47% and 0.64%. The beam design included shear reinforcement to ensure a flexural failure. All of the specimens had #3 stirrups spaced at 2 in. within the bearing area to prevent premature bearing failure as well as #3 stirrups spaced at 7 in. within the rest of the beam to avoid any shear failure.

Table 3.1 summarizes the test matrix used in this study. The beam designation included a combination of letters and numbers: F stands for flexural beams and numbers 6 and 7 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 within the bottom of the beam. Two beams were constructed and tested for each combination of variables shown in **Table 3.1** as well as each concrete type. The cross sections for these specimens are shown in **Figure 3.1**. **Figure 3.2** shows the load pattern and location of strain gauges on the test beams.

Table 3.1: Flexural Beam Test Matrix

Section	Bottom reinforcement	Top reinforcement	ρ
F-6	2#6	2#4	0.0047
F-7	2#7	2#4	0.0064

Figure 3.1: Cross Sections and Reinforcement Layout of the Beams

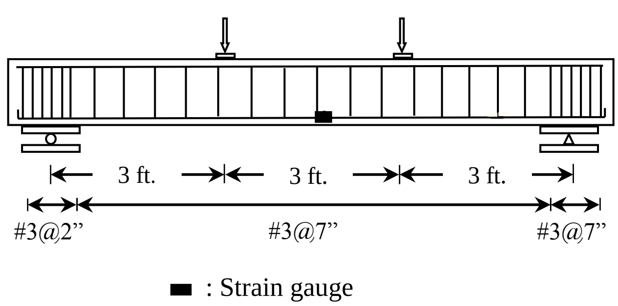


Figure 3.2: Load Pattern and Location of Strain Gauges on the Test Beams

3.3. MATERIALS

3.3.1. Concrete. For this study, two mix designs were produced and evaluated for flexural performance. A MoDOT Class B air-entrained mix design was used as a baseline for reference throughout the study and also as the parent material for the recycled concrete aggregate. The specified cement content in this mix was 535 lb., the water-to-cement ratio was 0.40, the target slump was 6 in., and the design air content was 6%. The specified amount of fine aggregate as a volume of total aggregates was 40%. For this mix, the typical dosage range of the MoDOT-approved air entrainment MB-AE 90 was 0.25-4.0 fl.oz./100 lb. of cement. The typical dosage of the Type A water reducer Glenium 7500 was 5.0 – 8.0 fl.oz./100 lb. of cement.

For the CC mix, the coarse aggregate consisted of crushed limestone with a maximum nominal aggregate size of 1 in. from the Potosi Quarry (Potosi, MO) while the fine aggregate was natural sand from Missouri River Sand (Jefferson City, MO). For the RAC mixes, the coarse aggregate consisted of RCA ground from the CC mix to a nominal maximum aggregate size of 1 in., with 100% replacement of the Potosi limestone. Test results for the coarse aggregate used in the CC mix design as well as the resulting RCA are shown in **Table 3.2**. As expected, the RCA had lower specific gravity and unit weight and considerably higher absorption. The Los Angeles abrasion test results were virtually identical.

Tables 3.3 and **3.4** present the mix designs and representative fresh and hardened strength properties, respectively, of the CC and RAC mixes. The mix incorporating RCA was a 100% direct replacement design. The total volume of coarse aggregate in the control MoDOT Class B mix was directly substituted with the laboratory-produced RCA and is subsequently referred to as RAC-100. In order to maintain consistency with the control specimens, the MoDOT Class B mix specifications were used to design the RAC. However, during laboratory trial batching, it was noticed from the slump test that the RAC-100 mix lacked cohesion. To remedy this situation, the mix was modified by increasing the amount of fine aggregate volume by 5% of total aggregates, which noticeably improved the cohesion of the mix.

Table 3.2: Aggregate Properties

Property	CC	RCA
Bulk Specific Gravity, Oven-Dry	2.72	2.35
Dry-Rodded Unit Weight, (lb/ft^3)	99.8	89.8
Absorption (%)	0.98	4.56
LA Abrasion (% Loss)	43	41

Table 3.3: Mix Designs per Cubic Yard

Constituent	CC	RAC-100
Cement (Type I) (lb)	535	535
w/cm	0.40	0.40
Natural Coarse Aggregate (lb)	1958	-
Recycled Coarse Aggregate (lb)	-	1650
Fine Aggregate (lb)	1253	1442
HRWR (fl. oz)	55	42
AE (fl. oz)	20	7

Table 3.4: Typical Fresh and Hardened Concrete Properties for CC and RAC Mixes

Property	CC	RAC-100
Slump (in.)	5.5	8
Air content (%)	8.5	6.5
Unit weight (lb/ft^3)	145.4	136.0
Split cylinder strength (psi)	505	370
Flexural strength (psi)	500	410
Compressive strength (psi)	5400	4350

3.3.2. Steel Reinforcement. Shear reinforcement for the test specimens consisted of A615, Grade 60 #3 reinforcing bars. Longitudinal reinforcement for the test specimens consisted of A615, Grade 60 #4, #6, and #7 reinforcing bars. All the steel reinforcement was tested in accordance with ASTM A370 (2011) "Standard Test Methods and Definitions for Mechanical Testing of Steel Products" to obtain the mechanical properties, which are summarized in **Table 3.5**. These results are the average of three replicate specimens.

Table 3.5: Mechanical Properties of Steel Reinforcement

Bar size	Yield strength (psi)
#3	71,650
#4	73,970
#6	71,540
#7	65,120

3.4. BEAM FABRICATION

All the test beams were fabricated in the Structural Engineering High-Bay Research Laboratory (SERL) at Missouri S&T. Steel formwork was used to cast the beams. The steel cage was assembled from reinforcement that was bent in the laboratory to the desired geometry. Due to the dimension of the beams, it was possible to cast two beams at a time. After casting, the top surface of the beams was covered with burlap and plastic sheeting, and a wet surface was maintained for three days to retain moisture for proper curing. Cylinders were cured in the same environment as the test beams by placing them next to the beams. The sheeting and burlap were then removed, and the beams were allowed to air cure in the lab environment. Photographs showing the construction process are shown in **Figures 3.3**.

(a) Formwork

(b) Concrete placement

(c) Concrete consolidation

(d) Concrete finishing

Figure 3.3: Beam Construction Process

3.5. TEST SET-UP

All the specimens were tested as simply supported and subjected to third-point loading with two actuators as shown in **Figure 3.4**. Two actuators, each with a 140-kip compressive capacity, were used to apply load to the beam specimens, as shown in **Figure 3.5**. The actuators applied load by pushing the steel beam downward to distribute the load onto two points of the test specimen. The loading frame assembly was designed to withstand at least two times the anticipated maximum load applied to fail the beams. Each test was performed under displacement control, and the load was applied in a series of loading steps of 0.05 in., which corresponded to a load of approximately 8 kips, until failure. Electronic measurements of strain and deformation were recorded throughout the entire loading history of the specimens, while hand measurements of strain and crack pattern formations were taken at the end of each load step while the load was paused. The total beam length was 10 ft, with a simply supported span length of 9 ft. The load was applied at 3 ft from each support, as measured from center of support to center of load. **Figure 3.6** shows a photograph of the test set-up.

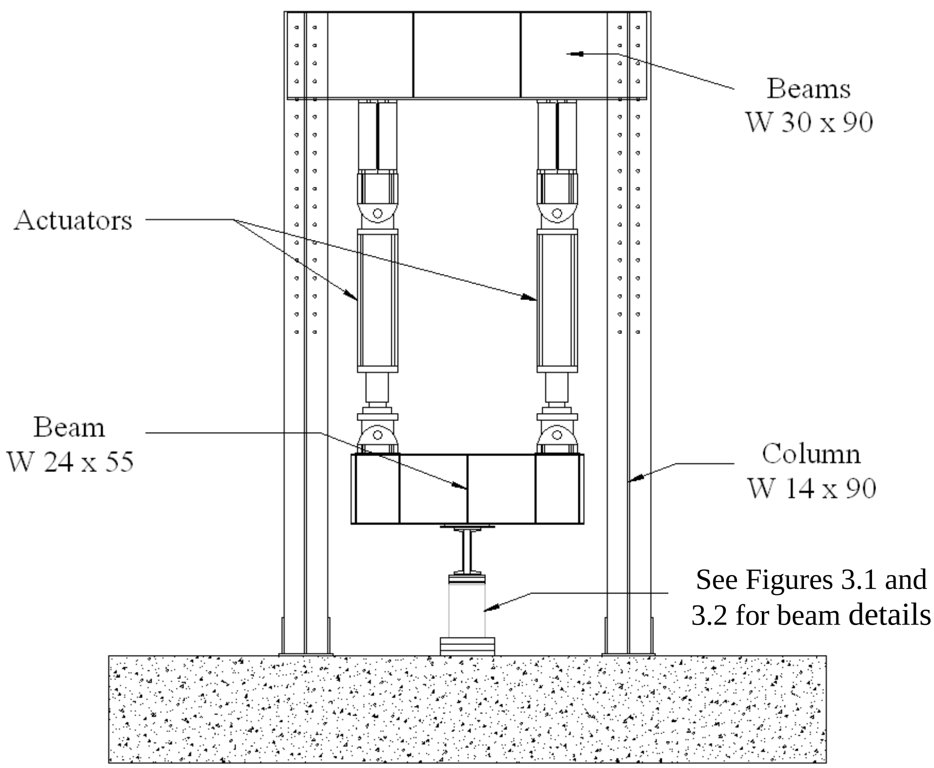


Figure 3.4: Details of Test Set-Up (1)

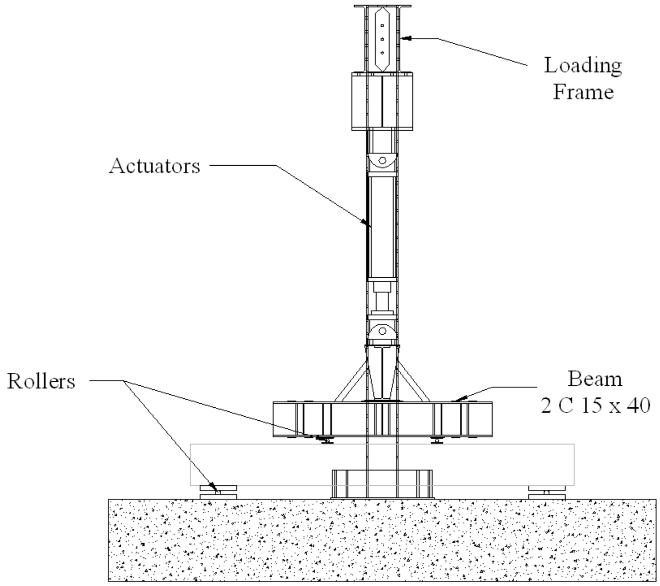


Figure 3.5: Details of Test Set-Up (2)

Figure 3.6: Photograph of Test Set-Up

3.6. INSTRUMENTATION

The specimens were instrumented with several measurement devices in order to monitor global and local deformations and strains. The load was directly measured from the load cell of the actuators. All devices were connected to a data acquisition system capable of reading up to 120 channels and all the data was recorded as shown in **Figure 3.7.**

Figure 3.7: Data Acquisition System

3.6.1. Local Deformations and Strains. Electric resistance gauges were used to monitor local strains in the longitudinal steel reinforcement of the test region. The strain gauges were purchased from Vishay Precision Group. They were made of constantan foil with 120 ohm resistance and had a linear pattern (uniaxial) with a gauge length of ¼ in.

One strain gauge was installed on longitudinal steel reinforcement in the test region as shown in **Figure 3.2.** The strain value obtained from the strain gauge is localized measurements at the point where the gauge is installed. It was located at the mid-span of beam.

3.6.2. Global Deformations. One Linear Variable Displacement Transducer (LVDT) was used to monitor vertical deflection of the test specimen. The LVDT was located at the midpoint of the test specimen, 3 in. from the top of the beam as shown in **Figures 3.8** and **3.9**.

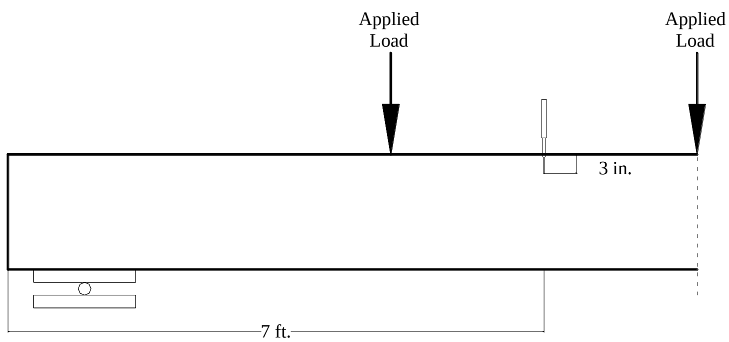


Figure 3.8: Location of LVDT to Measure Deflection

Figure 3.9: Detail of LVDT for Deflection Measurement

4. TEST RESULTS, BEHAVIOR & ANALYSIS

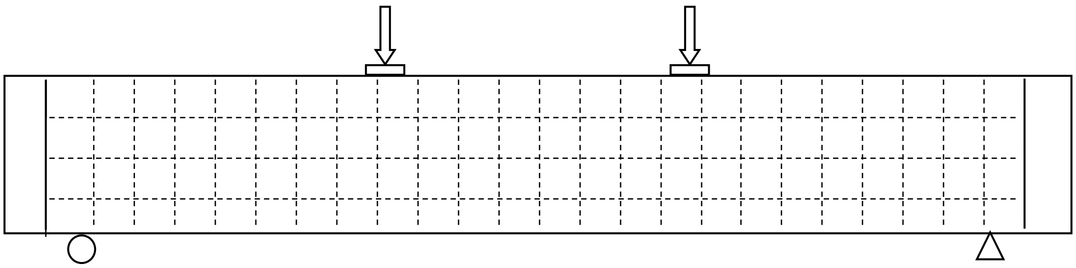
4.1. INTRODUCTION

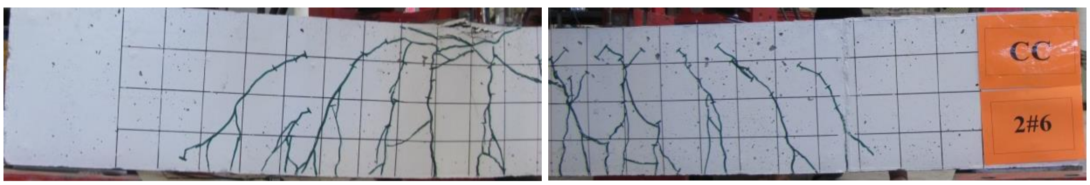
The purpose of this study was to evaluate the flexural behavior of full-scale reinforced concrete (RC) beams constructed from RCA, which has not been fully investigated in previous research studies. The objectives of this section are to: (1) discuss the general behavior of the specimens with regard to crack progression, crack morphology, and failure mode, (2) compare load-deflection behavior of the test specimens, (3) compare the RAC test specimen results with the control specimen test results, (4) compare the test results with predicted capacities based on applicable design standards, and (5) compare the test results with a flexural test database of conventional concrete specimens.

4.2. GENERAL BEHAVIOR

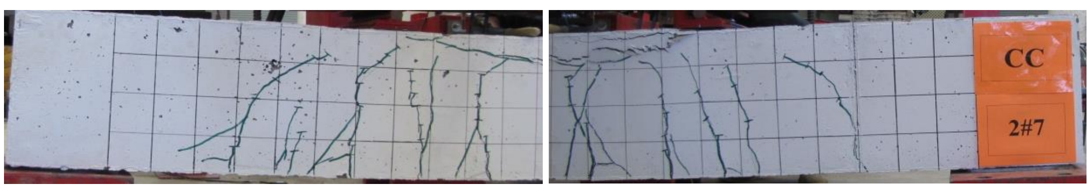
In terms of crack morphology and crack progression, the behavior of both CC and RAC beams was similar except for crack spacing – flexural cracks for the RAC beams were spaced closer compared to the CC beams. All of the beams failed in flexure. In all of the beams, the longitudinal tension steel yielded first, followed by the concrete crushing, which is a ductile mode of failure, normally called tension failure.

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. **Figure 4.1** 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 terms of crack spacing then has been reported by other researchers (e.g., Maruyama et al., 2004).

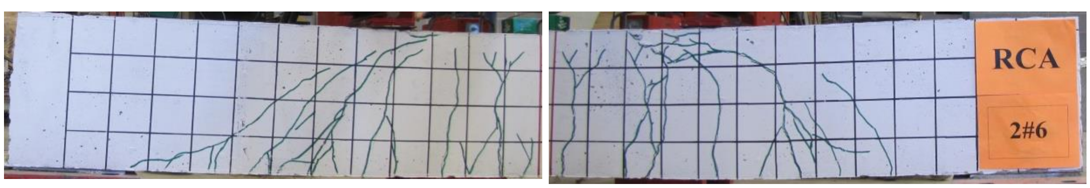




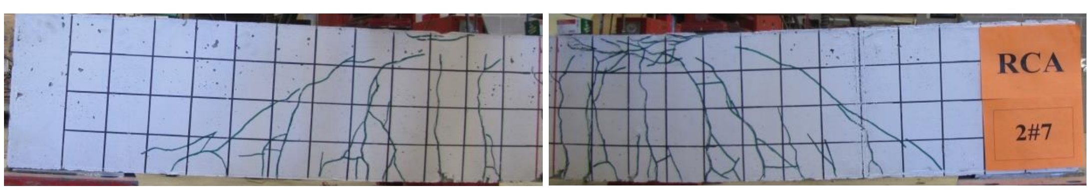
CC-F-6-1



CC-F-7-1



RAC-100-F-6-1



RAC-100-F-7-1

Figure 4.1: Crack Pattern of the Test Beams at Flexural Failure

4.3. LOAD-DEFLECTION BEHAVIOR

Figure 4.2 shows the load-deflection behavior for the test beams (the deflection was measured at midspan). Before the first flexural cracks occurred (point A), all of the beams displayed a steep linear elastic behavior. After additional application of load, the longitudinal steel yielded (point B). The beams then experienced the typical ductile plateau of RC flexural specimens. Eventually, sufficient rotation of the plastic hinge formed causing excessive strains in the compression zone of the beams and caused a crushing failure, resulting in failure of the specimens.

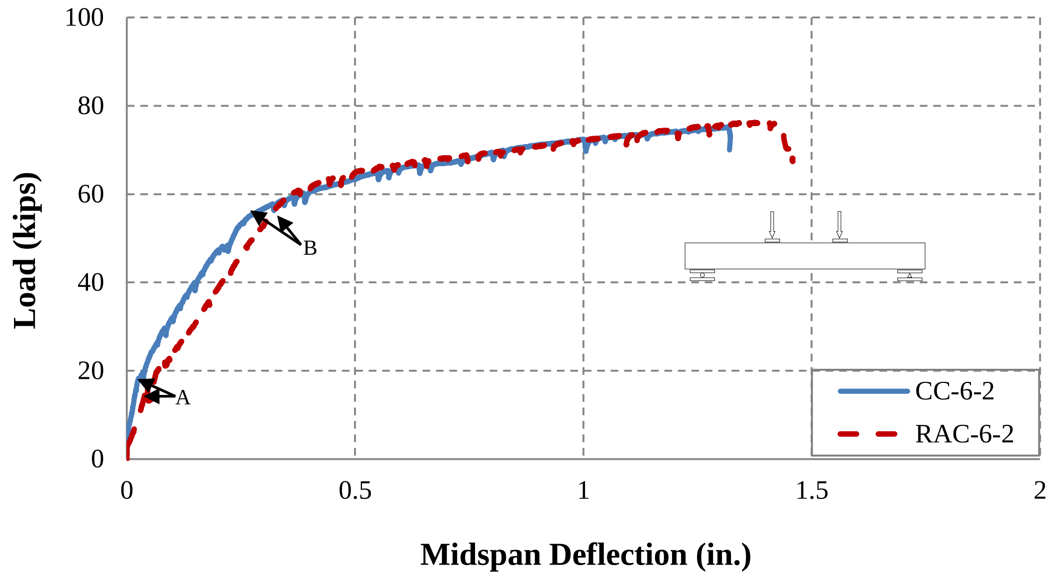
As shown in **Figure 4.2**, the RAC beams displayed lower cracking moment, which may be ascribed to the existence of two types of interfacial transition zones (ITZ) in the RCA beams (the ITZ between virgin aggregate and residual mortar in the RAC and also the ITZ between residual mortar and fresh mortar) compared with only a single ITZ (between virgin aggregate and fresh mortar) in the CC beams. Furthermore, the RAC beams showed lower stiffness after the cracking moments, which can be attributed to lower modulus of elasticity of the RCA mix compared with the CC mix due to the larger effective mortar fraction of the RAC.

4.4. COMPARISON OF CC AND RAC RESULTS WITH CODE PROVISIONS

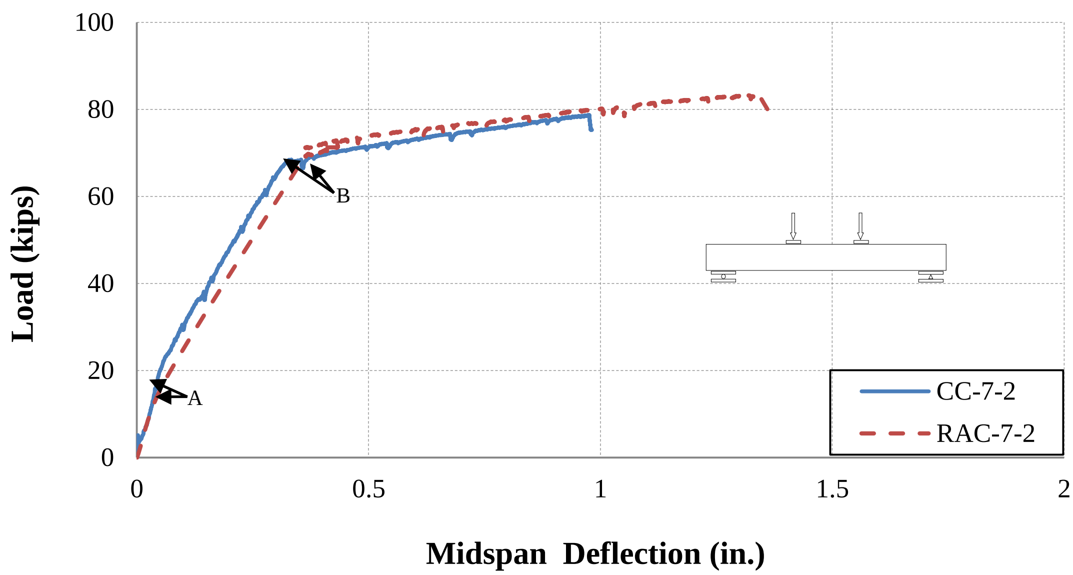
Table 4.1 summarizes the compressive strength of both the CC and RAC beams at time of testing, cracking moment, M_{cr} (**Equation 4.1**), yielding moment, M_y, nominal flexural strength, M_n (**Equation 4.2**), yielding deflection, δ_y, and ultimate deflection, δ_u.

$$M_{cr} = \frac{fr \times I_g}{y_t} \tag{4.1}$$

$$M_n = \rho f_y b d^2 (1 - .59 \rho \frac{f_y}{f_c^{'}}) \tag{4.2}$$



F-6



F-7

Figure 4.2: Load-Deflection of the Test Beams

Table 4.1: Test Results Summary

Section			f'_c	M_{cr} (Test)	M_{cr} (Predicted)	M_y (Test)	M_y (Predicted)	M_n (Test)	M_n (Predicted)	δ_y (Test)	δ_u (Test)
			psi	kips-in.						in.	
CC	F-6	1	5400	32.0	29.8	91.1	88.9	113.7	91.4	0.3	1.3
		2	4960	31.5	28.6	89.6	88.4	116.1	91.1	0.3	1.3
	F-7	1	5400	34.5	29.8	109.1	108.5	126.0	111.7	0.3	1.2
		2	4960	33.5	28.6	108.3	108.1	121.2	111.2	0.3	1.1
RAC-100	F-6	1	4450	25.5	26.9	88.0	88.0	110.4	110.3	0.4	1.4
		2	4550	26.5	27.5	92.5	88.5	114.3	110.7	0.4	1.4
	F-7	1	4450	31.0	26.9	108.8	107.7	127.4	90.4	0.3	1.4
		2	4550	31.5	27.5	109.4	108.1	124.9	90.7	0.3	1.3

The code prescribed equations underestimate the cracking moment for both the CC and RAC beams by 13% and 5%, on average, respectively. Although the equation overestimates the value for RAC-100-F-6 beams by approximately 5%. In terms of ultimate moment, the experimental moments for both the CC and RAC beams are 18% and 20% higher than the code provisions, respectively.

The RAC beams showed higher ultimate deflection compared with the CC beams, approximately 5% for F-6 and 22% for F-7 beams. This phenomena has been reported by other researchers (Maruyama et al., 2004; Sato et al., 2007; Ajdukiewicz et al., 2007) and is generally attributed to lower modulus of elasticity and also lower effective moment of inertia (increased flexural cracking) of the RAC beams compared with the CC beams.

4.5. COMPARISON OF TEST RESULTS WITH FLEXURAL TEST DATABASE

Figure 4.3 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 (Leet et al., 1997). **Figure 4.3** seems to indicate that the RAC 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 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 test values are very consistent with the wealth of flexural test data available in the literature and that the RAC beams possess equivalent flexural strength compared to CC beams.

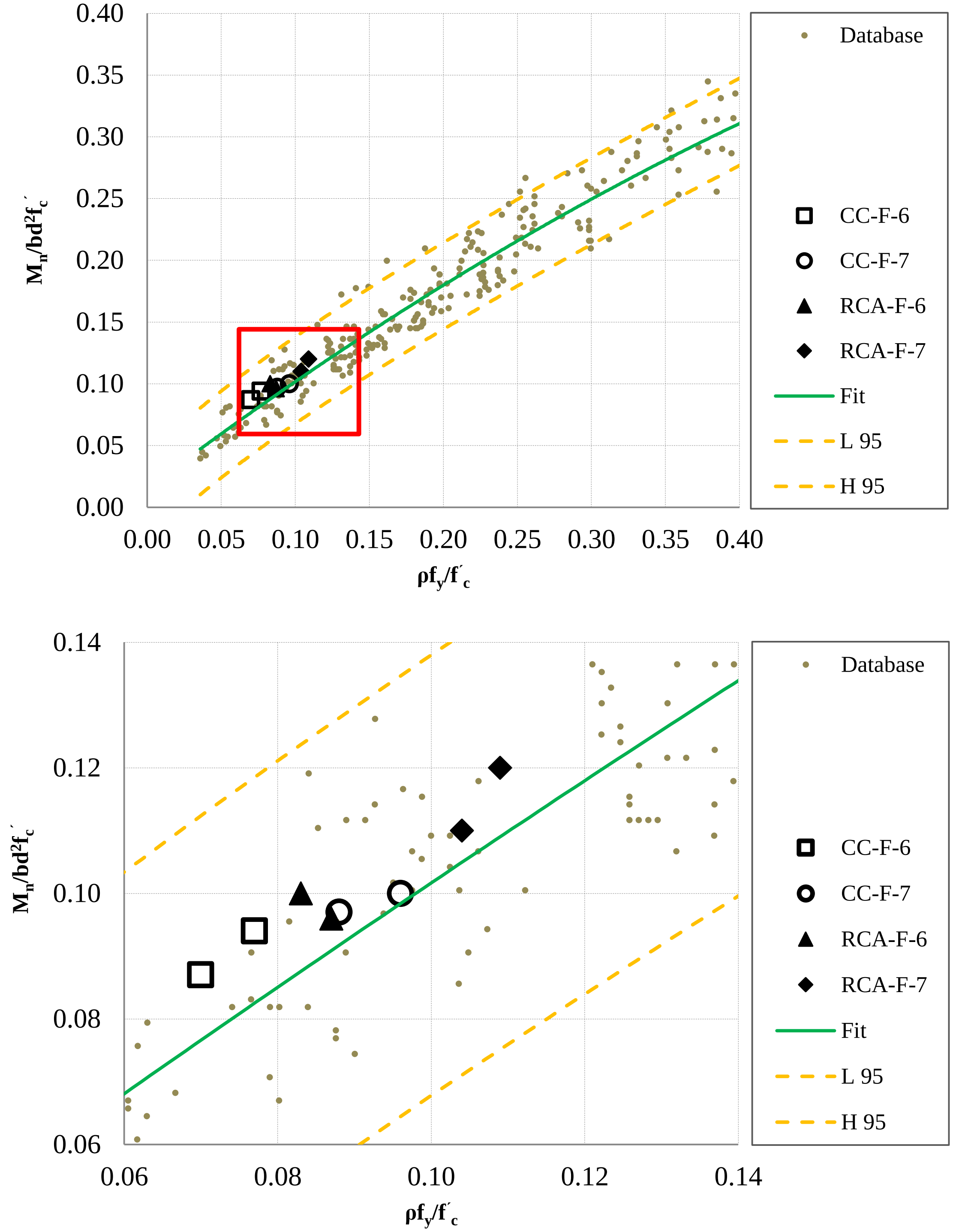


Figure 4.3: Normalized Flexural Strength vs. Normalized Longitudinal Reinforcement Ratio; Results from (Leet et al., 1997) and Test Results of this Study

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

The main objective of this research study was to evaluate the flexural behavior and response of RAC through material, component, and full-scale testing. The main feature of the experimental program consisted of eight tests performed on full-scale reinforced concrete beams. The principal parameters investigated were: (1) concrete type – RAC vs. CC, and (2) amount of longitudinal (flexural) reinforcement. The behavior of the RAC was examined in terms of crack progression, crack morphology and failure mode; load-deflection response; comparison with identical CC specimens; comparison with predicted strengths from design standards; and comparison with a flexural test database of CC specimens. This section contains the findings of the test program as well as conclusions and recommendations.

5.1. FINDINGS AND CONCLUSIONS

Based on the results of this research study, the following findings are presented with regard to flexural behavior and the use of recycled concrete as aggregate:

- In terms of crack morphology and crack progression, the RAC beams experienced a larger number, and corresponding closer spacing, of flexural cracks compared to the CC beams.
- In terms of load deflection behavior, the RAC beams showed lower stiffness both before and after the cracking moments compared to the CC beams.
- The RAC beams experienced lower cracking moments (around 7%) compared to the CC beams.

- No significant difference was observed between the yielding moments of the RAC and CC beams.
- The RAC beams showed higher ultimate deflection compared with the CC beams.
- The RAC beams showed comparable flexural capacity with the CC beams.
- The CC and RAC test results fall within a 95% confidence interval of a nonlinear regression curve fit of the CC flexural test database.
- Existing design standards conservatively predicted the flexural capacity of the RAC beams.

Based on the findings of this research study, the following conclusions are drawn with regard to flexural behavior and the use of recycled concrete as aggregate:

- The double interfacial transition zone (ITZ) for the RAC results in lower cracking moments compared to CC.
- The double ITZ for the RAC results in a higher number, and thus closer spacing, of flexural cracks compared to CC.
- The higher mortar fraction of the RAC results in a lower modulus of elasticity and thus stiffness compared to the CC, although the reduction is on the order of only 5% for the mixes studies in this investigation.
- Although limited based on the number of variables tested in this study, it would appear that replacing 100% of the virgin aggregate with RCA does not result in any decrease in ultimate flexural capacity compared to CC mixes.

5.2. RECOMMENDATIONS

Due to the limited number of studies of the flexural behavior of RAC, further research is needed to make comparisons and conclusions across a larger database. However, based on the findings and conclusions developed in this current study, the following preliminary recommendations are presented:

- Do not limit the percentage replacement of virgin aggregate with RCA based on ultimate flexural strength requirements, as it should not result in any noticeable decrease in capacity. Existing code provisions are applicable to concrete containing up to 100% RCA.
- Limit the percentage replacement of virgin aggregate with RCA to 50% where deflections or cracking are a serious design consideration.
- Additional testing is required to definitively determine whether RAC has the same flexural capacity compared to CC. This testing should investigate additional mix design variations, aggregate type and content, cross section aspect ratio, and type of loading. This database will then provide a basis for possible modifications to existing design standards.

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