12-2013

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FINAL REPORT

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OTREC-SS-725

December 2013

A National University Transportation Center sponsored by the U.S. Department of Transportation's Research and Innovative Technology Administration

CRACKING SUSCEPTIBILITY OF CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATES

Final Report

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by

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OTREC
OREGON TRANSPORTATION RESEARCH
AND EDUCATION CONSORTIUM

December 2013

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
OTREC-SS-725		

4. Title and Subtitle

Cracking Susceptibility of Concrete Made with Recycled Concrete Aggregate

5. Report Date

December 2013

6. Performing Organization Code

7. Author(s)

Dr. O. Burkan Isgor, Dr. Jason Ideker, Dr. Tengfei Fu, Matthew P. Adams

8. Performing Organization Report No.

9. Performing Organization Name and Address

O. Burkan Isgor
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

OTREC-2013-635

12. Sponsoring Agency Name and Address

Oregon Transportation Research
and Education Consortium (OTREC)
P.O. Box 751
Portland, Oregon 97207

13. Type of Report and Period Covered

Final Report
03/01/2013 – 12/31/2013

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

As high-quality, local, natural aggregate resources continue to become less available, and the cost of landfilling waste material rises, the need for alternative aggregates and recycling of waste material will increase. Using RCA in fresh concrete is one way to address both of these issues. However, there has long been a concern that RCA may negatively affect the properties of new concrete in which it is included. The results of the present investigation, however, indicate that the use of RCA in new concrete may not produce higher levels of free drying shrinkage as previously believed. Actually, these results show that when these RCAs were used for similar levels of free drying shrinkage, the cracking susceptibility of the concrete was reduced. The results demonstrate that even a small inclusion of RCA (25% replacement) may be a viable option to decrease the cracking susceptibility of concrete under drying conditions.

17. Key Words

Recycled Concrete Aggregate, Drying Shrinkage, Restrained Shrinkage, Cracking

18. Distribution Statement

No restrictions. Copies available from OTREC: www.otrec.us

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	34	

ACKNOWLEDGEMENTS

This project was funded by the Oregon Transportation Research and Education Consortium (OTREC).

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EXECUTIVE SUMMARY

As high-quality, local, natural aggregate resources continue to become less available, and the cost of landfilling waste material rises, the need for alternative aggregates and recycling of waste material will increase. Using recycled concrete aggregates (RCA) in new concrete is one way to address both of these issues. However, there has long been a concern that RCA may negatively affect the properties of new concrete in which it is included. In particular, since concrete produced with RCA typically contains a larger volume of mortar than conventional concrete, drying shrinkage has been considered to be a potential source of cracking in concrete. Excessive cracking in concrete can cause premature structural deterioration because it will lead to increased permeation of hazardous external contaminants (e.g., deicing salts), accelerated freeze-thaw damage, and corrosion of steel reinforcement. The present study seeks to address the identified gap in research by investigating how RCA as a replacement for natural aggregate in new concrete may affect the material's long-term cracking susceptibility.

In this research it was hypothesized that unique properties of concrete produced with RCA due to the presence of adhered mortar may provide a buffer against cracking, even though the concrete may go through higher amounts of shrinkage. If RCA can better endure these deformations, less stress will build internally, and subsequently, the cracking susceptibility may be reduced. The present research tests this hypothesis.

Shrinkage and cracking tendency of concrete produced with three levels (0%, 25%, and 100%) of RCA replacement was monitored using the ASTM C157 and ASTM C1581 testing procedures, respectively. Hardened mechanical properties, including compressive strength, splitting tensile strength and modulus of elasticity, were also measured. The RCA used in this research came from different courses: one type was created in the laboratory by crushing previously produced concrete following Oregon Department of Transportation (ODOT) guidelines for typical concrete bridge decks; another type was field RCA obtained from a demolished airfield pavement.

The results of the study demonstrated the following:

- Concrete made with RCA had similar mechanical properties and free drying shrinkage to comparable conventional concrete.
- In a restrained ring test, all RCA mixtures lasted longer before cracking, indicating that concrete produced with RCA outperformed the comparable control mixtures produced with natural aggregates.

These results indicate that the use of RCA in new concrete may not produce higher levels of free drying shrinkage as previously believed. Actually, these results show that when these RCAs were used, for similar levels of free drying shrinkage, the cracking susceptibility of the concrete was reduced. Even a small inclusion of RCA (25% replacement) may be a viable option to decrease the cracking susceptibility of concrete under drying conditions. This finding could possibly broaden the green options in concrete construction, especially in concrete pavement made from RCA.

It is important to note, however, that these results may only be valid for the aggregates presented here. Variability between different RCA types may result in different drying shrinkage properties. Therefore, it is important to test new materials which may be used for new concrete before including them in mixtures. This, perhaps, is the biggest true barrier to RCA usage.

Two students have made significant contributions to the present research. Doctoral student Matthew P. Adams was the main lead of the study, and was involved in all aspects of the work including planning, literature review, experimental design, testing, data analysis, and report writing. Undergraduate research assistant Adalberto Guerra Cabrera worked with Mr. Adams in the laboratory, and was instrumental in specimen preparation and quality control. In addition to these two students, a number of additional undergraduate and graduate students were also involved in the project, particularly during specimen preparation and continuous monitoring of the experiments.

This research has been presented as a poster in the Oregon BEST FEST '13 Research & Innovation Poster Session, which took place in Portland on September 11-12, 2013. In addition, the work was presented by Mr. Adams, a Ph.D. candidate, in the 2013 American Concrete Institute Fall Convention that took place in Phoenix, AZ, Oct. 19-22, 2013. Currently, a paper is being prepared to be submitted to a peer-reviewed international journal.

1.0 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Concrete is the most prevalent modern construction material and is widely used for all types of structures. In the fresh state, concrete typically contains about 12% cement and 80% aggregate by mass. Global construction industry uses approximately 1.6 billion tons of cement and 10 billion tons of sand, gravel and crushed rock annually (Neville, 2001). The world's annual cement production of 1.6 billion tons accounts for about 7% of the global carbon dioxide (CO_2) emission into the atmosphere. Producing one ton of Portland cement requires about four giga-joules of energy (Neville, 2001).

Extraction of natural virgin aggregates from the ground and riverbeds to produce concrete has severe environmental consequences. It destroys the natural habitat of species and causes deforestation, topsoil erosion, and loss of water storage capacity of the ground (Winfield and Taylor, 2005). Mining, processing and transportation of virgin aggregates also contribute significantly to greenhouse gas emissions (Abbas, Fathifazl et al., 2006). Therefore, there is an urgent need to mitigate these environmental impacts by reducing the amount of natural aggregates used in concrete; the use of recycled concrete aggregates (RCA) obtained from demolished concrete as a replacement for natural aggregates is motivated by this demand.

RCA are produced from demolished concrete structures and pavements. After demolition the concrete is cleaned of contaminants such as steel, masonry, wood, and asphalt, and then sent to crushing facilities where it is reduced to the appropriate grading for engineering applications (American Concrete Institute, 2001). When the material is graded and ready for use in engineering applications it is called recycled concrete aggregate, and can be used as aggregate in new concrete, riprap, road base or sub-base, and fills. This report will focus on the material's use as an aggregate in new concrete.

RCA consists of two-phase particles that contain both the original natural aggregate and the adhered mortar. The adhered mortar is composed of both the original cement paste and the original fine natural aggregate (Froundistou-Yannis, 1977; Fathifazl, Abbas et al., 2009). Much of the early research on the use of RCA in new concrete showed that RCA typically caused a reduction in mechanical properties of new concrete (Buck, 1977; Kikuchi, Miura et al., 1998; Dhir, Limbachiya et al., 1999). However, more recent work has shown that through modifications to mixture design, mechanical properties equaling or exceeding those of a similar natural aggregate concrete mixture can be obtained while still maintaining sufficient workability in the fresh concrete (Fathifazl, Razaqpur et al., 2010; Kou, Poon et al., 2011). RCA has been used successfully for several years now in new concrete applications, particularly in paving operations (Gress, Snyder et al., 2009). Several concerns regarding the durability still exist, however.

Despite diminishing supplies of high-quality virgin aggregates near construction sites and the need to minimize unsustainable disposal of demolished concrete, RCA is not widely used to produce new concrete. The two main reasons behind low utilization of RCA in new concrete applications is a lack of guidelines and specifications, and a perception that RCA is of substandard quality to virgin aggregates.

In a recent survey of state transportation departments performed by two of this report's authors, it was found that the use of RCA is still limited by a concern over the long-term durability of concrete made with the material. Of paramount concern was the effect the material had on shrinkage, alkali-silica reaction, and chloride ingress (Ideker and Adams, 2013). Drying shrinkage is one of the leading causes of concrete deterioration and is the focus of this report.

1.1.1 Drying Shrinkage

Drying shrinkage is the contraction of hardened concrete caused by the loss of capillary water to the surrounding environment. Drying shrinkage will occur until the internal relative humidity of the cement paste reaches equilibrium with the atmospheric relative humidity. Many factors affect drying shrinkage of concrete. These factors include the type and fineness of cement, type of aggregate, aggregate size, w/c, RH, admixtures used, duration of curing and the size of the concrete specimen (ACI-209.1R, 2005).

Drying shrinkage of unsealed concrete occurs in the cement paste due to a loss of water from capillary voids typically less than 50 nm in diameter (Mehta and Monteiro, 2006). Upon drying, the water held in larger pores is the first water to be lost. The loss of this water will not cause any significant shrinkage. Then, in smaller capillary pour or gel pours, the formation of the menisci (liquid-vapor interfaces) occurs due to water evaporation. As water evaporates into the surrounding environment, vapor pressure decreases and tensile stress in the remaining water increases. This eventually results in a capillary tension large enough that can lead to shrinkage and residue tensile strength throughout the entire paste matrix, which may lead to cracking.

Studies have shown that when using RCA as a straight replacement for coarse natural aggregate in concrete, an increase in drying shrinkage is typically observed (Ravindrarajah, 1996; Kikuchi, Miura et al., 1998; Khatib, 2005; Castano-Tabares, Domingo-Cabo et al., 2009). However, more recently, it has been shown that higher levels of shrinkage do not necessarily correspond to higher stress levels and earlier cracking in concrete containing RCA (Jeong, 2011; Corinaldesi and Moriconi, 2012).

1.1.2 Project Objectives

Since concrete produced with RCA typically contains a larger volume of mortar, drying shrinkage may be large enough to induce cracking. Excessive cracking in concrete can cause premature structural deterioration because it will lead to increased permeation of hazardous external contaminants (e.g., deicing salts), accelerated freeze-thaw damage, and corrosion of steel reinforcement. The proposed study seeks to address the identified gap in research by investigating how RCA as a replacement for natural aggregate in new concrete may affect the long-term cracking susceptibility of the material. This project examines the cracking susceptibility of concrete containing RCA. Specific objectives for this project were as follows:

- Determine whether concrete containing coarse RCA was more or less likely to crack than conventional concrete containing just natural aggregates;
- Understand the connection between mechanical properties, drying shrinkage, and cracking susceptibility of concrete containing RCA; and
- Understand the risk of cracking due to drying shrinkage in concrete containing RCA.

2.0 MATERIALS AND METHODS

2.1 MATERIALS

2.1.1 Aggregates

For the study presented herein a local natural river gravel and sand were used as well as two RCA. The aggregates that were used are described in more detail in Table 2.1.

Table 2.1: Aggregate properties and descriptions

Aggregate Name	Aggregate Source	Absorption Capacity (%)	Specific Gravity	Description
Control (coarse)	Oregon natural river gravel	3.15	2.52	Rounded, siliceous river gravel
Control (fine)	Oregon natural river sand	3.08	2.41	Siliceous river sand
AF-RCA	Demolished California airfield pavement	4.34	2.4	Recycled concrete aggregate that contains adhered mortar and rough, angular natural coarse aggregate. Source of natural aggregate unknown
LAB-RCA	Laboratory produced	5.71	2.24	Recycled concrete aggregate that contains adhered mortar and broken rounded gravel. Original natural aggregate is the control aggregate.

From Table 2.1, the absorption capacity of the RCA (AFRCA and LABRCA) is higher than the natural Control aggregate. Absorption capacity for RCA is typically higher than for natural aggregates due to the presence of adhered mortar, which is porous and absorbs more water than natural aggregates (Gómez-Soberón, 2002). Subsequently, the adhered mortar also affects the specific gravity of the RCA coarse aggregate, which is lower than that of the natural aggregate, due to lower density of the adhered mortar (Dhir, Limbachiya et al., 1999).

The AFRCA was obtained from a demolished airfield in California. Very little information is known about the parent concrete, however, the pavement was in good condition when demolished. It was unknown when the concrete was demolished, and when it was crushed. The material was received from a crushing facility, free of contaminants in sizes ranging from below 100 µm to 25 mm. The material was separated into various sizes in the laboratory and then the large material was crushed down to 12.5 mm. nominal maximum size aggregate. The RCA was then remixed to match a prescribed grading described below in Section 2.1.2.

The LABRCA was produced in the Oregon State University Infrastructure Materials Laboratory. For the original concrete from which the LABRCA was produced, a w/cm of 0.37 was used, with the total cementitious materials content was 375 kg/m^3, containing 30% class F fly ash and 4% silica fume as mass replacement. The coarse and fine aggregate content were 1,071 kg/m^3 (19mm maximum aggregate size), and 659 kg/m^3, respectively. The coarse and fine aggregate used were the Control aggregates listed above in Table 2.1. A high-range water reducer and air entrainer was used to target 150mm slump and 6% air content. Mechanical properties for this concrete can be seen below in Table 2.2.

Table 2.2: 28-day mechanical properties for LABRCA original concrete

Mechanical Properties	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Average	19.6	2.34	19.6
Standard Deviation	1.33	0.26	0.71

The concrete was allowed to cure in a 100% relative humidity chamber at 23 ± 2°C for 90 days, and was then removed and placed in a 23 ± 2°C room with no humidity control until it was crushed and used (approximately nine months to one year). The LABRCA was then broken apart using a sledge hammer to chunks with diameters of 50 mm – 125 mm. These were then passed through a laboratory scale crusher and broken down into smaller chunks ranging from 100 μm to 12.5 mm nominal maximum size aggregate. The RCA was then remixed to match a prescribed grading described below in Section 2.1.2.

2.1.2 Aggregate Grading

The grading of the RCA coarse aggregates was altered to match the natural coarse river gravel that was used as closely as possible. Some modifications were made due to limited RCA material resources. The coarse aggregate grading curves are presented below in Figure 2.1.

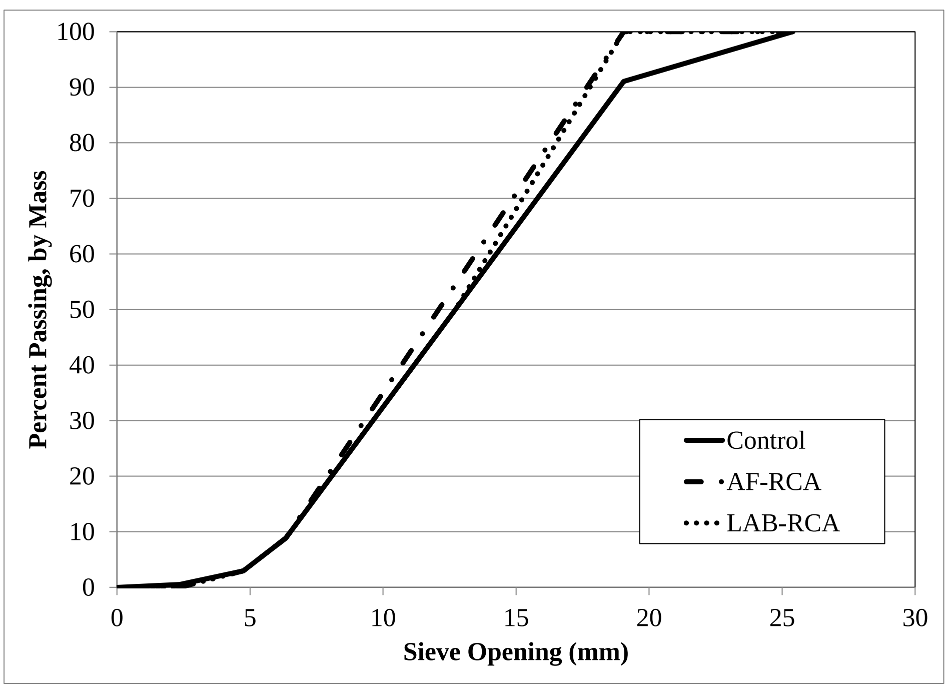

Figure 2.1: Coarse aggregate grading

As the grading curve indicates, the coarse RCA were graded to closely match the natural aggregate used in the control mixture. Both RCA mixtures were more gap-graded, however, than the control mixture due to a lack of available larger (15 mm and greater) material that prevented a more closely matched curve.

2.1.3 Cement

The cement used was a type I/II Portland cement. The oxide analysis for this cement is presented below in Table 2.3.

Table 2.3: Cement oxide analysis

Cement Oxide	%, by Weight
Silicon Dioxide (SiO_2)	20.5
Aluminum Oxide (Al_2O_3)	5.0
Iron Oxide (Fe_2O_3)	3.4
Calcium Oxide (CaO)	63.3
Magnesium Oxide (MgO)	0.9
Sodium Oxide (Na_2O)	0.3
Potassium Oxide (K_2O)	0.3
Titanium Dioxide (TiO_2)	0.3
Manganese Dioxide (MnO_2)	0.1
Phosphorus Dioxide (P_2O_5)	0.1
Strontium Oxide (SrO)	0.2
Barium Oxide (BaO)	0.1
Sulfur Trioxide (SO_3)	3.1
Loss on Ignition	2.5

2.2 MIXTURE DESIGN

The mixture design parameters and fresh properties for all concrete mixtures are shown in Table 2.4.

Table 2.4: Concrete mixture design and fresh properties

Mixture Name	w/c	Cement Content (kg/m^3)	Control Coarse Natural Aggregate (kg/m^3)	AFRCA (kg/m^3)	LABRCA (kg/m^3)	Natural Fine Aggregate (kg/m^3)	Air Content (%)	Slump (mm)	Fresh Unit Weight (kg/m^3)
Control	0.40	394	1092	0	0	682	1.5	76	2399
AFRCA 25%	0.40	394	819	273	0	682	1.5	95	2346
AFRCA 100%	0.40	394	0	1092	0	682	1.5	76	2399
LABRCA 25%	0.40	394	800	0	267	635	1.5	57	2350
LABRCA 100%	0.40	394	0	0	1067	635	1.5	57	2350

A water to cement (w/c) ratio of 0.40 was held constant for these mixtures as well as a cement content of 394 kg/m^3. The control aggregate was replaced with each RCA at 25% and 100% mass replacement levels.

Aggregates were not washed prior to their use in the mixtures to try to mimic probable usage in the field. Prior to each mixture, moisture content of the aggregate was measured, and the water content for the mixture was adjusted to ensure an effective w/c of 0.40. Air entraining admixtures were not used, and the measured air content of the mixtures match typical values for non-air entrained concrete (Kosmatka, Kerkhoff et al., 2008). Air content testing was performed in accordance with ASTM C 231 (ASTM Standard C231 2013, 2013). A polycarboxylate-based superplasticizer was used to increase workability in all mixtures, and acceptable slumps were achieved. Slump testing was performed in accordance with ASTM C 143.

2.3 TESTING METHODS

2.3.1 Mechanical Properties

Sample cylinders were cast according to ASTM C31(ASTM Standard C31, 2012) in plastic cylinder molds with a diameter of 100 mm and a height of 200mm. Compressive strength, splitting tensile strength, and modulus of elasticity testing were performed for each mixture at days 7, 14 and 28. Additionally, a set of 28-day mechanical properties tests were performed on cylinders that were match cured with the restrained shrinkage rings and free shrinkage prisms. These cylinders were cured for 14 days after casting in 100% relative humidity at 23 ± 2°C, and then moved to a chamber that was at 50% relative humidity at 23 ± 2°C for 14 additional days before testing.

Compressive strength testing was performed in accordance with ASTM C39 (Khatib, 2005). Splitting tensile strength testing was performed in accordance with ASTM C496 (ASTM Standard C496 2011, 2013). Modulus of elasticity testing was performed in accordance with ASTM C469 (ASTM Standard C469 2010, 2013). Results from the mechanical properties testing are presented in Section 3.1 of this report.

2.3.2 Free Drying Shrinkage

The ASTM C157 test was used to monitor the free drying shrinkage. The ASTM C157 test is the most commonly used method to determine the change in length of hardened concrete specimens prepared in the laboratory and subjected to drying. The length change was measured on hardened concrete prims (75mm × 75mm × 285mm). After being removed from the mold 24 hours after casting, the specimens (three prisms for each mixture) were stored in a moist room of 23 ± 2 °C and >95% RH for the 14 days for curing. Upon the end of the curing duration, the specimens were transferred to an environmental chamber with a controlled condition of 23 ± 2 °C and 50 ± 4 % RH (standard drying condition). During drying, the length change of each prism was monitored by a comparator. The mass change was also recorded.

2.3.3 Restrained Shrinkage Ring

Over the last few decades, the shrinkage ring test has been frequently used as a testing technique to identify potential cracking risks of certain concrete and mortar mixtures. Figure 2.2 shows the restrained ring test setup according to ASTM C1581 (ASTM Standard C1581 2009, 2013).

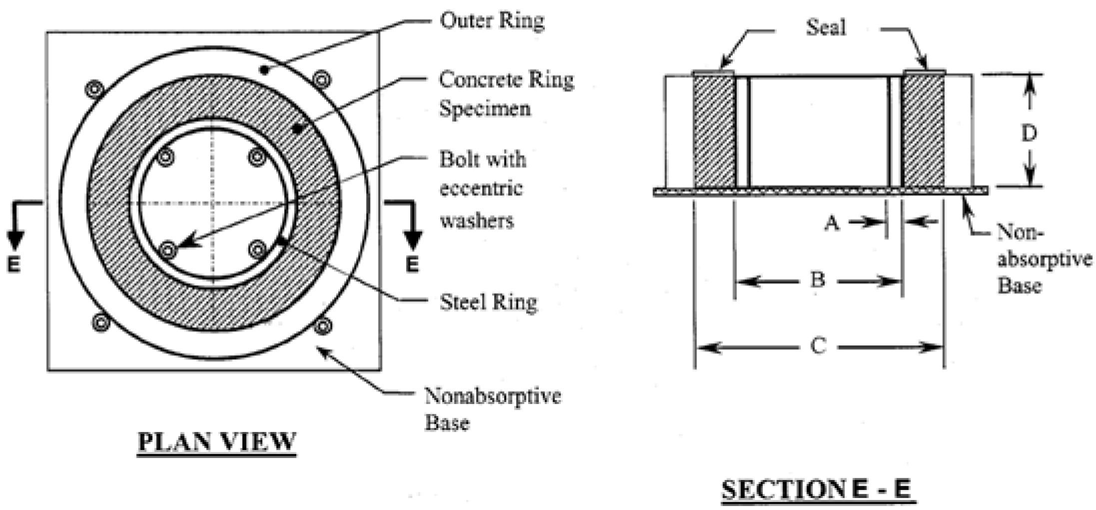

Figure Dimensions	ASTM
A	12.5 ± 0.13 mm
B	330 ± 3 mm
C	406 ± 3 mm
D	150 ± 6 mm

Figure 2.2: Dimension of restrained ring test setup (ASTM Standard C1581 2009, 2013)

A sample of freshly mixed concrete was compacted in a circular mold around an instrumented steel ring. The compressive strain developed in the steel ring caused by the restrained shrinkage of the specimen was measured from the time of casting. The specimens were moist cured using wet burlap covered with a polyethylene film for at least 24 hours at 23.0 ±2.0 °C. The outer ring was removed at 24 hours and the moist curing continued. During the curing process, the burlap was re-wetted as necessary to maintain a 100% RH under the polyethylene film. At the end of the curing process, the burlap was removed and the top surface of the specimen was sealed with a silicone sealant to allow for drying only in the horizontal (radial) direction. The strain gauge reading was monitored and recorded every three minutes until all three rings had shown visible cracking along the height of the ring.

After the burlap removal, the compressive strain gradually increases in the steel ring due to drying shrinkage of concrete ring. At the end of the test, a sharp jump in the strain gauge reading toward zero indicates the compression imposed by contraction of the concrete ring was released due to the cracking in the concrete. The time between exposure to drying and cracking is called time-to-cracking (days), which is an important parameter to evaluate the cracking resistance of the tested concrete. According to the strain gauge reading, an averaged stress rate (MPa/day) in the concrete could also be calculated as per ASTM C1581, and then used as another parameter in cracking evaluation. A detailed stress rate analysis and calculation could be found in the literature (See, Attiogbe et al., 2004). More information about the qualitative analysis of the restrained ring test can be found in the ACI Committee 231 report on early-age cracking (ACI Committee 231, 2010).

3.0 RESULTS

3.1 MECHANICAL PROPERTIES

Compressive strength, splitting tensile strength, and modulus of elasticity were measured for each of the mixtures cast. These values were measured at 7, 14 and 28 days for cylinders that were cured in the moist room for 28 days, and at 28 days for cylinders that were match cured (see Section 2.3.1 for more information on curing methods). Presented in this section are the results of the 28-day mechanical properties tests for each mixture. Seven- and 14-day data can be found in Appendix A.

Figure 3.1 shows the 28-day compressive strengths of the moist-cured and the match-cured cylinders from each concrete mixture.

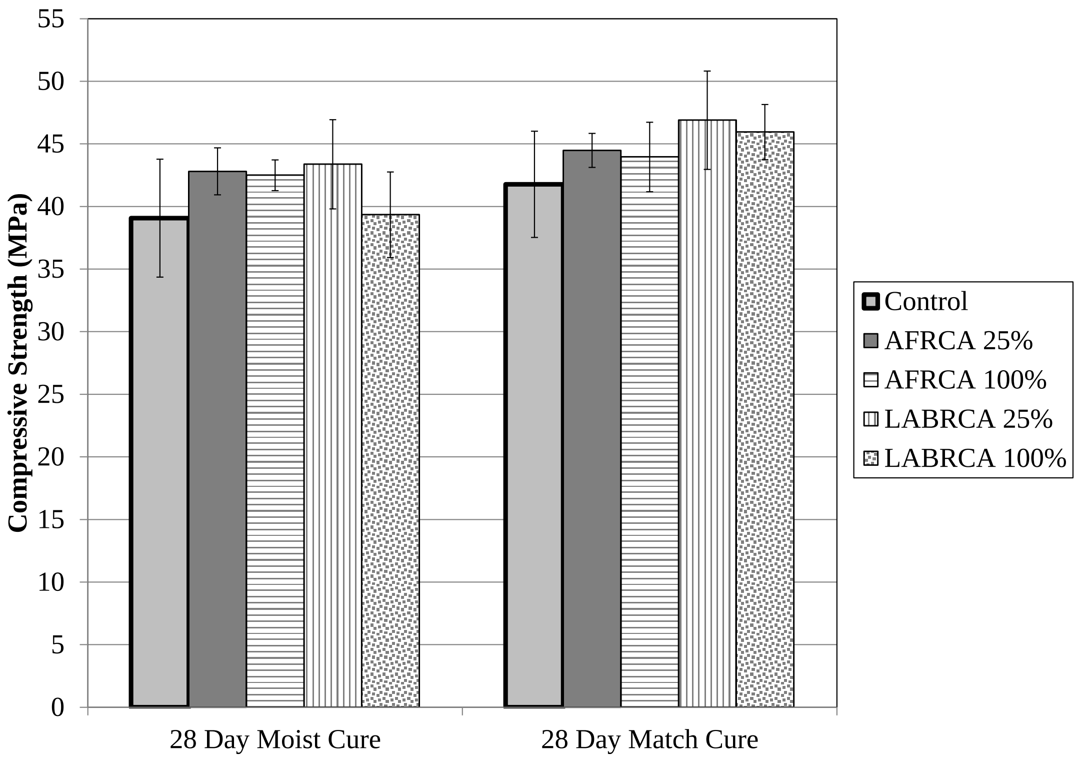

Figure 3.1: 28-day compressive strength for concrete mixtures

Compressive strengths were similar for all five mixtures. The match-cured concrete cylinders had higher average compressive strengths than the moist-cured cylinders, ranging from 1.7 MPa (AFRCA 25%) to 6.6 MPa (LABRCA 100%) higher. Additionally, the compressive strength of the mixtures containing RCA was higher than that of the control. The strengths of all mixtures are all similar and fell within standard testing error, and as such are not significantly different.

Figure 3.2 shows the 28-day splitting tensile strengths of the moist-cured and the match-cured cylinders from each concrete mixture. Splitting tensile strengths were also similar for all five mixtures. The match-cured concrete cylinders had higher average splitting tensile strengths than the moist-cured cylinders. Additionally, the splitting tensile strength of the mixtures containing RCA was higher than that of the control (excluding LABRCA 100%). The splitting tensile strength of each mixture was similar and fell within standard testing error, and as such is not significantly different.

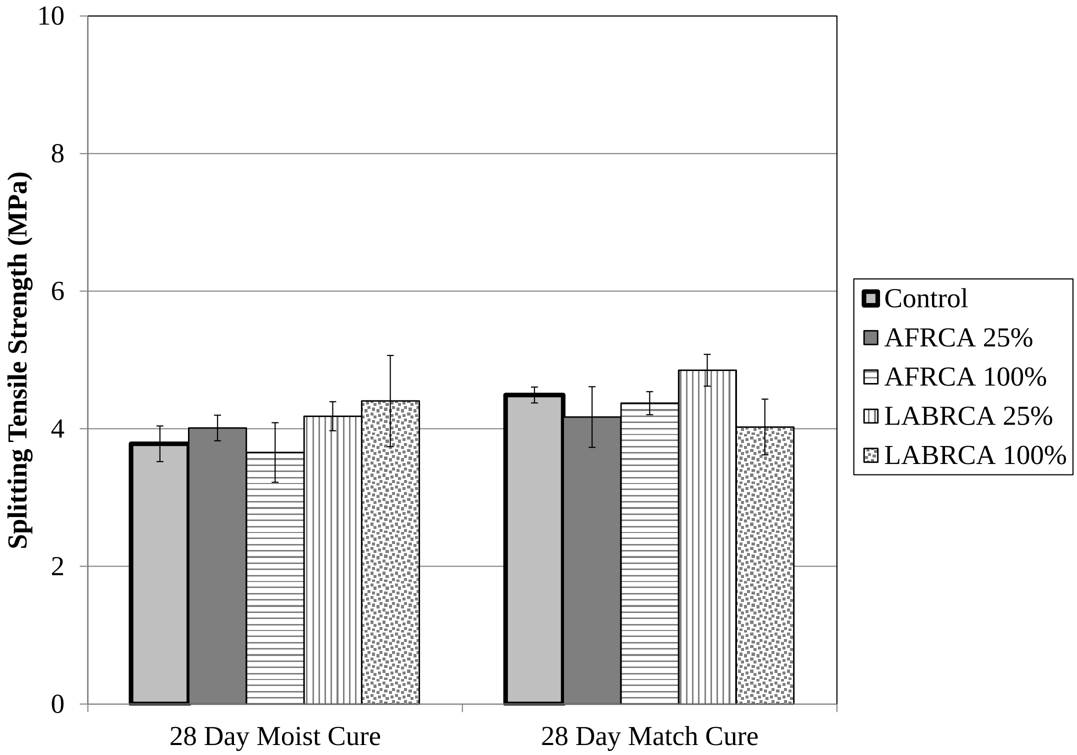

Figure 3.2: 28-day splitting tensile strength for concrete mixtures

Figure 3.3 shows the 28-day moduli of elasticity of the moist-cured and the match-cured cylinders from each concrete mixture. Moduli of elasticity were similar with differences at values below standard testing error. The inclusion of RCA did not significantly affect the modulus of elasticity, nor did the curing technique.

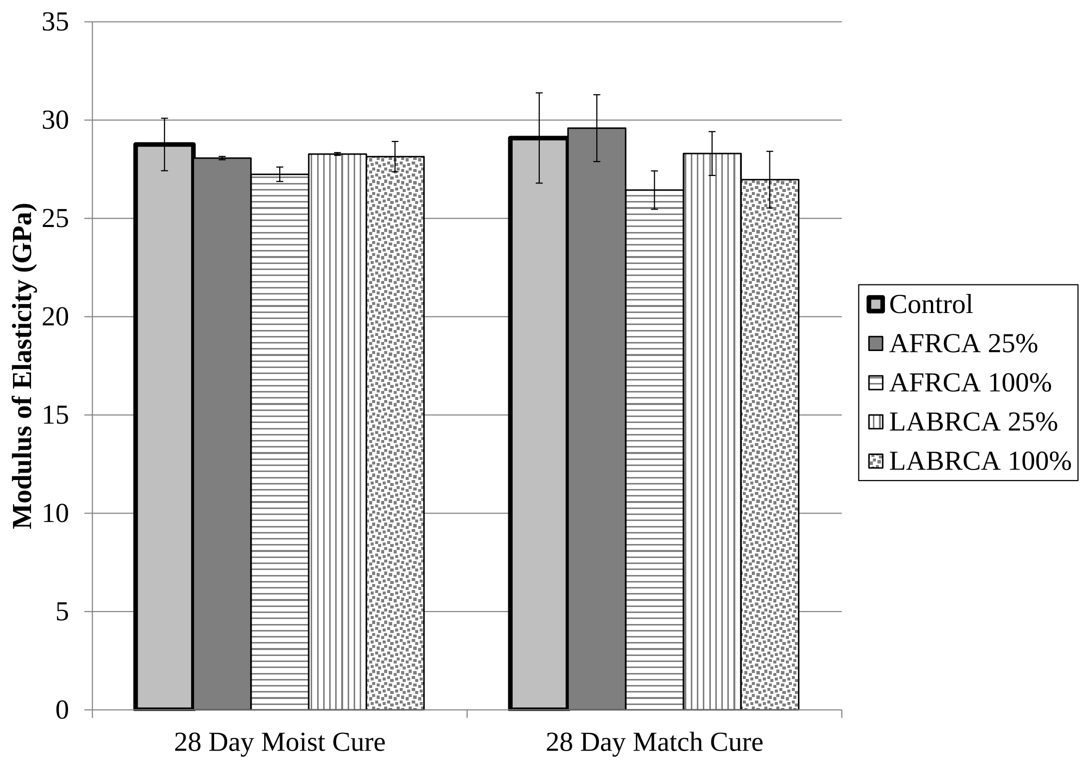

Figure 3.3: 28-day moduli of elasticity for concrete mixtures

3.2 FREE SHRINKAGE AND MASS CHANGE

Figure 3.4 shows the results of the free drying shrinkage test (ASTM C157) for all mixtures. These results indicate that the mixture that contained a 100% replacement of coarse LABRCA had the lowest drying shrinkage at 28 days, and the mixture that contained a 25% replacement of LABRCA had the highest drying shrinkage at 28 days. However, average values between all mixtures were not significantly different. All average 28-day length change values ranged from -0.053% to -0.063% with a 0.004% standard deviation between the average values of all sets.

Figure 3.5 shows the results of average mass loss due to drying of the free drying shrinkage prisms for all concrete mixtures. Mass change values were similar between all mixtures, and no significant differences between 28-day values were observed. Average mass change values ranged from -1.38% to 2.11% with a standard deviation of 0.30%.

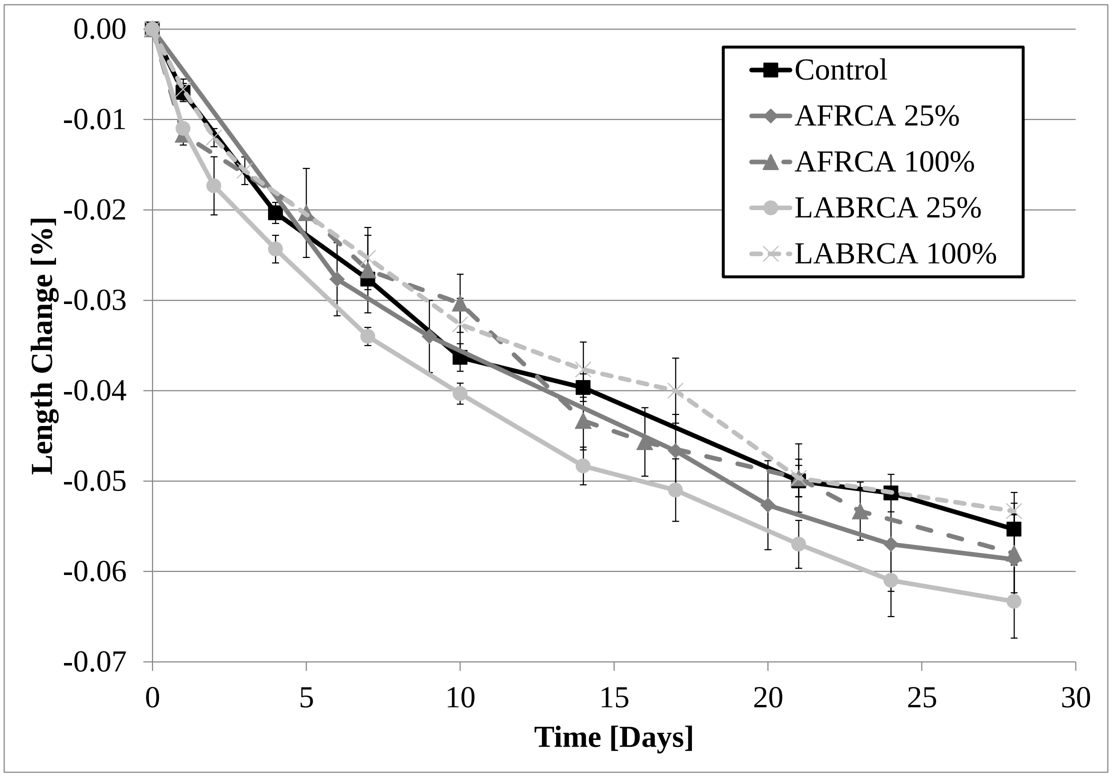

Figure 3.4: Drying shrinkage over time for concrete mixtures

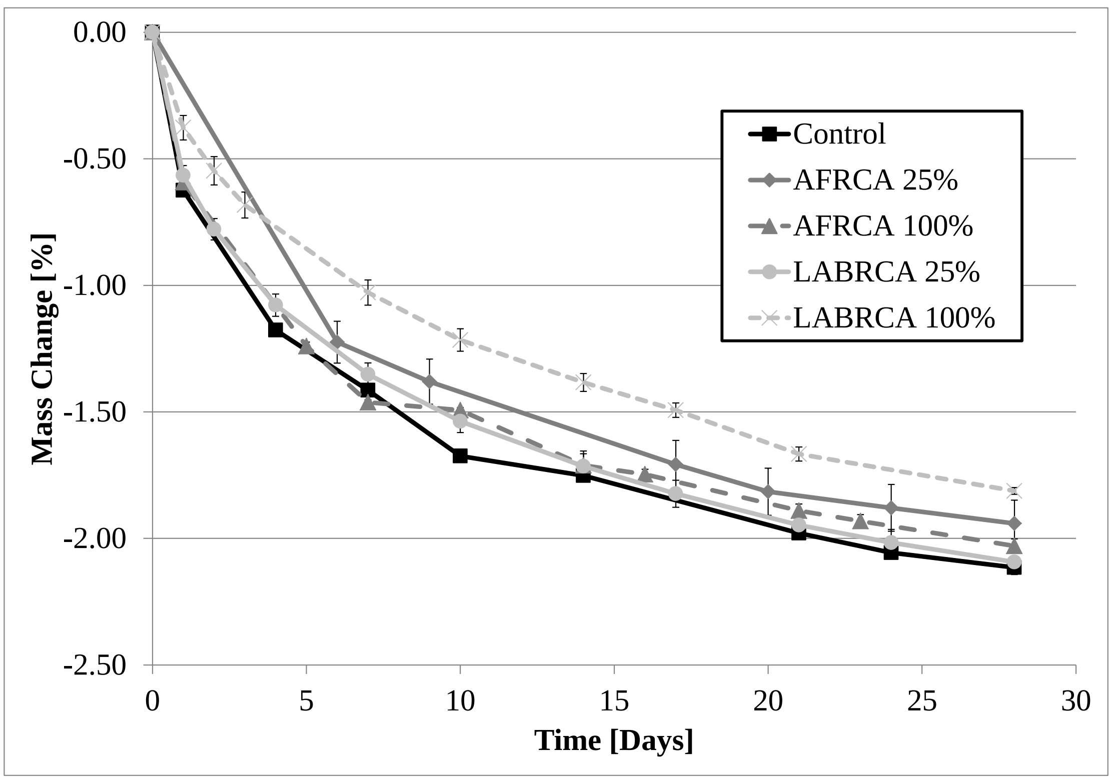

Figure 3.5: Mass loss due to drying over time for concrete mixtures

3.3 RESTRAINED SHRINKAGE RING

Table 3.1 gives a summary of the ASTM C1581 ring results, including time-to-cracking and the corresponding stress rate.

Table 3.1: Summary of time-to-cracking and stress rate of restrained shrinkage ring test

Mixture	Time-to-Cracking, Days				Stress Rate, MPa/Day				Cracking Potential Classification
	A	B	C	Ave.	A	B	C	Ave.	
Control	4.8	5.8	5.5	5.4	0.392	0.357	0.366	0.372	High
AFRCA 25%	7	8.2	8.4	7.9	0.271	0.248	0.268	0.263	Moderate High
AFRCA 100%	9.2	10.6	12.5	10.8	0.224	0.212	0.185	0.207	Moderate High
LABRCA 25%	6.1	7.7	7.9	7.2	0.403	0.296	0.279	0.326	Moderate High
LABRCA 100%	7.1	7.5	4.8	6.5	0.180	0.297	0.279	0.252	Moderate High

Time-to-cracking is the time elapsed between initiation of drying and the cracking in the rings. Upon cracking, a sudden change will show in two or more strain gauge, which can also be confirmed by visual inspection. Stress rate at time-to-cracking was calculated according to ASTM C1581. Based on time-to-cracking or stress rate, a cracking potential can be assigned to each mixture (as shown in Table 3.2).

Table 3.2: Cracking potential classification (ASTM Standard C1581 2009, 2013)

Time-to-Cracking, t_{cr}, Days	Stress Rate at Cracking, S, MPa/Day	Potential for Cracking
$0 < t_{cr} \leq 7$	$S \geq 0.34$	High
$7 < t_{cr} \leq 14$	$0.17 < S < 0.34$	Moderate-High
$14 < t_{cr} \leq 28$	$0.10 < S < 0.17$	Moderate-Low
$t_{cr} > 28$	$S < 0.10$	Low

It can be seen that the control mixture was rated high in cracking potential based on stress rate. All RCA mixtures fall in the Moderate High cracking potential based on stress rate results. In terms of time-to-cracking, all RCA mixtures outperformed the control mixture by sustaining longer before cracking in the rings.

3.4 DISCUSSION

The results of this investigation have shown that concrete produced with RCA responds differently (from conventional concrete) to stresses created by drying shrinkage. In general, it was observed that concrete produced with RCA has lower cracking susceptibility than conventional concrete. This difference is likely due to the fact that RCA is different from natural aggregates because it has two distinct components: original natural coarse aggregate and adhered mortar. Adhered mortar has lower density, higher plastic deformation capacity and higher water absorption capacity than natural aggregates; therefore, its presence in RCA alters the mechanical properties of the material and concrete made from it.

The reduction in cracking susceptibility of concrete produced with RCA can be hypothesized to be caused by the following properties of RCA concrete:

1) Unique plastic deformation capacity of RCA due to the presence of adhered mortar may provide a buffer against cracking, even though the concrete may go through higher amounts of shrinkage. If RCA can better endure these deformations, less stress will build internally and, subsequently, the cracking susceptibility may be reduced.

2) Virgin aggregates, either as part of the RCA or as conventional aggregates in RCA-concrete produced with partial aggregate replacement, might act as restraining points that increase the tensile forces in the concrete and promote crack initiation. In concrete produced with RCA, total mortar volume is larger, and virgin aggregates are further separated from each other compared to conventional concrete. Due to this, there may be less internal restraint and the concrete is able to accommodate more deformation prior to crack initiation.

The first hypothesis assumes that the modulus of elasticity of concrete produced with RCA would be lower than that of conventional concrete with similar mixture design (i.e., the lower modulus will allow the concrete to absorb additional stresses due to drying shrinkage). However, as presented in Section 3.1, the modulus of elasticity of concrete, along with other mechanical properties such as compressive and tensile strengths, did not show significant variations in the cases tested in this study. Both RCA concrete and conventional concrete specimens had reasonably comparable moduli. Therefore, for the samples tested in this study, this hypothesis does not explain the increase in cracking resistance of concrete produced with RCA. It should be noted that previous studies on the mechanical properties of concrete produced with RCA reported lower values of modulus of elasticity than comparable conventional concrete (Katz, 2003; Padmini, Ramamurthy et al., 2009). Therefore, it is likely that the RCA used in the present investigation had lower adhered mortar content than RCA used in other studies. Additional studies on the RCA used in this investigation need to be performed to characterize their residual mortar content. The hypothesis that RCA concrete has larger deformation capacity, hence higher resistance to cracking, is still plausible for different types of RCA. Additional studies are needed to investigate this possibility further.

On the other hand, the data obtained in this study provides support for the second hypothesis that virgin aggregates provide restraining points that cause tensile forces to build up in the concrete and promote crack initiation. Natural aggregates, in general, have higher moduli of elasticity than the cement paste that surrounds them (Mehta and Monteiro, 2006). In terms of absolute amounts of free drying shrinkage, this restraint can be beneficial because it will prevent the concrete from deforming and may reduce the amount of shrinkage observed in the concrete (Mehta and Monteiro, 2006). However, this same restraint also increases the amount of tensile forces that can develop in the surrounding area. This is due to the differential moduli of elasticity and drying shrinkage levels between the mortar and aggregate, which during drying will cause the mortar to deform more than the restraining aggregate (Goltermann, 1995; Idiart, Bisschop et al., 2012). This will promote cracking. In concrete containing RCA, the natural aggregates are spaced out further due to the addition of adhered mortar. And as a percentage of volume, there is less natural aggregate, and thus fewer locations where differential moduli of elasticity exist. This means that the concrete is allowed to deform more without the same level of restraint from the surrounding aggregates, reducing the amount of tensile forces that build up in the concrete compared to natural aggregate concrete. This will result in a lower propensity for crack initiation in these zones. Our results support this hypothesis. Although the concrete made with RCA had similar levels of free drying shrinkage, the time-to-cracking increased with the inclusion of RCA. The increase in adhered mortar through the inclusion of RCA, and the further spacing between natural aggregates due to the adhered mortar, reduced tensile forces that formed in the new mortar and extended the time-to-cracking in the specimens cast with RCA.

The replacement level of RCA (25% or 100%) did not seem to affect the time-to-cracking as much as just having RCA in the mixture did. The mixtures that contained AFRCA exhibited longer times-to-cracking when using a 100% replacement (10.8 days) than when using a 25% replacement level (7.9 days). The mixtures that contained the LABRCA exhibited a shorter time-to-cracking when using 100% replacement (6.5 days) than when using a 25% replacement (7.2 days). This may be due to the inherent variability of RCA as a material, however. Each RCA particle will not have the same amount of adhered mortar, and if the amount of adhered mortar varied greatly within the aggregate supply, then this may skew the results. The type of RCA may also be important. The AFRCA natural aggregate was a crushed, rough, angular aggregate of which we know little about. The LABRCA natural aggregate was the same natural aggregate, rounded river gravel, which was used in the control mixtures. While the modulus of elasticity of the concrete did not greatly vary with aggregate type or replacement level, it can be observed from Figure 3.3 that the match-cured specimens (identical curing regime to the restrained shrinkage rings) made with a 100% replacement level of AFRCA had the lowest modulus of elasticity. Though the modulus of elasticity did not vary greatly from the other mixtures studied here, the small difference may have been enough to accommodate more deformation before cracking and result in the longer time-to-cracking seen in the AFRCA 100% restrained shrinkage rings.

4.0 CONCLUSION AND RECOMMENDATIONS

As high-quality, local, natural aggregate resources continue to become less available, and the cost of landfilling waste material rises, the need for alternative aggregates and recycling of waste material will increase. Using RCA in fresh concrete is one way to address both of these issues. However, there has long been a concern that RCA may negatively affect the properties of new concrete in which it is included. These results indicate that the use of RCA in new concrete may not produce higher levels of free drying shrinkage as previously believed. Actually, these results show that when these RCAs were used, for similar levels of free drying shrinkage, the cracking susceptibility of the concrete was reduced. The results indicate that even a small inclusion of RCA (25% replacement) may be a viable option to decrease the cracking susceptibility of concrete under drying conditions.

It is important to note, however, that these results may only be valid for the aggregates presented here. Variability between different RCA types may result in different drying shrinkage properties. Therefore, it is important to test new materials which may be used for new concrete before including them in mixtures. This, perhaps, is the biggest true barrier to RCA usage.

The following recommendations for future work can be made:

1) Investigate different types of RCA, with varying adhered mortar content, so that the effect of adhered mortar content on cracking susceptibility is clearly understood. As part of this investigation, it is important to use RCA with large adhered mortar content to test the hypothesis that concrete produced with such RCA might have additional cracking resistance because of its lower modulus of elasticity than comparable conventional concrete.

2) Investigate the effect of different mixture proportioning techniques on the cracking susceptibility of concrete produced with RCA. In particular, investigate the role of direct RCA replacement in conventional mix designs, and the effect of specialized mix design procedures that control the amount of total mortar content in RCA concrete (Fathifazl, Abbas et al., 2009).

3) Develop a rapid series of testing that allows for the accurate determination of important concrete properties such as drying shrinkage susceptibility for a stockpile of RCA.

4) Investigate the field performance of concrete produced with RCA in terms of shrinkage-induced cracking to verify that the conclusions obtained here are valid in real applications as well.

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6.0 APPENDIX A

Appendix A contains additional results from mechanical properties testing of each mixture.

Figure 6.1 presents the compressive strength for all concrete mixtures over time.

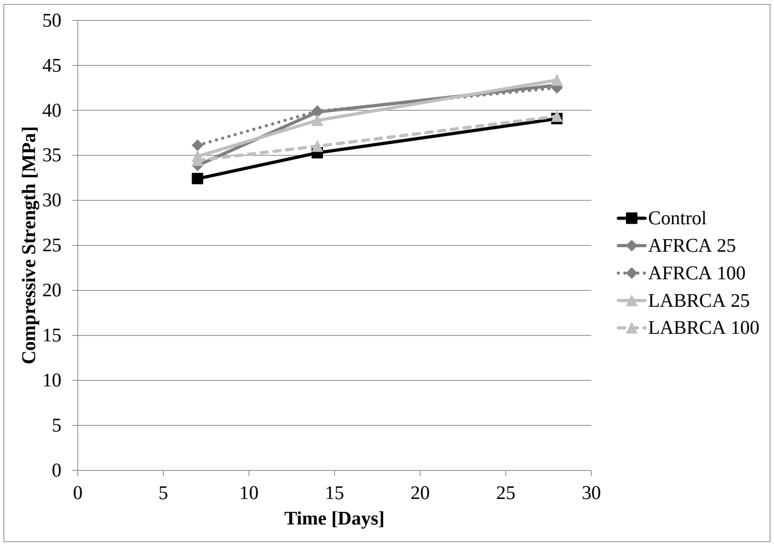

Figure 6.1: Compressive strength of concrete mixtures

Figure 6.2 presents the splitting tensile strength for all concrete mixtures over time.

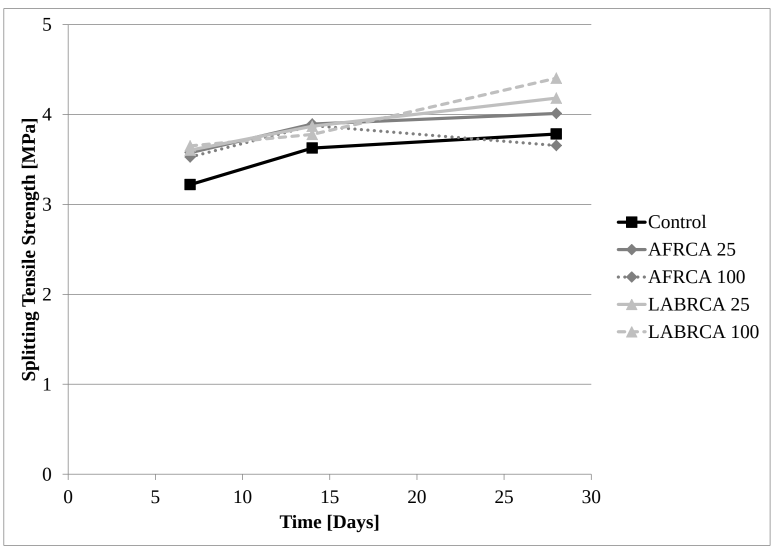

Figure 6.2: Splitting tensile strength of concrete mixtures

Figure 6.3 presents the modulus of elasticity for all concrete mixtures over time.

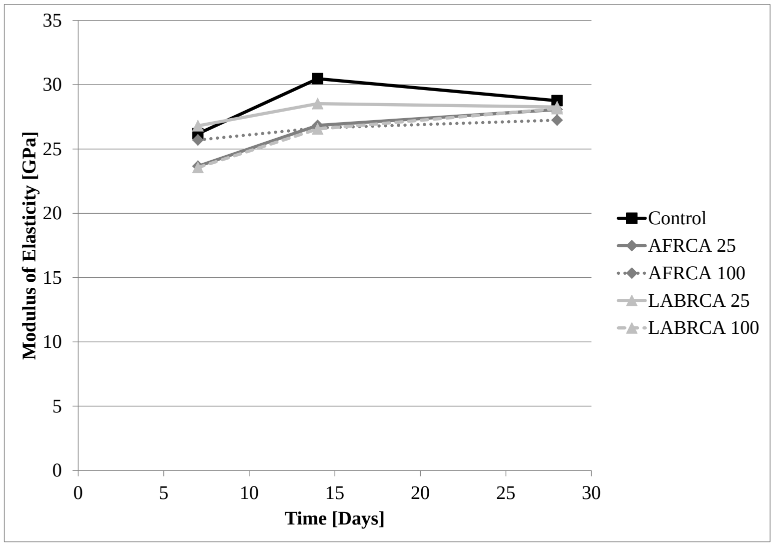

Figure 6.3: Modulus of elasticity of concrete mixtures

Figure 6.4 – 6.8 presents the strain gauge reading from the ring tests for all concrete mixtures over time.

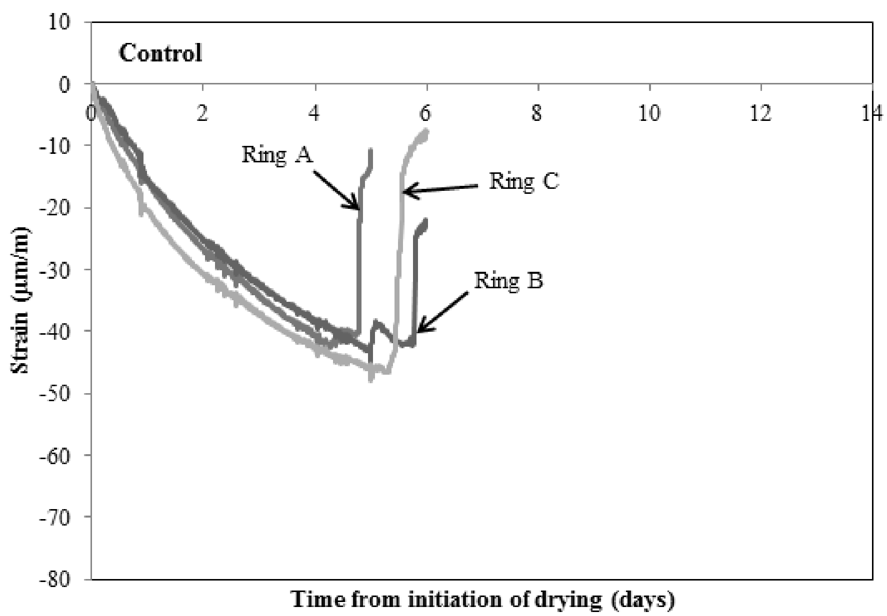

Figure 6.4: Strain gauge reading of mixture control

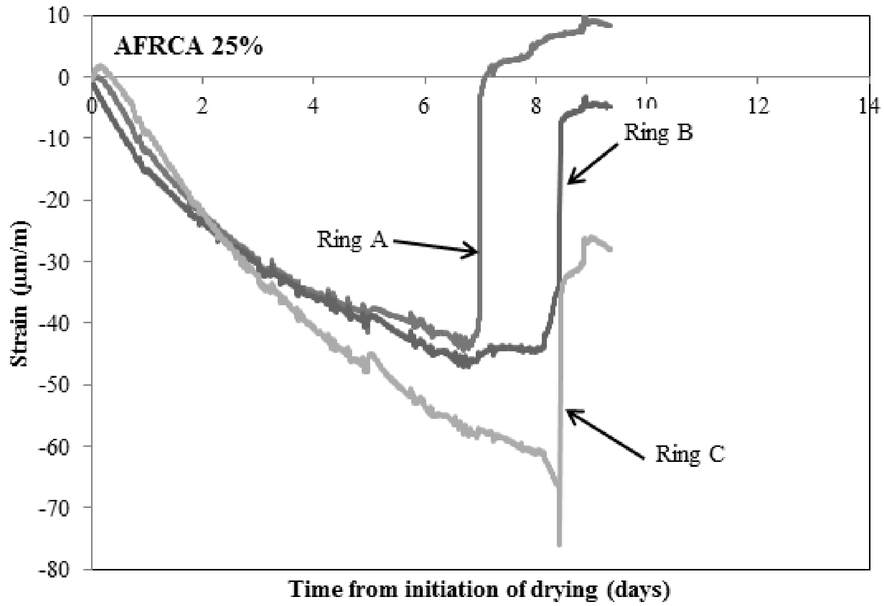

Figure 6.5: Strain gauge reading of mixture AFRCA 25%

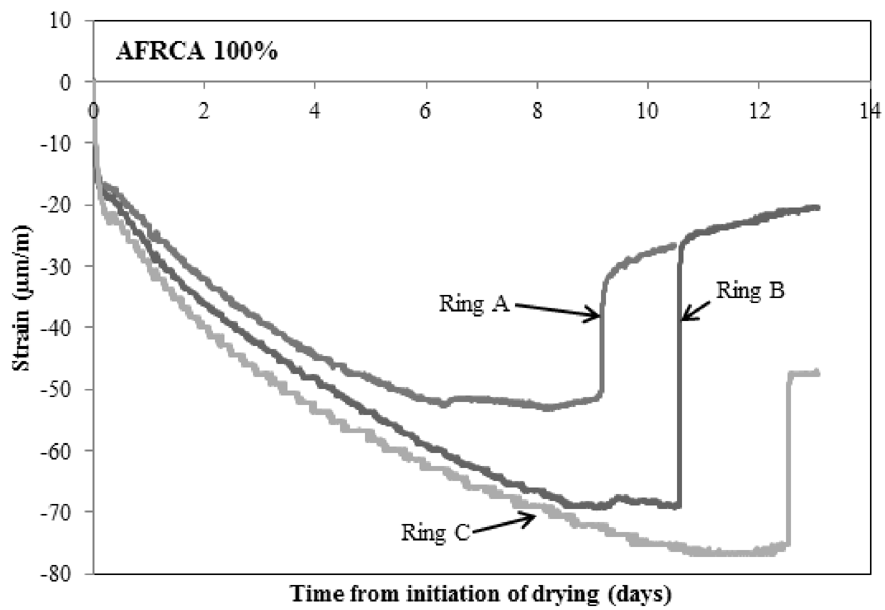

Figure 6.6: Strain gauge reading of mixture AFRCA 100%

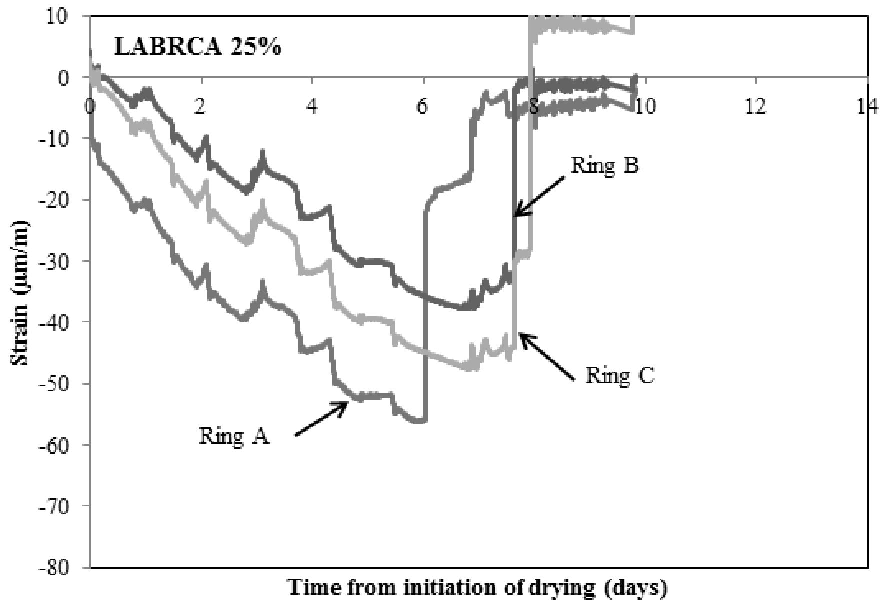

Figure 6.7: Strain gauge reading of mixture LABRCA 25%

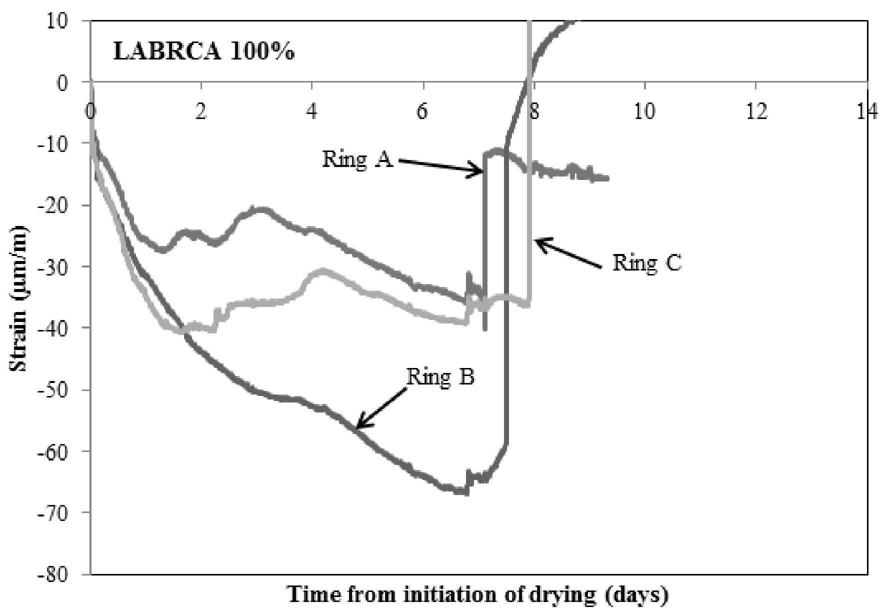

Figure 6.8: Strain gauge reading of mixture LABRCA 100%