FINAL Report B

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

Report B: Mechanical and Durability Properties of RCA Concrete

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ABSTRACT

The present project investigates the properties of sustainable concrete materials made with recycled concrete aggregate (RCA) as a partial replacement of coarse aggregate. Seven RCA-made experimental mixtures, as well as two mixtures made with virgin aggregates were used in this study. The study has focused on properties of a MoDOT Class B concrete mixture.

Several concrete mixtures with different amounts of RCA replacement varying from 30% to 100% were investigated. Two additional types of RCA concrete mixtures, mixed and proportioned according to different procedures, were also incorporated in the study. A mixture with 100% RCA replacement mixed according to the two stage mixing approach (TSMA) was studied to investigate the effect of TSMA on both the mechanical and durability properties of RCA-produced concrete. In addition, the equivalent mortar volume (EMV) method was used successfully to develop a mixture with approximately 30% RCA replacement.

Different fresh, mechanical, and durability properties were investigated in this study. Based on the results, it is concluded that it is possible to produce sustainable concrete mixtures using high volumes of RCA as replacement for virgin coarse aggregate in MoDOT Class B concrete.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

1.1. BACKGROUND

Sustainable solutions for the concrete industry are taking into account the durability, environmental impacts, and costs of the project (Kim 2013). Due to the increasing rate of demolition, it is essential to effectively reuse demolition waste in order to conserve the nonrenewable natural resources. Decreasing natural resources, as well as increasing problems with waste management, ecological hazards, landfill limitations and increasing distances between the natural resources and consumption markets, support the idea of recycled wastes to be used for new concrete production (Padmini et al., 2009). Besides, reducing the carbon footprint in such a highly consumed material is a key factor in decreasing the total emissions produced by the construction industry (Mclntyre 2009).

As a result of variable characteristics of recycled aggregates compared to virgin aggregate sources, there currently exists a conservative approach, limiting the use of recycled concrete aggregate (RCA) in field implementations (Surya 2013). RCA is mostly being used in granular bases, embankments, sound barriers, fills, and so on. (Kim 2013, Gabr 2012). Laboratory investigations on properties of concrete made with RCA has proved to be an issue of great interest during the past decades. However, there is a limited number of field implementations of RCA in structural applications, which is mainly due to a lack of proper selection criteria. The present study aims at investigating the feasibility of producing sustainable concrete materials for infrastructure applications. The research is mainly focusing on MoDOT Class B concrete mixtures.

1.2. OBJECTIVE AND SCOPE OF WORK

The main ***objective*** of this research study was to evaluate the fresh, mechanical, and durability properties of concrete mixtures made with RCA as virgin coarse aggregate replacement.

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 RCA concrete;
- Evaluate the fresh properties of the reference and RCA concrete;
- Evaluate the mechanical properties of the reference and RCA concrete;
- Evaluate the durability properties of the reference and RCA concrete;
- 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.

1.3. RESEARCH METHODOLOGY

The proposed research methodology included five (5) tasks necessary to successfully complete the study. They are as follows:

Task #1: The purpose of this task was to conduct a comprehensive and critical literature review of past experiences and previous research on RCA, with particular attention to the impact that these findings could have on the research plan. Specifically, the literature review focused on studies that investigated RCA properties (*e.g.*, absorption, durability) as well as the behavior of concrete containing RCA including the fresh and hardened properties (e.g., workability, compressive strength, flexural strength, shrinkage), and durability (*e.g.*, freeze-thaw resistance, permeability, scaling).

Task #2: Develop reference and RCA-made concrete mix designs. The purpose of this task was to develop concrete mixtures incorporating RCA as a partial or full replacement of virgin coarse aggregate. Alternative mixing procedures and experimental mix proportioning methods were also used for developing mixtures in this phase. Conventional concrete mix designs served as controls during this study.

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

Task #4: Analyze test data. The material, component, and test results were analyzed to evaluate the behavior of the developed mixtures compared to conventional virgin aggregate concrete. The test data included:

Fresh properties: Slump, air content, bleeding, and rheological properties.

Mechanical properties: Compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, shrinkage.

Durability: Permeable void volume, absorption, surface electrical resistivity, bulk electrical resistivity, freeze/thaw durability, and deicing salt scaling.

Task #5: Develop findings, conclusions, and recommendations. This task synthesized the results of the previous tasks into findings, conclusions, and recommendations on mechanical and durability properties of RCA-constructed concrete.

1.4. REPORT OUTLINE

This report includes five 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 producing concrete mixtures with different amounts of RCA replacement and using different mixing methods. This chapter also includes the properties of the material used in study, as well as details of the mixture proportioning methods used in research.

Chapter 4 presents the test results and the different analyses used to investigate the fresh properties, mechanical performance, and durability of the produced specimens.

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

With the introduction of waste legislation in the form of regulations and directives in many parts of world, a significant movement towards the sustainable management of construction and demolition (C&D) waste is becoming a legal requirement. In response, different sectors of the construction industry are undertaking various initiatives to minimize waste generation and improve the management of C&D waste to maximize economic and environmental benefits, generally by placing emphasis on increasing recycling for reuse (Limbachiya et al 2007).

The building industry in particular is a major consumer of materials and at the same time a major producer of waste (Padmini et al. 2009). According to Abbas et al. (2009) concrete accounts for up to 67% by weight of construction and demolition waste. The amount of demolition waste dumped at landfill sites in the United Kingdom is said to be in excess of 20 million tons per annum. The bulk of this material is concrete (50%–55%) and masonry (30%–40%) with only small percentages of other materials such as metals, glass and timber (Tam et al. 2007). In the Netherlands, about 14 million tons of building and demolition waste per annum are produced, in which about 8 million tons are recycled, mainly for unbound road base courses (Tam et al. 2007). It is also estimated that approximately 200 million tons of waste concrete are currently produced annually in the mainland of China (Xiao et al. 2012).

Due to the increasing rate of demolition, it is essential to effectively reuse demolition waste in order to conserve the nonrenewable natural resources. As a result of the mentioned problems, the idea of producing *green* recycled aggregate concrete (RAC), which is by definition a concrete in which recycled aggregate is used, has emerged. Recycled aggregate concrete will satisfy the three prerequisites of green materials (i) it can recycle and reduce natural resources and energy consumption; (ii) it will not affect the environment; and (iii) it can maintain sustainable development. However, there are some technical obstacles limiting the use of RCA in concrete production. In evaluation of the recycled aggregate characteristics, it should be kept in mind that each recycled concrete aggregate particle is still a piece of concrete composed of the original coarse aggregate (OCA) and the adhered mortar (AM). The recombined form of these concrete particles with a new matrix is called recycled aggregate concrete. For a clear understanding of the recycled aggregate and to predict its possible effects on concrete, the constituents of these composite particles must be identified separately (Nagataki et al. 2000).

It is a believed concept that the quality of RAC is tied to the properties of the original waste concrete, the new composition, the mixing approach, and the deterioration conditions of the recycled aggregates. Initial investigations on the use of recycled aggregate usually focused on incorporating recycled coarse aggregate and its influence on mechanical and durability properties of the RAC. It was an adopted concept that although the use of recycled coarse aggregate may be viable, a decrease in the performance of the RAC should be regarded as a normal outcome which can be mitigated through various approaches such as increasing cement content in mixture, etc. (Bagragi et al. 1990).

2.2. USE OF RECYCLED AGGREGATE AS COARSE AGGREGATE

2.2.1. Background. RCA is typically regarded as a double phase material consisting of the original virgin aggregate and the adhered residual mortar. The RAC will have more constituents: RCA aggregate, fresh mortar, and virgin coarse aggregates. Thus, there are two types of interfacial transition zones (ITZs) in RACs: one, the old ITZ between the original virgin coarse aggregate and the adhered mortar; and the second one between the new mortar and the RCA. (**Figure 2.1**)

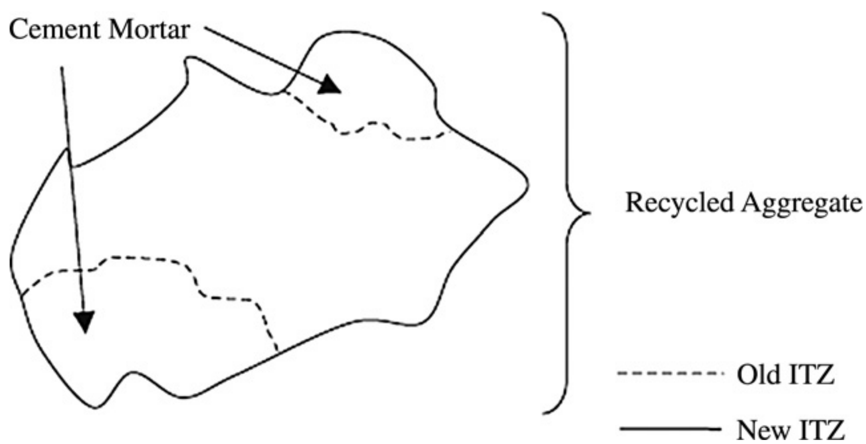


Figure 2.1 Schematic Sketch of RCA and ITZs (Xiao et al. 2012)

As a result of usually high amounts of adhered mortar content in recycled aggregates, these types of aggregates have high water absorption, low density, low specific gravity, and high porosity compared to natural aggregates (Kou et al. 2012). Some technical problems, including weak interfacial transition zones between cement paste and aggregate, porosity and traverse cracks within demolition concrete, high level of sulphate and chloride contents, impurity, poor grading, and high variations in quality, render the use of recycled aggregate difficult. It is usually believed that adhered mortar is the main cause of the lower properties of the recycled aggregates compared to the virgin natural aggregates.

2.3. PREVIOUS STUDIES RELATED TO RAC

2.3.1. Fresh Properties. As a result of usually high amounts of adhered mortar existing in RCA particles, the density of these aggregates are lower than those of virgin aggregates, which in turn results in a decrease in unit weight of concrete made with these types of aggregates. However, the conclusions on the workability properties of the recycled aggregate concretes are not always revealing inferior properties in these types of concrete mixtures.

Surface texture of the RCA particles may have positive or negative effects on workability of the mixture. Domingo et al. (2009), reported that a greater presence of recycled aggregates decreases the workability of the concrete which may be traced to the shape, texture, and absorption characteristics of recycled aggregates. They stated that is the reason why it is necessary to use saturated recycled aggregate or a greater amount of superplasticizers to maintain the workability.

On the other hand, Sagoe et al. (2001), reported that plant processing of recycled aggregate produces relatively smoother spherical particles, which leads to improved concrete workability in comparison with some natural aggregate concretes with equivalent grading and ratio of fine to coarse aggregate.

2.3.2. Mechanical Properties.

2.3.2.1. Compressive Strength. It is usually reported that the RCA replacement level has a significant effect on compressive strength of concrete. It is believed that using

RCA has a negative impact on strength properties of concrete. This is mainly due to the inferior properties of the residual mortar phase of the RCA particles. However, this effect is usually negligible for replacement levels up to 30%. Nixon (1978) also found that the compressive strength of RAC is somewhat lower compared with the strength of control mixes of conventional concrete. Hansen (1986) concluded that the compressive strength of RAC is largely controlled by a combination of the water to cement ratio of the original concrete and the water to cement ratio of the RAC when other factors are essentially identical.

Sagoe et al. (2001) observed no significant difference in the compressive strength of the specimens made with up to 100% replacement of coarse recycled aggregate with the reference concrete made with basalt coarse aggregates. The recycled aggregates were saturated before mixing.

Variations in compressive strength is mostly a function of the quality of RCA, which may result in various compressive strength values; no change in the strength, decrease, or even increase in the compressive strength when compared with the reference specimens. However, it is usually reported that decrease in w/cm and increase in cementitious materials content result in enhanced compressive strength of RAC (Xiao et al. 2012).

2.3.2.2. Splitting Tensile Strength. It is generally reported that RCA replacement results in a decrease in splitting tensile strength of concrete. Ravindrarajah et al. (1985) reported that the splitting tensile strength of RAC was consistently 10% lower than that of conventional concrete. Tabsh and Abdelfatah (2009) reported that about 25%–30% drop in the tensile strength was observed in concrete made with RCA.

Kou et al. (2012), observed that regardless of the type of the recycled aggregate used, the splitting tensile strength of the specimens decreased as a function of increasing RCA replacement ratio before the age of 28 days. However, for some types of the RCAs used, an increase in the splitting tensile strength at the age of 90 days is observed. Sagoe et al. (2001), reported that there is no significant difference between the splitting tensile strength of the reference and the recycled aggregate concrete specimens. On the other hand, Limbachiya (2012) and Yong and Teo (2009) reported that while replacing up to 50% of coarse aggregate with RCA, there was no difference in splitting tensile and flexural strengths between the RAC and the reference, but at complete replacement results were improved for RCA due to better interlocking.

2.3.2.3. Flexural Strength. It is usually reported that the RCA replacement does not have significant negative effects on flexural strength of concrete. Xiao and Li (2005), Hu (2007), and Cheng (2005) have reported that RCA replacement only has marginal effects on flexural strength of concrete. Ravindrarajah and Tam (1985) have also reported that increasing the RCA content does not have a significant effect on flexural strength. Topçu and Sengel (2004) have reported that the flexural strength is decreasing due to the increase in RCA replacement level.

2.3.2.4. Modulus of Elasticity. It is generally believed that the modulus of elasticity is decreasing as the RCA replacement ratio is increasing. This is believed to be due to the comparatively lower modulus of elasticity of the residual mortar attached to the RCA particles which will decrease the stiffness of the aggregate skeleton in RCA-made concrete (Xiao et al. 2012). Similar results were also reported by Hoffmann et al. (2012)

and Cabo et al. (2009), who observed that the modulus of elasticity is decreasing as a function of increasing the RCA replacement ratio.

2.3.2.5. Shrinkage. Kou et al. (2007), Kou and Poon (2012), Hansen and Boegh (1985), Fathifazl et al. (2011), Nassar and Soroushian (2012), and Gomez (2002) have studied the shrinkage behavior of the RCA-made concrete mixtures and observed that the shrinkage is increasing directly with an increase in RCA content. However, this increase is negligible up to 20% replacement ratio (Kou et al. 2007). This increase in shrinkage deformation is most probably due to the lower restraining capacity of the RCA particles due to an increase in the total mortar content and a decrease in the total stiff virgin aggregate portion in the mixture (Xiao et al. 2012).

Domingo-Cabo et al. (2009), found that the shrinkage of RAC increased after 28 days. The RAC with a RCA replacement level of 20% showed a similar shrinkage to the conventional concretes in the early stage. For a period of 6 months, the shrinkage in RAC was 4% higher. In the case of a RCA replacement level of 50%, the shrinkage was 12% greater than that of the conventional concrete after 6 months. Moreover, Sagoe et al. (2001), reported that the drying shrinkage of RAC was about 25% higher than that of conventional concrete, possibly due to the lower restraining capacity of RCA particles compared to natural aggregate.

Kou et al. (2012) reported that drying shrinkage of RAC increases as the coarse recycled aggregate replacement ratio increases. They also observed that recycled aggregates with lower water absorption capacities results in lower shrinkage rates.

Kim and Bentz (2008) investigated the drying shrinkage in concrete mixtures made with RCA. They have reported that the RCA particles can be used as a means of internal curing in concrete, which is useful in reducing the drying shrinkage. Similar results were reported by Hu et al. (2013) who reported that incorporating fine RCA is useful in decreasing the drying shrinkage through internal curing.

2.3.3. Durability.

2.3.3.1. Chloride Ion Permeability. It is usually reported that the chloride ion permeability of concrete made with RCA is inferior to that of conventional concrete. However, in the case of high quality RCA, it is observed that there is little difference between the chloride ion penetration of RAC and conventional concretes.

Sim and Park (2011) observed that in the case of concrete made with coarse RCA and partial replacement of fine recycled aggregates, there is no significant difference between the total charges passed through the specimens of up to 100% fine recycled aggregate replacement. However, as the curing time increases, the more fine recycled aggregate replacement results in a decrease in the total charge passed. Based upon their results, it seems that increasing the curing period as well as incorporating proper types and amounts of supplementary cementitious materials (SCMs), the chloride ion permeability may be controlled.

Kou et al. (2012), reported that the chloride ion permeability increases as a result of an increase in the coarse RCA replacement. However, the negative effect is more significant in the case of low grade RCA. Similar results were reported by Otsuki et al. (2001) and Shayan and Xu (2003).

2.3.3.2. Freeze/thaw Resistance. It is generally believed that the RCA-made concrete mixtures are more susceptible to damage due to the freeze/thaw cycles (Xiao et a. 2012). Medina 2013, Richardson (2011), Ajdukiewicz (2002), and Limbachyia (2000) have investigated the frost durability of the RCA-made concrete mixtures and reported that given the similar strength grade, there is not a significant difference in freeze/thaw resistance of the RCA-made and conventional concrete mixtures.

2.4. CONCLUDING REMARKS

Due to the lower quality of RCA particles compared to virgin aggregates, it is usually expected that the mechanical properties and durability of concrete made with RCA will be lower than conventional concrete. However, depending on the fresh concrete composition and source of RCA, this decrease might be negligible, and even in some cases better performance is expected.

3. EXPERIMENTAL PROGRAM

3.1. MATERIAL PROPERTIES

All the mixtures investigated in this study were proportioned with a binary blend of Type I/II Portland cement produced by Holcim, Inc. and Class C fly ash. Physical properties and chemical compositions of the cement are presented in **Table 3.1**.

Table 3.1 Physical Properties and Chemical Compositions of Cement

Physical properties	
Property	Type I/II Cement
Fineness:	
Blaine, m^2/kg	379
Specific gravity	3.15
Chemical compositions	
Component	% of weight
SiO_2	19.8
Al_2O_3	4.5
Fe_2O_3	3.2
CaO	64.2
MgO	2.7
SO_3	3.4
Na_2O	0.52 equivalent
LOI	2.6

Table 3.2 includes the typical chemical analysis of the Class C fly ash from the Ameren Labadie Power Plant (Labadie, MO) that was used in making the concrete mixtures.

The fine aggregrate was natural sand from Missouri River Sand (Jefferson City, MO), while two types of coarse aggregates were used; virgin coarse aggregate, which was a state-approved Potosi dolomite with a 1 in. maximum nominal aggregate size, and the laboratory produced RCA used as a partial replacement of the coarse aggregate. The RCA was produced from crushing the non-reinforced concrete beams produced at the High-Bay structural engineering laboratory at Missouri University of Science and Technology. The parent concrete was a mixture with w/c=0.4 made with the same virgin aggregate used in this study. The cement content in the parent concrete was 535 lb/yd^3. Dry-rodded unit weight, absorption, specific gravity, and Los Angeles abrasion resistance of the materials were determined according to ASTM standards for both the virgin and recycled aggregates.

Table 3.2 Chemical Compositions of Ameren UE Fly Ash [M.H. Wolfe 2011]

Chemical compositions	
Component	Range (%)
SiO_2	30.45 - 36.42
Al_2O_3	16.4 - 20.79
Fe_2O_3	6.78 - 7.73
CaO	24.29 - 26.10
MgO	4.87 - 5.53
SO_3	2.18 - .36
Na_2O	1.54 - 1.98
K2O	0.38 - 0.57
TiO2	1.42 - 1.56
P2O5	1.01 - 1.93
MnO	0.028 - 0.036
SrO	0.40 - 0.44
BaO	0.68 - 0.9
LOI	0.24 - 1.15

The residual mortar content of the RCA was determined based on the method proposed by Abbas et al. (2009). In this method, RCA particles are submerged in a saturated solution of sodium sulphate being subjected to cycles of freezing and thawing.

Due to the combined effect of the chemical solution and thermal stresses, the mortar phase of the RCA particles is separated from the old virgin aggregates. Two series of samples were used for measuring the residual mortar content of the RCA. Each of these samples contained four individual groups of aggregates remaining on the 3/4, 1/2, 3/8, and #4 sieves. The residual mortar content of each sample was calculated based on the weight of the separated mortar and grain size distribution of the RCA as suggested by Abbas et al. (2009).

Figure 3.1 shows one of the RCA sample series before the cycles and after removing the residual mortar.

Figure 3.1 RCA Particles before Separating the Mortar (left) and after Separating the Residual Mortar (right)

The residual mortar content is then computed as a percentage of the weight of the RCA particles. **Table 3.3** presents a summary of the properties of the fine and coarse aggregates. The gradation curve of the aggregates is compared to the ASTM C33 standard in **Figures 3.2** and **3.3**. **Figure 3.4** plots the amount of coarse aggregates retained on each of the sieves. This curve is indicative of the grain size distributions. The ideal shape of this diagram is a symmetric bell shaped one. As it is observed, both the coarse aggregates (virgin and RCA) have acceptable distributions. It should be noted that the Los Angeles abrasion results are the average values calculated for two series of samples obtained from the coarse aggregate piles.

Table 3.3 Physical Properties of the Aggregates

Aggregate	Specific gravity	Dry rodded unit weight (pcf)	Absorption (%)	LA abrasion (%)	Residual mortar (% of wt.)
Fine	2.641	-	0.5	-	-
Potosi dolomite	2.72	99.7	0.98	43	-
RCA	2.35	89.7	4.56	41	46

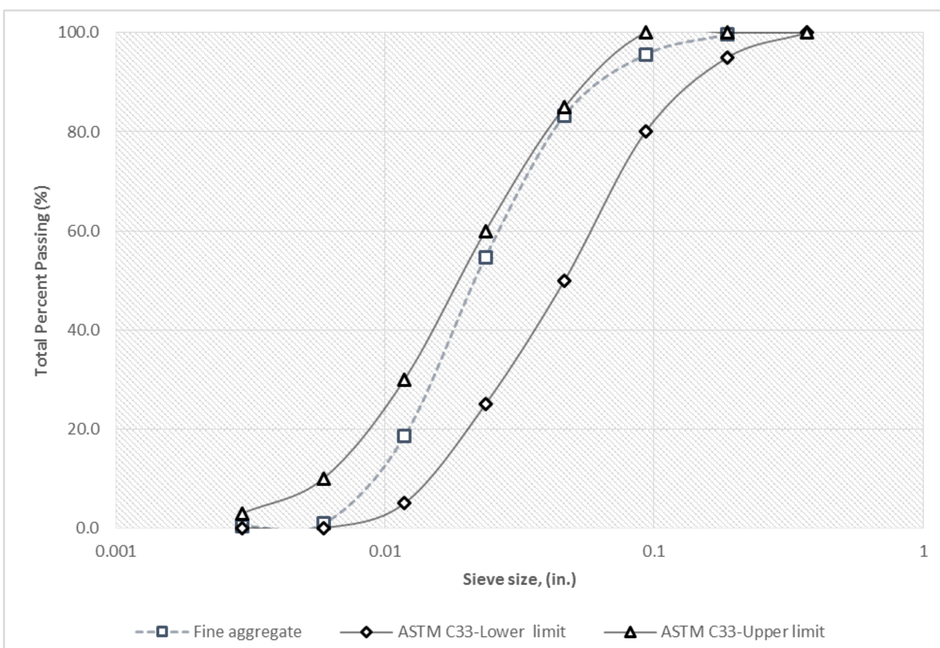


Figure 3.2 Particle Size Distribution of the Fine Aggregate

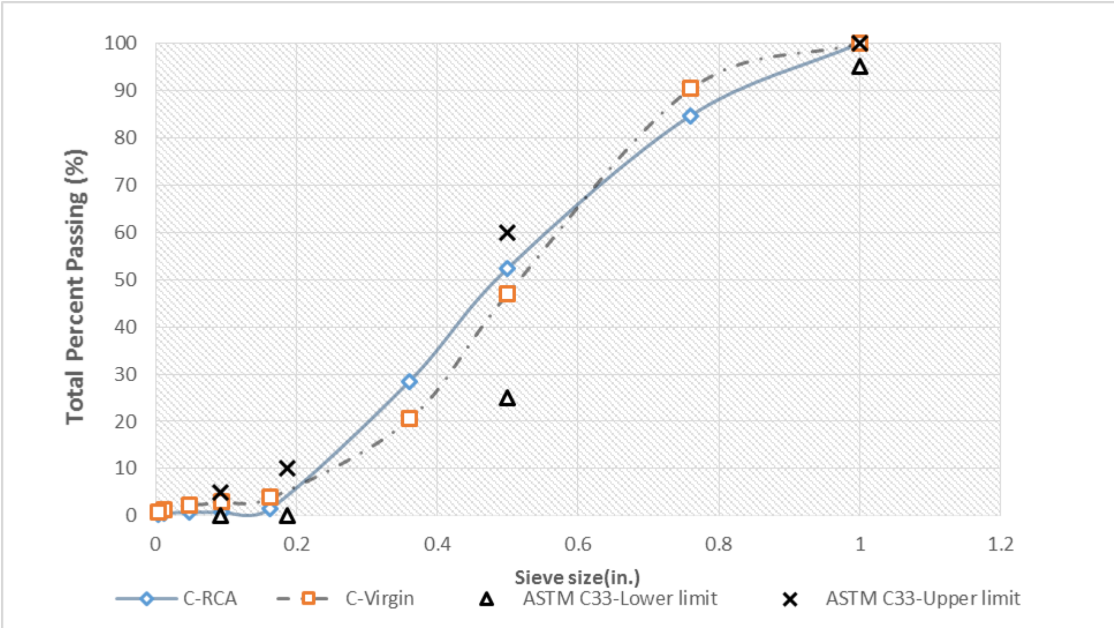


Figure 3.3 Particle Size Distribution of the Coarse Aggregate

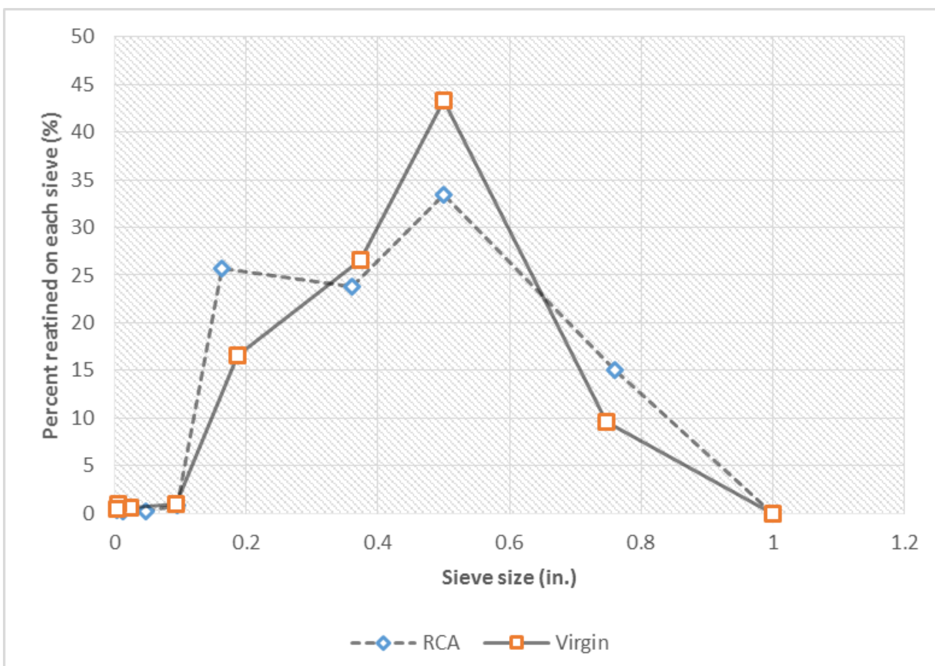


Figure 3.4 Individual Percentages Retained on Each Sieve

3.2. MIXTURE PROPORTIONS

3.2.1. Conventionally Proportioned Mixtures. The study focused on MoDOT Class B concrete mixtures. Seven of the investigated mixtures had a fixed water to cementitious materials ratio (w/cm) of 0.45 and a sand to total aggregate ratio of 42.5%, by volume. The total amount of the cementitious materials used in making the reference and the experimental mixtures was 535 lb/yd^3 except for the mixture proportioned according to the equivalent mortar volume (EMV) method. This method is introduced in Section 3.2.3. Twenty five percent of the weight of the cement was replaced with Class C fly ash to reduce the carbon footprint in these sustainable concrete mixtures. A total number of five conventionally proportioned concrete mixtures were produced in the laboratory, including the reference, and mixtures with different amounts of coarse RCA content varying from 30% up to 100% replacement by volume of the coarse aggregate. These mixtures were produced according to the conventional mixing sequence introduced by ASTM C192. It should be noted that two other concrete mixtures were also produced based on the two stage mixing approach (TSMA) and the EMV method. These two methods are introduced in Sections 3.2.2 and 3.2.3, respectively.

Two other concrete mixtures with the w/c of 0.4 and the same cement content with no fly ash replacement were also investigated in this research. These concrete mixtures were the same for casting the structural elements. One of these mixtures is made with no recycled aggregates and the second one was a mixture with full replacement of the coarse aggregate with RCA.

3.2.2. Two Stage Mixing Approach. A second type of mixture made with 100% RCA replacement was produced using the Two Stage Mixing Approach (TSMA). The main idea of the TSMA is to encapsulate the RCA particles with a low w/cm, of high quality cement paste in order to enhance the surface properties of the RCA as well as the interfacial transition zone (ITZ) formed between the RCA particle and the fresh surrounding hydrated cement paste (Otsouki et al. 2003, Ryu 2002, Tam et al. 2005, 2007, 2008, and 2009, Elhakam et al. 2012, Li et al. 2012). In order to produce the concrete with TSMA, the coarse RCA was loaded in the mixer along with a quarter of the water and the air entraining admixture. After one minute of mixing, the cementitious materials were added with mixing continuing for one minute. Then, half of the remaining water was introduced and allowed to mix for one minute to coat the RCA particles with a rich cement paste. The rest of the materials were then loaded followed by two minutes of mixing.

3.2.3. Equivalent Mortar Volume Mixture Proportioning Method. Fathifazl et al. (2009), have introduced a mixture proportioning method for making concrete with coarse RCA as a replacement for virgin coarse aggregates. Considering the residual mortar content of RCA as part of the total mortar content of the RCA-made concrete is the basis of this method of mixture proportioning. In the proposed method, the RCA-made concrete mixture is proportioned to have the same total mortar volume as a companion concrete mixture made entirely with fresh virgin (here also referred as natural) aggregates, with the companion mixture made with the same type of coarse aggregate as that in the RCA. Mixture proportioning based on the proposed method essentially involves proper determination of the amounts of RCA and fresh mortar in the RCA-made concrete. The method proceeds as follows (Fathifazl et al. 2009):

At the first step, a companion concrete mixture should be proportioned based on conventional concrete mixture proportioning methods, only with natural aggregate being used in the composition. It is assumed that the natural aggregate (NA) used in this mixture has the same gradation and maximum size as the RCA. This mixture is called natural aggregate concrete (NAC).

The next step is to design a second mixture containing both the natural aggregate and RCA. This mixture is called the RCA-concrete. The volume of NA in the RCA-concrete mixture is shown by $V_{NA}^{RCA-concrete}$.

The natural aggregate content ratio, R, is defined as:

$$R = \frac{V_{NA}^{RCA-concrete}}{V_{NA}^{NAC}} \tag{3-1}$$

Where $V_{NA}^{RCA-concrete}$ = volume of natural aggregate in RCA-concrete and V_{NA}^{NAC} = volume of natural aggregate in NAC.

R=0 refers to a concrete mixture with no NA (*i.e.*, 100% RCA) in composition, and R=1 corresponds to a mixture made with 100% NA (*i.e.*, no RCA). For the RCA-concrete and its NAC to have the same properties, the proposed method requires that the two following conditions to be satisfied:

1. The total mortar content in the NAC should be equal to the total mortar content of the RCA-concrete mixture. The total mortar content of the RCA-concrete mixture can be determined by the summation of residual mortar content attached to the RCA particles available in RCA-concrete mixture and the fresh mortar content of the same mixture.

2. The total NA content in the NAC to be equal to the total NA content of the RCA-concrete mixture. The total NA content of the RCA-concrete mixture can be determined by the summation of original virgin aggregate available in the RCA particles used in RCA-concrete mixture and the NA content of the RCA-concrete mixture.

These two conditions are summarized in the following Equations:

$$V_{TM}^{RCA-concrete} = V_{M}^{NAC} \tag{3-2}$$

$$V_{TNA}^{RCA-concrete} = V_{NA}^{NAC} \tag{3-3}$$

Where $V_{TM}^{RCA-concrete}$= total mortar (TM) volume in RCA-concrete, V_{M}^{NAC}= mortar volume in the companion concrete made entirely with natural aggregate, and $V_{TNA}^{RCA-concrete}$= total natural aggregate (TNA) volume in RCA-concrete.

Therefore, Equations (3-2) and (3-3) can be reformed as:

$$V_{TM}^{RCA-concrete} = V_{RM}^{RCA-concrete} + V_{NM}^{RCA-concrete} \tag{3-4}$$

$$V_{TNA}^{RCA-concrete} = V_{OVA}^{RCA-concrete} + V_{NA}^{RCA-concrete} \tag{3-5}$$

Where $V_{RM}^{RCA-concrete}$= residual mortar (RM) volume in RCA-concrete, $V_{NM}^{RCA-concrete}$ =volume of the fresh or new mortar (NM) in RCA-concrete; and $V_{OVA}^{RCA-concrete}$= original virgin aggregate volume in RCA concrete.

It is assumed that the differences between the strength and density of the residual mortar and the fresh mortar on the one hand and the differences between the original virgin aggregate (OVA) and fresh NA type and/or shape may have negligible effect on the overall properties of RCA-concrete compared to the companion NAC. It is also assumed that the severely damaged mortar will not survive the crushing process during RCA production. This ensures the quality of the residual mortar attached to the RCA particles.

In order to ensure the conditions stated in Equation (3-5), amount of original virgin aggregate in RCA-concrete should be quantified:

$$V_{OVA}^{RCA-concrete} = V_{RCA}^{RCA-concrete} \times (1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}} \tag{3-6}$$

Where $V_{RCA}^{RCA-concrete}$= volume of RCA in RCA-concrete and SG_b^{RCA} and SG_b^{OVA}= bulk specific gravities of RCA and original virgin aggregate (OVA) available in the RCA particles, respectively. Again it should be noted that the RMC is the residual mortar content of the RCA.

The required volumes of RCA and fresh natural aggregate in the RCA-concrete can be determined using the Equations (3-1), (3-2), (3-5), and (3-6):

$$V_{RCA}^{RCA-concrete} = \frac{V_{NA}^{NAC} \times (1 - R)}{(1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}} \tag{3-7}$$

$$V_{RCA}^{RCA-concrete} = V_{NA}^{NAC} \times R \tag{3-8}$$

$$W_{OD-RCA}^{RCA-concrete} = V_{RCA}^{RCA-concrete} \times SG_b^{RCA} \times 1000 \tag{3-9}$$

$$W_{OD-NA}^{RCA-concrete} = V_{NA}^{RCA-concrete} \times SG_b^{NA} \times 1000 \tag{3-10}$$

Where $W_{OD-RCA}^{RCA-concrete}$= required oven-dry weight of RCA in RCA-concrete, $W_{OD-NA}^{RCA-concrete}$= required oven-dry weight of natural aggregate in RCA-concrete, and SG_b^{NA}= bulk specific gravity of natural aggregate.

Next step is to determine the amount of required water, cement, and fine aggregate proportions in RCA-concrete mixture. The residual mortar content available in RCA-concrete should be quantified to satisfy the condition expressed in Equation (3-2).

$$V_{RM}^{RCA-concrete} = V_{RCA}^{RCA-concrete} \times [1 - (1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}] \tag{3-11}$$

The amount of fresh mortar in RCA-concrete can be determined using Equations (3-2), (3-4), and (3-11):

$$V_{NM}^{RCA-concrete} = V_M^{NAC} - V_{RM}^{RCA-concrete} \tag{3-12}$$

Where $V_{NM}^{RCA-concrete}$ is the new (fresh) mortar content in RCA-concrete, V_M^{NAC} is the total mortar content of natural aggregate concrete, and $V_{RM}^{RCA-concrete}$ is the volume of residual mortar in RCA-concrete.

The corresponding quantities of water, cement, and fine aggregate in RCA-concrete can be determined using the following Equations:

$$W_w^{RCA-concrete} = W_w^{NAC} \times \frac{V_{NM}^{RAC-concrete}}{V_M^{NAC}} \tag{3-13}$$

$$W_{c}^{RCA-concrete} = W_{c}^{NAC} \times \frac{V_{NM}^{RAC-concrete}}{V_{M}^{NAC}} \tag{3-14}$$

$$W_{OD-FA}^{RCA-concrete} = W_{OD-FA}^{NAC} \times \frac{V_{NM}^{RAC-concrete}}{V_{M}^{NAC}} \tag{3-15}$$

Where $W_{w}^{RCA-concrete}$ and W_{w}^{NAC} are the weights of water in RCA-concrete and natural aggregate concrete, $W_{c}^{RCA-concrete}$ and W_{c}^{NAC} are the weights of cement in RCA-concrete and natural aggregate concrete, and $W_{OD-FA}^{RCA-concrete}$ and W_{OD-FA}^{NAC} are the oven dried weights of fine aggregate in RCA-concrete and NAC respectively.

An upper limit exists for the RCA content in the RCA-concrete mixture in the EMV method. This limit is a function of residual mortar content of the RCA. The theoretical lower and upper limits of residual mortar content, 0 and 100%, respectively, should be examined to determine the effect of residual mortar content on RCA-concrete mixture proportioning. Given the fact that the maximum amount of any coarse aggregate, including RCA, which can be placed in a unit volume of concrete, is equal to the dry-rodded unit volume of that aggregate. Therefore, the upper limit of RCA content in RCA concrete is the dry-rodded volume of RCA ($V_{DR-RCA}^{RAC-concrete}$). Hence, the maximum volume of RCA that can be added to a unit volume of RCA-concrete can be calculated as:

$$V_{maxRCA}^{RCA-concrete} = \frac{SG_{DR}^{RCA}}{SG_{b}^{RCA}} \tag{3-16}$$

Where $V_{maxRCA}^{RAC-concrete}$ = maximum volume of RCA that can be added to a unit volume of RCA-concrete, SG_{DR}^{RCA}= dry-rodded specific gravity of RCA, and SG_{b}^{RCA} = bulk specific gravity of RCA.

The absolute volume of natural aggregate in natural aggregate concrete, in Equation (3-7) can be related to its dry-rodded volume as:

$$V_{NA}^{NAC} = V_{DR-NA}^{NAC} \times \frac{SG_{DR}^{NA}}{SG_{b}^{NA}} \tag{3-17}$$

Where V_{NA}^{NAC}= volume of natural aggregate in NAC, SG_{DR}^{NA}= dry-rodded specific gravity of natural aggregate, and SG_{b}^{NA} = bulk specific gravity of natural aggregate.

By substituting Equations (3-16) and (3-17) in Equation (3-7), the minimum replacement ratio ($R_{\min}$) can be calculated as:

$$R_{min} = 1 - \frac{(1 - RMC)}{V_{DR-NA}^{NAC}} \times \frac{SG_{DR}^{RCA}}{SG_{DR}^{OVA}} \times \frac{SG_{b}^{NA}}{SG_{b}^{OVA}} \geq 0 \tag{3-18}$$

Where RMC = residual mortar content of the RCA, V_{DR-NA}^{NAC} = dry-rodded volume of natural aggregate in natural aggregate concrete, SG_{DR}^{RCA} = dry-rodded specific gravity of RCA, SG_{DR}^{OVA} = dry-rodded specific gravity of original virgin aggregate available in RCA particles, SG_{b}^{NA} = bulk specific gravity of natural aggregate, and SG_{b}^{OVA} = bulk specific gravity of original virgin aggregate.

By assuming identical shape and size grading for RCA and NA, it can be written that:

$$\frac{SG_{DR}^{RCA}}{SG_{DR}^{NA}} = \frac{SG_{b}^{RCA}}{SG_{b}^{NA}} \tag{3-19}$$

Assuming the fresh natural aggregate that is used as replacement of RCA to be similar to the original virgin aggregate in RCA, the ratio $\frac{SG_b^{NA}}{SG_b^{OVA}}$ in Equation (3-18) would become one. Therefore, by substituting Equation (3-19) into Equation (3-18), one obtains:

$$R_{min} = 1 - \frac{(1 - RMC)}{V_{DR-NA}^{NAC}} \times \frac{SG_b^{RCA}}{SG_b^{NA}} \geq 0 \tag{3-20}$$

It should be noted that the negative value for R_{min} implies that one can make a concrete mixture with 100% RCA, without the need for any fresh natural aggregate.

As the residual mortar content increases and approaches 100%, the required volume of RCA in RCA-concrete in Equation (3-7) hyperbolically increases and approaches infinity ($V_{RCA}^{RCA-concrete}$ /$V_{NA}^{NAC} \rightarrow \infty$). However, if the (1-*R*) in the numerator of Equation (3-7) is set equal to it's denominator, ($(1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}$), the resulting equation would be valid for any residual mortar content. The physical interpretation of the latter action is replacement of residual mortar volume in RCA with fresh natural aggregate ($V_{NA}^{RCA-concrete}$ =$V_{RM}^{RCA-concrete}$) to compensate for the deficiency of the total natural aggregate in RCA-concrete compared to the companion natural aggregate concrete. Therefore:

$$R = \frac{V_{RM}^{RCA-concrete}}{V_{RCA}^{RCA-concrete}} \quad (3\text{-}21)$$

Where $V_{RM}^{RCA-concrete}$ = volume of residual mortar in RCA-concrete, and $V_{RCA}^{RCA-concrete}$ = volume of RCA in RCA-concrete.

By substituting Equations (3-21) and (3-11) into Equation (3-7), the required RCA and natural aggregate volumes can be found as:

$$V_{RCA}^{RCA-concrete} = V_{NA}^{NAC} \quad (3\text{-}22)$$

$$V_{NA}^{RCA-concrete} = V_{NA}^{NAC} \times [1 - (1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}] \quad (3\text{-}23)$$

Where $V_{NA}^{RCA-concrete}$ = required volume of natural aggregate in RCA-concrete.

Again it should be highlighted that the EMV method is completely detailed by Fathifazl et al. (2009).

3.3. TEST MATRIX

Table 3.4 summarizes the test matrix used in this part of the research for evaluating the effect of RCA replacement level on properties of concrete.

In the case of laboratory produced mixtures, three different concrete batches were produced to meet the required volume for sampling purposes. Two successive batches of

4.5 cubic feet were used to make samples for the mechanical properties and the durability performance. An extra batch of 2.5 cubic feet was also produced for investigating the fresh properties.

The design air content of the batches used for mechanical properties and durability sampling was 6±1%. Although MoDOT considers a maximum slump value of 6.0 in. while using water reducer admixtures, the targeted slump value was set to 7±1 in. to facilitate testing the fresh properties with the ICAR rheometer. The amount of required admixtures was determined by making trial batches of two cubic feet for all of the investigated mixtures.

Table 3.5 summarizes the mixtures used in the study to evaluate the properties of the concrete made with RCA.

Regarding the mixture proportioning for the EMV method, it should be noted that this mixture was initially produced with the RCA replacement levels determined by Fathifazl et al. (2009). However, the produced mixture was a harsh mixture with low content of fresh mortar and workability problems. Therefore, the RCA replacement ratio was decreased in mixture proportioning. Several mixtures with different replacement levels were investigated for fresh properties in the laboratory in order to find the maximum practical replacement ratio to make a workable concrete in the laboratory. Finally, the R= 0.834 was selected to plug in the equations. This yields approximately 30% replacement of RCA by volume of the coarse aggregate. The total amount of fresh mortar used in producing the EMV mixture was 15% less than the reference mixture. This means that the total amount of cementitious materials used for reducing the EMV mixture was 15% less than the reference mixture (i.e. 454 lb/yd^3). The sand content and the water amount was decreased by 15% as well. However, the w/cm of the fresh mortar was 0.45 same as the reference mixture.

Table 3.4 Test Matrix for Making Concrete Mixtures

w/cm	Mixing method	Coarse RCA replacement (% of volume)				
		0	30	50	70	100
0.45	Conventional	✓	✓	✓	✓	✓
	EMV		✓			
	TSMA					✓
0.4	Conventional	✓				✓

Similar to the other laboratory produced mixtures, 25% of the required Portland cement was replaced with Class C fly ash for the EMV mixture. The total amount of coarse aggregate content of this mixture was 2078 lb/yd^3 which is 13% more than the reference mixture. This simultaneous increase in coarse aggregate content and decrease in fresh mortar content results in inferior workability of the EMV mixture compared to the reference concrete mixture.

Table 3.5 Mixture Proportions of Concrete used in the Study

Mixture type	Laboratory produced mixtures							Sampled from truck	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Cementitious materials (lb/yd^3)	535	535	458	535	535	535	535	535	535
Cement type I (lb/yd^3)	401	401	344	401	401	401	401	535	535
Class C fly ash, replacement by mass (%)	25	25	25	25	25	25	25	-	-
Fly ash (lb/yd^3)	134	134	114	134	134	134	134	-	-
w/cm	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.4	0.4
Water content (lb/yd^3)	240.75	240.75	206	240.75	240.75	240.75	240.75	214	214
Sand/Aggregate, by volume (%)	42.5	42.5	36.5	42.5	42.5	42.5	42.5	40	45
Sand content (lb/yd^3)	1301	1301	1122	1301	1301	1301	1301	1253	1410
RCA replacement ratio by volume (%)	0	30	30	50	70	100	100	0	100
Coarse virgin aggregate content (lb/yd^3)	1835	1284	1518	917	550	-	-	1958	-
Coarse RCA content (lb/yd^3)	-	475	560	791	1108	1583	1583	-	1548

3.4. SAMPLING AND CURING

A variety of samples were taken from each type of the laboratory produced concrete mixtures to investigate the fresh properties, mechanical performance and durability according to **Table 3.6**. A vibrating table was used for consolidating the fresh concrete in molds.

Table 3.6 Test Methods and Standard used in the Study

Property	Test Method	Test Title/Description
Fresh Concrete Property Tests		
Unit Weight	ASTM C 138	Standard Test Method for Density (Unit Weight).
Air Content	ASTM C 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.
Bleeding	ASTM C 232	Standard Test Methods for Bleeding of Concrete.
Rheological properties		ICAR rheometer
Hardened Mechanical Property Tests		
Compressive Strength, 4×8 in. cylinders, (1, 7, 28, 56, and 91 d)	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.
Splitting Tensile Strength, 4×8 in. cylinders, (7, 28, and 56 d)	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.
Flexural Strength, 6×6×20 in. beams (28 and 56 d)	ASTM C 78	Standard Test Method for Flexural Strength of Concrete.
Modulus of Elasticity, 4×8 in. cylinders, (28, 56 d)	ASTM C 469	Standard Test Method for Static Modulus of Elasticity.
Shrinkage, 3×3×11.25 in. prisms	ASTM C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
Durability Tests		
Permeable void ratio, 4×8 in. cylinders, (28, 56, and 91 d)	ASTM C 642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
Elect. Resistivity, 4×8 in. cylinders, (28, 56, and 91d)	ASTMC 1760	Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete
Surface Resistivity, 4×8 in. cylinders, (28, 56, and 91d)	AASHTO TP 95	Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration
Freeze Thaw Resistance, Procedure A, 3×4×16 in. prisms	ASTM C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.
Deicing-salt Scaling Resistance, 3×10×11 in. panels	ASTM C 672	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals.

Samples were kept under wet burlap and covered by plastic sheets for 24 hours before demolding. After demolding the specimens, the curing process started. Specimens were placed in lime-saturated water with temperature of 70±5 ºF up to the age of testing.

4. RESULTS AND DISCUSSION

4.1. FRESH PROPERTIES

4.1.1. General. A batch of 2.5 ft^3 was produced for investigating the fresh properties of the concrete mixtures containing various amounts of RCA. All these batches were made with the constant w/cm of 0.45. Total number of six concrete mixtures were investigated in this phase. The studied fresh properties included bleeding potential and rheological properties. All these mixtures were produced with the same initial slump value and air content except for the EMV mixture. Due to the high amount of coarse aggregate and decrease in the fresh mortar content in this mixture, the slump value was lower than the other mixtures. Therefore, this mixture was not used for investigating the rheological properties. It should also be noted that the mixture made with 50% RCA replacement had slightly lower air content compared to the targeted range of 6±1%. However, given the fact that no sampling for durability or mechanical property testing was scheduled at this phase, this mixture was used for investigating the rheological properties and bleeding potential. **Table 4.1** summarizes the slump value and air content of the investigated mixtures.

Table 4.1 Slump Value, Air Content, and Unit Weight of Fresh Concrete Mixtures

Mixture type	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA
Slump (in.)	7.0	7.0	1.5	7.0	7.0	7.5
Air content (%)	5.5	5.8	4.8	4.0	5.5	5.2
Unit weight (pcf)	149.8	145.3	149.8	147.0	143.9	142.0

4.1.2. Bleeding. Bleeding is a form of segregation where some of the water in the concrete tends to rise to the surface of the freshly placed material. This arises due to the inability of the solid components of the concrete to hold all of the mixing water when they settle downwards (water being the lightest of all the mix constituents). Bleeding of the water continues until the cement paste has stiffened enough to end the sedimentation process (Mehta and Monteiro 2006). If the bleed water is remixed during the finishing of the top surface, a weak top surface will result. To avoid this, the finishing operations can be delayed until the bleed water has evaporated. Conversely, if evaporation of the surface water is faster than the rate of bleed, plastic shrinkage cracking may occur.

Bleeding potential of the mixtures was investigated according to the ASTM C 232 test method. A cylindrical container of approximately 0.5 ft^3 capacity with internal diameter of 10±0.25 in. and internal height of 11±0.25 in. was used for the test. Fresh concrete was cast into the container in three layers. The container was then placed on a flat and vibration free surface while covered with a wet towel to avoid evaporation. Accumulated water was collected from the surface of the specimen in different time intervals. In order to facilitate the collection of the bleed water, container was tilted by placing an approximately 1.5 in. thick block under one side of the cylinder two minutes before each recording. Results of the bleeding test are reported in **Table 4.2**.

No significant bleeding was observed in most of the mixtures. The mixture made with 100% RCA replacement had the maximum registered bleeding equal to 0.18 gm/in^2 of the surface area of the specimen.

Table 4.2 Results of Bleeding Measurements

Mixture type	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA
Accumulated bleeding water (gr)	0.0	0.8	0.0	6.5	3.1	14.0
Accumulated bleeding water (gm/in^2)	0.0	0.01	0.0	0.08	0.04	0.18
Last observation time (min)	120	120	130	120	130	180

4.1.3. Rheological Properties. Fresh concrete can be considered as a fluid. This means that fresh concrete can start to flow due to shear stress. Flow characteristics of fresh concrete are described using the "Bingham" equation:

$$\tau = \tau_0 + \mu D \qquad (4\text{-}1)$$

Where:

τ = shear stress (Pa)

τ_0 = yield stress (Pa)

μ = plastic viscosity (Pa/s)

D = shear rate (1/s)

Yield stress is defined as the minimum shear stress required to start the flow of a fluid and the viscosity is the measure of internal resistance to flow. **Figure 4.1** is a schematic pattern of rheological properties of a Bingham (non-Newtonian) fluid like concrete.

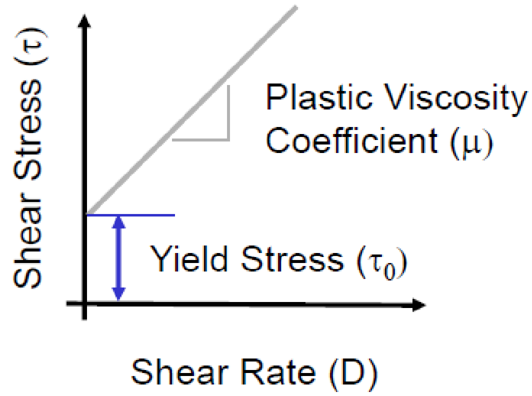


Figure 4.1 Bingham Model for Rheological Properties of Concrete (ICAR manual)

Concrete, however, is not a simple fluid because it displays thixotropic behavior, which means that the shear stress required to initiate flow is high when the concrete has been in an "at rest condition", but a lower shear stress is needed to maintain flow once it has begun. Such behavior is shown in **Figure 4.2** where variations in shear stress is depicted versus time for a slowly applied shear strain. From the start point, the shear stress is increasing up to reach to a maximum called "static yield stress". This maximum point is the initiation of flow and after this point the shear rate required for continuing the flow will decrease. The required shear stress for continuing the flow will stabilize after a few seconds. This stabilized shear rate is known as the "dynamic yield stress".

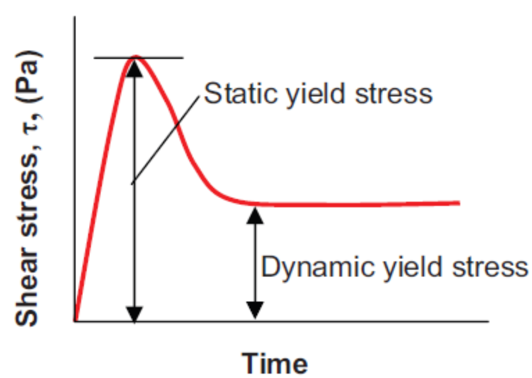


Figure 4.2 Yield Stress Analysis (ICAR manual)

A portable ICAR rheometer was used for determining the rheological properties of concrete mixtures. Both the stress growth and the flow curve tests were performed for the mixtures at different time intervals. **Figure 4.3** presents the interface of the ICAR software used for the rheological testing.

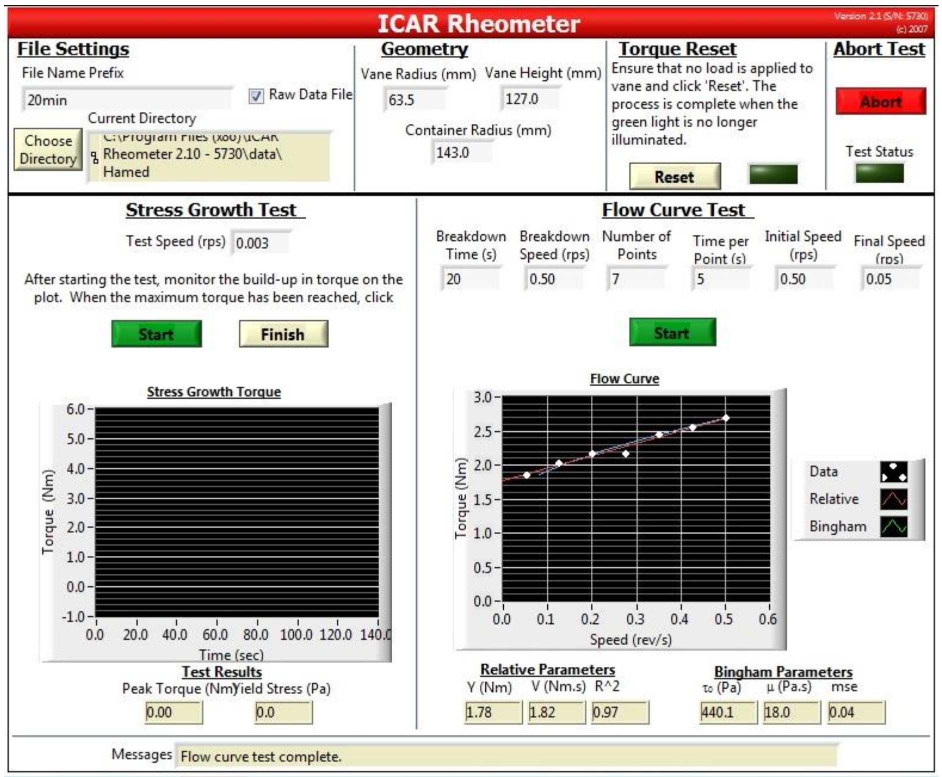


Figure 4.3 ICAR Rheometer Interface

As a rule of thumb, the ICAR rheometer is suitable for use with concrete mixtures with slump values higher than 4 to 5 in. Therefore it was not possible to use this rheometer to measure the rheological properties of the EMV mixture. **Table 4.3** includes the data obtained from the ICAR rheometer. The maximum yield stress was determined with the stress growth test. The flow curve test was performed to investigate the plastic viscosity and the yield stress of the samples.

Except for the concrete made with 100% RCA replacement, it was observed that the dynamic yield stress is generally higher in the case of RCA mixtures while compared to the reference. Most of the plastic viscosity results obtained for the RCA mixtures (besides that of the 50% mixture) is higher than the reference mixture. However, no clear trend of effect of RCA replacement ratio on rheological properties was observed. Similar results were reported by Hu et al. (2013).

Table 4.3 Rheological Properties of the Concrete Mixtures

Mixture	Max yield stress (Pa)	Plastic viscosity (Pa.s)	Yield stress (Pa)
Ref.	3272.4	37.3	659.3
30% RCA	4668.9	49.0	369.4
50% RCA	3523.9	28.3	639.0
70% RCA	3338.6	40.7	535.8
100% RCA	1829.8	47.4	252.2

4.2. MECHANICAL PROPERTIES

4.2.1. General. For each of the mixtures, a batch of 4.5 ft^3 concrete was produced to take samples of the mechanical properties. The targeted slump value and air content of the produced mixtures were 7.0 ± 1.0 in. and 6.0 ± 1.0% respectively. However, the air content of the mixture made with 50% RCA was slightly higher than the targeted range. **Table 4.4** includes the fresh properties of the mixtures.

Table 4.4 Fresh Properties of Mixtures used for Mechanical Property Sampling

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Slump (in.)	5.0	8.0	3.5	7.0	7.5	8.0	6.5	5.5	8.5
Air content (%)	6.4	7.0	5.0	8.0	5.8	5.3	5.0	8.5	6.5
Unit weight (pcf)	147.4	144.2	148.9	141.1	142.5	141.2	141.7	147.2	137.5

4.2.2. Compressive Strength. **Table 4.5** includes a summary of the compressive strength results of the specimens up to 91 days of age. For each testing age, three 4×8 in. cylindrical specimens were used for determining the compressive strength according to ASTM C39. A sulfur based capping compound was used for treating the specimen surfaces at all test ages.

With regard to the results presented in **Table 4.5** it was inferred that in the case of specimens made with w/cm=0.45 with varying RCA content from zero to 100% replacement, the maximum results were observed for the reference mixture made with virgin aggregates. A slight decrease was observed when using RCA as a replacement for coarse aggregate. However, the decrease was more in the case of specimens made with 30% and 50% RCA replacement. This may be mostly due to the higher air content of these two mixtures compared to the mixtures made with 70% and 100% RCA replacement. Another important point to mention, is that the RCA particles were made from parent concrete of w/c=0.4. This means that the fresh mortar with w/cm=0.45 may be the weaker mortar phase governing the strength.

These finding are in line with data obtained by Ryu (2002) who used three types of RCA to make concrete mixtures of w/c = 0.25 and 0.55. It was observed that the compressive strength of the concrete specimens with w/c of 0.55 were the same regardless of the RCA type. However, a similar trend was not observed in the case of specimens with w/c =0.25. Based on the results it was proposed that the strength of the concrete depends on the relative quality of the old and new ITZ formed in concrete made with RCA. In the case of low w/c, the strength of the concrete is governed by the quality of the RCA and the old ITZ in its structure. However, when the w/c is high, the new ITZ formed between the RCA and cement paste may be much weaker and govern the strength characteristics of the concrete.

Table 4.5 Compressive Strength Results

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for three specimens (psi)								
1 Day	2740	2300	2630	2130	2330	2480	2860	4170	3580
7 Days	4180	3670	4660	3650	4440	4510	4610	4980	4660
28 Days	5150	4670	5630	4470	5610	5540	5230	5810	5290
56 Days	5580	5230	6660	4720	5930	5610	6180	6550	5480
91 Days	6220	5360	6375	5040	6100	6200	6165	7880	6100

Given the 23% decrease in compressive strength due to full RCA replacement in concrete mixtures made with w/c=0.4, it may be concluded that the high quality concrete mixtures are more sensitive to RCA replacement. There was no significant difference in compressive strength of the reference and the 100% RCA mixtures with w/cm=0.45. This might be partly due to the 1.0% lower air content in the 100% RCA mixture as well.

Regardless of the first day compressive strength, there was no significant difference in compressive strength of the 100% RCA specimens made with 0.4 and 0.45 w/cm. It should be noted that the air content of the specimens made with w/c=0.4 was 1.2% higher than the other case. Pozzolanic reaction due to 25% replacement of cement with Class C fly ash in specimens made with w/cm = 0.45 might be another reason for this observation.

The TSMA seems not to be beneficial in increasing the compressive strength of the 100% mixture. The 56 day compressive strength of the TSMA mixture is approximately equal to the 91 day strength of the 100% RCA specimens. However, the 91 day results are similar. This finding is contradictory to the observations of Outsuki et al. (2001) who reported up to a 13% increase in compressive strength as a result of the double mixing method. Tam et al. (2005, 2007, 2009) have reported beneficial effects of TSMA for improving the compressive strength of RCA-made concrete mixtures.

The specimens made with the EMV method had the best performance among all the laboratory produced mixtures. Besides the first day strength, the compressive strength of these specimens were higher than the reference mixture for all the test ages up to 91 days. However, a slight decrease in 91 day compressive strength of the EMV specimens were observed while compared to 56 day results, which might be due to experimental errors, etc. Similar beneficial effects were reported by Fathifazl et al (2009).

All the obtained results were higher than the minimum requirement of 3000 psi at 28 days for MoDOT Class B concrete mixtures.

4.2.3. Splitting Tensile Strength. **Table 4.6** includes a summary of the splitting tensile strength results of the mixtures. For each testing age, three 4×8 in. cylindrical specimens were used to determine the splitting tensile strength according to ASTM C496 and the mean values were reported. The splitting tensile test setup is shown in **Figure 4.4**.

Compressive loads (P) are applied on the top and bottom of the specimens where two strips of plywood are placed to apply load along a vertical plane through the specimens. The load at failure is recorded as the peak load, and the tensile strength is calculated using the following equation.

$$F_t = \frac{P}{\pi D L} \qquad (4\text{-}2)$$

Where F_t = splitting tensile strength (psi), P = Ultimate load at failure (lb), D = Sample diameter (in.), and L = Sample length (in.).

Figure 4.4 Splitting Tensile Strength Test Setup

Specimens made with 30% and 50% RCA replacement had the lowest splitting tensile strength values at early age of 7 days. This might be related to the higher air content of these mixtures compared to the other specimens. Besides the results obtained for specimens of the EMV and 100% RCA-TSMA mixtures, there was not a great spread in data obtained for splitting tensile strength of the reference mixture and those made with RCA at 56 days. Mixture made with 100% RCA-TSMA had the lowest splitting tensile strength results at 28 and 56 days of age. On the other hand, the splitting tensile strength of the EMV specimens were 5% and 20% higher than the reference specimen at 28 and 56 days respectively.

Table 4.6 Splitting Tensile Strength Results

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for three specimens (psi)								
7 Days	440	345	450	360	410	425	420	415	380
28 Days	480	450	505	430	470	425	405	500	415
56 Days	505	480	605	470	520	480	440	605	435

Again it was observed that for the specimens made with w/c=0.4, the splitting tensile strength decreased drastically due to full RCA replacement. This decrease was only 4% in the case of specimens made with w/cm=0.45. In the case of specimens made with 100% RCA replacement, tensile strength of the specimens made with w/c=0.4 was not higher than those for the specimens made with w/cm=0.45. This might be due to higher air content of concrete made with w/c=0.4 as well as the pozzolanic effect of 25% Class C fly ash used in w/cm=0.45 specimens. Results are in line with data obtained by Sagoe et al. (2001), who reported that there is no significant difference between the splitting tensile strength of the reference and the recycled aggregate concrete specimens. The EMV results are similar to those reported by Fathifazl et al. (2011) who observed the positive impact of the EMV method on splitting tensile strength of concrete. However, the data obtained from TSMA was contradictory to that reported by Tam et al. (2005, 2007).

The splitting tensile strength of normal weight concrete can be estimated using the following equation provided by ACI 318:

$$f_{ct} = 6.7\sqrt{f'_c} \qquad (4\text{-}3)$$

Where:

f'_c = compressive strength of concrete (psi)

f_{ct} = splitting tensile strength (psi).

The predicted values using the suggested ACI equations and the variations from the test results are reported in **Table 4.7**.

It was observed that in most of the cases, the ACI equation overestimates the splitting tensile strength. The most accurate predictions were in the case of the reference mixture with w/cm = 0.45.

4.2.4. Flexural Strength. The flexural strength, also known as modulus of rupture, was measured on 6×6×21 in. beams in accordance with ASTM C78. Two specimens were tested for each concrete mixture at each testing age and the mean values were reported as flexural strength of the concrete. A four-point bending setup was used for testing the flexural strength. **Figure 4.5** depicts a schematic view of the test setup used for loading the beams. Two rigid supports were located approximately 1.5 in. away from each side of the specimen. The load was applied on the concrete beam and the failure load (P) was recorded. The flexural strength is then calculated using the following equation:

$$R = \frac{Pl}{bh^2} \tag{4-4}$$

Where R = modulus of rupture (psi), P = the ultimate load (lb), l = span length equal to 18 in., b = average beam width at fracture (in.), and h = average beam height at fracture (in.).

Table 4.7 Comparing the Splitting Tensile Strength Data with ACI 318 Equation

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Predicted value by ACI 318 (psi)								
7 Days	433	406	457	405	446	450	455	473	457
Variation (%)	-1.6	17.6	1.6	12.4	8.9	5.9	8.3	13.9	20.4
28 Days	481	458	503	448	502	499	485	511	487
Variation (%)	0.2	1.7	-0.5	4.2	6.8	17.3	19.6	2.1	17.4
56 Days	500	485	547	460	516	502	527	542	496
Variation (%)	-0.9	0.9	-9.6	-2.1	-0.8	4.5	19.7	-10.4	14.0

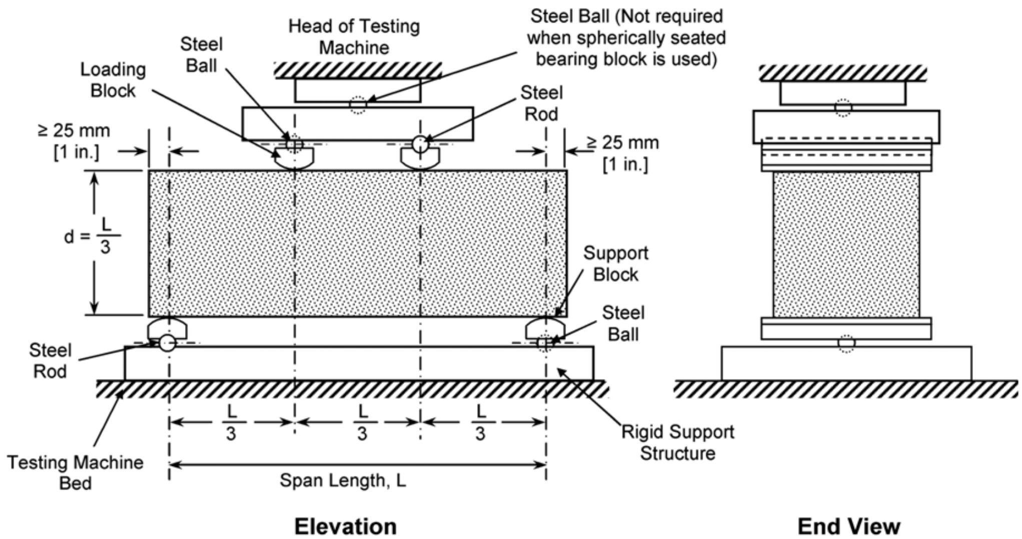


Figure 4.5 Simply Supported Beam for Determining the Flexural Strength (ASTM C78)

Table 4.8 includes the modulus of rupture data obtained from testing different specimens. Flexural strength of the specimens made with 30% and 50% RCA were lower than the reference specimens. This might be mostly due to the higher air content, especially in the case of 50% RCA specimens. The flexural strength of the specimens made with 70% and 100% RCA replacement were pretty close to the reference mixture. Similar results were published by Xiao and Li (2005) and Ravindrarajah and Tam (1985) who reported that increasing the RCA content does not have a significant effect on flexural strength. The high quality of RCA along with the rough surface texture which increases the aggregate interlock might be considered as the main reasons for these observations.

Contrary to the splitting tensile strength results, TSMA was effective in increasing the flexural strength of the specimens by 25% and 6% at 28 and 56 days respectively. Specimens made with the EMV method had very good flexural performance as well. The

28 day results obtained for this mixture was 24% higher than the reference mixture. However, both the mixtures had similar performance at 56 days.

Table 4.8 Flexural Strength Results

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for two specimens (psi)								
28 Days	590	635	730	610	630	605	760	645	680
56 Days	765	695	780	630	760	775	820	890	690

The flexural strength of normal weight concrete can be estimated using the following equation provided by ACI 318:

$$R = 7.5\sqrt{f'_c} \tag{4-5}$$

Where

f'_c = compressive strength of concrete (psi)

R = flexural strength (psi)

The predicted values using the suggested ACI equations are reported in **Table 4.9**. It was observed that for all the concrete mixtures in both the test ages, the ACI equation underestimates the flexural strength.

Table 4.9 Comparing the Flexural Strength Measurements with ACI 318 Equation

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Predicted value by ACI 318 (psi)								
28 Days	538	513	563	501	562	558	542	572	545
Variation (%)	-8.8	-19.3	-22.9	-17.8	-10.8	-7.7	-28.6	-11.4	-19.8
56 Days	560	542	612	515	578	562	590	607	555
Variation (%)	-26.8	-22.0	-21.5	-18.2	-24.0	-27.5	-28.1	-31.8	-19.5

4.2.5. Modulus of Elasticity. **Table 4.10** includes a summary of the static modulus of elasticity (Young's modulus) results. For each testing age, three 4×8 in. cylindrical specimens were used for determining the static modulus of elasticity according to ASTM C469. **Figure 4.6** shows the test setup used for measuring the modulus of elasticity.

The loading cycles were repeated three times for each sample. The vertical strain of the specimen corresponding to each stress level was measured using a LVDT system. The results were then used for determining the modulus of elasticity based on the following equation:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050} \tag{4-6}$$

Where E = Chord modulus of elasticity (psi), S_2 = Stress corresponding to 40% of the ultimate load capacity, S_1 = Stress corresponding to a longitudinal strain of 0.000050, and ε_2 = longitudinal strain caused by the stress S_2.

Figure 4.6 Modulus of Elasticity Test Setup

Table 4.10 Modulus of Elasticity Measurements

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for three specimens (ksi)								
28 Days	4780	4600	5350	4350	5030	4830	4670	6300	4700
56 Days	5700	5000	5480	4820	5100	5100	4630	6410	5020

It was observed that the modulus of elasticity is decreasing due to the use of RCA. This is due to the lower stiffness of the RCA particles compared to the virgin aggregate. Similar results were also reported by Hoffmann et al. (2012), and Cabo et al. (2009) who observed that the modulus of elasticity is decreasing as a function of an increase in the RCA replacement ratio.

Variations in modulus of elasticity is in line with the compressive strength results, with the lowest results observed in the case of specimens made with 30% and 50% RCA replacement. These specimens had the highest air contents in the fresh mixture. No improvement was observed in specimens made with 100% RCA-TSMA. While comparing to the reference mixture, the specimens made with the EMV method had 12% higher modulus of elasticity results at 28 days. However, the modulus of elasticity of the reference mixture was 4% higher than the EMV specimens at 56 days. No significant difference was observed between the modulus of elasticity of the 100% RCA specimens with w/c=0.4 and w/cm=0.45. It was also observed that the mixture with lower w/c was more sensitive to RCA replacement. A 22% decrease in 56-day modulus of elasticity was observed in the case of the mixture with w/c=0.4. This decrease was limited to 12% in the case of specimens made with w/cm=0.45.

Modulus of elasticity results are compared to the following equations provided by ACI 318 and AASHTO codes for estimating the modulus of elasticity based on the compressive strength:

ACI 318 :

$$E = 57000\sqrt{f_c{}'} \tag{4-7}$$

Where E is the modulus of elasticity (psi) and $f_c{}'$ is the compressive strength (psi).

AASHTO code:

$$E = 33000 W_c{}^{3/2} \sqrt{f_c{}'} \tag{4-8}$$

Where E is the modulus of elasticity (ksi), W_c is the unit weight of concrete (kcf=1000 pcf), and f'_c is the compressive strength (ksi).

Table 4.11 summarizes the ACI 318 estimations for the modulus of elasticity based on the compressive strength results at 28 and 56 days of age. It was observed that the ACI equation underestimates the modulus of elasticity for all the tested specimens at different ages. Shown in **Table 4.12** are the estimated values for the modulus of elasticity based on the equation provided by AASHTO. Similar to the ACI 318 equation, the equation provided by AASHTO underestimates the modulus of elasticity results. However, the difference between the ACI predictions and the laboratory measurements was less.

4.3. DURABILITY

4.3.1. General. For each of the experimental mixtures, the same volume of concrete (4.5 ft^3) was produced for the durability test sampling. The volume of these batches was selected to be the same as the batches for the mechanical properties to ensure the minimum possible difference in quality of the produced concrete. The mixture for durability investigations was produced directly after finishing the sampling of specimens for mechanical properties. The shrinkage specimens were cast from this batch. Therefore, the shrinkage results are presented along with the durability tests. Shown in **Table 4.13** are the fresh properties of the mixtures for durability sampling.

Table 4.11 Comparing the Modulus of Elasticity Measurements with ACI 318 Equation

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	ACI 318 estimation for MOE (ksi)								
28 Days	4091	3895	4277	3811	4269	4243	4122	4345	4146
Variation (%)	-14	-15	-20	-12	-15	-12	-12	-31	-12
56 Days	4258	4122	4652	3916	4389	4269	4481	4613	4220
Variation (%)	-25	-18	-15	-19	-14	-16	-3	-28	-16

Table 4.12 Comparing the Modulus of Elasticity Measurements with AASHTO Equation

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	AASHTO estimation for MOE (ksi)								
28 Days	3882	3545	4165	3470	3882	3727	3576	4122	3517
Variation (%)	-19	-23	-22	-20	-23	-23	-23	-35	-25
56 Days	4002	3764	4584	3608	4258	3731	3916	4760	3538
Variation (%)	-30	-24	-16	-25	-17	-27	-15	-26	-30

Table 4.13 Fresh Properties of Mixtures used for Durability Sampling

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Slump (in.)	6.0	7.0	4.0	5.5	8.0	8.5	6.0	5.5	8.5
Air content (%)	7.2	7.2	5.5	6.6	5.6	5.4	5.5	8.5	6.5
Unit weight (pcf)	146.0	143.6	148.5	144.2	143.1	141.0	140.5	147.2	137.5

4.3.2. Drying Shrinkage. Three 3.0×3.0×11.25 in. prisms were used for monitoring drying shrinkage of each of the concrete mixtures according to ASTM C157. The concrete specimens were demolded 24 hours after casting and placed in the lime-saturated water of 70±5 ºF for seven days. The samples were then kept in an environmental chamber with a temperature of 70±5 ºF and a relative humidity of 50±5% located at the Hy-Point facility. However, the temperature and/or relative humidity of the chamber were out of the mentioned ranges in periods of time. **Figure 4.7** shows the variations of the relative humidity and temperature of the environmental chamber.

A length comparator with digital indicator was used for measuring the length of the specimens immediately after removing them from the curing tank as shown in **Figure 4.8**.

This initial length was registered and used as the reference for determining the shrinkage deformation of the specimens. The same device was used for measuring the length of specimens at different time intervals after moving them to the environmental chamber. **Figure 4.9** presents the shrinkage deformation of the specimens.

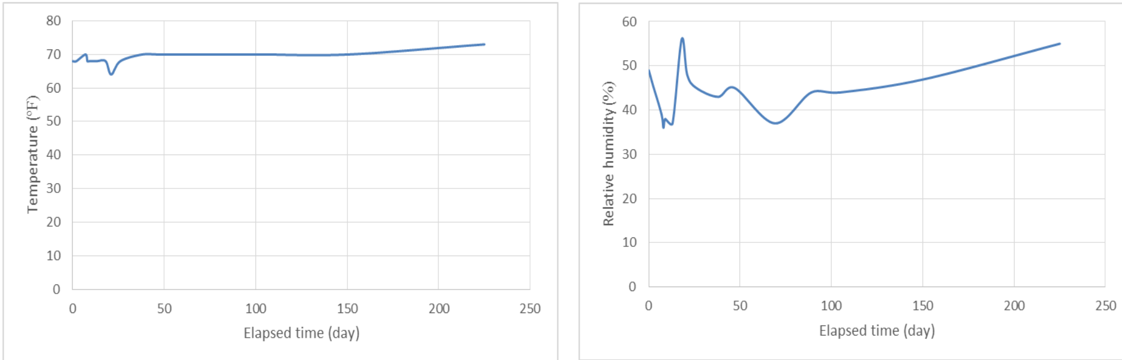


Figure 4.7 Variations in Relative Humidity and Temperature of the Environmental Chamber

Figure 4.8 Measuring the Length of the Shrinkage Specimens

It was observed that all the mixtures made with w/cm=0.45 had approximately similar shrinkage performance. An increase in shrinkage was observed in case of specimens made with 70% RCA. It is usually reported that the shrinkage is increasing as a function of an increase in RCA content. This is believed to be related to the lower stiffness and restraining capacity of the RCA particles due to the residual mortar and a decrease in the total stiff virgin aggregate portion in the mixture as stated by Xiao et al. (2012). On the other hand, Kim and Bentz (2008) and Hu et al. (2013) have observed that the RCA has beneficial effects on shrinkage properties. This might be due to the internal curing using absorptive RCA particles. Similar trends were observed in the case of laboratory made specimens with w/cm=0.45. Based on the obtained results, there is not a significant difference in shrinkage behavior of most of the specimens made with different percentages of RCA and w/cm=0.45. It should be noted that the absorption of the coarse RCA used in this study is 4.56% and aggregates were completely saturated at the beginning of the mixing process. The specimens made with the EMV method had good shrinkage performance which is due to the low fresh mortar content of this mixture. It also should be taken into account that the increased amount of coarse aggregate in this mixture has a positive impact on reducing the shrinkage. Deformations registered in the case of the laboratory made specimens made with 100% RCA-TSMA is slightly higher than the 100% RCA mixture (both with w/cm=0.45). No improvement in shrinkage behavior was observed as a result of using the two stage mixing method.

It also should be noted that the specimen made with virgin aggregates and w/c=0.4 had better shrinkage deformation compared to the mixture made with w/cm=0.45. However, a similar trend was not observed in the case of specimens made with 100% RCA. This might be due to use of Class C fly ash in specimens made with w/cm =0.45.

Differences in the shrinkage deformation of the specimens made with w/c=0.4 was more significant than those made with w/cm=0.45. This means that concrete made with lower w/c may be more sensitive to RCA replacement.

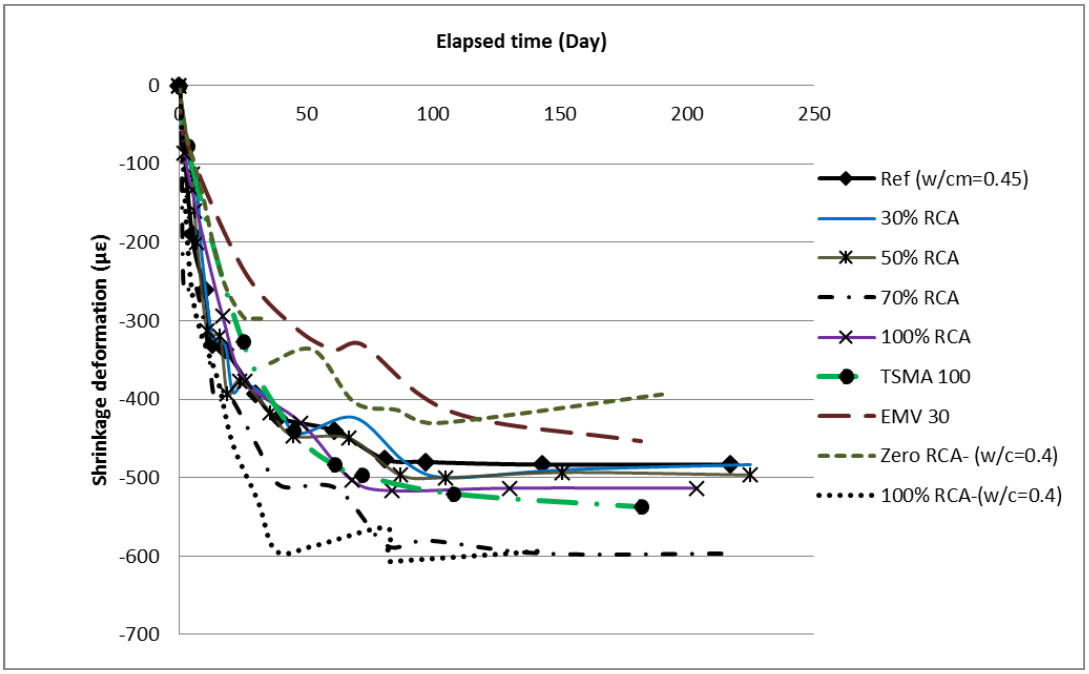


Figure 4.9 Drying Shrinkage Deformation of the Specimens

4.3.3. Surface Resistivity. Resistivity is a material property that quantifies the degree to which an object prevents the passage of an electrical current. While the solid material in concrete has a relatively high resistivity, the pores are partially to fully saturated with a concentrated alkaline solution that has a relatively low resistivity. Thus, electrical current flows primarily through the pore solution, giving an indirect measure of the quality of the microstructure.

The Resipod resistivity meter produced by Proceq Co. with a uniform electrode spacing of 1.5 in. was used to measure the surface resistivity of the cylindrical concrete specimens. The Resipod is a resistivity meter operating on the principle of the Wenner probe. The Wenner probe consists of four equally spaced, co-linear electrodes that are placed in contact with a concrete cylinder specimen. An alternating current is applied to the outermost electrodes and the voltage between the middle two electrodes is used to determine the resistance as shown in **Figure 4.10**.

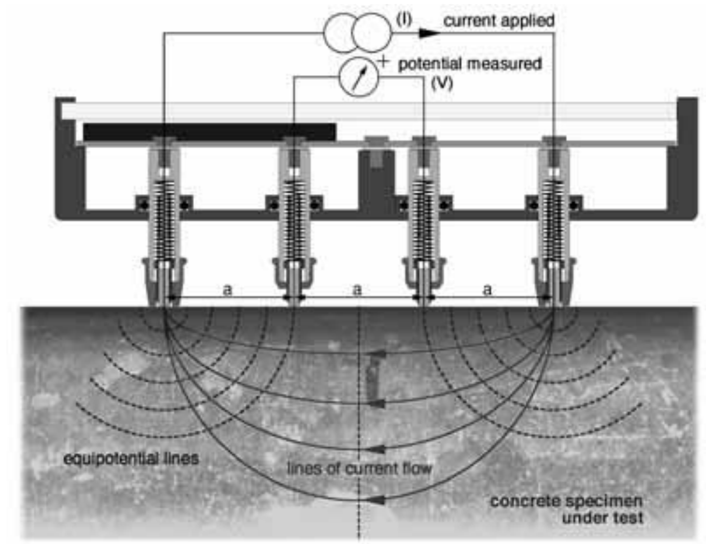


Figure 4.10 Schematic View of the Surface Resistivity Measurement Principles (Proseq SA 2013)

The current is carried by the ions available in the pore solution. The sample resistivity is calculated from the resistance, the distance between the electrodes and the dimensions of the cylinder using the following equation:

$$\rho = 2\pi aV/I \qquad (4\text{-}9)$$

Where:

ρ = surface resistivity (kΩcm)

a = electrode spacing (1.5 in.)

V = potential difference (V)

I = applied electric current

A correction factor equal to 1.1 was applied to the measurements for compensating the effect of lime curing according to AASHTO TP-95.

Considering the less time and effort required for conducting the surface resistivity test, many agencies are moving towards this method to replace alternative time consuming methods such as the rapid chloride ion permeability test (RCPT), chloride ponding, etc., (Chini et al. 2003). This method is also applicable for field measurements for predicting the likelihood of corrosion due to chloride diffusion as well as estimating the corrosion rate once depassivation of the steel has taken place. **Table 4.14** includes the empirical criteria suggested by Proceq Co. (2013) for measured resistivity which can be used to determine the likelihood of corrosion on flat surfaces in the field. **Table 4.15** includes the criteria introduced by Proceq Co. (2013) to predict the corrosion rate based on the surface resistivity on flat surfaces while referring to depassivated steel.

Table 4.14 Correlation between the Surface Resistivity and Likelihood of Corrosion

Concrete Resistivity	Likelihood of Corrosion
≥100 kΩcm	Negligible risk of corrosion
=50-100 kΩcm	Low risk of corrosion
=10-50 kΩcm	Moderate risk of corrosion
≤10 kΩcm	High risk of corrosion

Three 4×8 in. cylindrical specimens were used for determining the surface resistivity. The same specimens were used for tests at different ages to monitor the variations in electrical resistivity with time. Specimens were kept in lime saturated water up to the test time. Before starting the test, specimens were thoroughly washed to ensure performing measurements on a clean surface. **Figure 4.11** shows the surface resistivity measurement process.

Table 4.15 Correlation between the Surface Resistivity and Rate of Corrosion

Concrete Resistivity	Estimated corrosion rate
>20 kΩcm	Low corrosion rate
10-20 kΩcm	Low to moderate corrosion rate
5-10 kΩcm	High corrosion rate
<5 kΩcm	Very high corrosion rate

Figure 4.11 Surface Resistivity Measurement

A good connection between the electrodes and the concrete surface is the most important factor affecting the reliability of measurements. Therefore, the test surfaces were kept wet during the test period to have a good connection. For each specimen, four separate readings were taken around the circumference of the cylinder at 90-degrees Increments (0º, 90º, 180º, and 270º). Measurements were repeated several times at each angle to find the most reliable reading.

Table 4.16 summarizes the results of the surface resistivity at different ages. It was observed that for all the specimens, the resistivity is continuously increasing with time. This is due to the continuing hydration process that reduces the voids and pore space inside the concrete microstructure.

Table 4.16 Surface Electrical Resistivity Measurements

Mixture type	Laboratory produced mixtures (w/cm=0.45)						
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA
Age	Average values for three specimens (kΩcm)						
28 Days	6.3	7.4	6.0	7.6	7.0	5.0	5.2
56 Days	9.5	8.6	8.1	8.4	8.8	6.8	6.1
91 Days	11.6	11.8	9.1	11.6	9.1	8.1	7.2

It was observed that at 28 days of age, most of the RCA-made mixtures had higher resistivity values compared to the reference specimens. However, the surface resistivity measured for the reference specimens was higher than the RCA specimens at 56 days. There was no significant difference in surface resistivity of the reference mixture and the mixtures made with 30% and 50% of RCA at 91 days. But, the specimens made with 70% and 100% RCA replacement had significantly lower resistivity at this age. TSMA was not effective in enhancing the surface resistivity of concrete made with 100% RCA. The EMV mixture had less resistivity compared to the reference and the 30% RCA mixture as well.

Chini et al. (2003) have conducted a comprehensive study in collaboration with the Florida Department of Transportation (FDOT) to correlate the surface resistivity to other electrical resistivity test methods such as the rapid chloride ion permeability test (RCPT). Several types of concrete mixtures made with different types and amounts of pozzolans have been studied in different ages. **Table 4.17** proposed by Chini et al. (2003) compares the surface resistivity results with the RCPT values.

Table 4.17 Correlation between the Surface Resistivity and Chloride Ion Permeability

Chloride ion permeability	RCPT test	Surface resistivity (kΩcm)	
	Charge passed (Coulomb)	28 Days	91 Days
High	>4000	<12	<11
Moderate	2000-4000	12-21	11-19
Low	1000-2000	21-37	19-37
Very low	100-1000	37-254	37-295
Negligible	<100	>254	>295

With regard to the criteria introduced at **Table 4.17** the following conclusions may be made:

28 day test results: all the specimens, including the reference and the RCA-made concrete mixtures have “High” chloride ion permeability index.

91 day test results: The reference specimens and those made with up to 50% RCA replacement have “Moderate” chloride ion permeability. However, increasing the RCA content to 70% and 100% results in decreasing the electrical surface resistivity and increasing the chloride ion permeability to the “High” level. Similar results were observed for the specimens made with 100% RCA-TSMA and the EMV method with “High” level of chloride ion permeability.

Figure 4.12 depicts the variations in surface resistivity as a function of RCA replacement level for the reference specimens and those made with up to 100% RCA replacement.

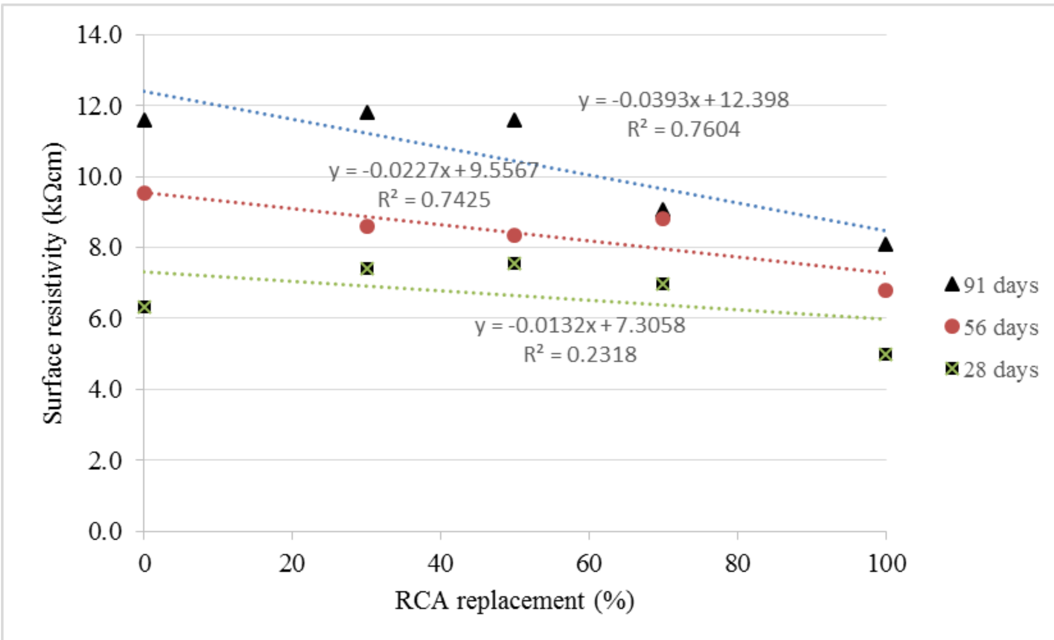


Figure 4.12 Correlation between the Surface Resistivity and RCA Replacement Ratio

A good linear relation exists between the RCA content and the resistivity at 56 and 91 days. It was observed that the surface resistivity decreases at a higher rate at 91 days compared to 56 and 28 days.

4.3.4. Bulk Electrical Conductivity. Besides the surface resistivity, the bulk electrical conductivity of the specimens were measured using the Resipod test setup. The same samples used for the surface resistivity test were used for measuring the bulk conductivity according to ASTM C1760. In order to conduct this test, it is required to put pieces of wet foam on top and bottom of the specimen, between the concrete surface and the metal plates of the test setup. The foam pieces ensure proper electrical contact to the cylinder. However, depending on the moisture condition, these foam pieces will also have some electrical resistivity that should be taken into account to determine the true value of the sample's bulk resistivity. **Figure 4.13** shows the three steps required for bulk resistivity measurements.

First, the resistivity of the upper foam should be determined (R_{upper}). Then, the bottom foam should be placed between the plates, with the specimen on the top plate to simulate the effect of the weight of the specimen on foam thickness and porosity. The resistivity of the bottom foam should be recorded (R_{lower}). Finally, the bulk resistivity of the sample with foam at top and bottom should be measured ($R_{measured}$). Using the following equation, the net bulk resistivity of the sample should be calculated:

$$R_{cylinder} = R_{measured} - R_{upper} - R_{lower} \quad (4\text{-}10)$$

Table 4.18 summarizes the results of the bulk electrical resistivity measurements. Similar to the surface resistivity measurements, most of the RCA made specimens had better performance while compared to the reference mixture at 28 days. However, the EMV specimens had inferior performance compared to 30% RCA specimens at 91 days. It was observed that the bulk resistivity is decreasing as a result of an increase in RCA content with the maximum values for the reference, and the minimum results for the 100% RCA replacement at 56 and 91 days. The TSMA was not effective in enhancing the bulk resistivity of the 100% RCA concrete mixture. The electrical resistivity of the EMV mixture was similar to the 30% RCA mixture and less than the reference at 56 days.

Figure 4.13 Measuring Bulk Electrical Resistivity. Top Foam (top left), Lower Foam (top right), and Specimen Resistivity (bottom photo)

Table 4.18 Bulk Electrical Resistivity Measurements

Mixture type	Laboratory produced mixtures (w/cm=0.45)						
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA
Age	Average values for three specimens (kΩcm)						
28 Days	6.3	7.4	6.7	7.4	6.7	5.3	5.2
56 Days	10.5	9.0	9.0	8.8	9.0	7.3	7.0
91 Days	13.1	12.4	10.2	11.7	10.3	9.4	8.2

Figure 4.14 compares the bulk resistivity measurements of the reference specimens with those of specimens made with various RCA contents ranging from 30% to 100% at different ages. A linear relationship was determined between the RCA content and bulk resistivity.

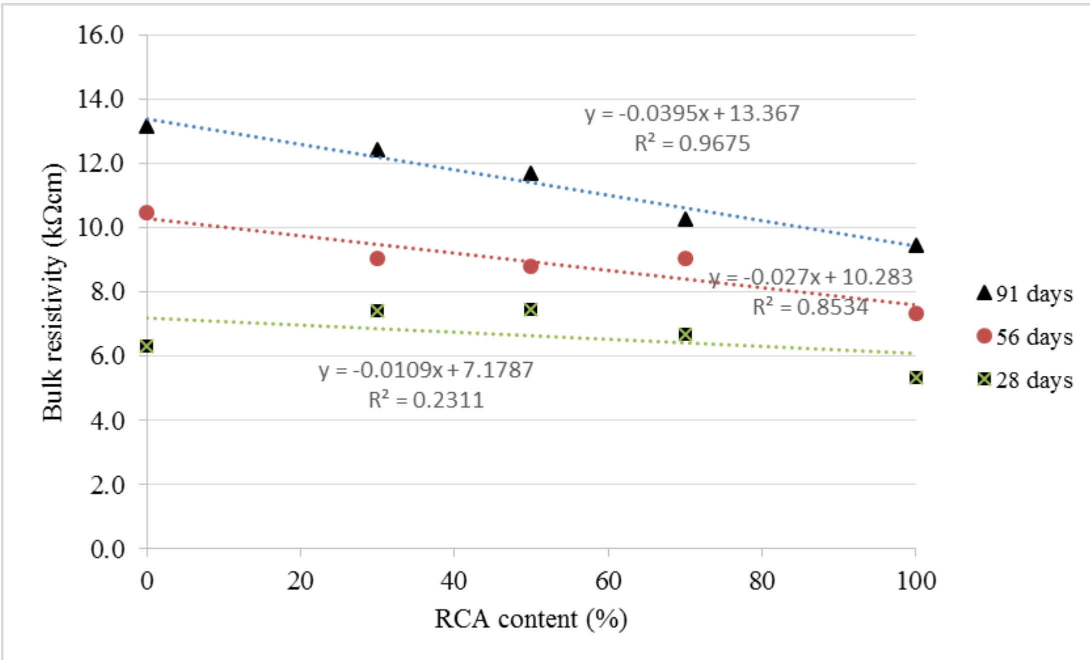


Figure 4.14 Correlation between the Bulk Resistivity and RCA Replacement Ratio

It was observed that the effect of RCA content is more significant at later ages with approximately 0.04 kΩcm decrease in bulk resistivity as a function of each percent increase in RCA replacement at 91 days. The decrease rate was approximately 0.03 kΩcm and 0.01 kΩcm at 56 and 28 days respectively.

Figure 4.15 depicts the correlation between the bulk electrical resistivity and the surface resistivity of the same specimens measured at different ages. A linear correlation exists between these two measured parameters with very little spread in data.

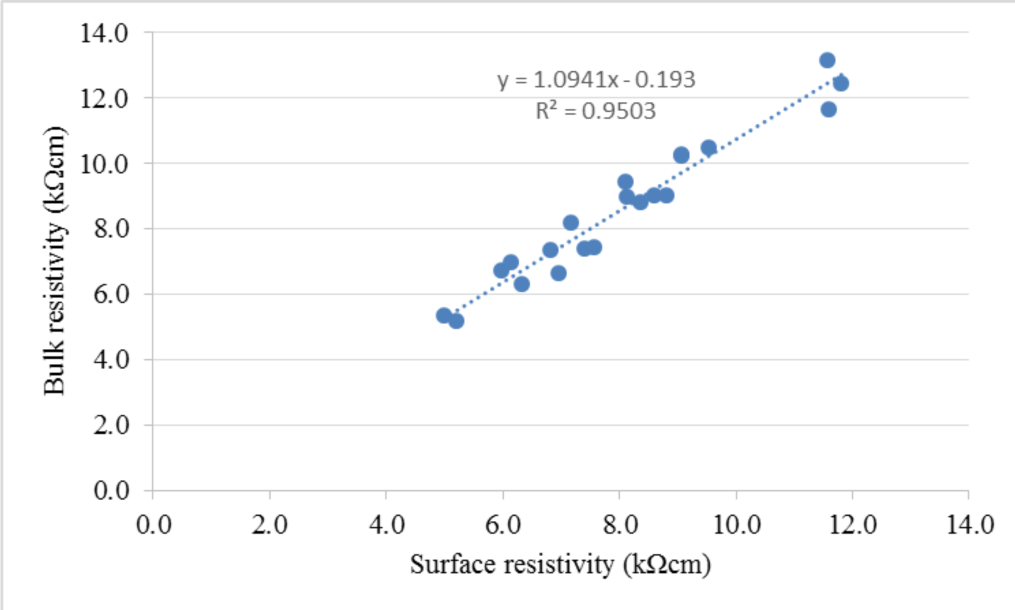


Figure 4.15 Correlation between the Surface and Bulk Electrical Resistivity Measurements

4.3.5. Permeable Void Volume. The ASTM C642 method measures the volume of permeable voids of a concrete sample as a percentage of the volume. This method determines the water absorption after immersion in water at room temperature and after immersion in boiling water for five hours. The high temperature affects both the viscosity and the mobility of the water molecules which may enable the greater displacement of water within the pore system of the hardened concrete (CCAA 2009). Two samples were used for determining the permeable void volume. These samples were half cylinders measuring 4 in. in diameter and 4 in. in height. These samples were obtained by cutting a 4×8 in. cylinder into two pieces. This way, each specimen had finished, formed, and cut surfaces exposed to water penetration. Samples were dried in an oven at a temperature of 220±40 °F up to a constant mass. The oven dried mass of the samples was measured after cooling down to room temperature (A). The specimens were then immersed in water in room temperature up to a time when the specimen was completely saturated and the saturated surface dried (SSD) mass of the specimen was constant. After registering this weight (B), the specimens were immersed in boiling water for five hours, followed by a 14 hours period of rest to cool down to room temperature. The SSD weight after boiling was measured in this step (C). Finally, the submerged weight of specimens was determined (D). The following equations were used for measuring the absorption, density, and permeable void volume of the specimens:

$$\text{Bulk dry density } (g_1) = [A/(C-D)]\times\rho\times100 \tag{4-11}$$

$$\text{Apparent density } (g_2) = [A/(A-D)]\times\rho\times100 \tag{4-12}$$

$$\text{Permeable void volume (\%)} = (g_2-g_1)/g_2 \times 100 \tag{4-13}$$

Where ρ is the density of water equal to 1 gm/cm^3

Table 4.19 includes a summary of the mean values calculated for the permeable void volume of the specimens. It was generally observed that the permeable void volume is increasing as a function of an increase in RCA content. This is due to the higher amount of permeable mortar introduced to the mixture through RCA particles.

The permeable void volume has been used by VicRoads (CCAA 2009) to classify concrete durability as shown in **Table 4.20**. It should be noted that vibrated cylindrical specimens were used for determining the permeable void volume in this study.

It was observed that both the mixtures with no RCA replacement, and the mixture proportioned according to the EMV method had permeable void volumes close to 11%, which means that these mixtures had “Excellent” performance. The mixtures made with 30% and 50% RCA replacement had permeable void volumes close to 12% can be categorized as mixtures with “Good” performance for all test ages. The mixture made with 70% RCA replacement had the permeable void volume close to 13.5%. This means that this mixture had “Normal” permeable void volume. Specimens made with 100% RCA replacement had “Marginal” performance with results ranging between 15% and 16% for all ages. However, the specimens made with 100% RCA-TSMA had “Normal” performance at 91 days of age.

Table 4.19 Permeable Void Volume Measurements

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for two specimens (%)								
28 Days	11.27	12.29	11.62	12.29	13.38	15.12	15.23	11.5	15.75
56 Days	11.36	12.34	11.18	12.29	14.58	15.07	14.32	-	-
91 Days	11.49	12.77	11.03	12.37	13.64	14.87	13.85	10.49	15.28

4.3.6. Absorption. Absorption of the concrete samples is measured for both the saturated and boiled conditions according to the ASTM C642 test method. The following equations are used for calculating the absorption of the samples after immersion and after boiling:

$$\text{Absorption after immersion} = [(B-A)/A] \times 100 \quad (4\text{-}14)$$

$$\text{Absorption after immersion and boiling} = [(C-A)/A] \times 100 \quad (4\text{-}15)$$

Where “A” is the oven dry weight, “B” is the SSD weight after immersion, and “C” is the SSD weight after immersion and boiling.

Table 4.20 Durability Classification based on Permeable Void Volume (CCAA 2009)

Durability classification indicator	Vibrated cylinders (Permeable void %)	Rodded cylinders (Permeable void %)	Cores (Permeable void %)
Excellent	< 11	< 12	< 14
Good	11-13	12-14	14-16
Normal	13-14	14-15	16-17
Marginal	14-16	15-17	17-19
Bad	> 16	> 17	> 19

Tables 4.21 and **4.22** summarize the measured absorption values. For both the immersed and boiled specimens, it was observed that absorption is increasing as a function of increase in RCA replacement ratio. Samples made with w/c=0.4 had relatively lower absorption values compared to samples made with w/c=0.45.

It was also observed that the absorption values registered for the specimens made with the EMV method were less than the reference specimens and those made with 30% RCA. The TSMA was shown to be beneficial in reducing the absorption values registered at 56 and 91 days.

Figure 4.16 depicts the correlation between the absorption values determined after immersion in boiling water versus the absorption values determined after immersion in water at room temperature. A strong linear relation between the absorption values determined after immersion and those determined after boiling exists.

Table 4.21 Absorption after Immersion

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for two specimens (%)								
28 Days	5.00	5.55	5.02	5.49	6.02	6.87	6.95	4.75	6.42
56 Days	5.06	5.53	4.74	5.67	6.28	7.11	6.61	-	-
91 Days	4.92	5.92	4.84	5.66	6.16	7.16	6.77	4.24	6.29

Table 4.22 Absorption after Immersion and Boiling

Mixture type	Laboratory produced mixtures (w/cm=0.45)							Sampled from truck (w/c=0.4)	
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA	0 % RCA	100% RCA
Age	Average values for two specimens (%)								
28 Days	5.06	5.67	5.13	5.67	6.18	7.15	7.26	4.62	6.60
56 Days	5.14	5.69	4.89	5.63	6.44	7.15	6.79	-	-
91 Days	5.15	5.96	4.82	5.68	6.32	7.02	6.74	4.14	6.49

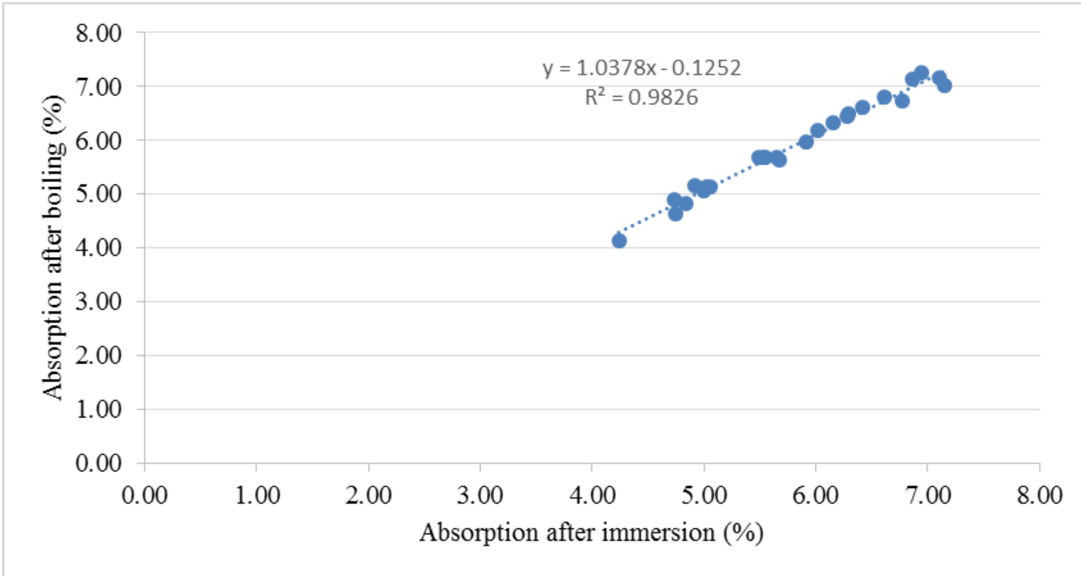


Figure 4.16 Correlation between the Absorption Values Measured after Immersion and Boiling

Immersion in boiling water results in an increase in absorption rate. The average values recorded for absorption after boiling are approximately 3.8% higher than average values registered after immersion in water at room temperature. Similar trends were observed by Thomas et al. (2013), Kou and Poon (2012) and Olorunsogo and Padayachee (2002) who observed an increase in absorption rates after boiling in concrete specimens made with virgin aggregates.

4.3.7. Deicing Salt Scaling. Deicing salts used for ice and snow on concrete contribute to surface scaling and spalling. The scaling and spalling in these cases is physical deterioration. Deicing salts induce mortar flaking, scaling and surface spalling of non-air-entrained concrete during frost conditions, and are thought to be one of the significant causes of this surface deterioration. In addition to leaving the surface deteriorated and rough, this phenomenon can also increase the permeability of the concrete (Mehta and Monteiro 2006). In order to investigate the scaling potential in concrete mixtures, the ASTM C672 test is developed. Slabs with minimum surface area of 72 in.^{2} and minimum thickness of three inches are recommended for this test. A dike is placed on the finished surface of the specimen. This dike is used for ponding the surface of the specimen with a solution of calcium chloride with a concentration of 5.34 oz./gal. Specimens should then be subjected to 50 daily cycles of freezing and thawing. The specimen surface will be washed and the damage will be assessed after each five cycles. The level of deterioration will be rated in a qualitative manner from zero up to four according to the criteria introduced in **Figure 4.17**. Examples of surface appearance corresponding to each of the ratings are also depicted in **Figure 4.17**.

Three slab specimens measuring 3×10×11 in. in dimension were cast for each mixture for deicing salt scaling test. Specimens were cured in lime saturated water for 28 days. It should be noted that according to the standard, the moist curing period is two weeks. But, this period was extended to four weeks to ensure hydration of the fly ash in the concrete mixtures.

The moist curing was followed by a two week period of curing specimens in an environment with constant temperature and relative humidity level. Silicon was used to cast the aforementioned dike on top of the specimens as shown in **Figure 4.18**. Specimens were then transported to the MoDOT material laboratory in Jefferson City, Missouri.

Table 4.23 includes the results of the deicing salt scaling test of the laboratory made specimens.

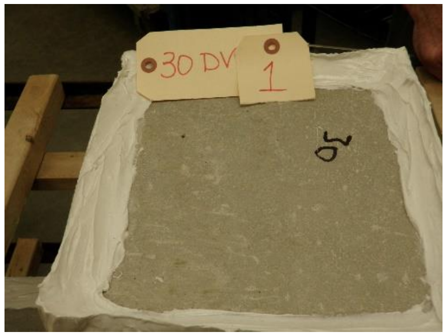
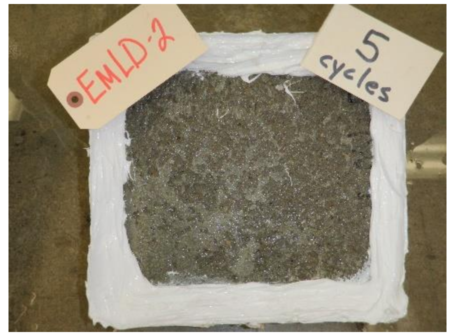
Rating	0	1
Condition of Surface	No scaling	Very slight scaling
Typical surface appearance		
Rating	2	3
Condition of Surface	Slight to moderate scaling	Moderate scaling
Typical surface appearance		
Rating	4	5
Condition of Surface	Moderate to severe scaling	Severe scaling
Typical surface appearance		

Figure 4.17 Rating Scale for Scaling Resistance (ASTM C672)

Figure 4.18 Silicon made Dike for Ponding the Surface of the Specimen with a Chloride Solution

It is observed that the scaling resistance of the RCA-made concrete specimens is less than the reference mixture. For the reference mixture (w/c=0.45) very slight scaling was observed by the end of test cycles. The specimens made with 30%, 50%, and 70% RCA had slight to moderate scaling issues at the same time.

Specimens made with 100% RCA had moderate to severe scaling. However, the specimens made with 100% RCA-TSMA have very slight scaling. It was observed that the EMV specimens are not resistant enough against scaling. For these specimens, moderate to severe scaling was observed by the end of 50 cycles.

Figure 4.19 includes sample photos taken from one out of three panels tested for each mixture at the end of 50 cycles of deicing salt scaling test.

4.3.8. Freeze/thaw Resistance. Saturated concrete is susceptible to damage due to freeze/thaw cycles. The water available in concrete pores can occupy 9% more space while frozen. If there is no space for this volume expansion, freezing may cause distress in the concrete. Distress to critically saturated concrete from freezing and thawing will start with the first freeze-thaw cycle and will continue throughout successive winter seasons resulting in repeated loss of concrete surface (Mehta and Monteiro 2006).

Table 4.23 Deicing Salt Scaling Data

Mixture		Number of cycles									
		5	10	15	20	25	30	35	40	45	50
Laboratory produced specimens (w/cm=0.45)	Ref.	0	0	0	1	1	1	1	1	1	1
	30% RCA	1	1	1	1	2	2	2	2	2	2
	EMV 30%	1	2	3	3	3	3	4	4	4	4
	50% RCA	1	1	1	1	2	2	2	2	2	2
	70% RCA	0	0	1	1	1	2	2	2	2	2
	100% RCA	2	3	3	4	4	4	4	4	4	4
	TSMA 100	1	1	1	1	1	1	1	1	1	1

Disruptive pressures will be developed in a saturated specimen of paste unless every capillary cavity in the paste is not farther than three or four thousandths of an inch from the nearest escape boundary. Such closely spaced boundaries are provided by the correct use of a suitable air-entraining agent. This creates a large number of closely spaced, small air bubbles in the hardened concrete. The air bubbles relieve the pressure build-up caused by ice formation by acting as expansion chambers (Mehta and Monteiro 2006). Prismatic samples measuring 3×4×16 in. were used to perform the freeze/thaw testing according to ASTM C666, Procedure A. For this procedure, specimens were cured in lime saturated water for a period of four weeks before being subjected to freezing and thawing cycles. It is important to note that the period of water curing of the standard test is

14 days; however, given the 25% fly ash replacement, the initial duration of water curing was increased to 28 days. This test subjects the specimens to 300 freezing and thawing cycles. Every 36 cycles, the specimens are removed and properties of the concrete are measured. The ultrasonic pulse velocity test was used for determining the dynamic modulus of elasticity of the specimens and its variation with the increase in freeze/thaw cycles as shown in **Figure 4.20**. **Figure 4.21** plots the variations of the durability factor of the specimens tested according to procedure A as a function of freeze/thaw cycles.

The durability factor reflects the residual dynamic modulus of elasticity of the concrete. A drop in durability factor reflects the presence of internal cracking of the concrete due to damage from repetitive cycles of freezing and thawing. Values of durability factor greater than 80% after 300 cycles of freezing and thawing reflect adequate frost durability.

The highest durability factor was observed in the case of the reference mixture. All the specimens made with up to 70% of RCA replacement had durability factors higher than 80%. This indicates the proper frost resistance of these concrete mixtures. However, the mixture made with 100% RCA had durability factor of 78.5% by the end of the test cycles. This means that the specimens made with 100% RCA replacement might be susceptible to damage due to freeze/thaw cycles. The specimens made with the EMV method had lower durability factor compared to the 30% RCA mixture. The specimens made with 100% RCA-TSMA mixture had acceptable durability factor of 83.7%. Summary of results is included in **Table 4.24**.

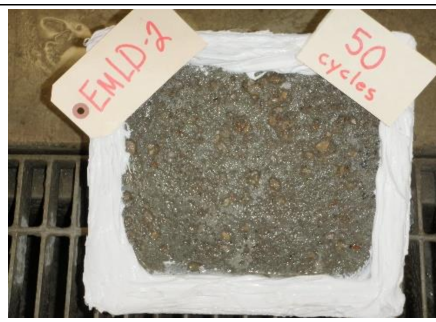
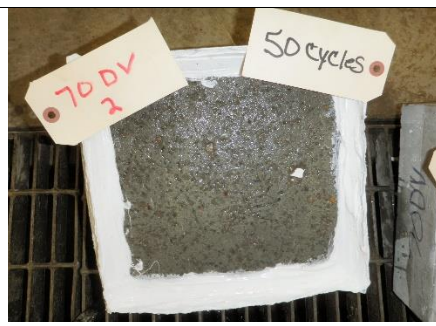
Reference (rating =1)		30% RCA (rating=2)	
30% RCA EMV (Rating=4)		50% RCA (rating=2)	
70% RCA (rating=2)		100% RCA (rating=4)	
100% RCA TSMA (rating=1)			

Figure 4.19 Appearance of the Specimen Surfaces after 50 Cycles of Deicing Salt Scaling Test

Figure 4.20 Freeze/thaw Testing, Procedure A, Freezing and Thawing in Water (left); Measurement of Pulse Velocity (right)

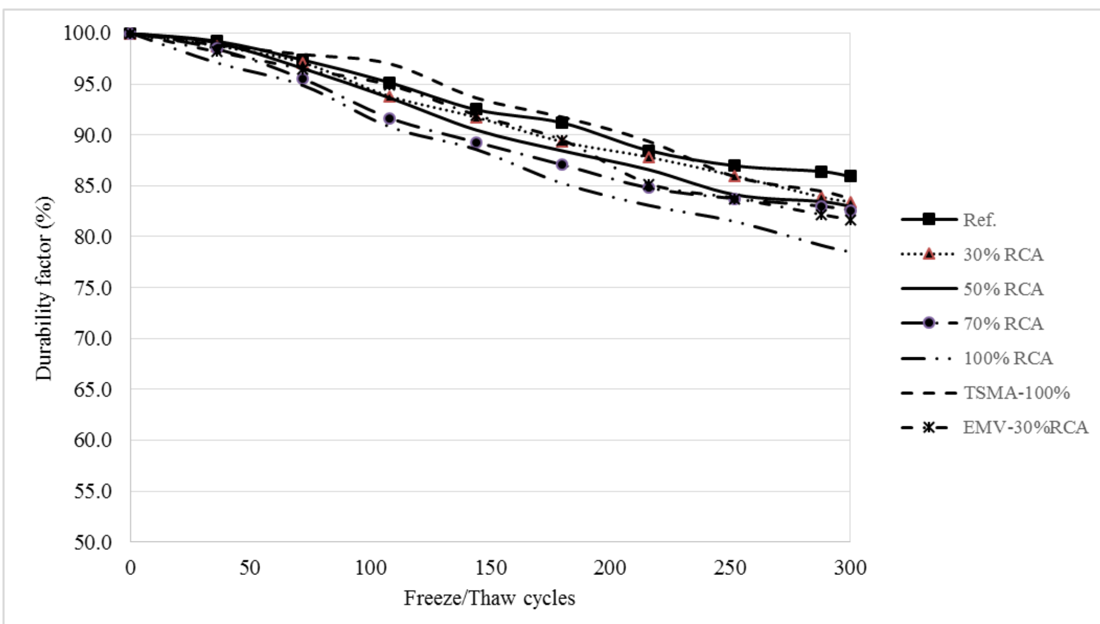


Figure 4.21 Variations in Durability Factor with Freeze/thaw Cycles

Table 4.24 Variations in Durability Factor of Specimens

Mixture type	Laboratory produced mixtures (w/cm=0.45)						
	Ref.	30% RCA	30% EMV	50% RCA	70% RCA	100% RCA	100% TSMA
Average values for three specimens (%)							
# Cycle	300	300	300	300	300	300	300
DF (%)	85.9	83.4	81.6	83.0	82.6	78.5	83.7

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

The main objective of this research study was to evaluate the fresh properties, mechanical performance, and durability of concrete made with RCA. The research was focused on MoDOT Class B concrete with normal strength level. The idea was to investigate the feasibility of producing highly consumed sustainable concrete mixtures with RCA as partial or full replacement of coarse aggregate. Several mixtures with different amounts of RCA and with different mixture proportioning methods and mixing sequences were produced.

5.1. FINDINGS AND CONCLUSIONS

Based on the results of the performed study, the following findings and conclusions are presented:

- There was not a significant difference between the fresh properties of the reference and the concrete mixtures made with RCA replacements up to 100%. However, the EMV mixture was a harsh mixture with significantly lower workability compared to the other mixtures. This result is likely due to the higher coarse aggregate content and lower fresh mortar in the EMV mixture.
- The RCA made in the study was a laboratory-based material. The mixture proportion of the parent concrete used for producing the RCA was similar to that of a MoDOT-PCCP mixture with a w/c=0.4. This results in producing a high quality RCA.

- There was not a significant difference in compressive strength of the concrete mixtures made with RCA replacements up to 70% and 100%. However, due to the higher air content, the mixtures made with 30% and 50% RCA replacement had lower compressive strength compared to the reference and other mixtures.
- Although the amount of cementitious materials used in the EMV mix was lower than the reference mixture, this method resulted in producing concrete with high compressive strength. The TSMA was not helpful in increasing the compressive strength up to 28 days. However, the 56 day compressive strength of this mixture seems to be improved compared to the 100% RCA traditional mixture. No significant difference was observed between the 100% RCA and 100% RCA-TSMA specimens at 91 days. It should also be noted that using the TSMA will increase the mixing time, which will potentially increase the costs of concrete production.
- There was not a significant difference in splitting tensile strength and flexural strength of the mixtures made with RCA. Specimens made with the EMV method had very good tensile and flexural performance compared to the reference mixture. The TSMA was not effective in enhancing the splitting tensile strength. However, flexural strength was improved with TSMA.
- Modulus of elasticity is shown to be affected by RCA replacement ratio. The modulus of elasticity decreases as a function of an increase in RCA content. The EMV mixture had very good modulus of elasticity results. The TSMA was not effective in increasing the modulus of elasticity.

- Contrary to most of the data available in the literature, increasing the RCA did not have a significant negative impact on shrinkage of concrete mixtures. This might be traced in the internal curing effect of the highly absorptive RCA particles. The specimens made with the EMV method had very low shrinkage deformations. This result is due to the lower fresh paste incorporated in this mixture, as well as an increased amount of coarse aggregate in the blend. No improvement in shrinkage behavior of the specimens made with 100% RCA was observed due to the use of the TSMA.
- Permeable void volume and absorption of the RCA mixtures is higher than the reference mixture. The EMV method was effective in reducing the absorption. No significant difference was observed due to using the TSMA.
- Both the surface and bulk electrical resistivity values decrease as a result of increases in RCA content. A decrease in electrical resistivity is more pronounced in replacement levels above 50%. This is due to the more porous mortar phase introduced to the mixture though the RCA particles. Care must be taken while using RCA in aggressive environments when working with reinforced concrete structures. The EMV method was not effective in enhancing the electrical resistivity. The TSMA was not beneficial in increasing the resistivity of the 100% RCA specimens as well.
- Performance of the specimens made with up to 70% RCA replacement seems to be acceptable while being subjected to deicing salt scaling. The mixture made with 100% RCA replacement, however, seems to be susceptible to damage. The EMV method was not effective in enhancing the scaling

resistance. However, the specimens made with 100% RCA-TSMA had very good scaling resistance.

- Durability factor values obtained for specimens made with up to 70% RCA were higher than the acceptable threshold level of 80%. The specimens made with 100% RCA seem to be susceptible to damage due to freeze thaw cycles. Mixtures made with the EMV method and the TSMA had acceptable frost resistance with durability factors higher than 80%.

5.2. RECOMMENDATIONS

It is possible to produce sustainable concrete mixtures with high replacement levels of RCA to be used in MoDOT Class B mixtures. Based on the results presented in this report, the following topics are proposed for further investigating the properties of RCA concrete for infrastructure applications:

- Using other supplementary cementitious materials, such as ground granulated blast furnace slag (GGBS), silica fume, glass powder, etc. as a replacement for Portland cement with the aim of further decreasing the carbon foot print in RCA produced concrete mixtures. Combinations of some supplementary cementitious materials can offset some of the drop in concrete performance resulting from using RCA, thus enabling greater replacements of the virgin aggregate using RCA.
- Investigating the feasibility of using fine RCA in sustainable concrete production.

- Investigating the feasibility of producing high volume recycled aggregate concrete mixtures for other applications (e.g. pavements, etc.).
- Investigating what tests are necessary to adequately characterize RCA sources for use in concrete.

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