FINAL Report A

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

Report A: Preliminary Mix Development

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ABSTRACT

To begin to analyze Recycled Aggregate Concrete (RAC) behavior using coarse aggregate consisting of Recycled Concrete Aggregate (RCA), a baseline concrete had to be selected and, for this study, a MoDOT Class B concrete was chosen. The baseline mix was then classified based on fresh and hardened concrete properties including slump, air content, compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity. Also cast from the baseline mix were numerous unreinforced concrete beams to be crushed to produce the RCA. The crushing process was performed by a local quarry so as to produce a one inch maximum aggregate size (MAS).

The RCA was classified using ASTM aggregate tests including density, relative density, absorption, gradation, and abrasion resistance. From that classification, the RCA was compared to the coarse aggregate used to produce the baseline mix as well as acceptable ranges for aggregate used in MoDOT Class B concretes. The RCA was then used as the coarse aggregate in the production of the RAC trial mixes. The acceptable criteria for the trial mixes were the same as those set for the baseline concrete as it was being designed to replace the baseline concrete. During mixing, it was observed that the RAC produced using forty percent fine aggregate was capable of meeting strength requirements but failed to meet slump requirements. The slump from the forty percent fine aggregate RAC displayed a more viscous behavior than conventional concrete. Using that observation and a combined gradation analysis, a new mix was designed using forty-five percent fine aggregate. The final mix used for the study was a composition similar to a MoDOT Class B mix with the only difference being the fine aggregate content.

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1. INTRODUCTION

1.1. BACKGROUND

Missouri S&T was contracted by MoDOT to determine the feasibility of using recycled concrete aggregate (RCA) in concrete used for structural purposes. Using RCA in concrete has been shown in recent studies to be able to produce adequately strong concrete with an inherent property of high paste content. Although high paste contents can lead to creep and durability problems, in many applications such as sidewalks and interior structural elements these problems are not detrimental to their integrity. The push in recent years to promote sustainable design was also a driving force in trying to use RCA in concrete along with the abundant supply of the current waste material. As a part of the overall study being conducted by Missouri S&T, this part of the study deals with the production of the RCA and the determination of a mix design to be used in future structural elements.

1.2. OBJECTIVES

The objectives of this portion of the study were to produce a typical MoDOT concrete to be processed into RCA and to develop the mix design to be used for future work in the project.

1.3. SCOPE

The scope of this study was limited to moderate strength MoDOT concrete mixes commonly produced and recycled as well as MoDOT approved admixtures for air entraining and water reduction. Both admixtures used in this study were Master® Builders products.

2. LITERATURE REVIEW

2.1. RECYCLED CONCRETE AGGREGATE (RCA)

2.1.1. Properties of RCA. In recent years, there has been a movement towards sustainable management of construction and demolition (C&D) waste. This movement is producing legal requirements. Due to this, sectors of the construction industry are undertaking various endeavors to minimize waste generation and improve the management of C&D waste (Limbachiya et al., 2007).

The building industry is a major consumer of materials as well as a major producer of waste (Padmini et al., 2009). According to Abbas et al. (2008), concrete accounts for up to 67% by weight of construction and demolition waste. This is not just a problem in the United States. Tam et al. (2007) published numbers in line with these values in many cases throughout the world as well as the fact that the rate of production of waste is ever increasing.

As a result of the increasing rate of demolition, it is becoming essential to effectively reuse demolition waste in order to conserve natural resources. Decreasing natural aggregate sources as well as increasing problems with waste management support the idea of using recycled waste as aggregate for new concrete production (Padmini et al., 2009).

As a result of the problems mentioned, the idea or producing “green” recycled aggregate concrete (RAC) has emerged. RAC is by definition a concrete produced using recycled aggregate. According to Kou et al. (2012), RAC will fulfill the three prerequisites of green materials: i) the material can recycle and reduce natural resources and energy consumption; ii) the material will not affect the environment; and iii) the material can maintain sustainable development. Although there are obvious positives from using RCA, there are some technical obstacles limiting its use in concrete production. It should be remembered that RCA is actually a small piece of concrete containing original coarse aggregate (OCA) as well as the adhered mortar (AM). For a clear understanding of the RCA matrix, the separate parts must be identified separately (Nagataki et al., 2000). This concept is visible in **Figure 2.1**.

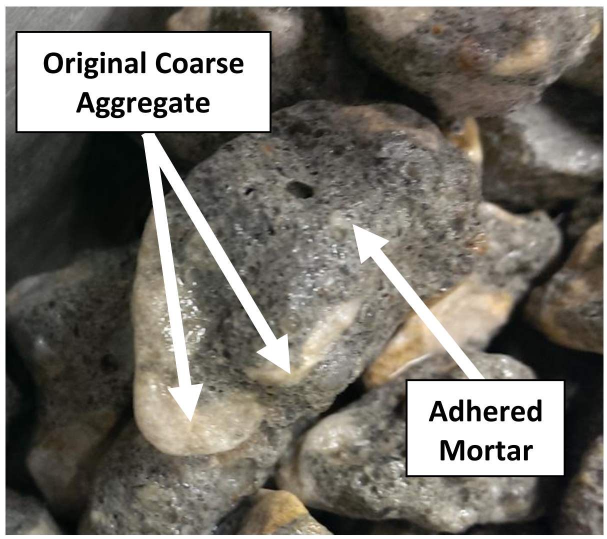

Figure 2.1: Magnified View of RCA Matrix

Li et al. (2012) proposed 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 of RAC looked into mechanical and durability properties. It was observed that although the use of RCA was viable, a decrease in performance of the RAC should be regarded as a normal outcome. Also, Nagataki et al. (2000) reported that the quality of the RCA was not always dependent upon the properties of the adhered mortar.

2.1.2. Effect of Parent Concrete Properties on RCA Characteristics. Padmini et al. (2009) performed studies to analyze the effects between the parent concrete properties on both the RCA as well as the RAC. Three different gradations of natural aggregates with differing maximum aggregate sizes were used to produce concrete. For each gradation, three different concrete compressive strengths were studied. Also, for each of those nine mixes, three different workabilities were studied to produce a total of twenty-seven mixes which are detailed in **Table 2.1**. Then, using a jaw crusher and adjusting its opening size to match the maximum size of the aggregate used in the parent concrete, recycled aggregates were produced to be used in making RAC specimens. The details of the concrete specimens made using RCA are included in **Table 2.2**.

Table 2.1: Details of Parent Concrete (Padmini et al., 2009)

Target mean strength (MPa)	Water-cement ratio	Workability (CF)	Mix proportion by weight and compressive strength with crushed granite aggregate of maximum size					
			10 mm		20 mm		40 mm	
			Mix	Compressive strength (MPa)	Mix	Compressive strength (MPa)	Mix	Compressive strength (MPa)
		0.75	1:1.9:3.1		1:2.0:4.1		-	
PC-1 21	0.58	0.85	1:1.8:3.0	35	1:1.9:3.9	37	1:1.9:4.8	31
		0.95	1:1.8:2.9		1:1.8:3.8		-	
		0.75	1:1.2:2.3		1:1.3:3.0		-	
PC-2 34	0.43	0.85	1:1.2:2.2	49	1:1.2:2.9	50	1:1.3:3.7	45
		0.95	1:1.1:2.1		1:1.2:2.8		-	
		0.75	1:0.9:1.7		1:0.9:2.3		-	
PC-3 45	0.34	0.85	1:0.8:1.7	56	1:0.9:2.2	57	1:0.9:2.9	52
		0.95	1:0.8:1.8		1:0.8:2.2		-	

Table 2.2: Details of Recycled Aggregate Concrete (Padmini et al., 2009)

Designation of recycled aggregate	Strength of parent concrete from which RA is derived (MPa)	Combinations of recycled aggregate concrete cast (three workabilities for each mix)		
		M15	M25	M35
RA10-1	35	RAC 10-1-1	RAC 10-1-2	RAC 10-1-3
RA10-2	49	RAC 10-2-1	RAC 10-2-2	RAC 10-2-3
RA10-3	56	RAC 10-3-1	RAC 10-3-2	RAC 10-3-3
RA20-1	37	RAC 20-1-1	RAC 20-1-2	RAC 20-1-3
RA20-2	50	RAC 20-2-1	RAC 20-2-2	RAC 20-2-3
RA20-3	58	RAC 20-3-1	RAC 20-3-2	RAC 20-3-3
RA40-1	31	RAC 40-1-1	RAC 40-1-2	RAC 40-1-3
RA40-2	45	RAC 40-2-1	RAC 40-2-2	RAC 40-2-3
RA40-3	52	RAC 40-3-1	RAC 40-3-2	RAC 40-3-3

Note: RA10-1 indicates that recycled aggregate of maximum sized 10 mm derrived from parent concrete of mix 1.

The results of the study indicated that:

1. As the strength of the parent concrete was increased, specific gravities increased marginally and the quantity of adhered mortar increased due to increased bond between the aggregate and the mortar.
2. The reduced specific gravity of recycled aggregate results in reduced amount of coarse aggregate in RCA.
3. The water absorption of the recycled aggregate was significantly higher than the parent aggregate, which was due to: i) type of parent aggregate, ii) strength of parent concrete, and iii) the maximum aggregate size used in the parent concrete.
4. The percentage of water absorption increased with increasing strength of parent concrete due to the higher content of adhered mortar on such recycled aggregates
5. Water absorption increased with decreasing maximum aggregate size used in the parent concrete due to the higher surface area available for mortar to adhere to said aggregates for equal volume of aggregates.

2.2. PROPERTIES OF CONCRETE MADE USING RCA

2.2.1. Fresh Concrete Properties. Hoffmann et al. (2012) reported that a relatively high amount of water is needed in concrete production to reach good workability due to high water absorption of the RCA if the aggregate is not pre-soaked. From that, and the known high absorption of the RCA, it is evident that accurate water amounts in the concrete can only be obtained from accurate moisture content measurements prior to mixing.

Domingo et al. (2009) reported that increasing the presence of RCA in the mix decreased the workability of the concrete, which may be traced to the shape, texture, and absorption of the RCA. They stated that due to that, it is necessary to use pre-saturated RCA or a larger amount of superplasticizing additives. Sagoe et al. (2001) however reported that plant processed RCA resulted in relatively smooth, spherical particles which lead to improved concrete workability when compared to natural aggregates.

Although it is generally accepted that using RCA reduces the workability of the concrete, it has been observed that through proper mix proportioning and the use of superplasticizing additives, workability goals can be met.

2.2.2. Mechanical Properties. In regards to the performance of the concrete, the workability of the concrete may yield a look into the mechanical behavior, but to see the complete picture it is necessary to test the hardened concrete. Although the relation between certain mechanical properties of normal concrete are moderately understood, those same relations may not hold true for new concretes. For that reason each property must be investigated individually

2.2.2.1. Compressive Strength. While making concrete for structural uses, the compressive strength is one of the main parameters that should be taken into account. For that reason, many researchers have worked to investigate the effect of replacing natural aggregates with recycled aggregates on compressive strength. It is generally believed that the concrete compressive strength decreases with the increase of RCA in the mixture.

However, typically it is observed that replacements of less than thirty percent produce a negligible effect on compressive strength.

Etxeberria et al. (2007) reported that concrete made with a complete replacement of natural coarse aggregate with RCA resulted in a twenty to twenty-five percent reduction in compressive strength for a given w/c ratio and cement. They also reported that a complete replacement of the coarse aggregate required a high amount of cement to obtain high compressive strengths and was therefore not economically feasible. They stated that when producing medium strength concretes, a maximum of twenty-five percent replacement was economical. Other researchers including Domingo et al. (2009) and Sim and Park (2011) reported increases in concrete strengths with increasing RCA replacement percentages.

Due to the controversies present in the literature review with the issue of compressive strength, very few conclusions can be made. It can be concluded that the w/c is one of the main contributors affecting the compressive strength. Also, with the increased absorption of the RCA, water management will be very important. Through proper water management, the effective w/c can be kept constant.

2.2.2.2. Splitting Tensile Strength. Kou et al. (2012) observed that regardless of the type of recycled aggregate used, the splitting tensile strength of the specimens before the age of twenty-eight days decreased as a function of increasing the RCA replacement ratio. However, they observed that for some types of RCA used, an increase in the splitting tensile strength at the age of ninety days was observed. Xiao et al. (2012) also reported decreasing splitting tensile strength with increasing RCA replacement ratios but did not report any trend of increases.

2.2.2.3. Modulus of Elasticity. Hoffmann et al. (2012) reported that the elastic modulus generally decreases with an increase of recycled aggregate content and with the content of crushed concrete, bricks, and tiles. Pereira et al. (2012) observed that although increasing the RCA replacement ratio resulted in a decrease of elastic modulus of the RAC, using proper type and amount of superplasticizer can increase the elastic modulus to values higher than those of reference concrete specimens with no superplasticizer.

Generally, it is believed that the modulus of elasticity decreases as the RCA replacement increases. The reason may be linked to the high volume of adhered mortar with comparatively low modulus of elasticity that is attached to the original aggregate in the RCA (Xiao et al., 2012).

2.2.3. Direct Volume Replacement (DVR) Mixture Proportioning. Knaack and Kurama (2011) used the direct volume replacement method for producing normal strength concrete mixtures with RCA. The DVR method considers the RCA as a single phase material. A predetermined volume of virgin aggregate is replaced by an equal volume of coarse RCA. The mix proportioning is similar to the method presented in ACI 211 (ACI Committee 211, 1991) for proportioning normal, heavyweight, and mass concrete. Based on the results of their study, it was reported that the workabilities of fresh concrete made with this method were similar to those of the virgin aggregate concrete.

3. TECHNICAL APPROACH

This study was performed in three phases: determination of RCA mix design, production of RCA, and determination of new mix designs implementing RCA. The production of RCA involved producing a selected MoDOT approved concrete mix and determining and using a method to produce a MoDOT approved aggregate gradation from the recycled concrete. Developing a mix design utilizing RCA involved working with multiple mixes until the preselected properties were met.

4. PHASE I – DETERMINATION OF RCA MIX DESIGN

4.1. EXPERIMENTAL DESIGN

A number of decisions needed to be made before the start of the study. The initial concrete to use, virgin aggregate sources, admixture types and dosages, test types, and testing equipment all needed to be decided upon.

The main design consideration impacting the final product was which MoDOT concrete mix to be used in the study. The concrete to be used was important because it dictated the mechanical properties of the aggregate to be produced but it also impacted the validity of the whole study. With the aim of this study to impact sustainability, the concrete to be chosen needed to be in an abundant supply and likely to be a source of recycling in the future. A MoDOT Class B concrete was ultimately selected to be studied. It was selected because it is a very common mix design used, it had a moderate strength requirement of around 4,500 psi, and it was a concrete that had been produced before at Missouri S&T.

By selecting a MoDOT Class B concrete, many mix design choices were simultaneously decided upon. The MoDOT Class B mix dictates strict guidelines for the type and amount of aggregates and cement, the water-cement ratio, the minimum air content, and type and amount of admixtures. The guidelines for a MoDOT Class B concrete can be seen in **Table 4.1**. Based on those guidelines, the virgin coarse aggregate was selected to be Potosi dolomite, Missouri river sand was selected to be the fine aggregate, a water-cement ratio of 0.45, and MB-AE 90 and Glenium 7500 were selected.

Table 4.1: Mix Design Guideline for a MoDOT Class B Concrete

Class B Concrete w/Air	
Cementitious Amount, lbs	535
w/c Ratio	0.40
Amount of Fine Aggregate (by volume), %	45
Design Air Content, %	6.0
Air Entrainment	**Typical Dosage**
Daravair 1400	0.5 - 3.0 fl. oz./100lbs of cement
MB-AE 90	0.25 - 4.0 fl. oz./100lbs of cement
AEA 92	0.1 - 4.0 fl. oz./100lbs of cement
Type A Water Reducer	**Typical Dosage**
Daracem 65	3.0 - 9.0 fl. oz./100lbs of cement
ADVA 140M	5.0 - 9.0 fl. oz./100lbs of cement
WRDA 82	3.0 - 5.0 fl. oz./100lbs of cement
Glenium 7500	5.0 - 8.0 fl. oz./100lbs of cement

The properties of the virgin concrete and RCA to be produced that were of interest to the study included slump, air content, compressive strength gain over time, shear strength gain over time, aggregate density, aggregate absorption, aggregate gradation, and aggregate abrasion resistance. ASTM standard test methods were chosen for each property to be determined.

4.2. REPLICATE SPECIMENS

For each laboratory trial mixture, the research team performed one slump test, one air content test, fifteen compressive strength tests, and ten tensile strength tests.

4.3. MATERIALS

4.3.1. Portland Cement. Type I/II cement was used for all trial batches in the laboratory as well as large scale specimens.

4.3.2. Water Reducer/High Range Water Reducer. The WR/HRWR used in the study was Master® Builders Glenium 7500.

4.3.3. Air Entraining Agent. The AE used in the study was Master® Builders MB-AE 90.

4.3.4. Coarse Aggregate. The coarse aggregate used in this portion of the study was virgin limestone aggregate from the Potosi Quarry (Potosi, MO).

4.3.5. Fine Aggregate. The fine aggregate used in this portion of the study was virgin natural sand from Missouri River Sand (Jefferson City, MO).

4.4. TEST EQUIPMENT AND PROCEDURES

4.4.1. Mixing Procedure.

4.4.1.1. Pre-Mixing Preparation. Prior to mixing of the concrete batches, the individual components were weighed and placed in their own separate containers. All aggregate types were tested for moisture content per ASTM C 566 (ASTM 2013) and adjusted properly. The mixing water was separated into four containers. The water container sizes were one half, three eighths, one sixteenth, and one sixteenth in relation to the total mix water. The two smallest containers were used to mix in the air entrainer and water reducing admixtures.

4.4.1.2. Mixing Method. The concrete batches for the strength specimens, slump, and air content were mixed using the same procedure. The mixing conformed to ASTM C 192 (ASTM 2007a). The drum mixer was first moistened by putting cement and water into the drum and allowing it to rotate. Once all surfaces inside the mixer were moist, the slurry was drained from the mixer. Next, the mixing drum was turned on and all of the coarse aggregates and all of the fine aggregates were added to the drum with half of the allotted mix water. After approximately three minutes, when the mix water had been mostly absorbed into the aggregate, all of the cement was added to the mixing drum along with three eighths of the total mix water. The concrete mixture was then allowed to mix for two minutes. At that point, the WR/HRWR along with the water it had been mixed with was added to the concrete. Thirty seconds after that the AE along with the water it had been mixed with was added to the concrete and the mixture was left to mix for three minutes. After those three minutes, the mixture was allowed to rest in the still drum mixer and then mixed for two more minutes. Immediately after the final two minute mixing, slump and air content tests were begun and, if the results were deemed acceptable, strength specimens were cast. The complete mixing sequence is shown in **Table 4.2**.

4.4.2. Strength Specimens.

4.4.2.1. Cylinder Compressive Strength. Fifteen replicate specimens per mixture were molded. Each cylinder mold was treated with a bond break solution prior to placing any concrete inside the molds. The placing, consolidation, and finishing of the cylinder specimens was done as outlined in ASTM C 192 (ASTM 2007a). Following the finishing of the cylinder specimens, the specimens were placed on a flat surface, covered with plastic, and allowed to cure for twenty-four hours in the laboratory. After the day of curing in the lab, the specimens that were not to be tested at day one were moved into a moist cure room conforming to ASTM C 192 (ASTM 2007a).

Three replicate specimens were tested each test day to determine the average strength per day. Prior to the testing of the cylinders, the two ends of the cylinder had to be made parallel. To prepare the cylinder, sulfur caps were added to the cylinder in accordance with ASTM C 617 (ASTM 2012a). With the cylinders prepared properly, the specimens were placed into a Forney testing machine and loaded at a rate corresponding to a stress rate on the specimen of thirty-five plus or minus seven pounds per square inch (35±7 psi), which is the limit set forth in ASTM C 39 (ASTM 2011a). The maximum load carried by the specimen was recorded and the strength of each cylinder was then calculated to be that load divided by the cross-sectional area of the cylinder.

Table 4.2: Mixing Method Sequence (MoDOT Class B)

Elapsed Time (mm:ss)	Action
0:00	Turn on the mixing drum Insert plenty of water into the mixer Insert a scoop of cement into the mixer
3:00	Drain the excess slurry Insert all of the aggregate and half of the total mix water
6:20	Insert all of the cement Insert three eighths of the total mix water
8:30	Insert the WR/HRWR along with the water it was mixed with
9:00	Insert the AE along with the water it was mixed with
12:00	Stop the drum from rotating
15:00	Re-start the mixer
17:00	Stop mixing the concrete Remove the concrete and begin testing

4.4.2.2. Splitting Tensile Strength. Ten replicate specimens were molded using the same procedure as that used for the compressive strength specimens. Also, the curing procedure for these specimens was identical to that for the compressive strength specimens. All cylinders cast were cured identically.

Two replicate specimens were tested each test day to determine the average splitting tensile strength per day. The splitting tensile strength test was performed in accordance with ASTM C 496 (ASTM 2011b). The cylinder was loaded with a diametrical compressive force along its length. That compressive load induces a tensile force along the plane containing the applied load. The splitting tensile strength specimens were also tested in a Forney testing machine. To determine the strength value for each specimen, the maximum carried load was divided by pi times the diameter squared.

4.4.3. Slump. For each concrete mixture produced, two tests were run on the fresh concrete. The first test run was the slump test. The slump test is used to measure the workability of the concrete mixture. In accordance with ASTM C 143 (ASTM 2012b), the slump test is run by placing and compacting, through rodding, concrete into a standardized conical mold and then raising the mold. The slump of the concrete is determined by measuring the distance the top face of concrete has fallen from its original position.

4.4.4. Air Content. The method chosen to determine the air content of the concrete mixtures produced was the pressure method as prescribed in ASTM C 231 (ASTM 2010a). In this method, a container is filled with compacted concrete and sealed such as to remove all air outside of the concrete. Pressurized air is then forced into the container and a calibrated dial is read to determine the air content present in the given concrete mixture. This method is very effective and accurate when using a properly calibrated machine as well as using the appropriate aggregate correction factors, as determined per ASTM C 231 (ASTM 2010a). The aggregate correction factor accounts for each aggregates innate tendency to accept air when the pressure pot has air forced into the container.

4.5. RESULTS AND DISCUSSION

After producing numerous design batches in the laboratory and running the strength and fresh concrete tests, it was decided that the appropriate admixtures required to produce a concrete conforming to the guidelines of a MoDOT Class B mix were 8.0 oz./cwt of Glenium 7500 and 0.5 oz./cwt of MB-AE 90. The Class B mix design and selected oven-dry (OD) mix design can be seen in **Tables 4.3** and **4.4**, respectively.

Table 4.3: General Mix Design Parameters

MoDOT Class B Mix Design	
Cementitious Amount, lbs	535
w/c Ratio	0.40
Amount of Fine Aggregate (by volume), %	40
Design Air Content, %	6.0
Design Slump, in.	5.0

Table 4.4: Oven Dry Mix Design Selected

OD Design Batch Weights	
Design Weight (lb/yd^3)	
Cement	535
Water	241
Missouri River Sand	1225
1" Potosi Dolomite	1915
Recycled Concrete Aggregate	0
Admixtures Dosage (fl.ozs/cwt)	
HRWR, Glenium 7500	8.0
AE, MB-AE 90	0.5

The selected mix produced an average air content value of six percent and a slump slightly larger than five and a half inches while also producing average strength values slightly larger than the required 4,500 psi on average.

5. PHASE II – PRODUCTION OF RCA

5.1. EXPERIMENTAL DESIGN

Once the mix design for the virgin aggregate concrete had been decided upon, the problem of producing the aggregate from the cast concrete specimens had to be addressed. Many ideas were discussed in the design meetings from using laboratory jaw crushers as seen in some of the literature review to using a mechanical jackhammer to pulverize the concrete specimens. Ultimately, the decision was made to approach Capital Quarries to see if it was possible to use their facilities to produce the RCA. The benefit of using the quarry was that after crushing the specimens, the material could be sieved to produce a MoDOT D Gradation similar to that of the Potosi limestone used as the virgin aggregate. If Capital Quarries agreed to crush the specimens, what size and shape the specimens needed to be for the quarry to crush them had to be addressed at that time. Capital Quarries agreed to crush and screen the concrete and said that concrete beams would be acceptable for crushing as long as there was no steel present in the elements.

After deliberating on a method to cast beams with no steel present and also be able to pick the beams up and transport them, it was decided to imbed two PVC conduits into each beams to create holes through the finished member. Those holes were used to place temporary steel bars in to create pick-points on the concrete beams. The layout of the molds with the conduits present can be seen in **Figure 5.1**. As shown in the figure, the long beam molds were used to cast two beams each by providing a break at their midpoint. This was done to make the beams safer to transport as well as easier for the quarry to handle. The conduit that was cast into the concrete beams was designed to be removed prior to crushing.

Figure 5.1: Concrete Beam Molds with PVC Conduits

With Capital Quarries agreeing to process the RCA, the next consideration was how much aggregate would be obtained from each cubic yard of concrete crushed and how many tons of aggregate would be required. It was determined that the production weight of RCA should be approximately thirty tons and assuming twenty-five percent loss in processing the beams, that would require twenty cubic yards of concrete beams. Rolla Ready Mix (RRM) was selected as the concrete provider for the large concrete pours due to the required amount of material.

5.2. REPLICATE SPECIMENS

In the laboratory, the space allocated for the RCA research project allowed the casting of five long concrete beams along with enough space for any small scale specimens that would be required for the research for each pour. Due to those space limitations, five different concrete pours producing four cubic yards of concrete beams each were scheduled. Along with the beams to be crushed, numerous small scale specimens were cast including compressive strength specimens, splitting tensile strength specimens, modulus of elasticity specimens, and modulus of rupture specimens. Also for each test, slump and air content were performed to confirm that the concrete being used was what was supposed to be delivered and also met the MoDOT Class B concrete requirements. Once the RCA had been produced, the aggregate was tested four times for gradation, density, absorption, dry-rodded unit weight, and abrasion resistance.

5.3. MATERIALS

For the RCA production phase (Phase II), the research team used the same materials as those used to produce the laboratory mixes of Phase I. Refer to Section 4.3 for a complete discussion of the various concrete constituents, including the Portland cement type, WR/HRWR admixture, AE admixture, and coarse and fine aggregates.

5.4. TEST EQUIPMENT AND PROCEDURES

5.4.1. Mixing Procedure.

5.4.1.1. Pre-mixing Preparation. Prior to ordering concrete from Rolla Ready Mix, the mix design was adjusted by removing a controlled amount of water from the batch weights. This step was done to help control the amount of mix water arriving from the batch plant. The WR/HRWR and AE admixtures were also prepared as these would be added to the concrete mixture when it arrived at the lab.

5.4.1.2. Mixing Method. When the concrete truck arrived at the lab, a slump test was performed on the concrete to determine if the appropriate w/c ratio was present in the concrete. If the mix was too dry, water was added until the expected slump occurred. At that point, the WR/HRWR was added to the truck and the concrete was allowed to mix for approximately one minute. After that, the AE agent was added to the truck and the concrete was allowed to mix for approximately five minutes. After that time, the concrete was ready to be placed in the appropriate molds.

5.4.2. Strength Specimens.

5.4.2.1. Cylinder Compressive Strength. Numerous replicate specimens were molded for each batch of concrete delivered by RRM during construction of the RCA parent material. Each cylinder mold was treated with a bond break solution prior to placing any concrete inside the molds. The placing, consolidation, and finishing of the cylinder specimens was done as outlined in ASTM C 192 (ASTM 2007a). Following the finishing of the cylinder specimens, the specimens were placed on a flat surface, covered with plastic, and allowed to cure for twenty-four hours in the laboratory. After the day of curing in the lab, the specimens were de-molded and placed next to their respective beams and allowed to cure in the same conditions.

Three replicate specimens were tested to determine the compressive strength of the concrete on selected days. The specimens were sulfur capped in accordance with ASTM C 617 (ASTM 2012a) and the compressive strength test was performed in accordance with ASTM C 39 (ASTM 2011a). Once the compressive strength reached a minimum of 2,000 psi, the beams were de-molded and stored until the most recent beam had reached the required 4,500 psi compressive strength. At such time, the beams were transported to the quarry for processing and the remaining compressive strength specimens were tested to characterize the parent concrete for the RCA.

5.4.2.2. Splitting Tensile Strength. Numerous replicate specimens were molded using the same procedure as that used for the compressive strength specimens. Also, the curing procedure for these specimens was identical to that for the compressive strength specimens. All cylinders cast were cured identically.

Two replicate specimens were tested to determine the splitting tensile strength of the concrete on selected days. The splitting tensile strength test was performed in accordance with ASTM C 496 (ASTM 2011b). Refer to Section 4.4.2.2 for a detailed discussion of the testing procedure. After the beams were transported to the quarry for processing, the remaining splitting tensile strength specimens were tested to characterize the parent concrete for the RCA.

5.4.3. Slump. The slump test was used during the beam pours to determine the amount of water present in the mix by comparing the slump measured with the slump expected as well as to check that the standards for a MoDOT Class B concrete were being met. The slump test was performed in accordance with ASTM C 143 (ASTM 2012b). Refer to Section 4.4.3 for a detailed discussion of the testing procedure.

5.4.4. Air Content. The air content was determined for each of the beam pours in accordance with ASTM C 231 (ASTM 2010a). Refer to Section 4.4.4 for a detailed discussion of the testing procedure.

5.4.5. Modulus Specimens.

5.4.5.1. Modulus of Elasticity. The modulus of elasticity was performed in accordance with ASTM C 469 (ASTM 2010b). The modulus of elasticity measures the relationship between stress and strain below the proportional limit. Prior to running the test, a linear measuring device is installed on the specimen to measure the strain. The test is then started by conditioning the specimen through loading and partially unloading the specimen. The test is then run by loading the specimen again and unloading it completely. The linear approximation of the data is then reported as the modulus of elasticity. This test was run once for each pour at the time of the concrete beams being processed at the quarry for the purpose of characterizing the parent concrete for the RCA.

5.4.5.2. Modulus of Rupture. The modulus of rupture was run in accordance with ASTM C 78 (ASTM 2010c). The modulus of rupture is a test to determine the flexural strength of an unreinforced beam using a third-point loading scheme. The test is considered valid if the specimen breaks between the top two loading points in the area of constant moment. This test was run three times for each pour at the time of the concrete beams being processed at the quarry for the purpose of characterizing the parent concrete for the RCA.

5.4.6. Gradation. The gradation analysis was performed in accordance with ASTM C 33 (ASTM 2007b). A washed gradation was performed on the RCA prior to each beam pour. The washed gradation is used to better classify the fine particles present in a gradation. The gradation is a breakdown of percent of particles falling between certain sizes and is run by stacking mesh baskets and shaking them until the particles have fallen to the tightest screen.

5.4.7. Density and Absorption. The density and absorption tests were run in accordance with ASTM C 127 (ASTM 2012c). The density is the mass per unit volume of a material. The absorption is defined by ASTM C 127 (ASTM 2012c) as the increase in mass of a material due to water penetration over a given length of time. These two tests are run together as the absorption is a function of the over-dry density and the saturated surface dry density.

The absorption is calculated by allowing an oven-dry sample of aggregate to be submerged in water for a given period of time. At such time, the sample is removed and the surface water is removed. With the sample completely full of water but having no water on its surface, the increase in mass from the oven-dry state is the mass of the absorbed water. That water mass divided by the oven-dry mass is the absorption.

The differing densities are calculated by weighing the sample in the air and underwater at varying degrees of saturation. The relationships between the differing masses are used to calculate the differing densities.

5.4.8. Abrasion Resistance. The abrasion resistance test chosen was the Los Angeles abrasion (LAA) test and it was performed in accordance with ASTM C 535 (ASTM 2012d). The LAA is run by rotating a specific gradation of material inside a steel drum along with steel ball bearings of specific weight and size. The material is rotated for a given number of turns and then the new gradation is sieved over a No. 12 sieve. The LAA loss by abrasion value for the given aggregate is then equal to percent of mass passing through the No. 12 sieve rounded to the nearest whole percent.

5.4.9. Dry-Rodded Unit Weight. The bulk density test was run in accordance with ASTM C 29 (ASTM 2009). The bulk density is the measure of the weight of a given aggregate packed into a container of a given volume, divided by that volume. The larger the bulk density, the tighter the aggregate are packed together. Another possibility is that it could be due to a very dense aggregate.

5.5. RESULTS AND DISCUSSION

The concrete beams were all processed at Capital Quarries just north of Rolla, MO. During the processing, the aggregate was sieved to yield a gradation acceptable by MoDOT Gradation D requirements as shown in **Figure 5.2**.

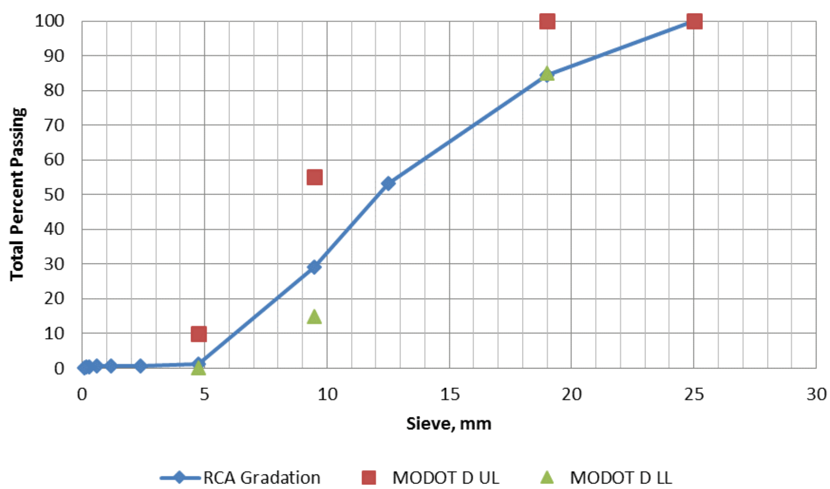

Figure 5.2: RCA Gradation with MoDOT Gradation D Limits

The aggregate product had more adhered mortar present than expected based on literature review and the moderate to low strength of the parent concrete. Photographs of the RCA that was produced can be seen in **Figures 5.3** and **5.4**.

When comparing the properties of the RCA to the virgin aggregate used in the parent concrete, the Potosi limestone, most of the data was as expected. The oven-dry bulk specific gravity was larger for the virgin aggregate. The bulk density was also higher for the virgin aggregate which, since the gradations are nearly identical and the specific gravity is larger, is quite obvious. Also, the absorption for the RCA was much higher than the virgin aggregate as expected. The interesting comparison comes from the LAA abrasion test. The RCA was slightly more resistant to abrasion than the virgin aggregate. All of this data is presented in **Table 5.1**.

Figure 5.3: Washed RCA

Figure 5.4: Close Up View of Washed RCA

Table 5.1: Virgin Aggregate and RCA Comparison

	Virgin Aggregate	RCA
Bulk Density	99.7 pcf	89.7 pcf
Bulk Specific Gravity, OD	2.72	2.35
Absorption	0.98%	4.56%
LAA Loss	43%	41%

6. PHASE III – DETERMINATION OF RAC MIX DESIGN

6.1. EXPERIMENTAL DESIGN

The main purpose in developing a design RAC mix for the study was to propose a design that could be implemented into use by MoDOT. The secondary purpose of the mix design development was to be able to replace the selected parent concrete with the proposed RCA. With those two purposes in mind, it was obvious that the mix design proposed needed to have a similar make-up and similar required properties as the parent concrete selected previously. For that reason, the requirements set forth for the RAC mix design were the same as for the MoDOT Class B mix and the starting point for the mix design was to replace the virgin coarse aggregate completely (volumetrically) with RCA. Again, the same admixtures were used to maintain consistency between the mix designs.

6.2. REPLICATE SPECIMENS

For each trial mixture, there were two slump tests (before and after addition of WR/HRWR), one air content test, fifteen compressive strength specimens, and ten tensile strength specimens produced.

6.3. MATERIALS

To develop the recycled aggregate concrete (RAC) mix design (Phase III), the research team used the same materials as those used to produce the laboratory and plant mixes of Phases I and II except for the coarse aggregate. The Potosi limestone coarse aggregate was substituted with the recycled concrete aggregate (RCA) produced during Phase II. Refer to Section 4.3 for a complete discussion of the Portland cement type, WR/HRWR admixture, AE admixture, and fine aggregate. Refer to Section 5.5 for details on the RCA.

6.4. TEST EQUIPMENT AND PROCEDURES

6.4.1. Mixing Procedure.

6.4.1.1. Pre-Mixing Preparation. Prior to mixing of the concrete batches, the individual components were weighed and placed in their own separate containers. All aggregate types were tested for moisture content per ASTM C 566 (ASTM 2013) and adjusted properly. The mixing water was separated into four containers. The water container sizes were one half, three eighths, one sixteenth, and one sixteenth in relation to the total mix water. The two smallest containers were used to mix in the air entrainer and water reducing admixtures into.

6.4.1.2. Mixing Method. The concrete batches for the strength specimens, slump, and air content were mixed using the same procedure. The mixing conformed to ASTM C 192 (ASTM 2007a). The drum mixer was first moistened by putting cement and water into the drum and allowing it to rotate. Once all surfaces inside the mixer were moist, the slurry was drained from the mixer. Next, the mixing drum was turned on and all of the coarse aggregate and all of the fine aggregate were added to the drum with half of the allotted mix water. After approximately six minutes, when the mix water had been mostly absorbed into the aggregate, all of the cement was added to the mixing drum along with three eighths of the total mix water. The concrete mixture was then allowed to mix for two minutes. At that point, the WR/HRWR along with the water it had been mixed with was added to the concrete. Thirty seconds after that the AE along with the water it had been mixed with was added to the concrete and the mixture was left to mix for three minutes. After those three minutes, the mixture was allowed to rest in the still drum mixer and then mixed for two more minutes. Immediately after the final two minute mixing, slump and air content tests were begun and, if the results were deemed acceptable, strength specimens were cast. The complete mixing sequence is shown in **Table 6.1**.

Table 6.1: Mixing Method Sequence (RAC)

Elapsed Time (mm:ss)	Action
0:00	Turn on the mixing drum Insert plenty of water into the mixer Insert a scoop of cement into the mixer
3:00	Drain the excess slurry Insert all of the aggregate and half of the total mix water
9:20	Insert all of the cement Insert three eighths of the total mix water
11:30	Insert the WR/HRWR along with the water it was mixed with
12:00	Insert the AE along with the water it was mixed with
15:00	Stop the drum from rotating
18:00	Re-start the mixer
20:00	Stop mixing the concrete Remove the concrete and begin testing

6.4.2. Strength Specimens. The same number of specimens and procedures outlined in Section 4.4.2 were also used during the laboratory mixes of Phase III. Refer to Sections 4.4.2.1 and 4.4.2.2 for detailed discussions of the testing procedures for compressive strength and splitting tensile strength, respectively.

6.4.3. Slump. The slump test was performed for each laboratory mix in accordance with ASTM C 143 (ASTM 2012b). Refer to Section 4.4.3 for a detailed discussion of the testing procedure.

6.4.4. Air Content. The air content was determined for each laboratory mix in accordance with ASTM C 231 (ASTM 2010a). Refer to Section 4.4.4 for a detailed discussion of the testing procedure.

6.5. RESULTS AND DISCUSSION

After producing multiple batches of RAC using the same exact mix design used for the parent concrete, it was evident that the slump was not behaving as required. Since the HRWR amount being used was already at the maximum suggested for a MoDOT Class B concrete, the AE amount was increased from half a percent up to one percent. That initial RAC mix design was made multiple times, but the mix was behaving poorly. The mix appeared "sticky" or more viscous than any of the parent mixes from the trial batches in both the mixing drum as well as during the slump test. The slump test required nearly three times the amount of time to settle for the initial RAC mix as compared to the parent mixes. The Class B mix design and selected oven-dry (OD) mix design are shown in **Tables 6.2** and **6.3**, respectively.

Table 6.2: General Mix Design Parameters (RAC)

MoDOT Class B Mix Design	
Cementitious Amount, lbs	535
w/c Ratio	0.40
Amount of Fine Aggregate (by volume), %	40
Design Air Content, %	6.0
Design Slump, in.	5.0

Table 6.3: Oven Dry Mix Design Selected (RAC)

OD Design Batch Weights	
Design Weight (lb/yd^3)	
Cement	535
Water	241
Missouri River Sand	1249
1" Potosi Dolomite	0
Recycled Concrete Aggregate	1662
Admixtures Dosage (fl.ozs/cwt)	
HRWR, Glenium 7500	8.0
AE, MB-AE 90	1.0

After observing the RAC mix behavior, the mix was reproduced while varying the amount of admixtures. Noticing that admixture adjustments did little to change the behavior of the mixture, it was decided to look into different mechanisms that could lead to a “sticky” mix. The mechanism that was investigated was the behavior of the particles and their relation to each other. That mechanism was selected because the “sticky” mix appeared to have particles rolling over each other. To look into the interactive particle behavior, the gradations between the two coarse aggregates from the study were analyzed. The two gradations are shown in **Figures 6.1** and **6.2**, respectively.

As can be seen from comparing the two plots, the RCA gradation has fewer small particles on the limiting sieves even though both aggregates meet MoDOT Gradation D limits. Also, there are almost no fine particles present in the RCA. Without the presence of enough fine particles, the aggregate will behave like marbles unable to maintain a dense packing formation.

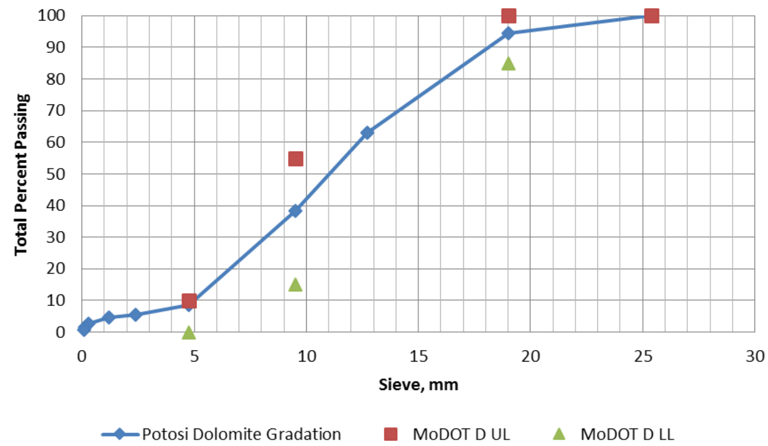

Figure 6.1: Virgin Coarse Aggregate Gradation

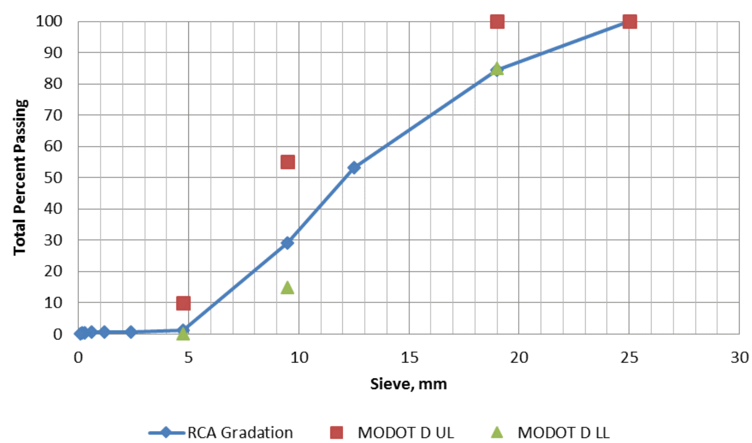

Figure 6.2: RCA Gradation

To better understand the behavior present in the "sticky" mix, a combined gradation was plotted. Along with the combined gradation, a plot of each gradation separately, fine aggregate and coarse aggregate, along with a modified combined gradation was also determined. These four plots are shown in **Figure 6.3**.

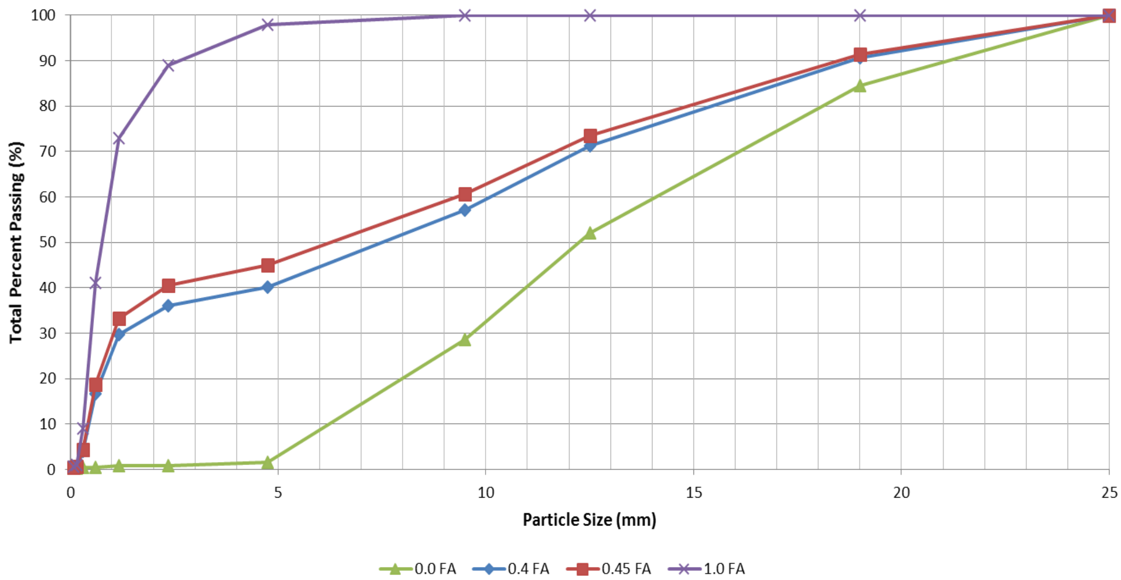

Figure 6.3: Combined Gradation Analysis

With this plot, it becomes visually evident that increasing the fine aggregate by only five percent, from forty percent to forty-five percent, the mix increases its fine aggregate volume by nearly fifteen percent and has little change in its coarse aggregate volume. Using this modified fine aggregate percentage, the MoDOT Class B mix was modified and batched using the initial RAC mix design with 8.0 oz./cwt HRWR and 1.0 oz./cwt AE. That batch appeared to have a more normal viscosity in comparison to those seen in the parent concrete mixes but with excessive slump. After refinement, the HRWR was reduced to produce the final RAC mix to be used for the remainder of the study. The final RAC mix design is detailed in **Tables 6.4** and **6.5**.

Table 6.4: RAC Mix Design Template

"Modified" MoDOT Class B Mix Design	
Cementitious Amount, lbs	535
w/c Ratio	0.40
Amount of Fine Aggregate (by volume), %	45
Design Air Content, %	6.0
Design Slump, in.	5.0

Table 6.5: RAC Oven-Dry Batch Weights

OD Design Batch Weights	
Design Weight (lb/yd^3)	
Cement	535
Water	241
Missouri River Sand	1405
1" Potosi Dolomite	0
Recycled Concrete Aggregate	1524
Admixtures Dosage (fl.ozs/cwt)	
HRWR, Glenium 7500	6.0
AE, MB-AE 90	1.0

7. SUMMARY AND CONCLUSIONS

The determination of the initial mix design was mainly governed by the choice to use a MoDOT Class B concrete. From that, the initial mix design was developed with the only questions to answer being which virgin aggregates to use, which admixtures to use, and what amount of admixture to use.

With the parent concrete mix designed, the task of processing the soon to be hardened concrete specimens into piles of aggregate lay ahead. The processing was handled by Capital Quarries. The only barrier to overcome with the large specimens that were being cast to be crushed was how to cast them without any steel embedments yet facilitate handling. The solution involved embedding PVC conduits into the beams to allow bars to be slid in and out of the concrete when movement by chains was required. Then, when the beams were processed into RCA, the small scale specimens that were cast alongside them were tested to analyze the RAC and the parent concrete on the day of processing because that is the day that the properties stopped gaining strength and rigidity. The RCA was characterized and it was found to be lighter and more porous than the virgin coarse aggregate, but it was slightly tougher when tested using the Los Angeles abrasion test.

Lastly, the development of the RCA mix design to be used for the remainder of the RCA study was developed. The mix design was initially developed exactly as a MoDOT Class B concrete with RCA as the coarse aggregate, but it was soon discovered that there were problems. The mix was behaving far more viscously than any of the previous concrete mix designs. After analyzing the particle characteristics for each aggregate source and the combined aggregates used to produce the RAC, it was determined that a lack of fines was causing viscosity issues in the concrete. The fine aggregate percent by volume was increased from forty percent up to forty-five percent. With that change, the HRWR was able to be reduced to three quarters of that used in the parent concrete while producing similar strength, air content, and slump. That final mix design was then to be used for the remainder of the study of RAC.

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