Recycled Concrete Aggregate (RCA) for Infrastructure Elements

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Missouri Department of Transportation
Construction and Materials

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16. Abstract
With a growing demand for new construction and the need to replace infrastructure stretched beyond its service life, society faces the problem of an ever-growing production of construction and demolition waste. The Federal Highway Administration (FHWA) estimates that two billion tons of new aggregate are produced each year in the United States. This demand is anticipated to increase to two and a half billion tons each year by 2020. With such a high demand for new aggregates, the concern arises of the depletion of current sources of natural aggregates and the availability of new sources. Similarly, construction waste produced in the United States is expected to increase. From building demolition alone, the annual production of construction waste is estimated to be 123 million tons (FHWA). Currently, this waste is most commonly disposed of in landfills.

To address both the concern of increasing demand for new aggregates and increasing production of waste, many states have begun to recognize that a more sustainable solution exists in recycling waste concrete for use as aggregate in new concrete, or recycled concrete aggregate (RCA). This solution helps address the question of how to sustain modern construction demands for aggregates as well as helps to reduce the amount of waste that enters already over-burdened landfills. Many states have begun to implement RCA in some ways in new construction. For instance, forty-one states have recognized the many uses of RCA as a raw material, such as for rip-rap, soil stabilization, pipe bedding, and even landscape materials. Thirty-eight states have gone a step further in integrating RCA into roadway systems for use as aggregate course base material. However, only eleven states have begun using RCA in Portland cement concrete for pavement construction. Furthermore, at the start of this research project, there were no acceptable standards or guidelines in the U.S. for utilizing RCA in structural concrete.

The objective of this research was to determine the implications of using RCA in the production of new concrete. Specifically, the study evaluated the fresh and hardened properties, durability, and structural behavior of concrete containing RCA and, based on these results, developed guidelines on its use in infrastructure elements for MoDOT.

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EXECUTIVE SUMMARY

On behalf of the Missouri Department of Transportation (MoDOT), Missouri University of Science and Technology (Missouri S&T) completed a research study on recycled concrete aggregate (RCA) derived from materials indigenous to the State of Missouri. The report, entitled *Recycled Concrete Aggregate (RCA) for Infrastructure Elements*, consists of a summary report followed by five detailed technical reports. Taken together, these reports document the background, detailed approaches, experimental procedures and processes, results, findings, conclusions, and recommendations of the study.

The research work plan included nine tasks consisting of the following: (1) Task 1: Literature Review, (2) Task 2: RCA Characterization, (3) Task 3: Mix Development & Fresh Concrete Properties, (4) Task 4: Hardened Mechanical Properties, (5) Task 5: Durability Performance, (6) Task 6: Bond and Development Length, (7) Task 7: Full Scale Specimen Tests, (8) Task 8: Recommendations & Specifications for Implementing RCA in Concrete, and (9) Task 9: Value to MoDOT and Stakeholders to Implementing RCA in Concrete.

Based on the results of Tasks 1 through 7, the researchers recommend the implementation of RCA in concrete for construction of transportation-related infrastructure in the State of Missouri. However, the investigators also recommend initially limiting the RCA replacement levels to 50% in order to prevent any decreased performance compared to conventional concrete. Higher RCA replacement levels are possible but will depend on the specific application.

Concrete recycling protects natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete, including in-place recycling. Recycled concrete is less expensive than virgin aggregate sources, and its use would remove a sizeable amount of material from landfills, turning a waste product into a viable construction material. This value aligns with both MoDOT's Tangible Result of being environmentally and socially responsible and MoDOT's Research Need for strategies to reduce energy consumption. The results presented in this research report provide the methods, standards, and guidelines necessary to implement RCA in the construction of transportation infrastructure within the State of Missouri, turning a waste product into a viable construction material.

ACKNOWLEDGEMENTS

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The authors would also like to thank the National University Transportation Center (NUTC): Center for Transportation Infrastructure and Safety (CTIS) housed at Missouri University of Science and Technology (Missouri S&T), which provided valuable match funding from the United States Department of Transportation through RITA and the UTC Program. This match funding allowed for more extensive testing and research on the many factors critical to success of the project.

The authors would also like to thank the companies that provided material and equipment contributions necessary for the successful completion of this project, including the Ameren Corporation, BASF Corporation, and Capital Quarries.

Finally, the authors would like to thank Missouri S&T for their valuable contributions to the research. The university awarded two Chancellor's Fellowships to graduate students working on this project. These individuals represent some of the finest graduate students at Missouri S&T. The authors also appreciate the tireless staff of the Department of Civil, Architectural, and Environmental Engineering and the Center for Infrastructure Engineering Studies. Their assistance both inside and out of the various laboratories was invaluable to the successful completion of this project.

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1. INTRODUCTION

1.1. REPORT ORGANIZATION

The following report documents a research project on recycled concrete aggregate (RCA) performed by Missouri University of Science and Technology (Missouri S&T) on behalf of the Missouri Department of Transportation (MoDOT). The report consists of a Summary Report followed by five detailed technical reports. Section 1 of the Summary Report presents the report organization and background for the study. The project work plan is presented in Section 2 to familiarize the reader with the overall objectives, project tasks, and scope of the research study. Following the project work plan, the summary findings, conclusions, and recommendations are presented task by task in Section 3. Detailed Technical Reports A through E are attached following the Summary Report, which provides the detailed specifics undertaken in this research investigation. The Summary Report is designed to provide the reader with the project highlights in terms of findings, conclusions, and recommendations, while Technical Reports A through E provide the background, detailed approaches, experimental procedures and processes, results, findings, conclusions, and recommendations.

1.2. BACKGROUND

The construction of buildings, bridges, roadways and other infrastructure continues to increase in the twenty-first century, especially in areas with ever-growing populations. Existing structures and highways require repair or replacement as they reach the end of their service life or simply no longer satisfy their intended purpose due to the growing population. As modern construction continues, two pressing issues will become more apparent to societies: an increasing demand for construction materials, especially concrete and asphalt aggregates, and an increasing production of construction and demolition waste. Already, the Federal Highway Administration (FHWA) estimates that two billion tons of new aggregate are produced each year in the United States. This demand is anticipated to increase to two and a half billion tons each year by 2020. FHWA also estimates that the annual production of construction waste from building demolition alone is approaching 123 million tons.

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

Concrete recycling protects natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete, including in-place recycling. However, the successful application of RCA requires a thorough understanding of its effect on the fresh and hardened properties of the resulting concrete. For instance, recycled aggregate usually has higher absorption and lower specific gravity than virgin sources. Both of these issues require adjustments during the mix design process. Concrete made with RCA can also experience increased creep, shrinkage, and permeability – as well as decreased stiffness and compressive strength – compared to concrete produced from virgin aggregate. Nonetheless, proper application of RCA can decrease the cost of transportation-related infrastructure and remove a significant amount of material from landfills, increasing the sustainability of concrete.

2. PROJECT WORK PLAN

As with most research projects, the project work plan evolved during the course of the study as results became available. The work plan described below reflects the work as completed on the project.

The ***objective*** of the research was to determine the implications of using RCA in the production of new concrete. Specifically, the study evaluated the fresh and hardened properties, durability, and structural behavior of concrete containing RCA. The ***project work plan*** included nine (9) tasks necessary to reach this goal and consisted of the following:

1. Task 1: Literature Review
2. Task 2: RCA Characterization
3. Task 3: Mix Development & Fresh Concrete Properties
4. Task 4: Hardened Mechanical Properties
5. Task 5: Durability Performance
6. Task 6: Bond & Development Length
7. Task 7: Full-Scale Specimen Tests
8. Task 8: Recommendations & Specifications for Implementing RCA in Concrete
9. Task 9: Value to MoDOT and Stakeholders to Implementing RCA in Concrete

The following sections discuss each of these individual tasks.

2.1. TASK 1: LITERATURE REVIEW

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 may have on the work 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, creep, shrinkage), structural properties (*e.g.*, bond, shear), and durability (*e.g.*, freeze-thaw resistance, permeability, scaling).

2.2. TASK 2: RCA CHARACTERIZATION

In this task, the research team evaluated the properties of RCA made from concrete containing virgin aggregates indigenous to the state of Missouri. Critical properties studied included density, relative density (specific gravity), absorption, gradation, and abrasion resistance – properties that are also critical for virgin aggregate sources. A standard MoDOT Class B air-entrained mix served as the baseline concrete and as parent material for the RCA. The test methods and protocols are shown in **Table 1**.

2.3. TASK 3: MIX DEVELOPMENT & FRESH CONCRETE PROPERTIES

The aim of this task was to develop, test, and evaluate a series of mixes containing RCA that were targeted for pavement construction and structural concrete with 28-day compressive strengths of 3,500 to 5,500 psi. The higher absorption typical of RCA tends to increase the “harshness” of the mix and often requires alternative methods of

Table 1 Concrete Test Methods and Protocols

PROPERTY	TEST METHOD	TEST TITLE/DESCRIPTION	TASK
RCA CHARACTERIZATION TESTS			
Density, Relative Density, & Absorption	ASTM C 127	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.	2
Gradation	ASTM C 136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.	2
Abrasion Resistance	ASTM C 131	Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.	2
FRESH CONCRETE PROPERTY TESTS			
Unit Weight	ASTM C 138	Standard Test Method for Density (Unit Weight).	3
Air Content	ASTM C 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.	3
Rheology	Non-ASTM	Establish Bingham parameters (yield stress and plastic viscosity).	3
Slump, Slump Retention	ASTM C 143	Standard Test Method for Slump of Hydraulic-Cement Concrete.	3
Bleeding	ASTM C 232	Standard Test Methods for Bleeding of Concrete.	3
HARDENED MECHANICAL PROPERTY TESTS			
Compressive Strength	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.	4
Splitting Tensile Strength	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.	4
Flexural Strength	ASTM C 78	Standard Test Method for Flexural Strength of Concrete.	4
Modulus of Elasticity	ASTM C 469	Standard Test Method for Static Modulus of Elasticity.	4
Drying Shrinkage	ASTM C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete.	4
Fracture Energy	RILEM TC 50-FMC	Determination of the Fracture Energy of Mortar and Concrete by Means of Third Point Bend Test on Notched Beams	4
DURABILITY TESTS			
Resistivity	Non-ASTM	Surface and Bulk Resistivity Measurements	5
Bulk Electrical Conductivity	ASTM C 1760	Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete	5
Permeable Pore Volume & Absorption	ASTM C 642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete.	5
Scaling Resistance	ASTM C 672	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals.	5
Rapid Freeze Thaw Resistance	ASTM C 666, A	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.	5
MILD STEEL BOND AND DEVELOPMENT TESTS			
Third Point Loading Splice Test Specimens	Non-ASTM	Generally regarded as the most realistic test method for development length and splice length, see Fig. 1.	6
FULL SCALE SPECIMEN TESTS			
Shear Test Specimens	Non-ASTM	Full-scale tests to study the shear behavior of beams containing RCA and evaluate the contributions from the concrete, Vc, and transverse (shear) reinforcement, Vs, see Fig. 2.	7
Flexural Test Specimens	Non-ASTM	Full-scale tests to study the flexural behavior of beams containing RCA, see Fig. 2.	7
Non-ASTM – refers to a test method that is not a standard ASTM test. The test is either a generally accepted research practice test or standard undertaken at Missouri S&T for similar studies.			

determining the concrete proportions, such as the Equivalent Mortar Volume (EMV) method of proportioning. The research team developed mixes containing 30%, 50%, 70%, and 100% replacement rates of virgin coarse aggregate with RCA and also evaluated the effect of changes in paste volume and sand-to-coarse aggregate contents on optimum contents of RCA. A standard MoDOT Class B air-entrained concrete served as the baseline mix for the study. The test methods and protocols are shown in **Table 1**.

2.4. TASK 4: HARDENED MECHANICAL PROPERTIES

The objective of the proposed research was to determine the implications of using RCA in the production of new concrete. As such, in this task, the investigators focused on the hardened mechanical properties of concrete containing RCA compared to concrete containing virgin aggregates. The research team used the optimum mix designs from Task 3 to evaluate the impact of different substitution rates and types of RCA on the basic mechanical properties of concrete, such as compressive strength and shrinkage. The primary issue evaluated was whether or not RCA had a negative influence on the resulting concrete properties, and, if so, at what substitution rates do these negative influences begin. Furthermore, how do changes in the properties of RCA impact the substitution rates at which the negative influences begin? For instance, if the RCA maximum aggregate size is reduced from 3/4 in. to 1/2 in. through additional grinding, can the concrete use 30% more RCA before suffering any increase in shrinkage? The test methods and protocols are shown in **Table 1**.

2.5. TASK 5: DURABILITY PERFORMANCE

Previous studies have shown mixed results as to the effect of RCA on the durability performance of concrete. Thus, the aim of this task was to assess the durability performance of concrete containing RCA compared to concrete containing virgin aggregates. Specifically, the research team investigated the effect of RCA on concrete resistivity, conductivity, permeability, absorption, scaling resistance, and freeze-thaw resistance. As with Tasks 3 and 4, the test matrix included different substitution rates of RCA for virgin coarse aggregate. The test methods and protocols are shown in **Table 1**.

2.6. TASK 6: BOND AND DEVELOPMENT LENGTH

The issue to be addressed under this task was to determine whether the current AASHTO *LRFD Bridge Design Specifications*[1] for development length are appropriate for concrete containing RCA. In other words, does RCA enhance, compromise, or not affect the relationship between development length and compressive strength as previously formulated for concrete containing virgin aggregates. This task investigated development length of mild steel in concrete containing RCA compared to concrete containing virgin aggregates.

Two types of tests were used to evaluate the bond performance of mild steel bars in concrete containing RCA. The first test was a direct pull-out test based on protocols recommended in the RILEM Standard 7-II-128.[2] Although this test does not offer a realistic stress state in terms of bond performance in a flexural member, it does offer a convenient relative comparison of bond between different concrete types. The second test was a full-scale beam splice specimen, which is generally regarded as the most realistic test method for evaluating bond.[3,4]

The investigators constructed and instrumented several direct pull-out specimens for testing. Data recorded during the test included load and bar slip. The test variables involved bar size and concrete type (concrete with or without RCA), with the RCA including two replacement levels: 50% and 100%.

The investigators also constructed and instrumented full-scale rectangular beams for splice specimen testing as shown in **Figure 1**. Specimen instrumentation consisted of strain gauges placed at the start of each lap. Data recorded during the tests included load and deflection of the specimen as it was tested to flexural or bond failure. The test variables involved lap length and concrete type (concrete with or without RCA), with the RCA including two replacement levels: 50% and 100%. The test method and protocols are also shown in **Table 1**.

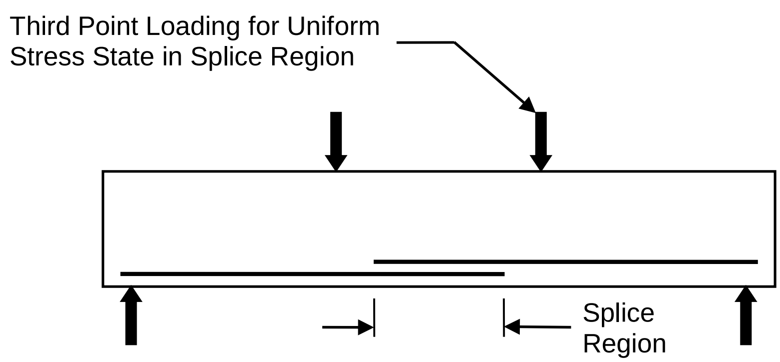

Figure 1 Beam Splice Test Setup

2.7. TASK 7: FULL SCALE SPECIMEN TESTS

This task involved testing of full-scale specimens constructed from concrete containing RCA for comparison with concrete containing virgin aggregates. The full-scale specimens included beam specimens for both shear and flexural testing. This task involved two (2) subtasks. Details regarding the test methods to be investigated are summarized in **Table 1**.

2.7.1. Subtask 7a: Full-Scale Beam Shear Tests. This subtask involved full-scale beam tests to study the shear behavior of concrete containing RCA, which is critical since aggregate properties have such a significant impact on shear strength of concrete. The investigators constructed, instrumented, and tested rectangular beams in the configuration shown in **Figure 2**, which applies a uniform shear over a significant portion of the beam. The variables included amount of longitudinal (flexural) reinforcement and concrete type (concrete with or without RCA). Specimen instrumentation consisted of strain gauges and linear variable displacement transducers (LVDTs). Data recorded during the tests also included load and deflection of the specimen as it was tested to shear failure.

2.7.2. Subtask 7b: Full-Scale Beam Flexural Tests. This subtask involved full-scale beam tests to study the flexural behavior of concrete containing RCA. The investigators constructed, instrumented, and tested rectangular beams in the configuration shown in **Figure 2**, which applies a uniform moment over a significant portion of the beam. The variables included amount of longitudinal (flexural) reinforcement and concrete type (concrete with or without RCA). Specimen instrumentation consisted of strain gauges and LVDTs. Data recorded during the tests also included load and deflection of the specimen as it was tested to flexural failure.

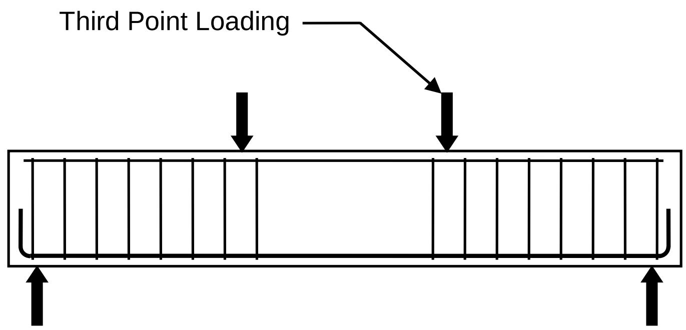

Figure 2 Full Scale Beam Test Setup

2.8. TASK 8: RECOMMENDATIONS & SPECIFICATIONS FOR IMPLEMENTING RCA IN CONCRETE

Based on the results of Tasks 1 through 7, the investigators developed recommendations for the use of RCA in concrete for infrastructure elements. Based on these recommendations and the results of this research study, the investigators also developed a suggested MoDOT specification for the use of RCA in concrete for transportation-related infrastructure.

2.9. TASK 9: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING RCA IN CONCRETE

The issue to be addressed under this task was to quantify the benefit to MoDOT of applying the results of this research project – specifically, to determine a “value to MoDOT and the residents of Missouri” in the event that RCA is incorporated into construction of the State’s transportation-related infrastructure. Concrete recycling protects natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete, including in-place recycling. Recycled concrete is less expensive than virgin aggregate sources, and its use would remove a sizeable amount of material from landfills, turning a waste product into a viable construction material. This value aligns with both MoDOT's Tangible Result of being environmentally and socially responsible[5] and MoDOT's Research Need for strategies to reduce energy consumption.[6]

Overall, this task sought to establish a basis for whether or not RCA should be used by MoDOT, based upon the results from Tasks 1 through 8.

3. TASK SUMMARIES: FINDINGS, CONCLUSIONS & RECOMMENDATIONS

The following descriptions summarize the major findings, conclusions, and recommendations for project Tasks 1 through 9. Each sub-section refers to the specific Technical Report A through E where the background, detailed approach, experimental procedures and processes, results, findings, conclusions, and recommendations may be referenced for much greater detail. Report designations (*i.e.*, “Report A”) are provided as a reference such that the specific detailed report located in the appendix may be consulted to gain an improved understanding of how this particular finding or conclusion was established.

3.1. TASK 1: LITERATURE REVIEW

Detailed Technical Reports A through E each provide a thorough literature review related to the topic of study at hand. The reader is referred to the detailed technical reports for topic specific literature reviews on RCA. However, the more notable general findings include the following:

Technical Reports A through E:

- RCA is a double phase material consisting of virgin coarse aggregate with varying amounts of adhered mortar.
- RCA results in a double interfacial transition zone in the new concrete, with the first zone between the original virgin aggregate and the adhered mortar and the second zone between the adhered mortar and the paste of the new concrete mixture.

- The quality of RCA is tied to the properties of the original waste concrete, the new composition, the mixing approach, and the deterioration conditions of the recycled aggregates.
- RCA generally has lower specific gravity and unit weight and considerably higher absorption and porosity compared to natural aggregates as a result of the adhered mortar.
- As the strength of the parent material increases, the quantity of adhered mortar increases due to increased bond between the aggregate and mortar.
- As the maximum aggregate size used in the parent material decreases, the quantity of adhered mortar increases due to increased surface area of the virgin aggregate.
- Although the use of RCA reduces workability due to increased water demand, proper mix proportioning and the use of superplasticizing admixtures will result in workable concrete mixtures.
- In general, as the percentage of RCA increases, compressive strength decreases, but the effect is negligible at replacement rates of 30% or less.
- In general, as the percentage of RCA increases, splitting tensile strength decreases due to the double interfacial transition zone.
- In general, as the percentage of RCA increases, the modulus of elasticity decreases due to the lower modulus of the adhered mortar.
- In general, as the percentage of RCA increases, the amount of shrinkage increases due to the lower restraining capacity of the RCA compared to virgin aggregate, although the effect is negligible at replacement rates of 30% or less.

- Conclusions with regard to durability resistance have been mixed and performance appears to be more a function of the quality of the parent material.
- Research on bond of mild steel in recycled aggregate concrete (RAC) has been very limited, with most studies performing only pull-out tests, tests on small-scale specimens, or limiting the RCA replacement levels below 50%.
- Research on shear strength of recycled aggregate concrete (RAC) has been limited and is generally contradictory, with studies showing either a decrease in shear capacity with increasing RCA replacement levels or no effect at all.
- Research on flexural strength of RAC has been limited but, in general, has shown that as the percentage of RCA increases, the number and size of flexural cracks increases and the deformations are much higher.

3.2. TASK 2: RCA CHARACTERIZATION

A standard MoDOT Class B air-entrained mix served as the parent material for the RCA. The research team cast 20 cubic yards of the MoDOT mix into concrete blocks for processing at a local quarry. The quarry then crushed, screened, and sieved the material to produce a MoDOT D Gradation similar to that of the Potosi limestone used in the parent material. The research team then evaluated the properties of the RCA necessary for developing the recycled aggregate concrete (RAC) mix designs. The findings and conclusions from this task consist of the following:

Technical Reports A & B:

- The RCA met the requirements for a MoDOT D Gradation.

- The bulk density of the RCA measured 89.7 pcf compared to 99.7 pcf for the Potosi limestone.
- The specific gravity of the RCA measured 2.35 compared to 2.72 for the Potosi limestone.
- The absorption of the RCA measured 4.56% compared to 0.98% for the Potosi limestone.
- The Los Angeles Abrasion of the RCA measured 41% compared to 43% for the Potosi limestone.
- The residual mortar content of the RCA measured 46% by weight.

3.3. TASK 3: MIX DEVELOPMENT & FRESH CONCRETE PROPERTIES

This portion of the study involved developing and evaluating a series of mixes containing the RCA produced in Task 2. The MoDOT Class B mix design served as the guideline for developing the mixes, and the study examined replacement levels of 30%, 50%, 70%, and 100%. The findings and conclusions from this task consist of the following:

Technical Reports A & B:

- The research team successfully developed recycled aggregate concrete (RAC) mixes containing 30%, 50%, 70%, and 100% RCA. The mixes met MoDOT requirements for slump and air content for an air-entrained Class B mix.
- As the RCA replacement level increased, the workability of the mixes decreased, requiring additional water reducing admixture and, for the 100% RCA mix, a modification to the fine aggregate percentage to improve workability.

- As the RCA replacement level increased, the unit weight of the concrete mixture decreased due to the lower specific gravity of the RCA.
- As the RCA replacement level increased, bleeding of the fresh concrete increased, although even at 100% replacement, the amount of bleeding was still at an acceptable level for conventional concrete.
- Except for the concrete made with 100% RCA replacement, it was observed that the yield stress was generally higher for the RAC mixtures compared to the baseline.
- Most of the plastic viscosity results obtained for the RCA mixtures (excluding the 50% RCA mix) were higher than the baseline. However, no clear trend existed.

3.4. TASK 4: HARDENED MECHANICAL PROPERTIES

This portion of the study evaluated the hardened mechanical properties of the mixes developed in Task 3. The objective of this task was to determine the implications of using RCA in the production of new concrete. The findings and conclusions from this task consist of the following:

Technical Report B:

- In terms of compressive strength, there was not a significant decrease for the 70% and 100% RCA mixes compared to the baseline mix. However, due to higher air contents, the mixtures made with 30% and 50% RCA replacement had lower compressive strengths compared to the baseline and other RCA mixtures.
- Although the amount of cementitious materials used in the Equivalent Mortar Volume (EMV) mixes was lower than the baseline mixture, this method produced concretes with relatively high compressive strengths.

- The Two Stage Mixing Approach (TSMA) did not result in increased compressive strengths except for a slight increase in the 56-day strength of the 100% RCA mix. No significant difference was observed between the 100% RCA and 100% RCA-TSMA specimens at 91 days.
- In terms of splitting tensile strength and flexural strength, in general, the RCA mixes showed a slight decrease in performance compared to the baseline mix. However, specimens made with the EMV method had very good tensile and flexural performance compared to the baseline mix. However, the TSMA was not effective in enhancing splitting tensile strength, although it did improve flexural performance.
- As the RCA replacement level increased, the modulus of elasticity decreased. However, specimens made with the EMV method had comparable values to the baseline mix, while the TSMA specimens showed the same decrease in performance as the standard RCA mixes.
- In terms of shrinkage, the RCA mixes had comparable values to the baseline mix, which is contrary to most of the data available in the literature. This result may be traced to the internal curing effect of the highly absorptive RCA used in this research. Specimens constructed using the EMV method revealed very low shrinkage compared to the baseline mix, most likely the result of the very low amount of fresh paste and higher coarse aggregate content for these mixes. No improvement in shrinkage behavior of the specimens made with 100% RCA was observed due to the use of the TSMA.

Technical Reports C, D & E:

- The splitting tensile strength decreased 12% for the 50% RCA mix and 29% for the 100% RCA mix compared to the baseline mix.
- The fracture energy decreased 14% for the 50% RCA mix and 22% for the 100% RCA mix compared to the baseline mix.
- It is important to note that for the bond (Report C), shear (Report D), and flexural (Report E) studies, due to the quantity of material required, the recycled aggregate concrete (RAC) was produced by a local ready-mix supplier and not from a laboratory produced mix.

3.5. TASK 5: DURABILITY PERFORMANCE

Previous studies have shown mixed results as to the effect of RCA on the durability performance of concrete. Thus, the aim of this portion of the study was to assess the durability performance of concrete containing RCA compared to concrete containing virgin aggregates. Specifically, the research team investigated the effect of RCA on concrete resistivity, conductivity, permeability, absorption, scaling resistance, and freeze-thaw resistance. The findings and conclusions from this task consist of the following:

Technical Report B:

- Both permeable void volume and absorption of the RCA mixtures was higher than the baseline 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 decreased as a result of increased RCA content. This decrease was greatest at replacement levels of 50% or more and is likely due to the higher porosity of the RCA compared to the virgin aggregate. Both the EMV method and TSMA were not effective in enhancing the electrical resistivity of the 100% RCA mix.
- In terms of deicing salt scaling, mixtures containing up to 70% RCA performed at an acceptable level. However, the 100% RCA mix suffered serious scaling damage. The EMV method was not effective in improving resistance to scaling. However, the specimens made with 100% RCA-TSMA had very good scaling resistance.
- In terms of freeze/thaw resistance, mixtures containing up to 70% RCA performed at an acceptable level. However, the 100% RCA mix had durability factors below the acceptable threshold level of 80%. Both the EMV method and TSMA were effective at improving freeze/thaw resistance for the 100% RCA mix, with durability factors above 80%.
- The use of fly ash increased the durability performance of all RCA mixes.

3.6. TASK 6: BOND AND DEVELOPMENT LENGTH

The mix designs tested for bond and development consisted of the baseline mix and two RCA replacement levels – 50% and 100% – subsequently referred to as RAC-50 and RAC-100, respectively. The baseline mix is subsequently referred to as the virgin aggregate concrete or VAC. Two test methods were used for the bond strength comparisons. The first was a direct pull-out test based on RILEM 7-II-128[2] "RC6: Bond test for reinforcing steel. 1. Pull-out test." The second test method consisted of full-scale beam splice test specimens subjected to third point loading until failure of the splice. The findings and conclusions from this task consist of the following:

Technical Report C:

- All concrete material properties were negatively impacted with increasing replacement of coarse natural aggregates with RCA. The most drastic decreases were seen in splitting tensile strength and fracture energy, both of which play a crucial role in bond strength. The splitting tensile strength decreased 12% and 29% for the RAC-50 and RAC-100 mixes, respectively. The fracture energy decreased 14% and 22% for the RAC-50 and RAC-100 mixes, respectively.
- For the #4 pull-out tests, based on a square root normalization for compressive strength, there was essentially no difference in average peak bond stress between the VAC and RAC-50 mixes. However, there was a slight increase of 6.0% in the RAC-100 over the VAC mix.
- For the #4 pull-out tests, based on a fourth root normalization for compressive strength, there was a slight increase in average peak bond stress between the VAC and both RCA replacement levels, 7.9% for the RAC-50 mix and 12.9% for the RAC-100 mix.
- For the #6 bar pull-out tests, based on a square root normalization for compressive strength, there was essentially no difference in average peak bond stress between the VAC, RAC-50, and RAC-100 mixes.
- For the #6 bar pull-out tests, based on a fourth root normalization for compressive strength, both the RAC-50 and RAC-100 mixes had 7.1% higher bond stress than the VAC mix.

- For the beam splice specimen tests, based on a square root normalization for compressive strength, the RAC-50 specimens had a slight increase in average peak bar stress of 5.9% over the VAC specimens while the RAC-100 specimens suffered a decrease of 16.9%.
- For the beam splice specimen tests, based on a fourth root normalization for compressive strength, both RCA mixes suffered a decrease in average peak bar stress compared to the VAC specimens, 5.0% for the RAC-50 specimens and 19.5% for the RAC-100 specimens.
- Based on an analysis of the test results, particularly those for the more realistic beam splice specimens, RCA replacement levels above 50% result in a noticeable decrease in bond strength which parallels the decrease in splitting tensile strength and fracture energy.

3.7. TASK 7: FULL SCALE SPECIMEN TESTS

The mix designs tested in the full-scale specimens consisted of the baseline mix and two RCA replacement levels – 50% and 100% – subsequently referred to as RAC-50 and RAC-100, respectively. The baseline mix is subsequently referred to as the virgin aggregate concrete or VAC. Most research to date has consisted only of the evaluation of the strength and durability of RCA concrete mixtures, while only a limited number of studies have implemented full-scale testing of specimens constructed with recycled aggregate concrete (RAC) to determine its potential use in the industry. For this research, a laboratory testing program was developed to investigate the shear and flexural performance of reinforced concrete beams constructed with RCA. The experimental program consisted of 26 tests – 18 for shear and 8 for flexure – performed on full-scale reinforced concrete beams. The findings and conclusions from this task consist of the following:

Technical Report D (shear):

- In terms of crack morphology, crack progression, and load-deflection response, the behavior of the VAC and RAC beams was virtually identical.
- Statistical data analyses – both parametric and nonparametric – showed that there was no statistically significant difference between the normalized shear capacities of the VAC and RAC-50 specimens.
- Statistical data analyses – both parametric and nonparametric – showed that there was a statistically significant difference between the normalized shear capacities of the VAC and RAC-100 specimens, and as a result, the RAC-100 specimens had, on average, 11% lower shear capacity than the VAC.
- For the RAC-50 test beams, the splitting tensile strength, flexural strength, and fracture energy decreased between 1% and 6% compared to the VAC, with the shear strength of the RAC-50 specimens experiencing a decrease of only 1%.
- For the RAC-100 test beams, the splitting tensile strength, flexural strength, and fracture energy decreased between 9% and 22% compared to the VAC, with a corresponding reduction in shear strength of 11%.
- The decrease in shear capacity is most likely due to the double interfacial transition zone that exists when using recycled concrete as aggregate, and the effect is more pronounced as the percentage replacement increases.

- Although limited based on the number of variables tested in this study, it would appear that replacing more than 50% of the virgin aggregate with RCA will result in a noticeable decrease in shear capacity, 11% for the mixes studied in this investigation.

Technical Report E (flexure):

- In terms of crack morphology and crack progression, the RAC beams experienced a larger number, and corresponding closer spacing, of flexural cracks compared to the VAC beams.
- In terms of load deflection behavior, the RAC beams showed lower stiffness both before and after the cracking moments compared to the VAC beams.
- The RAC beams had comparable flexural capacity to the VAC beams.
- Existing design standards conservatively predicted the flexural capacities of the RAC beams.
- Although limited based on the number of variables tested in this study, it would appear that replacing 100% of the virgin aggregate with RCA does not result in any decrease in ultimate flexural capacity compared to VAC mixes.

3.8. TASK 8: RECOMMENDATIONS & SPECIFICATIONS FOR IMPLEMENTING RCA IN CONCRETE

Based on the results of Tasks 1 through 7, the investigators recommend the implementation of RCA in concrete for the construction of transportation-related infrastructure in the State of Missouri. However, the investigators also recommend initially limiting the RCA replacement levels to 50% in order to prevent any decreased performance compared to conventional concrete. In general, when limiting the replacement level to 50%, there are no special requirements in order to utilize RCA in concrete production. However, the following general recommendations should be followed:

- With regard to the RCA, follow the standard MoDOT requirements for virgin aggregate sources in order to characterize the RCA from the specific parent material source. In particular, evaluate the RCA for contamination from chlorides and for signs of D-cracking. With regard to chloride contamination, acceptable levels will depend on a variety of factors including: (1) overall chloride level of the processed RCA (chloride levels vary within exposed concrete with high levels near the surface and negligible levels away from the surface, and when mixed together, acceptable average levels may result in the processed RCA), (2) specific application with regard to type of concrete (*e.g.*, unreinforced concrete, reinforced concrete, prestressed concrete), and (3) specific application with regard to location (*e.g.*, pavement, foundation, retaining wall, bridge deck). With regard to D-cracking, perform identical tests used to evaluate virgin aggregate sources.
- With regard to mix design, follow the standard MoDOT requirements. The only modifications will likely involve increases in the amount of water-reducer or super-plasticizer in order to reach the desired level of workability.

3.9. TASK 9: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING RCA IN CONCRETE

With a growing demand for new construction and the need to replace infrastructure stretched beyond its service life, society faces the problem of an ever-growing production of construction and demolition waste. The Federal Highway

Administration (FHWA) estimates that two billion tons of new aggregate are produced each year in the United States. This demand is anticipated to increase to two and a half billion tons each year by 2020. With such a high demand for new aggregates, the concern arises of the depletion of current sources of natural aggregates and the availability of new sources. Similarly, construction waste produced in the United States is expected to increase. From building demolition alone, the annual production of construction waste is estimated to be 123 million tons (FHWA). Currently, this waste is most commonly disposed of in landfills.

To address both the concern of increasing demand for new aggregates and increasing production of waste, many states have begun to recognize that a more sustainable solution exists in recycling waste concrete for use as aggregate in new concrete. This solution helps address the question of how to sustain modern construction demands for aggregates as well as helps to reduce the amount of waste that enters already over-burdened landfills. Based on a survey by FHWA in 2002, many states had begun to implement recycled concrete aggregate in some ways in new construction. For instance, forty-one states had recognized the many uses of RCA as a raw material, such as for rip-rap, soil stabilization, pipe bedding, and even landscape materials. Thirty-eight states had gone a step further in integrating RCA into roadway systems for use as aggregate base course material. Unfortunately, only eleven states had begun using RCA in Portland cement concrete for pavement construction.

However, over the intervening 12 years, the use of RCA has increased significantly, particularly within the last 5 years, and the Missouri Department of Transportation (MoDOT) has instituted a very aggressive program to increase the use of recycled materials in transportation-related construction, including the use of RCA. Nevertheless, at the start of this research project, there were no acceptable standards or guidelines in the U.S. for utilizing RCA in structural concrete, which became one of the main objectives of this research study.

Concrete recycling protects natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete, including in-place recycling. Recycled concrete is less expensive than virgin aggregate sources, and its use would remove a sizeable amount of material from landfills, turning a waste product into a viable construction material. This value aligns with both MoDOT's Tangible Result of being environmentally and socially responsible[5] and MoDOT's Research Need for strategies to reduce energy consumption.[6] The results presented in this research report provide the methods, standards, and guidelines necessary to implement RCA in the construction of Missouri's transportation infrastructure, turning a waste product into a viable construction material.

4. BIBLIOGRAPHY

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3. Ramirez, J.A. and Russell, B.W. (2008). *Splice Length for Strand/Reinforcement in High-Strength Concrete*, NCHRP Project 12-60 Report, Transportation Research Board, Washington, D.C.

4. ACI Committee 408 (2003). "Bond and Development of Straight Reinforcing Bars in Tension (408R-03)," *Technical Documents*, American Concrete Institute, Farmington Hills, MI.

5. MoDOT Tangible Results – Environmentally and Socially Responsible, http://www.modot.mo.gov/about/MissionValuesTangibleResults.htm.

6. Stone, W. (2010). "Update on MoDOT's Research Activities and Needs," http://library.modot.mo.gov/RDT/Forum/y10/BillStoneLunchDiscussion.pdf.

5. TESTING STANDARDS

1. AASHTO – American Association of State Highway Transportation Officials: http://www.trasportation.org

2. ACI – American Concrete Institute: http://www.concrete.org

3. ASTM International – American Society of Testing Methods: http://www.astm.org

4. PCI – Prestressed/Precast Concrete Institute: http://www.pci.org

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

APPENDIX E