RESEARCH & DEVELOPMENT

Using Recycled Concrete Aggregate in Nonstructural Concrete on NCDOT Projects in Eastern North Carolina

George C. Wang, PhD, PE, FASCE
Donna A. Hollar, PhD, PE
Department of Construction Management
College of Engineering and Technology
East Carolina University
Greenville North Carolina

NCDOT Project 2017-06

FHWA/NC/2017-06

December 2018

Using Recycled Concrete Aggregate in Nonstructural Concrete on NCDOT Projects in Eastern NC

By

George Wang, Ph.D., P.Eng., F.ASCE, Professor
Donna Hollar, Ph.D., P.E., M.ASCE, Associate Professor
At
The Department of Construction Management
The College of Engineering and Technology
East Carolina University
Greenville, North Carolina

And

Robert Poole, Quality Control Manager
At
S.T. Wooten Corporation
Garner, North Carolina

Final Report

Project: RP2017-06

December 2018

TECHNICAL REPORT DOCUMENTATION PAGE

1. **Report No.** FHWA/NC/2017-06	2. **Government Accession No.**	3. **Recipient's Catalog No.**
4. **Title and Subtitle** Using Recycled Concrete Aggregate in Nonstructural Concrete on NCDOT Projects in Eastern NC		5. **Report Date** December 2018
		6. **Performing Organization Code**
7. **Author(s)** George Wang, PhD, PE, FASCE, orcid.org/0000-0003-3593-5925 Donna Hollar, PhD, PE Robert Poole		8. **Performing Organization Report No.**
9. **Performing Organization Name and Address** East Carolina University Greenville, NC 27858-4353		10. **Work Unit No. (TRAIS)**
		11. **Contract or Grant No.**
12. **Sponsoring Agency Name and Address** North Carolina Department of Transportation Research and Development 1020 Birch Ridge Dr. Raleigh, North Carolina 27601		13. **Type of Report and Period** Final Report **August 2016 to December 2018**
		14. **Sponsoring Agency Code**
15. **Supplementary Notes:**		

16. **Abstract**

This study evaluates the use of recycled concrete aggregate (RCA) in nonstructural concrete through laboratory tests. Removed concrete bridges and slabs were selected from NCDOT bridge demolition and reconstruction projects in NCDOT Divisions 1, 2, and 3 and was processed into coarse aggregates for Class B concrete as per the 2018 NCDOT Standard Specifications for Roads and Structures. The coarse RCA were undergone a series of laboratory testing and used in concrete mixing. Engineering and cost analyses were performed based on the data collected from the survey, literature review and the results obtained from the laboratory testing. The results show that the processed RCA from demolished bridges meet NCDOT requirements for concrete aggregates. The 7-day, 28-day, and 90-day compressive strength surpass the strength requirements for Class B concrete. From the laboratory test results, literature study, survey responses, technically there is no hindrance in using RCA in nonstructural concrete, and the concrete made using RCA in this study processes competitive properties to the concrete containing natural aggregates. The properties of RCA concrete could be modified by blending use of other recycled material(s). Concrete containing RCA and steel slag aggregates has higher compressive strength. A pioneer study was conducted during the project that provides directions of future research on blending use of RCA and other recycled materials in concrete. The results will benefit the bridge and road construction projects specified in the State Transportation Implementation Plan. Eastern North Carolina will benefit by the comprehensive use recycled concrete aggregate through conservation of natural resource and balancing economic, environmental, and societal needs.

17. **Key Words** Nonstructural Concrete, RCA, Recycled Concrete Aggregate	18. **Distribution Statement**

19. **Security Classif. (of this report)** Unclassified	20. **Security Classif. (of this page)** Unclassified	21. **No. of Pages** 316	22. **Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the views of East Carolina University. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The recycled concrete aggregate research team at East Carolina University (ECU) acknowledges the North Carolina Department of Transportation (NCDOT) for supporting and funding this project. The team especially extends our thanks to the current and former Project Steering and Implementation Committee members including:

Brian Hunter (Project Steering and Implementation Committee Chair)
Kevin Bowen
Aaron Earwood
Cabell Garbee
Robert Hayes
Wiley Jones
Jessica Kuse
Phillip Johnson
Chris Peoples
Jim Phillips
Anthony Roper
Nilesh Surti
Lamar Sylvester
Alyson Tamer
Neil Mastin
Mustan Kadibhai (Project Manager)

The research team appreciates Mr. Shawn Mebane and Mr. David Otts of NCDOT Division 1, Mr. Bryce Eatmon and Rhett Gerrald of NCDOT Division 2, and Mr. Robert Moore of NCDOT Division 3 for their support of this project. The team also thanks Mr. Mustan Kadibhai, the Project Manager of the NCDOT for good communication and assistance throughout the project.

Technical supports from S.T. Wooten Corporation are acknowledged, which include coordinating shipping the concrete panels to concrete processing plant in Wilson, NC, arranging concrete slab crushing, and provide concrete lab facilities.

We appreciate Harsco Metals in Cofield, NC and Nucor Corporation to provide steel slag samples and Liberty Tire Recycling to provide shredded scrap tire rubber samples for this study.

Without the help of all the above individuals, the project could not have been completed in such a successful manner.

EXECUTIVE SUMMARY

This study evaluates the use of recycled concrete aggregate (RCA) in nonstructural concrete on NCDOT projects in Eastern North Carolina (ENC). Concrete panels were selected from NCDOT bridge demolition and reconstruction projects in Divisions 1, 2, and 3, and was processed to coarse aggregates for Class B concrete as per the 2018 NCDOT Standard Specifications for Roads and Structures (Section 846 and Section 1000-4; and Table 1000-1). The coarse RCA were undergone a series of laboratory testing and used in concrete mixing for making Class B concrete. Engineering and cost analyses were performed based on the data obtained from the laboratory testing, the survey responses, and industry interviews.

To investigate the suitability and practicality of using the recycled concrete aggregate from Eastern North Carolina as an aggregate in nonstructural concrete, concrete slabs were selected from demolished concrete bridges in three counties in this region. The concrete bridge panels were crushed, separated from reinforcing steel, sieved, and examined in laboratory for making nonstructural concrete. Fresh concrete properties, and strength related properties were evaluated and compared with natural aggregate concrete (control mix).

The laboratory testing includes properties of RCA such as LA abrasion, bulk specific gravity, absorption, and potential alkaline-silica reaction. Fine particles and impurities incorporated in the RCA generated during crushing were also measured. Concrete related testing includes mix proportion, fresh concrete test and strength test. A pioneer study was conducted for trials to evaluate the possibility to add other recycled materials, steel slag, for instance, in the later core study.

Five mix designs were prepared using the three RCA samples from three locations. RCA and crushed granite aggregate were used. Normal concrete design method was used to make concrete mixes containing 0% (control mix), 15%, 30%, 50%, and 100% RCA. The requirements of the Standard Specifications for Class B (nonstructural concrete) by North Carolina Department of Transportation was used as criteria when proportioning the concrete mixes, which include minimum cement content, maximum Class F fly ash content, workability, and air content. To evaluate compressive strength testing, 7-day, 28-day and 90-day compressive strength results were obtained.

To verify the possibility of using steel slag produced in Eastern North Carolina with RCA in nonstructural concrete, electric arc furnace (EAF) slag was used to examine the strength changes. In this trial, mixes containing 0% (100% RCA), 20%, and 50% of EAF slag replacement were prepared and tested.

For engineering analysis purpose, cyclic stress and strain curves were obtained under universal testing machine for selected 28-day cylindrical specimens to check any brittleness index (related to interface between aggregates and cement mortar) change due to possible

changes of bonding of the interface between different aggregates and cement paste. Rapid chloride penetration test was conducted for selected concrete specimens.

The results show that the processed RCA samples from demolished bridges generally meet NCDOT requirements for concrete aggregate. The 7-day, 28-day, and 90-day compressive strengths surpass the minimum strength requirements for Class B concrete. The RCA concrete is very competitive to the concrete containing natural coarse aggregates. Concrete containing RCA and steel slag aggregates shows higher compressive strength that contains natural coarse aggregate and RCA.

A pioneer study was conducted during the project that provided preliminary results and information for adding steel slag into RCA concrete and directions for future research on blending use of RCA and other recycle materials in concrete.

Guidelines and procedures for RCA uses in Class B concrete can be developed based on the results and recommendations. A revision of specification for concrete coarse aggregate to include recycled concrete aggregate in the Standard Specifications is recommended. It is anticipated that the research results and products will assist NCDOT in developing alternative concrete aggregate and provide contractors opportunity to use RCA in NCDOT's projects. The results will benefit the bridge and road construction projects specified in the 10-year STIP plan for 2016-2025, and beyond. The sustainable development in Eastern North Carolina - one of the fastest growing regions in the State of North Carolina is also supported by the comprehensive use recycled concrete aggregate through conservation of natural resource and balancing economic, environmental, and societal needs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Recycled concrete aggregate (RCA) is a granular material manufactured by removing, crushing, and processing portland cement concrete (PCC) for reuse in similar situations as virgin natural aggregate. In many economically fast-growing areas, such as Eastern North Carolina, one of the problems facing is the decline of available disposal sites for demolished debris and lack of good quality aggregate resources for infrastructure construction. Research and construction practice have proven that processed recycled concrete aggregate from demolition can meet or exceed the technical requirements for aggregates and can be used as aggregates for granular base, portland cement concrete and hot mix asphalt (HMA).

RCA possesses different properties from natural aggregate, mainly because the resultant crushed material is composed of both the original natural aggregate and reclaimed mortar, which greatly affects the properties and behavior of materials produced with RCA. Specific steps must be taken in the design and construction process. The composition of RCA can be highly variable, which may contain contaminants such as clay, brick, asphalt or other construction and demolition (C&D) waste. However, when its characteristics are properly considered and accounted for, RCA can be used effectively in concrete. Some US states have used RCA in concrete in DOT’s projects. In addition, some other states have conducted research and formulated new specifications and guidelines to allow RCA use in nonstructural concrete.

This research is to investigate the possibility to use processed RCA from the demolished concrete bridges in ENC in nonstructural concrete, with focus on RCA, fresh and hardened concrete property testing in laboratory.

1.1 Background Information

Currently more than 140 million tons of RCA are produced each year in the US (CIDA, 2018). The quantity is increasing as the nation’s civil infrastructures are becoming aged and being reconstructed. In the US, research has been conducted on the use of RCA in concrete for the last two decades. New standard specifications and guidelines have been enacted in some states to allow the use of RCA in new concrete.

The North Carolina State Transportation Improvement Program (STIP) for 2016-2025 stipulates the requirements for approximate 150 bridge replacement and 700 miles of road construction projects in the 28 counties under NCDOT Divisions 1, 2, and 3. A huge amount of concrete debris will be generated, and a large quantity of new concrete will be needed including nonstructural concrete. However, good quality concrete aggregate is not economically available in ENC. It has been reported that contractors and concrete producers in ENC have to drive long hauling distance to west of I-95 to obtain concrete aggregates. It is imperative to conduct this research and improve the current specifications to provide guidance for the use of coarse RCA in Class B concrete for nonstructural concrete construction.

This research selected three typical bridge replacement projects from NCDOT Divisions 1, 2, and 3 during the research period, processed the aggregate to the NCDOT standards for concrete, and a series of conventional and special laboratory tests for RCA, fresh and hardened concrete were conducted. Engineering and cost analyses have been performed based on the data collected from the testing, literature review, and industry survey. The practical method to process RCA and making nonstructural RCA concrete is recommended. A thorough literature study on the state-of-the-practice of using RCA in concrete was conducted at the beginning of the research. A survey to state highway agencies, ready mix concrete suppliers, and construction companies on experience on RCA use in concrete was conducted and summarized.

1.2 Research Objectives

The goal of this study is to determine the efficacy and practicality of using coarse RCA in nonstructural concrete on NCDOT projects in Eastern North Carolina to meet the requirements of Class B concrete as per Section 1000-4 of NCDOT 2018 Standard Specifications. Through field and laboratory investigation, survey of the users of RCA, engineering and cost analyses, the following primary research objectives were achieved and validated.

- Determine the properties of RCA processed from the demolished concrete and detail the processing of RCA so that NCDOT requirements for Class B concrete aggregate is met;
- Determine the strength related properties of concrete containing coarse RCA;
- Adjust and validate the conventional mix design method for RCA concrete mixes when necessary; and determine any other possible modifications needed for fresh and hardened concrete properties, and concrete mix design method using RCA;
- Compare and analyze the costs of natural aggregates, RCA processing, RCA concrete, and economical, environmental, and social benefits;
- Propose the possible revision of the Specifications to incorporate RCA as an option for using as an aggregate in Class B concrete. Provide information including processing RCA, using RCA in Class B concrete, mix design, and strength and durability related requirements for guidelines development.

1.3 Research Scope

Primarily the major work conducted in the project include

- Identify the scheduled bridge replacement projects and road construction projects in the project period in NCDOT Divisions 1, 2, and 3 through a thorough study of the State Transportation Improvement Program (STIP) 2016-2025 and other related documents. Meet and interact with division, district, and NCDOT Engineers;

- Select candidate projects for the research in Divisions 1, 2, and 3 (matching the project construction schedules);
- Collect information on the parent concrete and their properties;
- Design, distribute, and collect a survey questionnaire targeted to the state highway agencies, concrete producers, and construction companies across the country regarding their previous experience on using RCA;
- Conduct field processing, sampling, and laboratory testing for RCA, which include but not limited to sieve analysis (separate the sampled materials from field by using #4 sieve), specific gravity, impurities content, LA abrasion and absorption;
- Conduct laboratory testing of concrete, including preparing concrete mix design and specimens using RCA to replace coarse crushed aggregate (CA, > 4.75 mm), volume at 0% (control), 15%, 30%, 50%, and 100% levels. Slump, air content, and density to be tested for fresh concrete. To maintain the required workability by NCDOT specifications, Type F fly ash to be used;
- Compressive strengths at 7, 28, and 90 days to be conducted;
- Potential alkali-silica reaction test of RCA samples, and rapid chloride penetration test for selected concrete to be conducted;
- Locally available steel slag aggregate is to be sampled and used with RCA to verify the strength contribution to concrete (blending use with RCA);
- Conduct an engineering analysis;
- Conduct cost analysis. This will be based on the survey data obtained from the contractors and ready mixed plants, mix design data, RCA and concrete testing results and other involved costs. Other factors will also be considered, for example, landfill cost if concrete debris is disposed of.

1.4 Outcomes and Benefits

The research results can be used for the development of guidelines and training materials for RCA use as an aggregate in nonstructural concrete, and outline procedure to process RCA. Revised specification concerning the use of RCA in Class B concrete is recommended. It is anticipated that the results and products will assist NCDOT in decision-making on selecting alternative concrete aggregates. The results will benefit the bridge and road construction projects specified in STIP 10 years plan, and the sustainable development in Eastern North Carolina - one of the fastest growing regions in the State of North Carolina. The results will also benefit future transportation improvements in a long term.

1.5 Report Organization

The remainder of the report is organized into chapters that present the project's major areas and sequences in detail. Chapter 2 covers the literature study conducted by the team. Chapter 3 provides the summary of the survey results and responses from the state highway agencies, ready mix concrete suppliers, and construction companies. Chapter 4 deals with the concrete bridge selection and RCA process. Chapter 5 covers concrete mix design, testing, and results. Chapters 6 and 7 provide engineering analysis and cost analysis and economic, environmental and societal benefits. Chapters 8 and 9 present conclusions and recommendations on future research in development of RCA use in nonstructural concrete. Chapter10 presents technology transfer plans of the research project. Chapters 11 and 12 are references cited and appendices to the report.

2.0 LITERATURE REVIEW SUMMARY[1]

Recycled concrete aggregate is a granular material processed by removing reinforcing steel, crushing, and processing portland cement concrete for reuse in construction as virgin natural aggregate. RCA's properties are different from natural aggregate, mainly because the resultant crushed material is composed of both natural aggregate in demolished concrete and reclaimed mortar, which significantly affects the properties and behavior of materials produced with RCA unless specific steps are taken in the design and construction process. The composition of RCA can be highly variable, which may contain contaminants such as clay, joint sealant, asphalt or other construction and demolition wastes. However, when its characteristics are properly considered and accounted for, RCA can be used effectively in concrete.

The practical use of RCA as an aggregate in new concrete can be traced back to the 1940s internationally. Normative documents or standard specifications have been used in many countries and organizations, for example in Germany: DIN 4226-100; UK: BS 8500-2; Brazil: NBR 15.116; Japan: BCSJ-97; Hong Kong: WBTC 12-2002; the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM): RILEM-1994; and Cement and Concrete Australia. It has been reported that the use of RCA in concrete can maximize the economic benefits by matching or exceeding the technical requirements for concrete containing natural aggregate. It is very common worldwide that partial replacement 30%-50% of natural aggregate in concrete used in sidewalks, curbs and gutters; also for structural concrete with mix adjustments and inferior permeability and shrinkage properties.

In the US, the quantity of RCA production is increasing as the nation's civil infrastructures are becoming aged and being reconstructed. RCA has been used in various paving layers. New standard specifications and guidelines have been enacted in some states to allow the use of RCA in new concrete. The production of RCA typically includes the following steps, evaluation of the source concrete, preparation of the concrete structure (bridge, pavement) for demolition, concrete breaking and removal, removal of the embedded steel, crushing and sizing, evaluation and sorting (separate good from bad), and stockpiling.

2.1 Processing of Recycled Concrete Aggregate

Although the traditional method and same basic equipment to process virgin aggregates can be used to crush, size, and stockpile RCA, the selection of crushing process can affect the amount of mortar that clings to the RCA particles and, therefore, the properties of the RCA. Jaw crushers generally are more effective at producing higher quantities of RCA, but

---

[1] A Full Literature Report by the Research Team can be found in the Quarterly Progress Report of December 31, 2016.

generally result in relatively high amounts of reclaimed mortar in RCA particles. Impact crushers can be lower in productivity, but more effective to remove mortar from RCA, therefore the coarse RCA is more similar to virgin aggregate (Snyder, 2016). Figure 2.1.1 shows the plant RCA processing procedures (Eguchi, et al., 2007). The production of RCA can be completed on site by one piece of integrated equipment. Figure 2.1.2 presents the Terex Finlay J-1170 compact and tracked jaw crusher for crushing, screening, and magnetic separation. Concrete debris can be crushed, screened into two adjustable sizes, and undergo magnetic separation at the same time within the single machine. Transportation cost to the plant is incurred as part of the costs of production.

The advantages of onsite processing include using the processed aggregate nearby by allowing the coarse RCA to be added to the ready-mix concrete trucks that have base concrete mixes (partial coarse aggregate), thereby saving transportation costs; and the integrated process uses one crusher, which increases the productivity and recovery rate. Coarse aggregate can be recovered up to 77% of the processed volume. Adding RCA as coarse aggregate in concrete is illustrated in Figure 2.1.3.

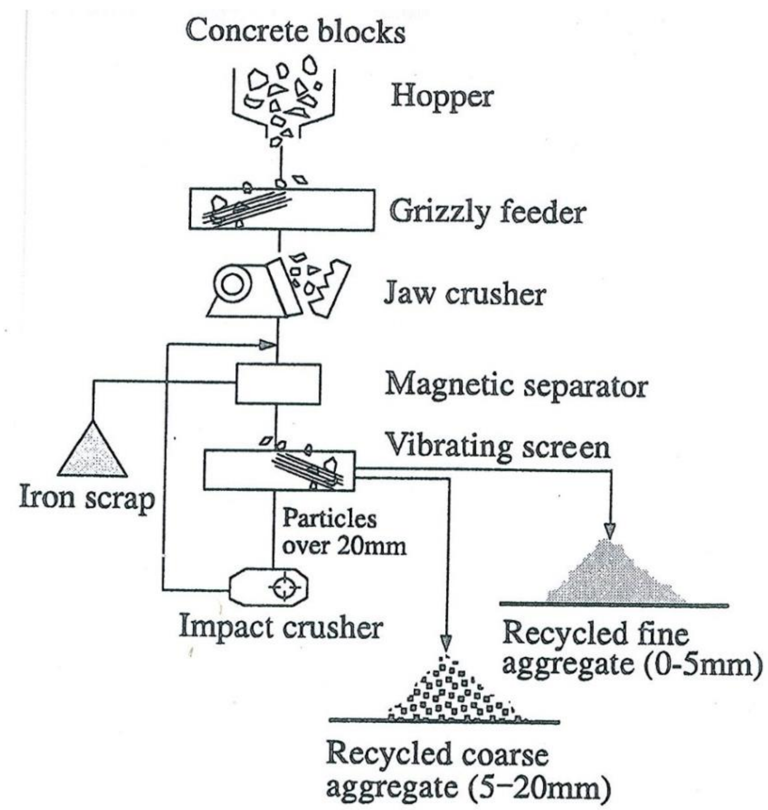


Figure 2.1.1 Flow Chart for Plant Processing of RCA

(Diagram courtesy of Eguchi, et al., 2007)

Figure 2.1.2 Terex Finlay J-1170 Compact and Tracked Jaw Crusher

(Photo taken by George Wang; courtesy of Hills Machinery, Greenville, North Carolina)

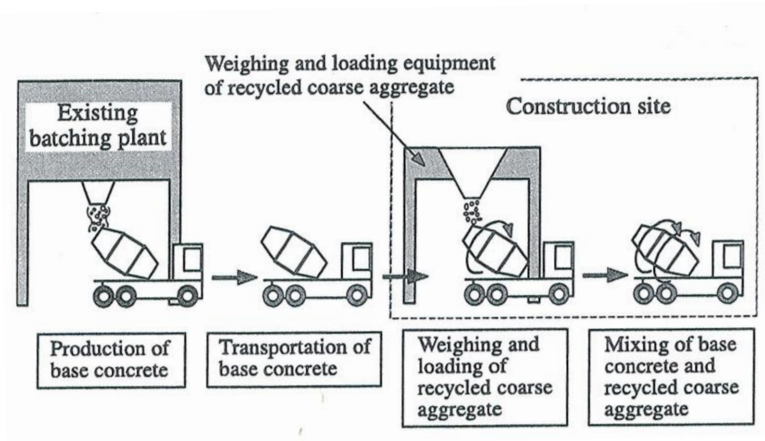


Figure 2.1.3 Onsite Production Procedure of RCA Concrete

2.2 Properties of Recycled Concrete Aggregate

RCA has several unique characteristics and properties that must be considered during the mix design and construction stages. These properties include lower specific gravity, which decreases with increasing amount of reclaimed mortar; higher absorption, which increases with increasing amount of reclaimed mortar; greater angularity; increased abrasion loss, which increases with increasing amount of reclaimed mortar; presence of unhydrated cement, which may alter its behavior and complicate stockpiling, especially the fines (passing #4 sieve); the fines produced during the crushing operation are angular, which tend to make RCA concrete mixtures very harsh and difficult to work.

Not all RCA is appropriate for use in concrete. For example, RCA made from concrete exhibiting materials-related distress (MRD) such as alkali silica reactivity (ASR) or D-cracking may not be used in concrete unless certain mitigation methods are employed. Additionally, RCA may have high chloride contents due to extended exposure to deicing chemicals, which may make it unsuitable for use in reinforced concrete. The low abrasion resistance may lead to poor performance in an application where intimate aggregate interlock is relied upon for load transfer (for example, in undoweled joints or at transverse cracks of reinforced slabs).

The crushing process to generate RCA exposes unhydrated fines, which can lead to cementation when exposed to water or particularly humid conditions, thus changing the physical properties of the RCA. On the contrary to most virgin aggregates, RCAs typically fail the sulfate soundness test (ASTM-C88 2008) using sodium sulfate, but tended to perform well using magnesium sulfate in a limited study.

RCA may contain as much as 40% of mortar, which would accordingly affect such deformation properties of RCAs as elasticity, creep, and shrinkage. More water may be needed to enhance workability (Topçu and Şengel, 2004).

2.3 Mix Design of Concrete Containing Recycled Concrete Aggregate

In principle, the mix design of recycled aggregate concrete is not different from that of conventional concrete and the same mix design procedures can be used. In practice, slight modifications are required. These include:

When coarse RCA is used with natural sand, it may be assumed at the design stage that the free water-to-cement (W/C) ratio required for a certain compressive strength will be the same for RCA concrete as for conventional concrete. If trial mixes show that the compressive strength is lower than required, an adjustment of the W/C should be made which would be up to10 liters/m^3 (or 5%) higher than for conventional concrete. In some cases, if free water content of RCA concrete is increased, the cement content may also need to be higher to maintain the same W/C ratio.

The unit weights of concrete made using RCA are within 85% to 95% of the original concrete mixture. Air contents of RCA concrete are up to 0.6% or higher. The optimum ratio of fine-to-coarse aggregate is the same for RCA as it is for concrete made from virgin materials.

Trial mixtures are mandatory (ACI, 2001). It is believed that the reduction in the residual mortar, when the concrete is recycled more than one time, makes the recycled RCA concrete perform better than the RCA concrete (Hole, 2013).

It is the practice that the use of coarse RCA (up to 30%) is normally recommended but the addition of superplasticizer is often considered necessary for achieving the required workability of new concrete (Parekh and Modhera, 2011). Higher than 50% RCA may cause higher shrinkage of the concrete (Malešev, Radonjanin, and Marinković, 2010).

2.4 Applications of Concrete Containing Recycled Concrete Aggregate

RCA concrete perform well on nonstructural concrete such as curb and gutter, valley gutter, sidewalks, concrete barriers, driveways, temporary pavement, interchange ramps with ADT less than 250, and on pavement types such as JRCP, and CRCP. The use of fine RCA has more limited use in new concrete mixtures. Some states specify that coarse RCA is only allowed to be used for lower priority applications (Van Dam, et al., 2015). Some specifications state that RCA may not be used in concrete for mainline pavements or ramps with an ADT equal to or in excess of 250, concrete base courses, bridges, box or slab culverts, headwalls, retaining walls, prestressed concrete, or other heavily reinforced concrete.

2.5 Workability of Fresh Concrete

RCA concrete workability is strongly affected by the shape and texture of the coarse recycled aggregates surface; at the hardened state, the elasticity modulus and strength of RCA concrete are comparable to those of conventional concrete, or even better if the same W/C ratio is considered. Shrinkage strain is negatively influenced using recycled concrete aggregates, regardless the W/C used. On the contrary, creep results appear less sensitive to W/C ratio (Manzi, Mazzotti, and Bignozzi, 2013a; 2013b).

It is reported that in order to maintain the functionality of RCA concrete, the water content in the concrete mix may be ~10% higher than what is needed to make natural concrete while other researchers reported different results (Ravindrarajah, and Tam, 1985; Hashim, 2013).

2.6 Strength Related Properties

Research has confirmed that the use of RCA in substitution of virgin aggregates leads to concretes having lower strengths and higher permeability. Concrete made with 100% coarse RCA has 20-25% less compressive strength than conventional concrete at 28 days at the same W/C ratio and cement quantity. Concrete made with 100% RCA requires a high amount of cement to achieve a high compressive strength (Etxeberria, et al. 2007). However, concrete made with 25% of RCA can achieves the same mechanical properties as that of conventional concrete employing the same quantity of cement and the equal effective W/C ratio. Lower RCA addition can achieve similar strength of natural aggregate concrete (Deshpande, Kulkarni, and Pachpande, 2012). Medium compressive strength concrete made with 50% or 100% of RCA needs 4-10% lower effective W/C ratio and 5-10% more cement than conventional concrete to achieve the same compression strength at 28 days.

The modulus of elasticity of RCA concrete is lower than that of conventional concrete. However, the tensile strength of recycled aggregate concrete can be higher than that of conventional concrete (Chen, Yen, and Chen, 2003; Katz, 2003). Results by different researchers exhibited similar conclusions. Research also shows that when fly ash is used, free shrinkage of RCA concrete is reduced and 48 MPa concrete can be made in laboratory containing RCA with low W/C ratio (Nelson, 2004).

The use of fly ash in RCA concrete enhances its physical and mechanical properties thus mitigating the worsening effect of the recycled aggregates (Adnan, et al., 2007; Ali, et al., 2014; Caggiano, 2012; Breccolotti, et al., 2015; Dabhade, Chaudari, and Gajbhaye, 2014; Ganiron , 2015; Hansen and Narud, 1983; Murali, et al., 2012; Kim, Sim, and Park, 2012; McNeil, Thomas, and Kang, 2013; Rahman, Hamdam, and Zaidi, 2009). The results show that specific gravity and compressive strength decrease and the water absorption rate increase (Yaprak, 2011).

To increase the strength of RCA concrete, researchers used steel slag (Qasrawi, 2014), and NaOH (Anuar, Ridzuan, and Ismail, 2011).

2.7 Sustainability Benefit of Using RCA in Concrete

Concrete is the second most consumed materials on the Earth after water. To produce cement, the major constituting material of concrete, produce greenhouse emission, 2.5 billion tons of CO_2 per year, 160 million tons of CO_2 is produced due to aggregate production (Figure 2.7.1). Total CO_2 emission from concrete sector is about 5.9 billion tons, including cement, aggregate, steel, and transportation (Sakai, 2009).

The many economic, environmental, and societal benefits of concrete recycling and using RCA in concrete include the following:

- Lower reliance on virgin quarried aggregates
- Reduced energy consumption
- Reduced use of landfill space
- Reduced greenhouse gas emissions
- Time savings associated with haul time reductions
- Recaptured value of prior investments in concrete paving materials

Economic design is critical to all infrastructure projects. Utilization of RCA as aggregate for new construction can minimize cost, but also reserve virgin aggregate resources thereby decreasing environmental pollution from concrete waste (Hawkins and Brown, 2010). Using RCA can have approximately 11% savings in construction budget.

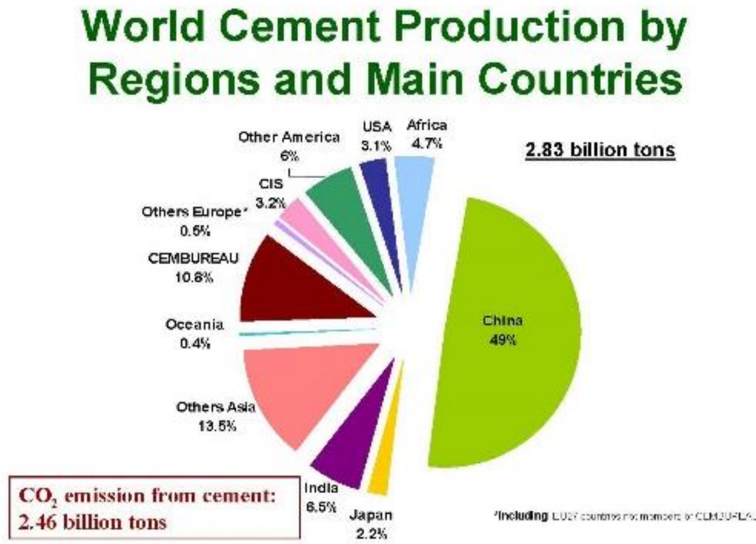


Figure 2.7.1 Cement Production and CO_2 Emission

The sustainability benefits of recycling concrete pavements can be quantified using life cycle cost analysis (LCCA), life cycle analysis (LCA), and rating systems. LCCA is an economic analysis technique that is principally used to quantify the economic component of sustainability. LCA is most suitable for analyzing and quantifying the environmental impacts of a specific project or strategy over a life cycle. Rating systems rely heavily on providing incentives (points and recognition) for addressing a broad set of sustainability best practices. The approach, assumptions, and analysis techniques used by each tool are different but, when utilized or in concert, various aspects of sustainability can be quantified. The goals of stakeholders should be carefully considered prior to selecting one or more approach (Cavalline, 2016). Each of these types of tools provides one or more means of incorporating recycling-related activities and materials choices into the analysis and evaluation, provides guidance and potentially reward (recognition). As outlined in the case studies presented, these tools have been successfully used by several agencies to justify and support concrete recycling activities. More extensive utilization of these tools could provide incentive to stakeholders to utilize concrete recycling more frequently in pavement construction, moving towards a more sustainable highway infrastructure.

Research found that concrete containing recycled concrete aggregates have 13-27 % lower thermal conductivity than the reported literature values for the dry concrete with approximately the same density. Concrete sandwich panel wall containing RCA has 16.6% lower U-value than similar precast concrete wall panels on the market and has higher thermal mass than metal sandwich panel and that results with 11 % less energy needed for cooling and 22 % less energy needed for heating in buildings. With this research, it was shown that by using RCA as recycled aggregate in the concrete mixes, sound insulation of precast wall systems can be improved (Pečur, 2014).

Financial analyses conclude that using RCA can create a sustainable end use for concrete waste, and reduce the demand for natural aggregates, and lead to natural resource preservation. Probabilistic estimation of the price difference between RCA concrete and normal concrete concludes that ready mixed concrete plants having aggregate feeding mechanism with front-end loader would be an appropriate entry for industrial scale manufacturing of RCA concrete (Wijayasundara, et, al., 2016).

2.8 Standards and Specifications for Recycled Concrete Aggregate Use in Concrete

Some state DOTs have specifications for RCA use in concrete. For example, TxDOT 2004 Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges specifies nonhazardous recyclable material (NRM) to be used on TxDOT projects (TxDOT, 1998; 2008). RCA must meet the requirements of departmental material specification DMS-1 1000, "Evaluating and Using Nonhazardous Recyclable Materials Guidelines." Item 421, Hydraulic Cement Concrete, specifies that RCA can be used as a coarse aggregate, if it meets the specification requirements. TxDOT does not allow RCA in structural concrete.

California Department of General Services, Division of the State Architect (DSA), issued Interpretation of Regulations Document, IR 19-4 which clarifies the use and acceptance of RCA on projects under the purview of the Division of the State Architect: Coarse and fine RCA may be used only in exposed minor concrete applications such as sidewalk, curb, gutter, parking strip, and pavement in an amount not to exceed 50% of the total dry aggregate mass. RCA should be thoroughly cleaned and washed before use and must not contain any deleterious materials and must meet the requirements of the California Building Code, and its referenced standards, i.e. ASTM C33, and satisfy specific project requirements. California DOT allows up to 100% of RCA in minor concrete and lean concrete. South Carolina DOT allows 100% of coarse RCA in PCC if the source is approved.

The statewide use of RCA in PCC in Michigan is permitted by the MDOT Standard Specifications of Construction, in Aggregate Section 902.03 Part B, 902.04 and 902.06. It allows the use of RCA as coarse aggregate in PCC for curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps and shoulders.

Internationally, many countries have established specifications for RCA use in concrete. In Brazil, specification NBR 15.116 "Recycled aggregates from construction and demolition waste (CDW)" (2005) allows the use of RCA only in nonstructural concrete, and both coarse and fine fractions are permitted in concrete production. CDW is separated into four classes (A, B, C and D). RCA belongs to Class A which can be considered as aggregate for use in concrete.

Germany has two standards; the first refers to the requirements of CDW aggregate, while the second proposes rules for the implementation of these aggregates in concrete. DIN 4226-100 "Aggregates for Mortar and Concrete - Recycled Aggregates" specifies requirements for aggregates with particle density higher than 1,500 kg/m^3 for use in mortar and concrete. It also specifies the system of production control and conformity assessment. The particle size must follow the requirements specified in DIN 4226-1 "Aggregates for concrete and mortar--normal density and high density aggregates". Using DIN 4226-100, CDW aggregates are classed into four types: (i) waste concrete, (ii) CDW, (iii) Masonry waste, (iv) mixed material. The first type, waste concrete, is mainly composed of recycled concrete.

Hong Kong's Works Bureau Technical Circular, WBTC No. 12/2002 outlines the use of recycled aggregates in concrete production and the construction of base and subbase of road pavement. Two alternatives are suggested in this specification for the use of RCA in concrete. The complete replacement of natural aggregate by RCA can be used for concrete in less demanding structures, such as benches, flowerbeds or cyclopean concrete. Only 20 % replacement of natural aggregate by RCA is allowed in structural concrete with a 28-day compressive strength in the range of 25-35 MPa.

In Japan the Building Contractors Society of Japan issued a "Proposed standard for the use of recycled aggregates and RCA" (1977). RCA is allowed to be used in concrete. This document does not limit the use of masonry material.

The Japanese guideline "TR A006 2000 - Concrete using recycled aggregate" provides information on the use of RCA in concrete. The main principle is that the mortar component will decrease quality, and this becomes evident as higher water absorption when the mortar content is increased. Classification is based on the amount of mortar. The mortar phase increases water absorption. With a higher mortar amount, the quality of recycled aggregate is lowered. The amount of absorption should be less than 7 % for coarse aggregate and less than 10 % for fine aggregate. This regulation includes also the methods for quality control.

In Japan the use of recycled aggregate is recommended only for concrete without frost attack. The amount of RCA is determined on case by case basis. It can be 100 % of coarse aggregate, or 50 % of both coarse and fine aggregates (Kuosa, 2012).

A quality assurance system was created on the supply and utilization of coarse RCA in relation to existing product standards in Australia to produce concrete from clean uncontaminated crushed concrete (particle density >2,100 kg/m^3, including < 2 % of brick, stony material or other forms of contaminants). Physical contaminant levels typically less than 2% were achievable under existing manufacturing practices. The need for assessing chemical contaminant levels was recommended. Such contaminants have the potential to alter concrete rheology, setting characteristics and concrete durability. Class 1 RCA was deemed to be suitable for production of plain unreinforced and reinforced concrete up to and including 40 MPa concrete, with no mandatory limits on RCA substitution levels. Extra care must be taken to ensure satisfactory compliance to acceptance criteria based on standard deviation of compressive strength test results. The issue of concrete durability was considered of great concern in respect of chemical contaminants such as sulphur-based residues that can induce deleterious expansive reactions as well as impact of chloride contaminants on the corrosion of embedded steel reinforcement. Medium and long-term field durability tests were recommended.

The RILEM - TC 121-DRG recommendation (1994) is a specification that deals with recycled coarse aggregates with minimum size of 4 mm for concrete. As the properties of RCA fines are vastly different from those of natural sand, there is no specification for the fine fraction in the RILEM specification. It classes the recycled coarse aggregates and indicates the scope of application for concrete containing these RCA classes in terms of acceptable environmental exposure classes and concrete strength classes. Recycled coarse aggregates are classed as follows: Type I - aggregates which are implicitly understood to originate primarily from masonry rubble; Type II - aggregates which are implicitly understood to originate primarily from concrete rubble; Type III - aggregates which are implicitly understood to consist of a blend of recycled and natural aggregate; the composition shall have at least 80 % natural aggregate and up to 10 % Type I aggregate.

Within the United Kingdom, the British Standard BS 8500-2:2002 "Concrete - Complementary British Standard to BS EN 206-1 - Part 2: Specification for constituent materials and concrete" specifies requirements for coarse RCA only, excluding the use of fine RCA for concrete production.

In some concretes any amount of RCA is possible in UK. For instance, low grade flooring (small garages) with no reinforcement and some pavement curbs can include high amounts of RCA. In other allowable cases the amount of RCA is usually limited to 20 % of total aggregate, though also 30 % has often only minor effects on especially the critical concrete properties in low exposure classes (Kuosa, 2012).

In the Netherlands, the Dutch center CUR has developed specifications for the use of RCA. In 1984, a specification was released for the use of aggregates from crushing concrete. In 1986, CUR developed a specification for the use of recycled aggregate generated from masonry. Subsequently, another specification was developed for the use of crushed mortar as aggregate.

In Portugal, National Laboratory of Civil Engineering (LNEC) issued E 471: 2006 in 2006, prepared pre-norm, prE 469 "Guide for the use of recycled coarse aggregates in hydraulic binder concrete", which classes the coarse RCA covered by NP EN 12620 "Aggregates for concrete" and establishes the minimum requirements that they must meet in order to be used in the manufacture of hydraulic binder concrete. Recycled aggregates requirements and their applications are not shown for fine RCA since they have a high percentage of particles with dimensions less than 0.063 mm and greater water absorption capacity, making it difficult to control the workability and impairing the mechanical strength of concrete containing that fraction.

In Belgium, a recommendation for the use of recycled aggregate in concrete was compiled by a working group in 1990. A series of information on the document were presented. This recommendation is divided into three parts: the first contains the requirements of the recycled aggregate, the second regulates the scope, and the third is related to the calculations of the coefficients and their characteristics. This standard defines RCA only for coarse fraction. It excludes the fine fraction as in several other specifications.

In Switzerland, 0T70085 - The Swiss document was published in 2006, Objective Technique OT 70085 "Instruction technique. Utilisation de materiaux de construction minerauxsecondairesdans la construction d' abris". It creates a wide range of applications for RCA, with different approaches depending on user demands. This application is regulated together with the standard SIA 162/4, 1994 "Beton de recyclage". The document establishes requirements to be met by RCA as well as their application conditions.

In Russia, the former Soviet Union introduced a specification in 1984, developed by a scientific research institute, for the use of RCA in plain and reinforced concrete. Regarding the scope of the standard, it specifies that the replacement ratio of natural aggregate by RCA can reach 100 % if the concrete is used in foundations or reinforced concrete with strength below 15 MPa. If the replacement ratio is not more than 50 %, it can be applied in concrete structures with strength over 20 MPa.

In Finland there is a national specification on the use of aggregate in concrete, 43 2008. In this specification the use of recycled aggregate is allowed. If recycled aggregates are used, it must be proven beforehand that the recycled aggregate is suitable for the specific intended use. Relevant preliminary testing is needed. Requirements on RCA can be set based on the standard [EN 12620 + A1] (Aggregates for concrete).

It is suggested that a specification for the use of RCA in Finland is needed. Without comprehensive guidelines, the use of recycle aggregates in concrete would be unsound and very limited also in the future. National specifications should be based on local climatic conditions, and all the other local circumstances. The aim should be value-added sustainable application of recycled aggregates. Also, the use of RCA in wider applications should be studied and promoted. Considerable attention is required to the control of construction and demolition waste processing and subsequent sorting, crushing, separation and grading of aggregates for use in concrete, and possibly also in other materials, especially cement based materials (Kuosa, 2012).

European Standard: The technical committee, CEN/TC 154, "Aggregates" has developed an amendment, currently known as EN 12620:2002/PRA.1: 2006. This standard is to be a European regulation, changing the current EN 12620:2002 and its national versions. The standard establishes requirements for the composition of the coarse RCA, beyond the water absorption and density. This amendment also includes a clause reserved for alkali-silica reactions, establishing that all RCA should be classed as potentially reactive unless it is specified that they are not reactive.

3.0 RCA USE IN THE UNITED STATE – A NATIONAL SURVEY SUMMARY[2]

Survey questionnaires were prepared by the PI and sent to the Project Steering and Implementation Committee for review and comments. The finalized questionnaires were sent to (i) the state highway agencies, (ii) ready mix concrete suppliers, and (iii) construction companies. The questionnaires and survey listing were input into the Qualtrics survey software and disseminated from the facility with weekly reminders.

This part of the report describes the survey results from the three entities. The questions focused on their experience using RCA, equipment availability, and cost related information involved in using RCA and natural aggregate. In the survey process, data for RCA, quality aggregate availability, specifications, any issued in the use of RCA in concrete were obtained.

3.1 Survey to State Highway Agencies

The survey to the state highway agencies (SHAs) was regarding their experience with RCA and its uses in each state. The survey covered RCA use in concrete, specific applications, RCA testing requirements, specifications or practices, issues with use of RCA. Survey questions were disseminated to 50 states approximately 150 engineers. A total of 35 states responded, and 16 states responded use RCA as an aggregate in concrete. The summary of the responses is presented thereafter. Although RCA as granular materials are reported by some agencies, it is not included in the summary as the use of RCA in concrete is the focus. The survey questions to SHAs are as follows:

1. Does your agency allow the use of crushed recycled concrete aggregate (RCA) as an aggregate in new concrete for transportation infrastructure construction?
2. Please describe how your agency's practices or specifications differ for the use of RCA compared to virgin aggregate in concrete.
3. Which application(s) RCA is commonly (often) used?
4. What are your agency's limitations of RCA, by percent weight of total aggregate, to a new concrete mix?
5. What are your agency's testing requirements or quality control procedures for using RCA as an aggregate in concrete?
6. Has your agency encountered any problems of using RCA as an aggregate in concrete for transportation infrastructure construction?
7. Has your agency considered expanding the use of RCA as an aggregate in concrete (higher allowed percentages or for more applications)?

[2] Complete survey lists and detailed responses from the three survey groups can be found in Chapter 12, Appendices, Sections 12.2 to 12.7.

8. If your agency allows (or requires) using admixtures to modify any properties of concrete containing RCA, please provide details: What type of admixtures? When are they used or required?

Among the 35 states, 20 states, accounting for 54.2%, are currently using RCA in nonstructural concrete (18), concrete pavement (2). Figure 3.1.1 and Figure 3.1.1 summaries the responses from SHAs.

Figure 3.1.1 Summary of Survey Responses from State Highway Agencies

Most of the 20 states indicated that they use RCA at a 50% substitution rate for the coarse aggregate while some states do not set the limit.

Testing requirements and quality control procedures for RCA is the same as that of regular concrete. The use of admixture in RCA is same as in virgin mixes. Water reducers and air entrainment are commonly used. Testing requirements for RCA include gradation, moisture content, sand equivalent, LA abrasion, unit weight, and various deleterious materials. Testing for concrete include air content, yield, slump, temperature, W/C ratio, 28-day compressive strength, 28-day flexural strength, and freeze-thaw testing.

In South Carolina the use of recycled PCC pavement as coarse aggregate in new PCC pavement mixture is allowed at the option of the contractor with the following qualifications: only aggregate derived from this project existing pavement is permitted. Fine RCA aggregate will not be allowed. Coarse RCA aggregate must meet the requirements of SCDOT Specification Subsection 701.2.10 requirements for coarse aggregate for portland cement concrete, except for that the LA abrasion and sulfate soundness requirements do not apply. All joint sealant and backer rod material must be removed from the existing pavement prior to removal for recycling. Ensure that the resulting RCA aggregate is free from steel reinforcement and other contaminants. Aggregates derived from limestone or slag are not allowed. Absorption of coarse RCA shall not exceed 10%. A quality control plan to produce RCA must be approved by SCDOT prior to beginning production. This plan must include consideration for controlling moisture content, stockpile management, and trial batching. The agency includes it as an option for the contractor rather than requiring it.

Table 3.1.1 Summary of RCA Uses in Concrete

STATES	USAGES												
	Sidewalks	Curb &gutter or slopes	Footings for lighting, signs	Median barriers	Pipe or pull box filler	Lean concrete base	Controlled low strength	Culvert backfill	Low volume roads	High volume roads/	Bridge substructures	Bridge superstructures	Other applications
Alaska					x	x	x	x					
California	x	x	x	x	x	x	x	x					
Colorado	x	x	x	x	x	x	x	x	x	x	x	x	Lean concrete base
Florida								x					
Illinois										x			
Indiana													(Not indicated)
Kansas						x		x					Cement treated base
Louisiana													(Not indicated)
Minnesota	x	x	x		x				x	x			
Montana													(Not indicated)
North Carolina													Class B concrete
Ohio	x	x						x	x	x			Dump rock
Oklahoma	x	x	x							x			
Pennsylvania													(Not indicated)
South Carolina										x			
Tennessee							x	x					
Texas										x	x	x	
Virginia	x					x	x	x	x				roller compacted concrete
Washington	x	x					x						
Wisconsin	x	x		x		x				x			

3.2 Survey to Ready Mixed Concrete Suppliers

The survey questions to the ready mixed concrete suppliers regarding their experience with RCA use in concrete are as follows:

1. Has your company or plant ever used RCA as an aggregate to make new concrete? If yes, what are the applications?
2. Is the RCA provided to your ready-mix facility by a supplier in a ready-to-use format or your ready mix facility processes its own RCA on-site?
3. Is the fresh concrete containing RCA mixed at your mixing plant or at a construction site?
4. How does your practice, including mix design, differ for the use of RCA compared to virgin aggregates?
5. What are your company's testing requirements or quality control procedures for using RCA as aggregate in concrete?
6. Has your plant ever encountered any problems in using RCA as an aggregate?
7. Do you think the use of RCA as an aggregate in concrete will expand if the specifying agency allows using RCA in concrete?
8. Please provide any additional comments you may have about your company's use of RCA in concrete.

A total of 17 companies or ready mixed associations responded. Among the 17 respondents, 11 have used RCA in concrete. They indicated that (i) most of the suppliers have used crushed RCA in residential concrete (footings, slabs, walls, etc.); (ii) the testing requirements or quality control procedures for using RCA as aggregate in concrete is the same as testing any other concrete that the company manufacture, air, slump, temperature, and cylinders; (iii) no technical problems, including strength deficiency issues, are encountered in using RCA as an aggregate. The key issue to concern is the source material of the RCA. Yards that accept all kinds of broken concrete can have significant inconsistencies in aggregate quality.

A ready mixed concrete supplier uses 30% aggregate replacement for 4,000 psi post tensioned, slab on grade mix designs; 30% aggregate replacement for 3,000 psi foundation mix designs; 100% aggregate replacement in 150 psi trench slurry mix designs. Their experience indicates tremendous success using 30% aggregate replacement in the mix designs.

Most ready mixed concrete suppliers crush the recycled concrete and make fresh concrete containing RCA at the company's mixing plant. They typically increase the amount of WRA in RCA mix design about 20% to account for slightly higher absorption and subsequent water demand, as RCA may decrease strength and slump, only able to use coarse.

The association thinks the use of RCA as an aggregate in concrete will expand if the specifying agency allows using RCA in concrete.

Most responses indicated that using RCA in concrete is a cost-effective way of disposing returned concrete and the interest in utilizing recycled concrete as coarse aggregate in concrete will continue to grow. If the specifying agency allows using RCA in concrete, the use of RCA as an aggregate in concrete may expand. Lack of quality aggregate is one of the reasons to use RCA in concrete, for example, in Montana, due to the lack of quality aggregate in some areas, companies have to ship their concrete aggregate from hundreds of miles away.

3.3 Survey to Construction Companies

The survey questions to the contractors regarding their experience with RCA use in concrete are as follows:

1. Has your company ever used crushed recycled concrete aggregate (RCA) as an aggregate in new concrete?
2. Please describe how your company's practices differ for the use of RCA compared to virgin aggregate in concrete.
3. For which application(s) RCA is used as an aggregate in new concrete? For which application(s) RCA is commonly (often) used?
4. What are your company's testing requirements or quality control procedures for using RCA as an aggregate in concrete?
5. Has your company encountered any problems in using concrete containing RCA?
6. If DOT allows using RCA in concrete in transportation applications would your company select RCA as an alternative aggregate or concrete containing RCA?
7. Please provide any additional comments you may have about your company's use of RCA in concrete.

A total of 18 construction companies responded, among them, six companies stated that they have used concrete containing RCA as an aggregate.

Similar to the ready mixed concrete suppliers, construction companies use RCA in concrete for RCA in sidewalks, curb and gutter or slopes, controlled low strength material, and low volume roads; also in footings for lighting, signs or fences, pipe or pull box filer, lean concrete base, and culvert backfill. These companies have not encountered main problems in using RCA; mix failure is limited and has not affected constructed products. One company stated that the use of RCA requires increased water demand, the handling of RCA in plant can be a challenge and water demand of RCA can be higher otherwise the material did not come out of bins very well.

The testing requirements and quality controls of RCA include air content and water demand. One company replaced 15% of the virgin aggregate both coarse and fine with RCA across most all their concrete mixes except architectural and ultra-high strength +10,000 psi. Another company in California produced several mixes for street base application that used 100% coarse RCA and 50% fine RCA. They have produced 6,000 psi structural concrete with 100% coarse RCA. The use of coarse RCA is straightforward, while the use of fine

RCA has more challenges specific to handling through production and increased water demand in the mix.

RCA is conditioned to assure SSD, combined aggregate RCA and virgin aggregates to meet ASTM C-33, grading, durability, LA abrasion. Several companies indicated that they would select RCA or concrete containing RCA as an alternative aggregate if DOT allows its use in transportation applications.

4.0 CONCRETE BRIDGE PROJECT SELECTION AND RCA PREPARATION

4.1 Concrete Bridge Selection

After careful review of the NCDOT STIP for 2016-2025, and meetings with the Engineers of NCDOT Divisions 1, 2, and 3, three candidate bridge construction projects were identified.

The three bridge replacement projects selected were located in (i) Pasquotank Currituck County in extreme northeastern NC (Division 1); (ii) Beaufort County in central NC (Division 2), and (iii) Sampson County southeastern NC (Division 3). Figure 4.1.1 shows the approximate locations of the bridges' demolition sites where the old concrete bridge slabs were selected, marked, removed, and transported to concrete crushing plant, i.e., S.T. Wooten's concrete recycling plant in Wilson, NC.

The removed slabs were paint marked and piled at the jobsites and were transported later to the concrete crushing plant for further crushing, processing, and sampling.

In general, the selected demolished concrete bridges were built in 1950-1960s and are in their 60-70 years of age. The bridges were reinforced concrete caps and supported by timber piles. It was assumed that the concrete properties from the three projects were similar, which were proved later by laboratory testing. More detailed information on the selected construction projects and bridges are as follows.

4.1.1 Division 1

The concrete slabs from Bridge #29 over the Little River in Pasquotank County, NC is located in northeast of the state of North Carolina. The saw-cut slabs were delivered to S.T. Wooten's Wilson plant for crushing and testing. These slabs were made up the deck or riding surface of the structure prior to saw cutting for demolition and sat atop 18 rows of 6″ × 14″ timber joists with reinforced concrete caps and timber piles. No asphalt wearing surface was used. The bridge, built in 1960, was a 4-span structure totaling 70 feet long. This structure had been posted before the construction (maximum load reduced) which led to proceeding with replacement.

Figure 4.1.2 presents the PI working with NCDOT Division 1 Engineers to review the plan, verify the construction schedule from contractor, and select the candidate bridge and slab to be removed for further processing. The site visits were conducted in June 2017. Original construction documents and records of the bridge are not available. It was reinforced concrete deck and railing system. It was assumed that it consisted of Type A Concrete, which has a 28-day compressive strength of 3,000 psi or higher.

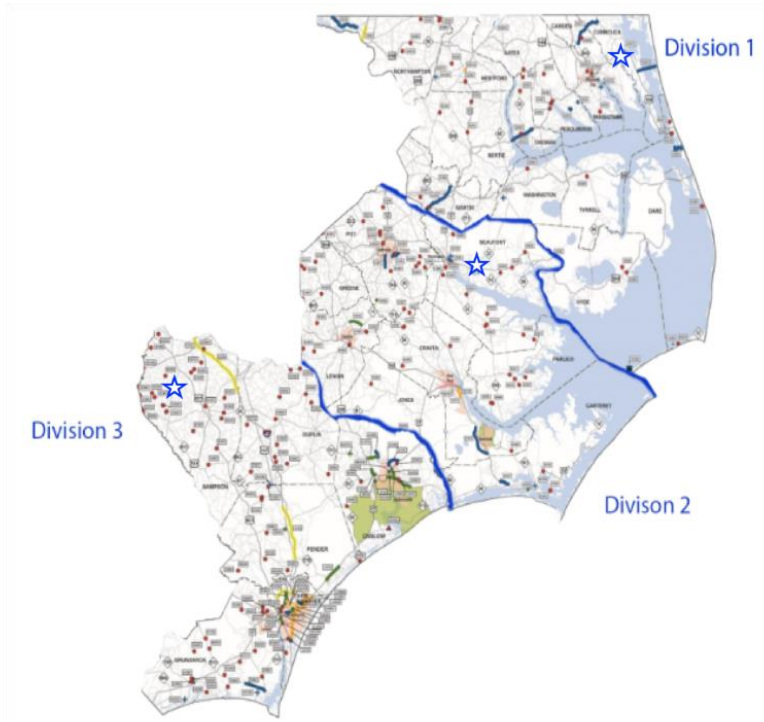


Figure 4.1.1 The Location Where the Bridge Projects Selected in three locations

Figure 4.1.2 The PI Working with NCDOT Engineers to Select a Project, Division 1

4.1.2 Division 2

In NCDOT Division 2, the candidate bridge project identified was NCDOT Project #DB00342, Bridge #110 which is located near 5288 Slatestone Road, Washington, NC in Beaufort County.

Bridge #110 was on SR 1507 (Slatestone Road) and was located 0.6 miles east of the junction of SR 1524 (Betsy Elbow Road). This bridge was built in 1959 and demolished in 2017 to make way for a new structure. The bridge's substructure was comprised of timber caps and piles. The superstructure was comprised of a concrete floor on timber stringers. At the time of demolition there was an asphalt wearing surface. The reinforced concrete deck and railing system consisted of Type A Concrete, which has a 28-day compressive strength of 3,000 psi.

Figure 4.1.3 shows the concrete was saw cut and slab was removed from the project site near 5288 Slatestone Road, Washington, NC in Beaufort County.

Figure 4.1.3 Concrete Slab from Bridge #10 in Beaufort County, NC, Division 2

4.1.3 Division 3

The bridge project selected in NCDOT Division 3 was Bridge #102 (Structure Number 810103) which was located on SR 1882, (Autryville Road), Salemburg, NC in Sampson County, which is 0.5 miles east of junction with SR 1002.

According to NCDOT structure safety report, the superstructure of Bridge #102 consisted of reinforced concrete floor and timber joist. The substructure included timber caps and piles. The construction year is not available. It is assumed the bridge is over 60 years, and the reinforced concrete deck and railing system consisted of Type A Concrete, which has a 28-day compressive strength of 3,000 psi.

Figure 4.1.4 presents the panels removed from bridge from demolition site in Salemburg in Sampson County (NCDOT Division 3).

Figure 4.1.4 Concrete Slab Selected in Sampson County, NC, NCDOT Division 3

4.2 Processing of RCA and Sampling

The selected concrete panels from three divisions were transported to S.T. Wooten plant and stockpiled separately with three color paint marked. The slabs firstly crushed using a concrete pulverizer (Figure 4.2.1). Figure 4.2.2 shows a close look of pulverizer and the jaw. The pulverizer removes the reinforcing steel (Figure 4.2.3). In the meantime, the pulverizer brings the slabs down to smaller sizes which fit the jaw crusher. Figure 4.2.4 presents the concrete slabs had been broken down to smaller sizes and were ready for crushing. In this project, Terex Finlay J-1170 Compact and Tracked Jaw Crusher was used for RCA processing, sieving and sizing. The concrete debris was crushed, screened into 1.5-inch size, and underwent further magnetic separation at the same time within the machine, and the reinforcing steel was complexly removed after the initial pulverizing and crushing.

Figure 4.2.1 Pulverizer Used to Size and Remove Rebar

Figure 4.2.2 Pulverizer Jaw

Figure 4.2.5 shows the crushing machine was working to process the recycled concrete. Figure 4.2.6 shows the 1.5-inch screener was used for the purpose to collect coarse aggregate to meet the gradation requirements for concrete proportioning.

Although the traditional method and same basic equipment to process virgin aggregates can be used to crush, size, and stockpile RCA, the selection of crushing process can affect the amount of mortar that clings to the RCA particles and, therefore, the properties of the RCA.

Figure 4.2.3   Reinforcing Steel was Removed After Pulverizing

Figure 4.2.4   Sized Concrete for Crushing and Screening

Figure 4.2.5 Terex Finlay J-1170 Compact Crusher Used for RCA Processing

Figure 4.2.6 A Separate 1.5-Inch Screener is Selected and Used for Sizing Crushed RCA

Jaw crushers generally are more effective for producing higher quantities of RCA, but generally result in relatively high amounts of reclaimed mortar in RCA particles. Impact crushers can be lower productivity, but more effective to remove mortar from RCA, therefore the coarse RCA is more similar to virgin aggregate, and more fine particles can be generated.

The production of RCA is almost completed on site by this integrated equipment and selected screener. Figure 4.2.7 shows the RCA after crushing and screening using 1.5-inch sieve for sampling. RCA materials were sampled and transported to the concrete lab in Garner, NC, for blending and testing (Figure 4.2.8).

Figure 4.2.7   Crushed Recycled Concrete Aggregate

Figure 4.2.8   Sampling of Recycled Concrete Aggregate, Division 1

4.3 Laboratory Testing of RCA Samples

The materials used for concrete specimens include the recycled concrete aggregates from the above mentioned three locations from NCDOT Divisions 1, 2, and 3, crushed natural aggregate (CA, granite), natural sand, Type I cement, Class F fly ash, electric arc furnace steel slag, water reducer, air-entraining agent. The properties of RCA and steel slag were examined for mix designs and concrete making.

The RCA from three locations were tested in laboratory for sieve analysis, gradation, impurities, specific gravity, absorption, LA abrasion test, and potential alkaline-silica reaction test.

4.3.1 Preparation of the RCA Samples

After transported to the S.T. Wooten's Concrete Lab in Garner, NC, the RCA samples from three locations were undergone screening test to (i) separate fine particle (less that #4 sieve or 4.75 mm) from coarse particles (particle size between #4 and 1.5 inch); (ii) examine the impurities, including metal, wood and/or asphalt pieces. Figure 4.3.1 exhibits the screening process by using the testing screen master sieve shaker. No. 4, 1.5 inch, sieves and pan were use in this process.

Figure 4.3.1 Screening to Obtain Particles Between #4 and 1.5 inch

Impurities were noted, collected, and weighed. The percentages of the impurities are low for all the samples from three Divisions. Table 4.3.1 summarizes the results which shows the impurities are 0.28%, 0.23%, and 0.26% respectively, with average of 0.26%. Figure 4.3.2

shows the impurities separated from the coarse RCA. From Table 4.3.1, it is seen that the impurities in the subject RCA samples are low and are within 0.3% which meets the required limit by the specification.

Figure 4.3.2 Impurities from the Coarse RCA

Fine particles passing #4 were separated and weighed in this process to determine the percentage range of fine particles generated from RCA crushing process. This is an important indicator that will help to (i) evaluate the potential usage of each size fraction based on the quantity of fine particles generated during the crushing process; (ii) conduct economic benefit evaluation based on sizes of the RCA products. The percentage range of fine particles (Table 4.3.1) are 39.0%, 49.6%, and 41.6% for the RCA samples from Divisions 1, 2, and 3, respectively, with an average of 43.4%, which conforms to the data from other research reports (Topçu and Şengel, 2004).

Table 4.3.1 Particle Size and Impurities of RCA

Samples	**Fines (Less Than #4) (%)**	**Larger Than 1.5 Inch (%)**	**Impurities (%)**	**Coarse RCA Particles for Concrete Testing (%)**
Division 1	39.0	0.24	0.28	60.3
Division 2	49.6	0.13	0.23	50.3
Division 3	41.6	0.16	0.26	58.2
Average	43.4	0.18	0.26	56.2

4.3.2 Sieve Analysis and Gradation

The RCA samples from each division were blended and sieve analysis was conducted. NCDOT Standard Specifications for Roads and Structures (January 2018) provides typical gradations of various aggregates and their applications. Table 4.3.2 summarizes #57, #67, and #78M aggregates for concrete mixes.

The gradations for the three blended RCA samples are presented in Table 4.3.3. The results indicate that the gradation of the crushed RCA samples marginally meets #57 stone gradation, with 1″ size being slightly smaller than the specified. That means the RCA is slightly coarser at 1″ (25 mm) size. It was decided no further crushing was conducted to verify the concrete strength properties using the available RCA as in general 10 mm particle size is optimal size to make high strength concrete. Using the available RCA would place the results in a conservative or safe side. Also, in RCA production practice, minor adjustment in crushing and screening is easy and will not create hurdle or difficult to produce final products that meet the gradation requirements.

Table 4.3.2 NCDOT Specifications Table 1005-1 - Coarse Aggregate Gradation

Std. Size #	**2″**	**1 ½″**	**1″**	**¾″**	**½″**	**#4**	**#8**	**½″**	**#10**	**#16**	**#40**	**#200**
57	-	100	95-100	-	25-60	0-10	0-5	25-60	-	-	-	0-0.6
67	-	-	100	90-100	-	0-10	0-5	25-45	-	-	-	0-0.6
78M	-	-	-	100	98-100	20-45	0-15	98-100	-	-	-	0-0.6

(Table Courtesy of NCDOT)

Table 4.3.3 Gradation of the RCA Samples

Sieve Size	**Percentage passing (%)**			**#57 Stone gradation by NCDOT**
	Division 1	**Division 2**	**Division 3**	
1.5″	100	100	100	100
1.0″	89.5	86.5	83.7	95-100
0.5″	40.2	50.5	42.0	25-60
#4	2.6	2.9	2.7	0-10

4.3.3 Specific Gravity and Absorption Value

It is known that RCA has several unique characteristics and properties that must be considered during the mix design and construction stages. These properties include lower specific gravity, which decreases with increasing amount of reclaimed mortar; higher absorption, which increases with increasing amount of reclaimed mortar; greater angularity; increased abrasion loss, which increases with increasing amount of reclaimed mortar; presence of unhydrated cement, which may alter its behavior and complicate stockpiling, especially the fines (passing #4 sieve); the fines produced during the crushing operation are angular, which may make RCA concrete mixtures very harsh and difficult to work. For mix design considerations, bulk specific gravity and absorption were examined. For this testing, AASHTO T 85 – 2014: Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate (Equivalent to ASTM Designation: C 127-15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate) was followed.

Table 4.3.4 includes the results of the bulk specific gravity and absorption of the RCA samples from three locations. The values of the three subject RCA samples are very close with the average of specific gravity of 2.27 and absorption value of 5.11%.

Table 4.3.4 Specific Gravity and Absorption Value of the RCA

RCA from	Bulk Specific Gravity	Absorption (%)	Note
Division 1	2.27	4.97	Average of two parallel samples for each material
Division 2	2.25	5.33	
Division 3	2.29	5.02	
Average	2.27	5.11	

4.3.4 Potential Alkali-Silica Reactivity[3]

It is understood that not all RCA is appropriate for use in concrete. For example, RCA made from concrete exhibiting materials-related distress such as alkali-silica reactivity (ASR) or D-cracking may not be used in concrete unless certain mitigation methods are employed. Additionally, RCA may contain high chloride contents due to extended exposure to deicing chemicals, which may make it unsuitable for use in reinforced concrete. Although when selecting the candidate concrete bridges, it had been made clear that the old bridges demolished from NCDOT Divisions 1, 2, and 3 had not suffered ASR and D-cracking, the three RCA samples were examined for susceptibility of ASR. ASTM C1260 Potential Alkali Reactivity of Aggregate, Mortar Bar Method was followed.

Test results from the potential alkali reactivity of aggregate show that the RCA samples from three locations are 0.02%, 0.06%, and 0.02% at 14-day, and 0.05%, 0.10%, and 0.04% at 28-day respectively.

[3] The results of potential alkali reactivity of aggregate (Mortar Bar Method, ASTM C1260) is presented in the Appendices, Section 12.10.

4.3.5 LA Abrasion Test

LA Abrasion Test was conducted according to AASHTO T 96 or ASTM C 131: Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. The results indicate (i) the abrasion values of the three RCA samples are close; and (ii) the average of abrasion value is 35.6% (Table 4.3.5) which is within the range of LA abrasion values of RCA reported by literature, i.e., 30% - 50% (Topçu and Şengel, 2004).

Table 4.3.5 LA Abrasion Test Results

Materials	Division 1	Division 2	Division 3	Average
LA Abrasion Value	35.4%	35.7%	35.8%	35.6%

4.3.6 Expansive Properties of Steel Slag Aggregate

The advantages of steel slag as aggregates are well known (Wang, 2010, 2016; Arribas, et al., 2015; Fronek, et al., 2012) in providing strength and durability. To investigate the effect of steel slag aggregate on the strength of the concrete containing RCA, ¾″ (19-mm) EAF steel slag was sampled from Nucor Steel Plant in Cofield, Hertford County, NC and used in concrete batching. Figure 4.3.3 shows the sampling of EAF slag at Nucor Steel Plant. The steel slag samples were transported to ECU Construction Lab for stability disruption testing.

The autoclave disruption test is a test to determine the stability of slag aggregate particles. In this test, slag samples were separated into several particle size fractions. After visual examination and petrographic analysis, a certain number, 50 coarse particles from each size fraction were chosen and washed, and then placed into an autoclave to be treated for three hours. The ratio of the number of slag particles that show cracking, powdering, or containing visually observed cracks after treatment to the total number of slag particles selected is defined as the particle-disruption ratio R. It is generally agreed that autoclave testing can accelerate the hydration of free lime and especially periclase, which has slow hydration rate. Therefore, this test can provide an assessment and indication of long-term stability of steel slag aggregate particles due to free magnesium and water reaction. This is a simple test and has been proved it is useful and reliable. The R value is an important factor in evaluating the overall stability of steel slag aggregate in concrete matrices where steel slag is incorporated and other constrained conditions.

The volumetric stability of slag samples was tested using the above test method in a pressure cooker for three hours, and disruption ratios were calculated. Figure 4.3.4 shows the slag particles after three-hour treatment. The disruption ratio is zero. The result indicates the slag particle is volumetrically stable under ambient conditions.

Figure 4.3.3 Sampling of Steel Slag Aggregate at Nucor Steel in Hertford County, NC

Figure 4.3.4 EAF Steel Slag Aggregate After Pressure Cooker Treatment

5.0 CONCRETE MIX DESIGN, TESTING, AND RESULTS

5.1 Mix Designs of Concrete Containing RCA[4]

The crushed natural aggregate (CA) and RCA samples were washed and soaked and drained to maintain saturated surface dry (SSD) condition for concrete making in the Concrete Lab.

The steel slag aggregate, produced at Nucor Steel Hertford, NC and processed by Harsco Metals in Cofield, NC, was sampled and tested (during the pioneer study in 2017). The content of cement and fly ash and W/C ratio were kept the same as those of the control mix to examine the changes of fresh concrete properties and compressive strength. The procedure and program employed for the mix design were kept the same as normal concrete production used in this study.

The RCA and steel slag aggregates were soaked 24 hours then maintained in SSD condition before the concrete batching. This is consistent with the current ready-mix concrete production practices.

In principle, the mix design method and procedure used for the concrete containing RCA and steel slag aggregates is not different from that of conventional concrete because SSD condition s are maintained.

In practice, depending on the purposes of the designs and products required, slight modifications are required. These may include:

To keep the same strength, when coarse RCA is used with natural sand, it may be assumed at the design stage that the W/C ratio required for a certain compressive strength may be the same for RCA concrete as for conventional concrete. If trial mixes show that the compressive strength is lower than required, an adjustment of the W/C should be made which would be up to 5%. In some cases, if free water content of an RCA concrete is increased, the cement content may also need to be higher to maintain the same W/C ratio.

Literature suggests that the unit weights of concrete made using RCA are within 90% to 100% of the control concrete mixture. Air contents of RCA concrete are up to 5% higher. The optimum ratio of fine-to-coarse aggregate is the same for RCA as it is for concrete made from virgin materials.

It is the practice and recommended that addition of superplasticizer is necessary for achieving the required workability of new concrete. Higher than 50% RCA may cause higher shrinkage of concrete. Although up to 50% of RCA was proposed in the proposal, 100% of RCA was tested to check the strength development trend and other properties.

[4] Detailed mix design forms are presented in Appendices, Section 12.8.

Five concrete mixes containing RCA samples, namely, 0%, 15%, 30%, 50%, and 100% were selected. 0% of RCA is a control mix. This is a typical Class B mix that has been used. The control mix was used for comparison with concrete mixes containing varied levels of RCA content. All other parameters, including cement, fly ash, fine aggregate, natural coarse aggregate (crushed aggregate, CA), W/C, admixtures were kept the same to avoid unnecessary factors that could affect the properties of mixes and strengths. Table 15.1.1 presents the summary of the mix designs. Properties of fresh concrete, including slump, unit weight, and air content are also presented in Table 5.1.1.

Table 5.1.1 Summary of Mix Designs for the Concrete Containing RCA

Mixes (Percent of RCA)	**Materials (in lb Per Cubic Yard)**						**Fresh Concrete Properties**		
	RCA	**67 Stone**	**Cement**	**Fly Ash**	**Sand**	**W/C**	**Slump (in.)**	**Unit Weight (pcf)**	**Air Content (%)**
0%	0	1750	436	131	1192	0.47	3.5	147.7	3.5
15%	227	1488	436	131	1192	0.47	3.5	140.9	5.5
30%	453	1225	436	131	1192	0.47	1.5	143.5	4.5
50%	755	875	436	131	1192	0.47	4.5	138.3	5.5
100%	1510	0	436	131	1192	0.47	3.5	134.8	5.5

To investigate the function of steel slag aggregate in nonstructural concrete containing recycled concrete aggregate, concrete mixes containing EAF steel slag and RCA samples, namely, 20% steel slag and 80% RCA, and 50% steel slag and 50% RCA, were prepared. Research reports have reported that the compressive strength of concrete containing RCA is lower than normal concrete with the increase of RCA content. It is also reported that concrete containing coarse steel slag aggregate exhibits higher strength than ordinary concrete. The electric arc furnace slag is produced in Eastern North Carolina by Nucor Steel – Hertford Plate Mill located Cofield. The slag is processed by Harsco, Inc., Facilities. The coarse slag aggregate was sampled and tested in summer and fall of 2017 and the results showed the slag was volumetrically stable and the concrete slices containing the EAF slag is stable under pressure cooker test. A pioneer study was conducted before using the steel slag aggregate with RCA in this study. In the pioneer study, strength, stability of concrete specimens, micro level examinations were conducted (refer to Chapter 6, Engineering Analysis).

Table 5.1.2 presents the summary of the mix designs for concrete containing RCA and steel slag. Properties of the fresh concrete containing EAF slag including slump, unit weight, and air content are also presented in Table 5.1.2.

In the concrete batching, Darex® II AEA air entraining agent was used. It is an air-entraining admixture which generates a highly stable air void system for increased protection against damage from freezing and thawing, severe weathering, or deicer chemicals. This admixture is a complex mixture of organic acid salts in an aqueous solution specifically formulated for use as an air-entraining admixture for concrete and is manufactured under rigid control which provides uniform, predictable performance.

MIRA® 85 was used as water reducer in the mixes. It is a mid-range water reducer specifically formulated to produce concrete with enhanced finishing characteristics and neutral set times. It provides superior water reduction and versatile mid-range water reducer performance across a wide range of concrete slump requirements. It is an aqueous solution of complex organic compounds, each of which contributes uniquely to the concrete's final properties.

Figure 5.2.1 shows the equipment and materials were ready in front of the Concrete Lab before concrete batching.

Figure 5.1.1 Equipment and Materials are Ready for Concrete Batching

Table 5.1.2 Summary of Mix Designs for the Concrete Containing RCA and EAF Slag

Mixes	Materials (in lb Per Cubic Yard)						Fresh Concrete Properties		
	EAF Slag	RCA	Cement	Fly Ash	Natural Sand	W/C	Slump (in.)	Unit Weight (pcf)	Air Content (%)
1-20%+80%	473	1078	436	131	1192	0.47	5.8	137.3	5.3
2-50%+50%	1101	776	436	131	1192	0.47	6.0	143.3	4.3

5.2 Properties of Fresh Concrete

5.2.1 Workability

RCA concrete workability is strongly affected by the shape and texture of the coarse recycled aggregates surface. By using the same W/C ratio, slightly increased water reducing agent is needed to keep the required workability. However, for the mixes containing 15% to 100% RCA, the same amount water reducer (45.4 ml for two cubic feet batch) was used, the slump values are generally in the same level, i.e. 3.5 to 4.5 inch slump, except for the mix containing 30% of RCA which a system error might be introduced during design/batching. Figure 5.2.2 shows the slump test for fresh concrete.

Figure 5.2.1 Slump Test for Fresh Concrete Containing RCA

5.2.2 Unit Weight and Air Content

The concrete samples were taken immediately for determination of unit weight (density) and air content tests after the concrete had been discharged from mixer.

From Tables 5.1.1 and 5.1.2, it shows that the unit weight of concrete decreases with the increase of the RCA content. The unit weight ranges from 147.7 pcf to 134.8 pcf from 0% RCA to 100% RCA.

The results were anticipated for the concrete containing EAF slag and RCA. For the concrete containing 20% EAF slag and 80% RCA the unit weight is 137.3 pcf comparing with the one containing 50% EAF slag and 50% RCA which weights 143.3 pcf.

Air contents of all mixes are within the range of 5.0% ± 1.5% that NCDOT Standard Specifications require for moderate exposure concrete.

Figure 5.2.2 Unit Weight and Air Content Test of Fresh Concrete Containing RCA

5.3 Strength Related Properties[5]

Concrete cylinders were stored in the standard curing room at S.T. Wooten Concrete Lab in Garner, NC for testing (Figure 5.3.1). Cylinders were broken at 7-day, 28-day, and 90-day of age. The results of concrete containing RCA and RCA and steel slag are presented below respectively.

Figure 5.3.1 Concrete Cylinders in Curing Room

5.3.1 Strength of Concrete Containing RCA

Table 5.3.1 presents the compressive strengths of the concretes from three divisions at the three ages.

The results have confirmed that the use of RCA in substitution of virgin aggregates from 15%, 30%, 50% to 100% can make concrete meet NCDOT Class B concrete (2,500 psi at 28-day) and, however, slightly lower strengths. Concrete made with 100% coarse RCA reached 2,500 psi at 7-day of age. The strength differences between 0% RCA and 100% RCA are in 20% for 90-day strength, 24% for 28-day strength, and 18% for 7-day strength. In between, 0% to 100% RCA, the declining trend follows an approximate straight line. Figure 5.3.2 presents the strength declining trend based on the averaged compressive strength value for 7-day, 28-day, and 90-day.

[5] Detailed 7-day, 28-day, and 90-day strength test record for all cylinders are presented in Appendices, Section 12.9.

Table 5.3.1 Summary of Compressive Strength of Concrete containing RCA

Location	Age	Compressive Strength at 7-day, 28-day, and 90-day (psi)				
		0% RCA 100%CA*	**15% RCA 85% CA**	**30% RCA 70% CA**	**50% RCA 50% CA**	**100%RCA 0% CA**
Division 1	7-day	3,410	3,164	3,488	2,851	2,825
	28-day	5,466	5,011	5,379	4,375	4,312
	90-day	6,205	5,747	6,260	5,160	5,049
Division 2	7-day	3,410	3,308	3,635	2,992	2,845
	28-day	5,466	4,798	4,900	4,311	4,193
	90-day	6,205	6,018	5,940	4,999	5,026
Division 3	7-day	3,410	3,329	3,634	2,986	2,873
	28-day	5,466	4,992	5,209	4,267	3,909
	90-day	6,205	5,848	5,608	4,924	4,791
Average	7-day	3,410	3,267	3,586	2,943	2,848
	28-day	5,466	4,934	5,162	4,318	4,138
	90-day	6,205	5,871	5,936	5,028	4,955

*Note: CA denotes crushed natural aggregate.

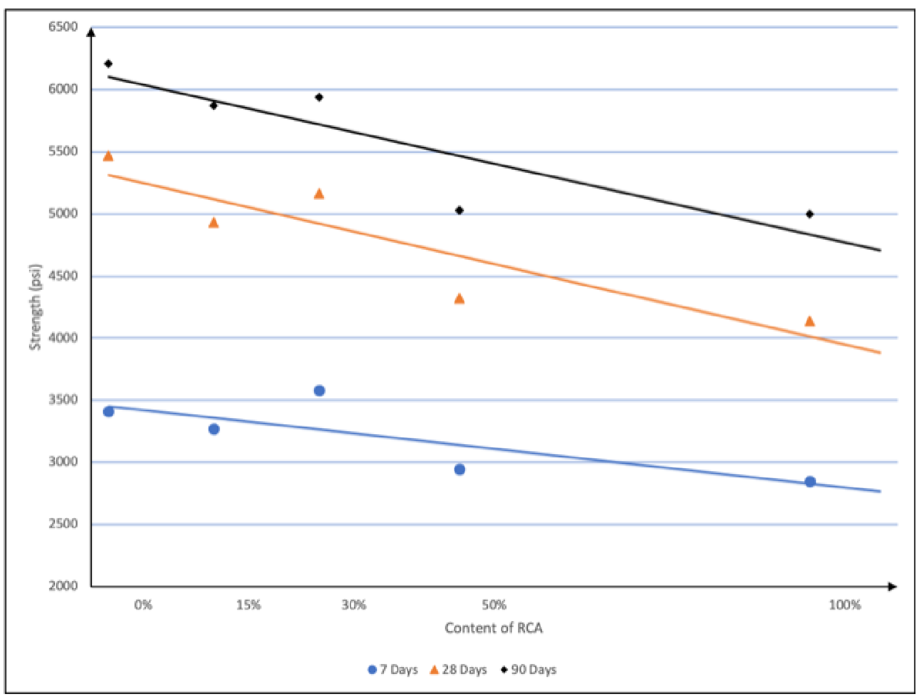


Figure 5.3.2 Compressive Strength For Concrete Containing RCA

5.3.2 Strength of Concrete Containing RCA and EAF Slag Aggregate

Concrete cylinders containing RCA and EAF slag were broken at 7-day, 28-day, and 90-day of age. Table 5.3.2 presents the summary of the results. Figure 5.3.3 shows breaking 90-day cylinders with 50%+50% RCA and steel slag aggregates.

The results have confirmed that the use of RCA and EAF slag as coarse aggregate meets the strength requirements at 7-day (3,168 psi, 20% slag + 80% RCA). Conforming to what has known, the strength increases with the content of slag increases. The strength increases by 11%, 14%, and 2% for 90-day, 28-day, and 7-day respectively from 20% to 50% of EAF slag. Figure 5.3.4 presents the strength gains of the concrete containing 25% slag and 50% EAF slag.

Table 5.3.2 Summary of Compressive Strength of Concrete with RCA and EAF Slag

Age	Compressive Strength at 7-day, 28-day, and 90-day (psi)		
	0% EAF Slag; 100% CA	**20% EAF Slag; 80% CA**	**50% EAF Slag; 50% CA**
7-day	2,848	3,168	3,241
28-day	4,138	3,838	4,373
90-day	4,955	4,939	5,504

Note: Blended RCA from Divisions 1, 2, and 3 were used;

Figure 5.3.3 Breaking 90-day Cylinder Containing RCA and EAF Slag Aggregate

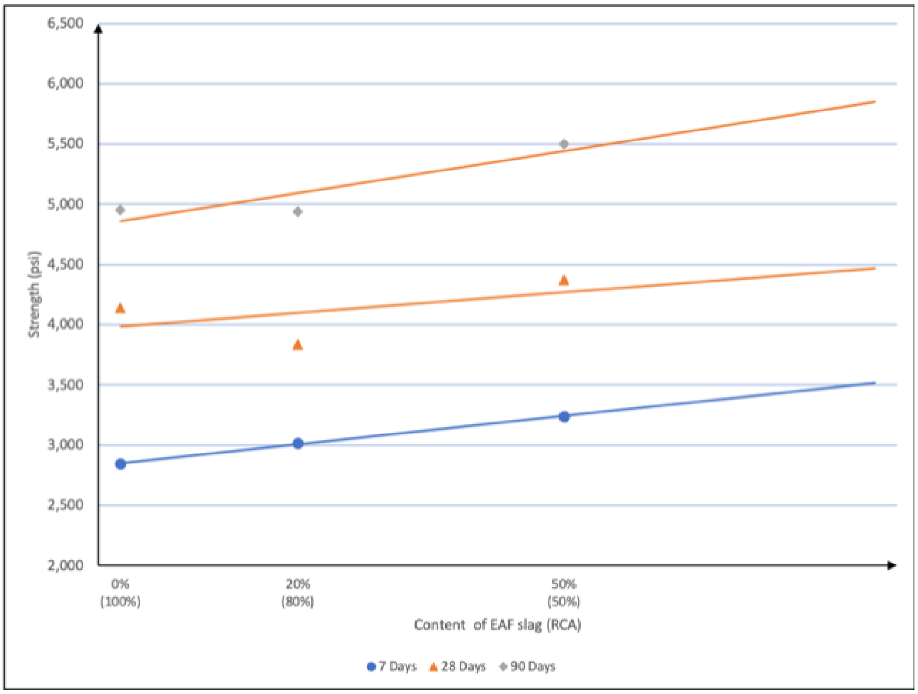


Figure 5.3.4 Compressive Strength for Concrete Containing RCA and EAF Slag

6.0 ENGINEERING ANALYSIS

6.1 Strength Related Properties

Table 6.1.1 presents the requirements for Class B concrete by NCDOT Specifications. For comparison, the requirements for Class A concrete is also included in the table. From Tables 5.3.1 and 5.3.2 it can be seen that

- all the mixes including the mixes containing RCA and RCA with EAF slag replacement gained the strength requirements for Class B concrete at 7-day of age (2,500 psi at 28-day);
- all the mixes including the mixes containing RCA and RCA with EAF slag replacement meet the strength requirements for Class A concrete at 28-day of age (3,000 psi at 28-day);
- in general, the strength decreases with the content of RCA increase at 7-day, 28-day and 90-day strength trend;
- by replacing 20% and 50% of RCA by steel slag aggregate, strength increases at 7-day, 28-day and 90-day of age;
- the percentage strength loss comparing with control mix is in the range of 4.2%-16.5%, 9.7%-24.3%, and 5.4%-20.1% respectively for 7-day, 28-day, and 90-day strength (Table 6.1.2).
- The strength increases or strength loss is reduced when steel slag is added (Table 6.1.3)

Table 6.1.1 NCDOT Specifications Table 1000-1 - Requirements for Concrete

Class of Concrete	Minimum Comp. Strength at 28-day	Maximum W/C Ratio		Consistency Max. Slump		Cement Content	
		Air-Entrained (Rounded)	Air-Entrained (Angular)	Vibrated	Non Vibrated	Vibrated	Non Vibrated
A	3,000	0.488	0.532	3.5	4	564	677
B	2,500	0.488	0.567	2.5	4	508	610

(Table courtesy of NCDOT)

Figure 6.1.1 shows the saw-cut specimens of concrete containing 15%, 30%, 50%, and 100% of RCA aggregate and concrete with 20% and 50% replacement of RCA with EAF slag aggregate. The volumetric stability of concrete containing EAF slag was conducted in the pioneer study (Section 6.3) by pressure cooker treatment.

Table 6.1.2 Strength Loss for RCA Concrete

Age	Strength Loss			
	15% RCA	30% RCA*	50% RCA	100% RCA
7-day	-4.2%	-	-13.7%	-16.5%
28-day	-9.7%	-	-21.0%	-24.3%
90-day	-5.4%	-	-16.1%	20.1%

*Data not calculated.

Table 6.1.3 Strength Loss and Gain for Concrte with EAF Slag

Age	Strength Loss and Gain (-; +)			
	Compare with Control Mix		Compare with 100% RCA Mix	
	20% EAF Slag	50% EAF Slag	20% EAF Slag	50% EAF Slag
7-day	-7.1%	-5.0%	+11.2%	+13.8%
28-day	-30.0%	-20.0%	-7.2%	+5.7%
90-day	-20.4%	-11.3%	-0.3%	+11.1%

When a conventional aggregate is replaced by a recycled aggregate such as RCA or slag, it is interesting to investigate any possible changes between the coarse aggregate and cement paste, mechanically, physically in macro- or micro-levels. Sections 6.2 and 6.3 summarizes the related study and findings.

Figure 6.1.1 Saw-Cut Specimens Containing RCA and EAF Slag Coarse Aggregate

6.2 Aggregates/Mortar Interface Verification

Portland cement concrete is a structural sensitive material. That means any localized failure could result in the entire structure failure. Concrete is a brittle material, which is contributed by (i) the phase of cement paste (mortar); (ii) the phase of aggregates, and (iii) the phase of interface transition zone (bonding) between aggregate and cement paste.

To investigate any changes that could happen in the three-phase system due to RCA incorporation, the concept of brittleness index is introduced. The brittleness index is obtained from the cyclic repetitive loading and the full stress-strain (σ-ε) curve of each cylinder (Figure 6.2.1) and is defined as in Figure 6.2.2. Figure 6.2.3 is a specimen under testing to obtain the full stress-strain curve.

As illustrated in Figure 6.2.2, brittleness index B is calculated as the ratio of the area of elastic recovery (elastic deformation energy) to that of the nonelastic portion (irreversible deformation energy) corresponding to the peak point of the σ–ε curve (i.e., B = area II/area I).

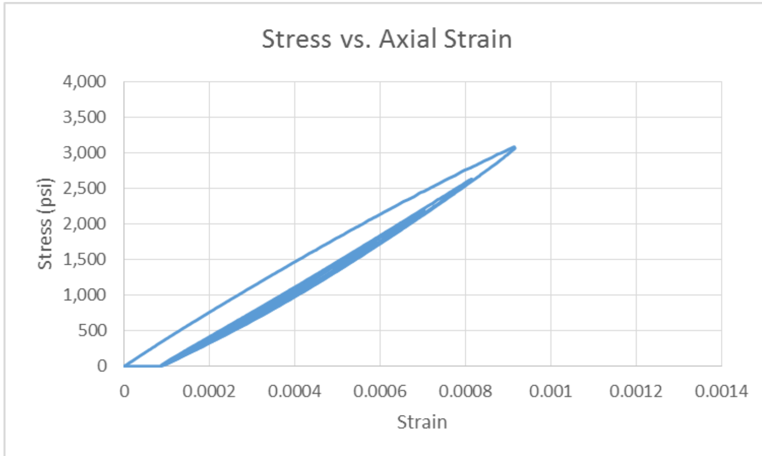


Figure 6.2.1 A Full Stress-Strain (σ-ε) of 50% RCA and 50% EAF Slag Concrete

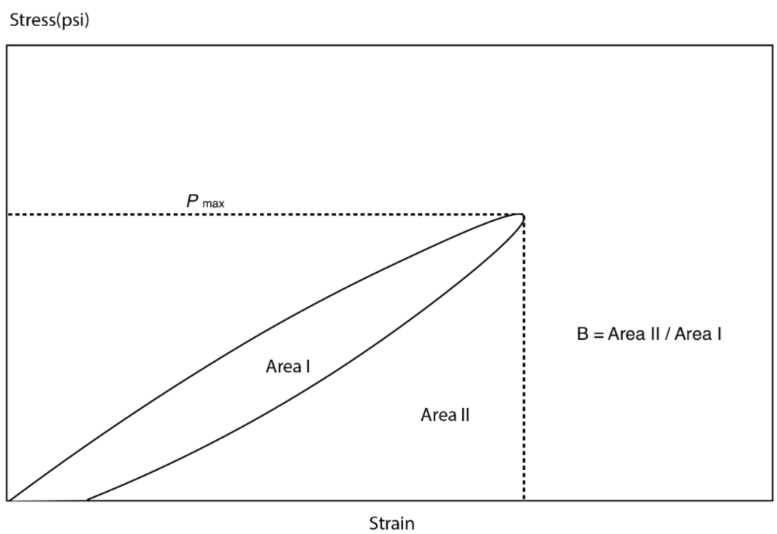


Figure 6.2.2 Defined Brittleness Index by Using Full σ-ε Cyclic Curve and Areas

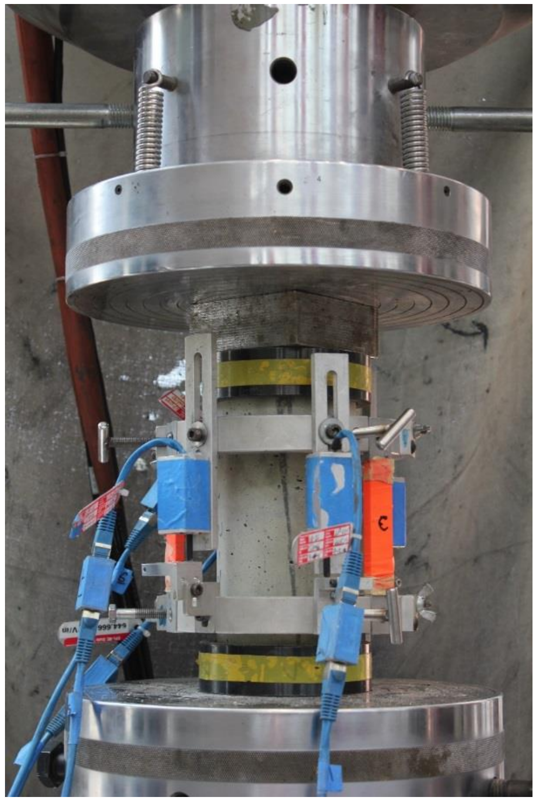


Figure 6.2.3 Specimens to Obatin Cyclic Full σ-ε Curve

The results are presented in Table 6.2.1 for four mixes, namely, 15%, 30%, 50% and 100% RCA and Table 6.2.2 for two mixes containing 20% and 50% of EAF slag.

For concrete containing RCA, it shows that there is slight increase in terms of brittleness index but it is considered not significant (can this be modified by adding fine particles of processed tire rubber? It is discussed later). For two concrete mixes with replacement of EAF slag, the similar trend is found. Figures 6.2.4 and 6.2.5 plot the data obtained from testing and calculation.

Table 6.2.1 Brittleness of RCA Concrete from Full σ-ε Curve

Mixes	Area II	Area I	B = II/I
15% RCA + 85% CA	1.434	0.591	2.426
30% RCA + 70% CA	1.593	0.526	3.030
50% RCA + 50% CA	1.210	0.450	2.690
100 RCA + 0% CA	1.215	0.433	2.903

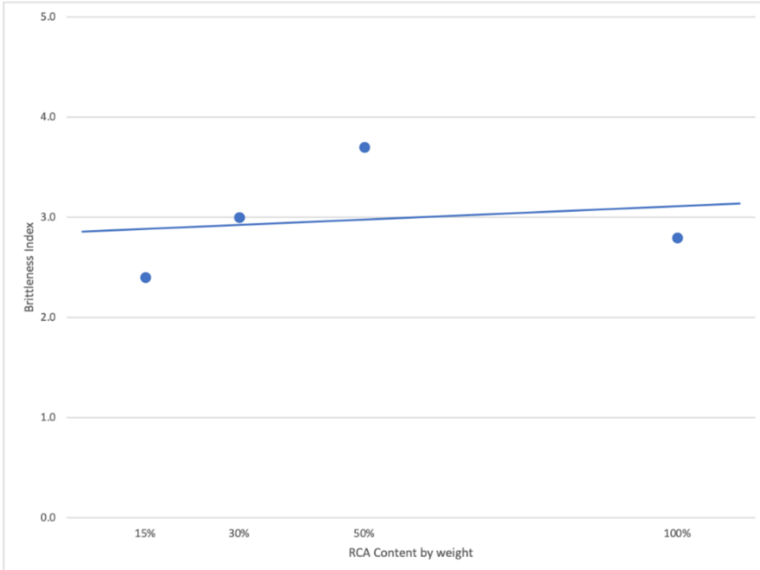


Figure 6.2.4 Brittleness Index vs. RCA Content

Table 6.2.2 Brittleness of RCA + Slag Concrete from Full σ-ε Curve

Mixes	Area II	Area I	B = II/I
20% EAF Slag + 80% RCA	1.010	0.331	3.052
50% EAF Slag + 50% RCA	1.1584	0.3706	3.126

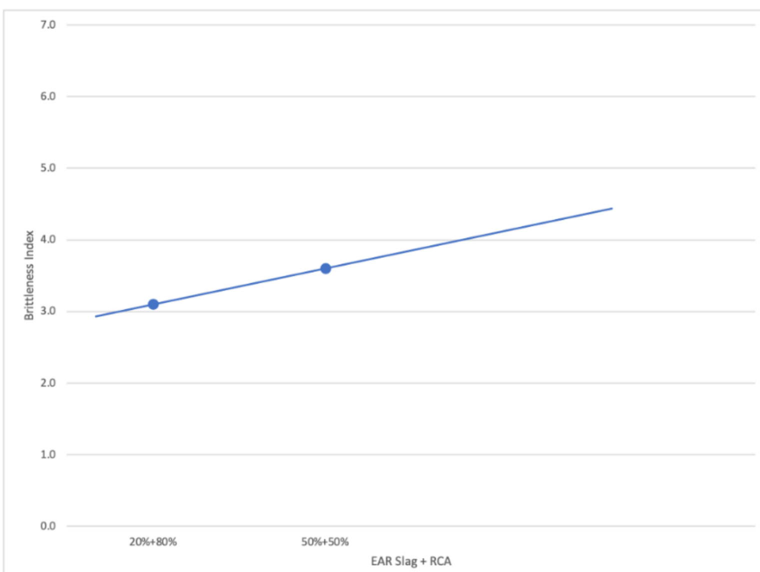


Figure 6.2.5 Brittleness Index vs. RCA and EAF Slag Content

6.3 Pioneer Study for the Use of RCA and Other Recycled Materials

Using a recycled or nontraditional material in concrete or construction is a complicated process which requires a thorough understanding of the virgin material, the recycled material(s) involved, the designated end product, and their interactions.

Blending use of RCA with another recycled material(s) to make concrete may modify and enhance the properties and performance of the concrete (or other end product). It is imperative to develop a wide range of environmentally acceptable, technically sound, and economically viable uses for RCA and other recycled materials and to transfer various "waste" streams, into useful material "resource" streams. During the project selection, transportation and crushing concrete panels, a pioneer study was conducted in 2017. The purpose of the pioneer study was to (i) prepare for the forthcoming laboratory study on using RCA in concrete, especially conduct trial testing using EAF slag with RCA in concrete to verify the feasibility; (ii) to obtain technical information and preparation for future study of using RCA and broader locally available recycled materials in Eastern North Carolina.

6.3.1 Materia Selection

To incorporate other recycled materials with RCA in nonstructural concrete for this research project and future studies, EAF slag and shredded scrap tire rubber (STR) were selected for the pioneer study.

The main purpose to use EAF slag and STR in the pioneer study is to verify the strength of concrete with the recycled materials and micro-level observations on the interface transition zone between aggregate and cement paste (mortar). By testing the sampled slag, a decision can be made during the RCA concrete batching to make the testing work efficient and effective.

Scrap tires are generated each year in North Carolina. Ground tire rubber (GTR) use in road paving is successful, however the utilization rate is low. In a recent report (NAPA, IS #138), over 30 states have increased the use of processed scrap tire in infrastructure construction. The STR used in this study is produced by Liberty Tires Recycling in Cameron, NC.

Other reasons to select the EAF slag and STR include that (i) both materials are locally available processed recycled materials in North Carolina; (ii) steel slag possesses excellent mechanical properties, however the density of EAF slag is heavy in nature. STR has notable lighter weight. Blending use of them with RCA in nonstructural concrete may modify the properties of the concrete; (iii) EAF slag can contribute concrete strength, however it is may be volumetrically expansive prone. Adding STR may eliminate potential expansion; and make similar strength concrete containing natural aggregate and similar unit weight; (iv) by adding appropriate amount of STR, elastic energy ratio of the concrete may change to make the concrete is less brittle (brittleness index is defined by Figure 6.2.2); (v) the elastic nature of rubber would allow certain expanded volume in steel slag (if any) to be absorbed if used as bound and unbound applications. Figure 6.3.1 shows the EAF slag and STR samples for physical property testing before batching.

Figure 6.3.1 EAF Slag and Shredded Scrap Tire Rubber (STR) for the Pioneer Study

6.3.2 Strength Related Properties

Mix designs for the pioneer study included 0% of EAF slag, 35% of EAF slag, 65% EAF slag, and 100% of EAF slag. Each mix has 25% STR fine aggregate and 100% natural sand. The mix designs are presented in Table 6.3.1.

Table 6.3.1 Mix Proportions of Concrete in Pioneer Study

Mixes	**Coarse Aggregate**		**Fine Aggregate**		**Cementitious Materials**	**W/C Ratio**
	Natural Aggregate	**EAF Slag**	**Natural Sand**	**STR**	**Portland Cement**	
1	100%	0%	100%	0%	596.5lb/cy	0.57
2	100%	0%	75%	25%	596.5lb/cy	0.57
3	0%	100%	100%	0%	596.5lb/cy	0.57
4	0%	100%	75%	25%	596.5lb/cy	0.57
5	65%	35%	100%	0%	596.5lb/cy	0.57
6	65%	35%	75%	25%	596.5lb/cy	0.57
7	35%	65%	100%	0%	596.5lb/cy	0.57
8	35%	65%	75%	25%	596.5lb/cy	0.57

Figure 6.3.2 presents saw-cut slices of the concrete (i) 100% natural coarse aggregate; with 75% of natural sand and 25% of STR; (ii) 35% natural coarse aggregate and 65% EAF slag; with 75% of natural sand and 25% of STR.

The concrete cylinders containing steel slag were saw cut and treated under pressure cooker. All the slices are stable, no distress is observed after the treatment (Figure 6.3.3). The results in the pioneer study helped make the decision for the mixes by adding steel slag coarse aggregate.

Table 6.3.2 Strength Realted Properteis

Mixes	28-day Compressive Strength (psi)	Modulus × 10^6 (psi)	Brittleness Index	Bulk Specific Gravity (pcf)
1	4,970	3.097	-	148.2
2	5,220	2.492	-	138.8
3	5,680	4.662	-	153.6
4	3,260	4.711	-	146.5
5	5,830	6.697	4.580	162.0
6	3,160	3.761	-	151.5
7	5,720	5.797	-	163.0
8	3,080	4.403	3.347	154.9

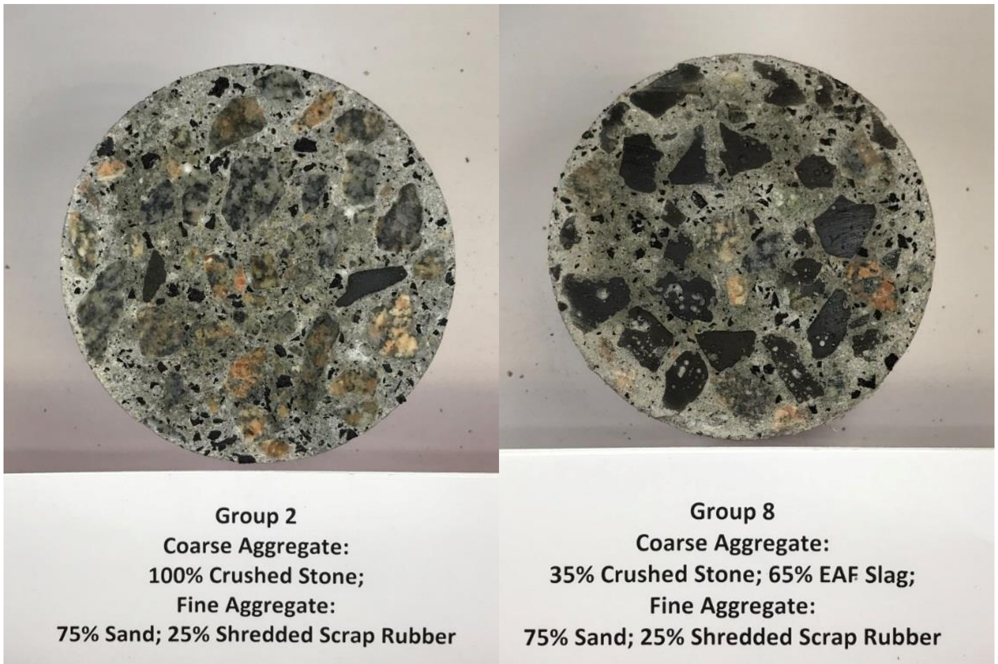


Figure 6.3.2 Slices of Concrete Containing STR, Slag, and Natural Aggregates

Figure 6.3.3 Concrete Containing Nucor Steel Slag after Pressure Steam Trentment

6.3.3 Micro-level Observations of Concrete Containing EAF Slag and STR

Saw cut concrete slices from the eight mixes were observed by using Leica MZ125 Stereoscope and Quanta 200 FEG Scanning Electron Microscope (SEM).

Observations under Leica MZ125 Stereoscope

Figure 6.3.4 shows missing STR fine particle on concrete slice surface.

Figure 6.3.5 shows the interface between STR and cement mortar under MZ125 Stereoscope 100 × magnification (Mix 4). Gap between STR particle and cement paste was found on the cut slice of Mix 4 concrete.

Figure 6.3.6 shows pores on the surface of the slice.

Figure 6.3.7 shows Interface boundary between EAF slag particle and cement mortar.

Observations under Quanta 200 FEG SEM

Figure 6.3.8 presents cement paste image under 2500 × magnification on a saw-cut specimen in Quanta 200 SEM variable pressure low vacuum mode with 20 kV, spot 4.5, Bach-Scattered. Electrons were used to form image.

Figure 6.3.9 shows EAF slag surface image under 2100 × magnification in Quanta 200 SEM Variable pressure low vacuum mode with 20 kV, spot 4.5, Bach-Scattered. Electrons were used to form image.

Figure 6.3.10 points the approximate position where imagess on Figures 6.3.7, and 6.3.8 were taken.

Figures 6.3.11 and 6.3.12 show the hydrates on the interface transition zone between slag and cement (Mix 7) in 4000 × and 8000 × magnification respectively. Quanta 200 SEM Variable pressure low vacuum mode with 20 kV, spot 4.5, Bach-Scattered, and electrons were used to form image.

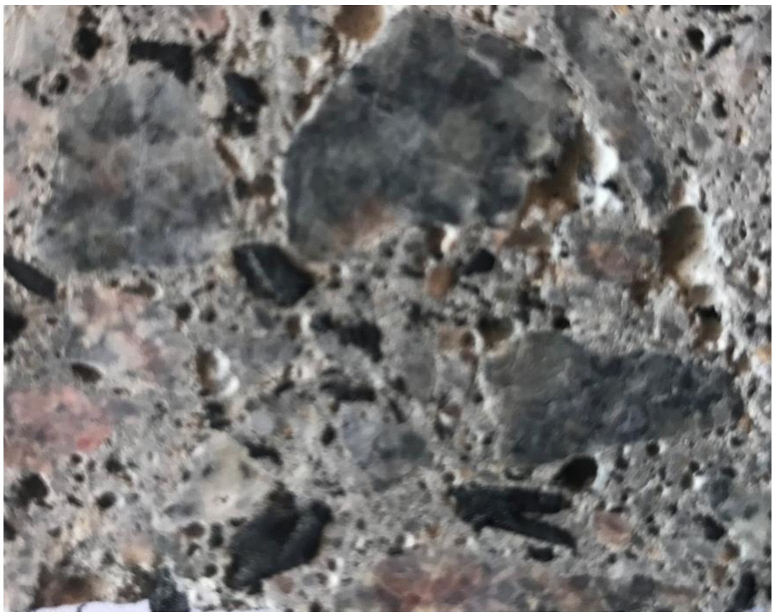


Figure 6.3.4 Missing STR Fine Aggregate Particles on Concrete Surafce

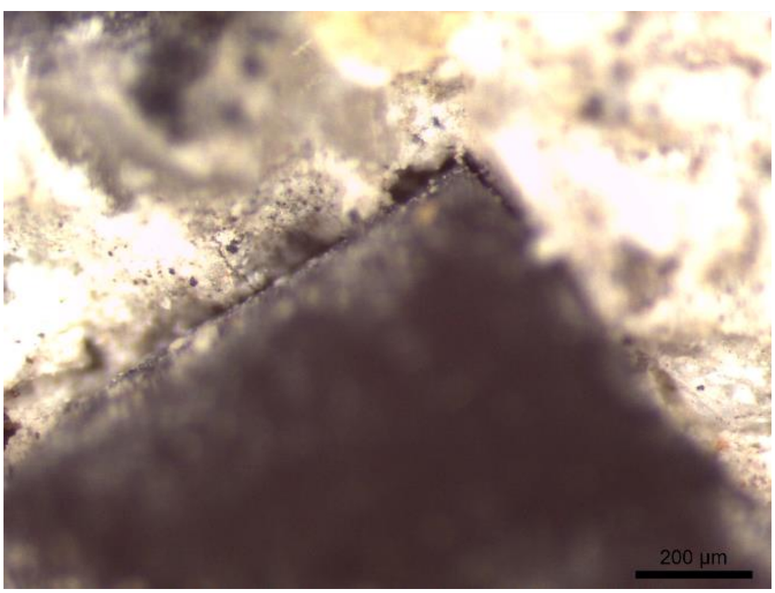


Figure 6.3.5 Interface Between STR and Mortar Leica MZ125 Stereoscope 100 ×

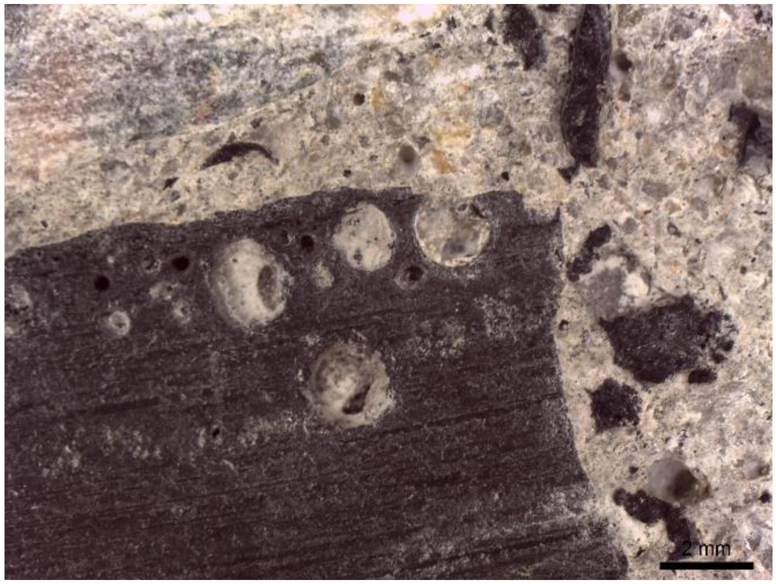


Figure 6.3.6   Pores on the Surface of the Slice, Leica MZ125 LED Lighting 8.0 ×

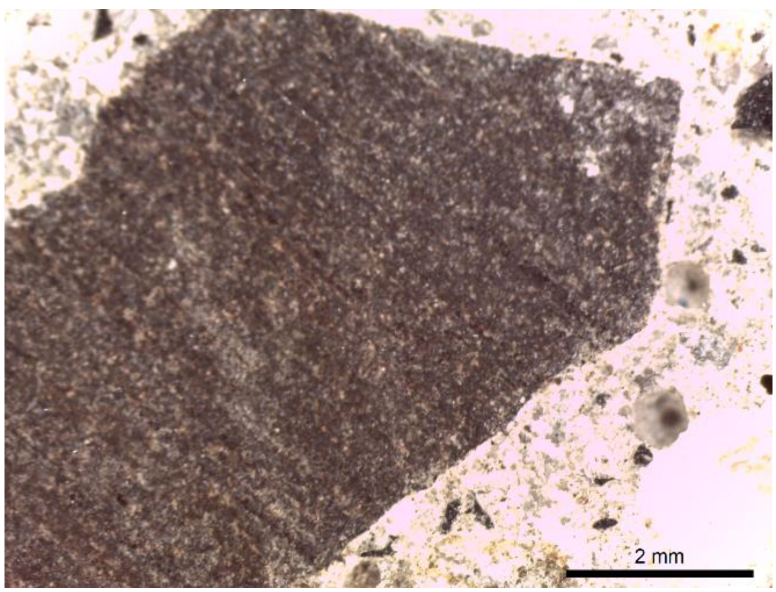


Figure 6.3.7   Interface Between EAF Slag Particle and Mortar, Leica MZ125 16.0 ×

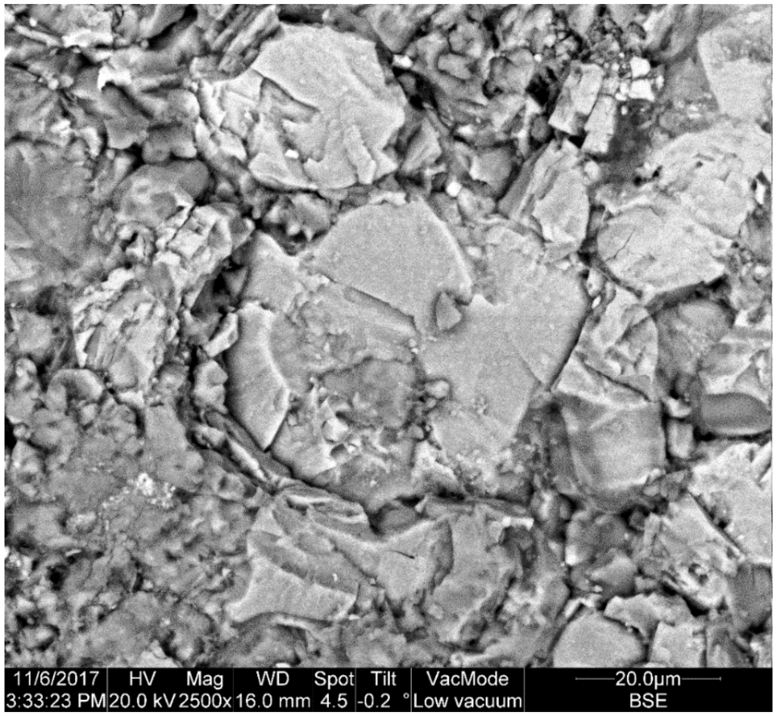


Figure 6.3.8 Cement Paste Image Under 2500 × Magnification of Cut Specimen

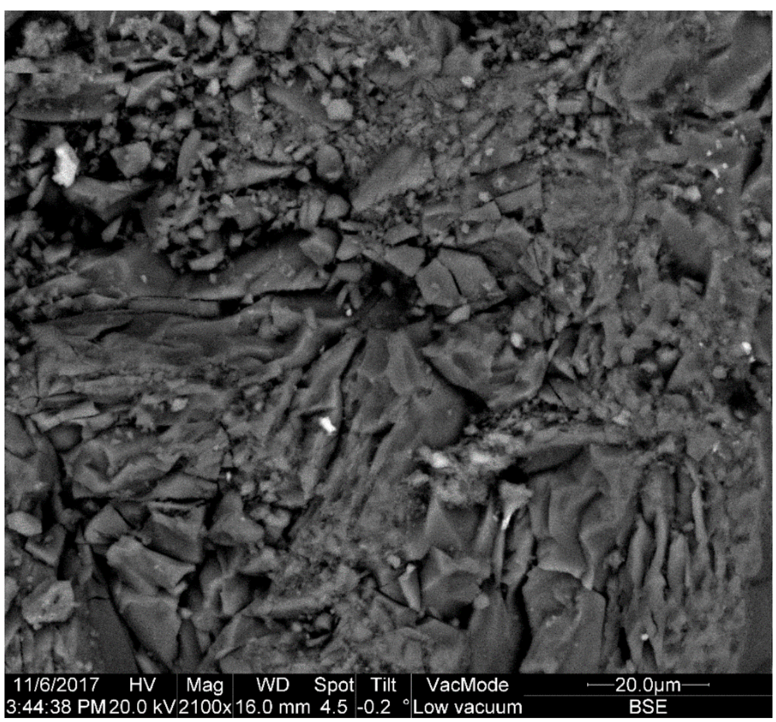


Figure 6.3.9 Image of EAF Slag Surface, 2100 ×

Figure 6.3.10 The Location Where Images 6.3.6, 6.3.7, and 6.3.8 Taken

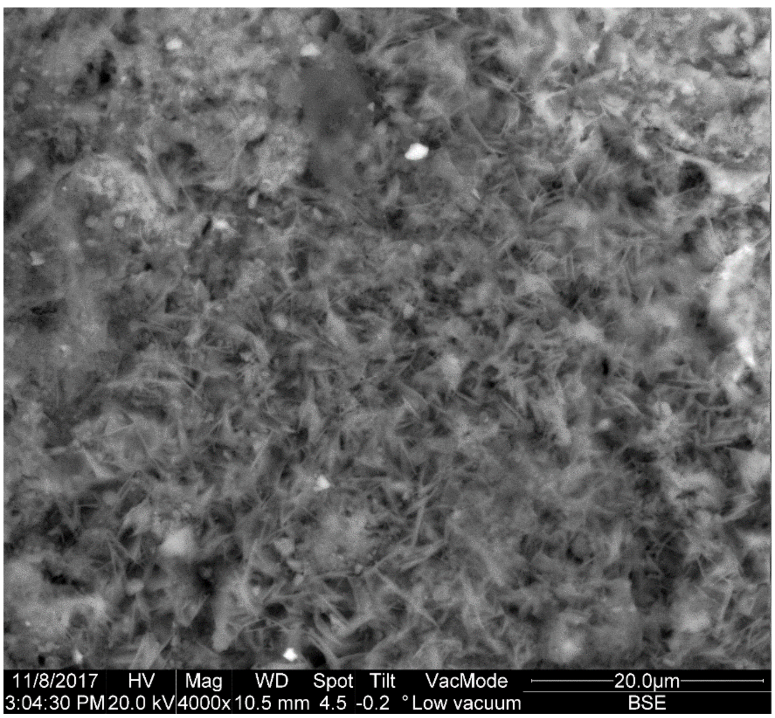


Figure 6.3.11 Hydrates on the Transition Zone Between Slag and Cement 4000 ×

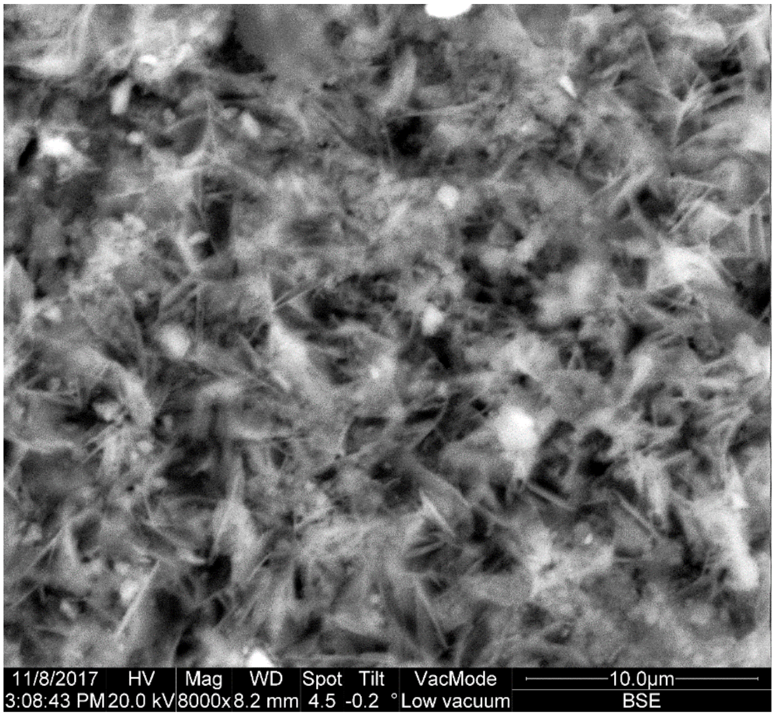


Figure 6.3.12 Hydrates on the Interface Transition Zone Slag-Cement, 8000 ×

6.3.4 Conclusions Drawn from the Pioneer Study

From the pioneer study, it was found that the EAF slag sample proposed to be used is volumetrically stable under pressure cooker treatment. Concrete slices with EAF slag with or without fine STR are volumetrically stable after pressure cooker treatment.

Compressive strength of the concrete containing EAF slag increases with the increase of the content of the slag. All mixes conform to the requirements of Class B concrete requirements. Fine STR lowers the 28-day compressive strength slightly. From Table 6.3.2, the brittleness index is reduced when EAF slag is lower and with fine STR aggregate is added.

Brittleness index which is defined as the ratio of elastic deformation energy and irreversible deformation energy. This is a proper method to measure any mechanical behavior changes in terms of the aggregate and cement mortar interface transition zone by adding nontraditional coarse aggregates.

7.0 COST ANALYSIS, ECONOMIC AND ENVIRONMENTAL BENEFITS

The use of recycled concrete aggregate as a coarse aggregate in new concrete represents an inevitable trend. This is not only because the technical feasibility exists as proved in the previous chapters in terms of laboratory testing and comparison (RCA and concrete containing RCA), also because increasing cost of dumping demolished concrete to landfilling site and increasing cost of natural aggregates. More importantly, the significance also lies in the growing concerns over the environmental impact of aggregate extraction and the continued rise in aggregate demand in Eastern North Carolina. A brief analysis on the direct cost of using RCA in nonstructural concrete and the benefit in environmental aspect are provided as follows.

7.1 Direct Cost Comparison of Concrete Containing Normal Aggregate and RCA

Cost related data were collected from the industry by interviewing ready mix concrete producers. The cost includes concrete composing materials, transportation, and landfilling cost for demolished concrete debris.

For demolished concrete landfilling, the cost is approximately $20/ton in Eastern North Carolina. The cost of natural concrete aggregate is approximately $25-$30/ton in Eastern North Carolina. The cost of RCA is in the range of $10.0 - $16.0/ton including crushing, magnetic removal, processing and moisture maintaining at concrete plant. Table 7.1.1 presents the summary of some materials' cost. The table keeps the dollar values of natural aggregate and RCA blank. Since coarse account for approximately 50% of the quantity of concrete and 20% of the total cost, by using the table and the equation provided below, the actual cost of RCA concrete and/or savings can be calculated.

Table 7.1.1 Summary of Concrete Composing Materails Cost

Materials	Cost ($)	
	Cost/Ton	Cost/lb
Type I Cement	141.42	0.07071
Fly Ash	61.20	0.03060
Ground Blast Furnace Slag	110.00	0.0550
NCDOT #67 Stone	-	-
Natural Sand	9.35	0.00468
Darex II	2.86	0.0223
Mira 85	5.86	0.0458
Recycled Concrete Aggregate	-	-

The materials cost for normal Class B concrete ranges from $55 - $65 per cubic yard. For Class B concrete the natural coarse aggregate cost accounts for approximately 25% of the total. If 50% natural coarse aggregate is replaced by RCA, savings will be obvious (10-20%) for Class B concrete.

To calculate the savings by replacing natural aggregate with RCA, the following equation is developed to estimate the approximate savings.

$$C_{SCY} = C_{CA} (T_A - T_A \times R_R) - C_{RCA} \times T_A \times R_R$$

Or, in another form:

$$C_{SCY} = C_{CA} \times T_A - T_A \times R_R (C_{CA} - C_{RCA})$$

Where:

- C_{SCY} = cost savings (actual cost after replacement of RCA) per cubic yard of concrete, \$/cy;
- T_A = total coarse aggregate in one cubic yard of concrete, ton/cy;
- C_{CA} = cost of natural aggregate, \$/ton;
- C_{RCA} = cost of recycled concrete aggregate, \$/ton;
- R_R = Replacing rate, from 0% to 100%.

By using the unit prices included in the mix design forms (see Chapter 12 Appendices, Section 12.8) the cost differences can be calculated. Using the numbers that slightly variable in Eastern North Carolina gives that if RCA is used to replace 50% of natural crushed aggregate, approximately 10% - 20% savings per cubic yard of concrete can be achieved.

7.2 Economic and Environmental Benefits

In addition to the direct costs that can be calculated based on unit prices of materials, the significant impact to natural resources and environment protection due to aggregate mining needs to be considered.

Global climate change is the critical challenge human beings are facing on Earth in the 21st century. Climate change by human activities releasing an over-abundance of greenhouse gases into the atmosphere. Construction is one of the largest industries in the world. The construction industry constitutes around one-tenth of gross domestic product worldwide. In the US, the construction industry (including aggregate and quarry operations) is a major player in the nation's economy, contributing over $1 trillion including $770.4 billion of private construction and $316.6 billion in the public sector (Wang, 2016). Construction activities consume tremendous amounts of materials, including concrete and aggregate, which are made from winning and processing natural minerals. During this process, a huge amount energy is used, and greenhouse gas emission takes place. Reuse and recycle construction materials including concrete can significantly save natural resources and contribute to sustainability in environmental, social, and economic aspects. The benefits of sustainable design and construction, materials and method selection offer the potential to change the way in which we as humans face the challenges in the future. These challenges are not insignificant.

The quarry and mining industry have been the focus of environmental and social controversy. Mining and quarry impacts are many and varied. It is not uncommon that economically valuable rocks deposits do not occur below low-value surface environments, which are sometimes located in or near ecological reserves and protected areas.

Pressures on the environment from aggregate and rock extraction, wastes generated, and related emissions have increased because quarry activities have generally moved from small or rural areas to large surface and densely populated areas. In terms of emissions, the quarry and mining industry is not unlike other industries, easily accessible rock reserves diminish over time; consequently, quarry and mining projects often last only 20-40 years, although occasionally longer.

Pollution occurs due to extracted and processed aggregate, as does altered physical-chemical conditions at the quarry site. Societies can respond to mining or quarry-induced changes in a variety of ways. One is the reduction of demand for natural aggregates through substitution of traditional materials with recycled ones. Demand can be further reduced by product recycling; by reworking of various “wastes” as secondary resources; and by use of material efficient technologies. Although necessarily long term, ultimately such measures can relieve pressure on the environment.

In the cement industry, a large percentage of the weight of limestone is released as CO_2. In addition to CO_2 release and energy use, mining of limestone and other minerals, the major raw material in cement, or aggregate can cause habitat destruction, increased runoff, and pollutant release to the air and water. Some limestone mining operations are abandoning open-pit mining techniques in favor of underground mining. This technique may reduce some habitat and pollution impacts yet may increase cost.

Also, the production of cement is an energy-intensive process using primarily fossil fuel sources. Cement comprises about 10% of a typical concrete mix but accounts for 92% of its energy demand. An average of almost 5 million BTUs is used per ton of clinker. In 2004, the cement sector consumed 422 trillion BTUs of energy, almost 2% of total energy consumption by US manufacturing. Emissions from portland cement manufacturing include carbon dioxide (CO_2), particulate matter, carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NOx), total hydrocarbons and hydrogen chloride (HCl), and fine particles of PM2.5 (particulate matter with a diameter less than or equal to 2.5 μm) are the greatest cause for concern as they have the greatest negative impact on human health.

Aggregates, which make up between 60% and 75% of the concrete volume, are either mined or manufactured. The primary impacts of aggregate extraction and processing are habitat alteration and fugitive dust. It is difficult to capture dust in operations of mining and blasting, quarry roads, loading and unloading, crushing, screening, and storage piles. Primary impacts of crushed rock, aside from mining impacts, stem from fugitive dust released during crushing and screening operations. Processing of aggregates, particularly the commonly used silica sand, releases particulates into the air that can cause eye and respiratory tract irritations in humans.

Mining, dredging, and extraction of sand and gravel alter plant and animal habitats and contribute to soil erosion and air and water pollution. Mining for sand and gravel near or in water bodies causes sedimentation and pollution in water and disrupts aquatic habitats. The operation of mining equipment consumes energy and releases emissions from internal combustion engines. Energy to produce coarse and fine aggregates from crushed rock is estimated by the Portland Cement Association's Life Cycle Inventory to be 35,440 kJ per ton. The energy to produce coarse and fine aggregate from uncrushed aggregate is 23,190 kJ per ton.

The concept of sustainability has gained popular momentum over the last 20 years. The goals of sustainability are to enable all people to meet their basic needs and improve their quality of life, while ensuring that the natural systems, resources, and diversity upon which they depend are maintained and enhanced, for both their benefit and that of future generations. There exists a significant opportunity to mitigate environmental problems associated with construction activities while contributing to a high quality of life for the society. The construction industry is beginning to adopt the concept of sustainability in all construction activities including using RCA in transportation infrastructure construction.

Use of RCA can contribute to environmental sustainability, and to economic sustainability and social sustainability indirectly.

Recycled RCA, along with others such as and slags, pulverized rubber tires, and other post-industrial recycled materials that serve as nonconventional materials for construction applications can provide and maximize both technical benefit and economic and environmental benefit.

8.0 CONCLUSIONS

This research has investigated the feasibility of using crushed and processed recycled concrete aggregate in making nonstructural concrete (Class B). Based on the project's requirements, a thorough literature review, survey to state highway agencies, ready mix concrete suppliers, and construction companies, three bridge demolition projects were selected. The concrete slabs were transported to processing plant, crushed, and processed. Recycle concrete aggregates were sampled and tested. Concrete mix designs were conducted for 0%, 15%, 30%, 50% and 100% RCA replacement. The strength results and other properties of the RCA concrete conform to the research results obtained previously by other researchers. The results indicate that the coarse recycled concrete aggregate processed in Eastern North Carolina can be used to make Class B concrete, and there are potential economic benefits if the recycled concrete aggregate is used in this region.

From this study, it is proved that the recycled concrete aggregate from three NCDOT Divisions is a good aggregate material after proper processing, including slab removing, crushing, sieving, which can be used in similar situations as virgin natural aggregate. RCA possesses different properties from natural aggregate, mainly because the resultant crushed material is composed of both original natural aggregate and reclaimed mortar, which may affect the properties and behavior of concrete produced with RCA, specific steps may be needed to be taken in the design and construction process.

8.1 Candidate Concrete Bridge Selection and RCA Processing

The typical bridge demolition projects in ENC are suitable for recycled concrete aggregate processing. The results have indicated that the RCA properties obtained from the three bridges selected for this project are very similar in terms of unit weight, absorption value, LA abrasion value, fine particles generated. As the main contaminated or impurity materials come from the stockpiling and processing stage, all candidate bridges and concrete structure should be marked and stockpiled separately for concrete RCA processing if used as an aggregate in concrete.

8.2 The Properties of Processed RCA

The crushed RCA contains 39% to 49% of fine particle passing #4 sieve. This is typical for RCA undergone jaw crushing. The impurities is below 0.3%. From observation, the impurities come from storage and processing stage not from the concrete slabs.

The gradation by NCDOT can be met if sieving control is maintained. The gradation control is necessary to ensure the final product to meet the graduation requirements of the coarse aggregates.

8.3 Fresh RCA Concrete and Strength Related Properties

8.3.1 Mix Design

It is proved that the conventional mix design method can be used for concrete incorporating RCA. As usual, bulk specific gravity and absorption values of RCA must be carefully measured and included in the composing material calculation.

Although the research plan was to investigate the practicality of using up to 50% RCA to replace natural concrete, the mixes of 100% of RCA was also conducted to verify the strength development trend and other factors which can be used to determine the optimal content of RCA and RCA properties.

All the design parameters required by NCDOT Specifications for Class B concrete are generally met. Minor adjustment will not affect the strength and other major properties of fresh and hardened concrete. Water reducer was slightly adjusted due to the high void ratio and absorption value of the RCA aggregate.

8.3.2 Fresh Concrete

Residual adhered mortar on aggregate is the major factor that influences the density, porosity, and water absorption of RCA, therefor the RCA concrete. It is found that the unit weight of concrete containing RCA decreases by 8.7% from control mix to 100% RCA mix. The unit weight reduction is mainly because the bulk relative density of RCA is approximately 7-9% lower than that of natural aggregate. The residual mortar in RCA with higher pore ratio causes the lower density of RCA.

When 20% and 50% EAF slag were added to replace the RCA, unit weight increased from 134.8 pcf to 137.3 pcf and 143.3 pcf respectively, comparing the control mix with 147.7 pcf of unit weight. This indicates that by using two recycled materials (RCA and EAF slag) the concrete strength can be higher than ordinary concrete or RCA concrete, and the density can be similar to or lower than ordinary concrete.

Slump test results indicate that the workability is consistent in 3.5 inch to 4.5 inch[6] with approximately adjusted content of water reducer. This range indicates that the concrete with RCA coarse aggregate meets the workability requirements by NCDOT Specifications (2018) for Class B concrete, with or without adjustment of water reducer (Table 1000-1 of NCDOT Specifications (2018) specifies 2.5 inch for vibrated concrete and 4.0 inch for non-vibrated concrete).

[6] Except for the mix with 30% RCA. There might be a system error occurred in the mixing process for 30% RCA mix.

The slump tests for concrete with 20% and 50% of RCA replaced with EAF slag, the slum values are 5.8 and 6.0 inch, respectively.

Air contents test results for RCA concrete containing 15% to 100% RCA range from 4.5% to 5.5%. The results indicate that the air content generally meet the requirements by NCDOT Specifications for Class B concrete, with or without minor adjustment of air entraining agent. Table 1000-1 of NCDOT Specifications (2008) specifies 0.488 for rounded aggregate and 0.567 for angular aggregate for Class B concrete.

Similar to RCA concrete, when 20% and 50% of RCA are replaced with EAF slag, the air content is 5.3% and 4.3% for 20% replacement and 50% replacement, respectively.

From the properties of unit weigh, slump, and air content test results, the concrete mixes containing RCA and with EAF slag can be satisfactory in terms of workability, durability requirement by using sump values and entrained air content criteria.

8.3.3 Strength Related Properties

All concrete specimens with RCA and EAF slag were tested at 7-day, 28-day, and 90-day of age. In general the results show that all RCA concrete mixes overwhelmingly surpass the requirement for Class B concrete (2,500 psi at 28-day).

The minimum strength reached at 7-day is 3,168 psi (20% slag + 80% RCA). Strength gains up to 14% at 90-days.

Strength decreases with the increased content of RCA aggregates at 7-day, 28-day and 90-day of age. All the mixes including the mixes containing RCA and RCA with EAF slag replacement gained the strength at 7-day for Class B, i.e., 2,500 psi at 28-day.

All the mixes including the mixes containing RCA and RCA with EAF replacement meet the strength requirements for Class A concrete at 28-day (3,000 psi at 28-day). By replacing 20% and 50% of RCA by steel slag aggregate, strength increases at 7-day, 28-day and 90-day of age;

Strength decreases at 28-day strength with the increase of the RCA content, from 5.4%-20.1%. The strength increases when RCA is replaced with EAF slag.

8.4 Findings from the Pioneer Study

Shredded scrap tire rubber (STR) and EAF slag were used in the pioneer study. Steel slag possesses higher unit weight which has been an inhibitor in use in concrete even it provides higher strength. STR has lighter unit weight, with elastic characteristic, but lower strength. The results in the pioneer study show the blending use of the two recycled materials with

RCA can balance the disadvantages and enhance their advantages. This result encourages the idea of *blending use* of multiple recycled materials in future research.

8.5 Engineering and Cost Analyses

Brittleness index was introduced to evaluate the boundary or interface transition zone between aggregate and cement mortar. Results show that brittleness index is slightly increased with the RCA increase. The same trend is found with EAF slag and RCA concrete. The changes is not significant, but it is interesting. It is necessary to further investigate to see if it relates to other long-term properties, such as durability or creep.

Observation under Stereoscope and SEM indicate that the hydrate products are generated between cement mortar and steel slag. It indicates that slag processes hydraulic characteristics which can enhance the bond strength between aggregate and cement mortar while natural rock is chemically inert. This can explain the strength increase by adding EAF slag with RCA in concrete.

From cost analysis, it is obvious that the direct cost of concrete with RCA will be lower in approximately in the range of 10-20%, compared with normal concrete. Because using RCA to replace natural aggregate, which makes up approximately 70% of concrete volume, environmental and natural resource conservation benefit will be significant.

9.0 RECOMMENDATIONS

Currently more than 140 million tons of RCA are produced each year in the US. The quantity is increasing as the nation's civil infrastructures are becoming aged and being reconstructed. The North Carolina State Transportation Improvement Program (STIP) for 2016-2025 stipulates the requirements for approximate 150 bridge replacement and 700 miles of road construction projects in the 28 counties under NCDOT Divisions 1, 2 and 3. A huge amount of concrete debris will be generated, and a large quantity of new concrete will be needed including nonstructural concrete. However, good quality concrete aggregate is not economically available in this region. It is important to investigate the feasibility of RCA using as coarse aggregate in non-structural concrete construction for suitable projects in the next ten years and beyond.

In this study three typical bridge replacement projects from NCDOT Divisions 1, 2, and 3 were selected. The concrete slabs were processed to coarse aggregate to the NCDOT standards for Class B concrete, and a series of conventional and special laboratory tests for RCA, fresh and hardened concrete containing natural aggregate (granite), RCA, steel slag, were conducted. The results are promising and will benefit the bridge and road construction projects, and the sustainable development in Eastern North Carolina - one of the fastest growing regions in the State of North Carolina.

9.1 General Recommendations

It has been proved that it is feasible to use RCA in nonstructural concrete and RCA should be considered an alternative aggregate for Class B concrete construction for NCDOT projects in ENC. The results from this study can be developed and transferred to NCDOT divisions and personnel. The information in this report can be developed into as a training material for Engineers in Divisions 1, 2, and 3.

9.2 Future Research

This laboratory evaluation covers conventional tests for aggregate and concrete. The focus of this study has been placed on the RCA aggregate and concrete testing. The durability and mechanical properties of the concrete containing RCA should be evaluated in the future research. By using traditional tests for specification and acceptance, slump, air content, and compressive strength, for instance, the goal of comprehensive utilization of various recycled materials cannot be reached. This study has performed some special tests, including elastic and plastic energy during cyclic loading (brittleness index), autoclave test for expansive-prone steel slag, and microscope level observation on concrete slices especially the interfacing transition zone between coarse aggregate and cement paste, 90-day strength and stability of concrete containing RCA and EAF slag. Some laboratory tests are necessary in future study, for example, creep of RCA concrete, resistivity, shrinkage, and super air meter test. All these can be conducted to investigate long service life expectation purposes.

Performance engineered mixtures (PEM) should also be considered in RCA concrete or concrete containing recycled materials. This includes optimized mixture designs, materials selection, gradation, cement content. This could provide improved durability and sustainability. It was found the strength criteria were well met 28-day strength at 7-day, with 100% RCA coarse aggregate. It indicates that there is a necessity to evaluate the design and field performance or RCA concrete to have relevant data collected, and design and preference evaluation parameters modified.

It is potential to expand the use of recycled materials or blending use of multiple recycled materials in concrete to enhance durability and sustainability of concrete. Steel slag and processed tire rubber were used in the pioneer study for initial investigation.

Multiple recycled material use in concrete is promising. For example, over 300 million scrap tires are generated each year in the US. In North Carolina, whole tires are banned from landfills. Waste tires have been environmental and financial issues. Ground tire rubber (GTR) use in road paving is successful, however, the utilization rate is low. To control the problems created by waste tires, governments have spent a large amount of money to remove, transport, store, and dispose the scrap tires. A better approach dealing with waste tires will find innovative and profitable uses and motivate business to collect and process them for their own self-interest and create multiple win–win situations. With blending use of slag and processed STR, concrete properties can be modified.

Blending use development - Blending use refer to one recycled material, RCA, for instance, with one or more other recycled material(s) to modify and enhance concrete properties and performance of the end product. Sustainability requires researchers to proactively respond to growing environmental concerns and natural resource shortages. The infrastructure construction industry consumes huge amounts of natural resources. A wide range of environmentally acceptable, technically sound, and economically viable uses for recycled materials and to transfer various “waste” streams, into useful material “resource” streams are needed.

Blending use is an innovative way to fully utilize solid recycled materials. Inhibiting factors exist for users and the public in recycled material utilization. These factors may come from the following: inherent variability, liability concerns for innovative technology, inappropriate environmental constraints, user conservatism, obsolete specifications, and lack of technical guidance.

Of these factors, only the last one is technically related (i.e., lack of technical guidance). Any restrictions that prohibit the use of recycled materials without technical basis should be removed. The questions facing researchers are what is the technical basis? How to develop the technical basis? Quantifying the properties, developing usability criteria, and developing the optimum proportions of multiple recycled materials can answer these questions and therefore enhance the properties of the concrete.

The probabilities and ultimate goals of the blending use can be asked by these questions: Can

$$1 + 1 > 2 ; \quad 1 + 1 = 1; \quad 1 + 1 = 0?$$

This is to solve the problem in the use of recycled materials:

1 Advantage + Advantage > 2 Advantage

1 Advantage + Disadvantage = 1 Advantage

1 Disadvantage + Disadvantage = 0 Disadvantage

Because the inherent properties of various materials vary, the right combination of them can create better composite end materials than by using a single material. Therefore, the goal of blending use is to minimize the disadvantages of each individual recycled material and maximize the advantages of the recycled and end products produced. From a RCA use point of view, we need to "marry" RCA with one or more recycled material to maximize the technical and economic benefits.

For example, steel slag possesses excellent mechanical properties. Its Los Angeles abrasion value and polish stone value are high. However, its specific gravity can be as high as 2.38-2.76 and its unit weight as low as 72-90 lb cf. (1,153–1,442 kg/m^3). Steel slag may contain free lime and periclase that could cause volume instability, and aging and treating are needed. High specific gravity has limited the use of slag in areas far from the source site.

However, the specific gravity of processed STR is much lower, in the range of 1.02–1.20, with higher void ratio. Without blending use with other materials, STR provides limited strength.

Considering use of slag and STR simultaneously, by adding 5–10% of scrap rubber, the specific gravity can be lowered to natural aggregate in approximately 2.5; by selecting optimum sizes, the void ratio of the blended material can be increased. The elastic nature of rubber would allow certain expanded volume in steel slag to be absorbed if used as unbound applications.

9.3 Specification Modification

The designated resources for aggregates for concrete can be extended to recycled concrete aggregate as a coarse aggregate in Class B concrete.

It is recommended that the following paragraph be added for crushed concrete use in Class B concrete in the NCDOT Specification Section 1014 – Aggregate for Portland Cement Concrete 1014-2 Coarse Aggregate (A) General Paragraph 2, as follows (in italic):

Use coarse aggregate that consist of crushed stone, crushed or uncrushed gravel, crushed air-cooled blast furnace slag, or other inert materials that have similar characteristics.

Crushed concrete aggregate can be used as a coarse aggregate in Class B concrete if the subject material meet all requirements in 1014-2 (A) through (E), or permitted by the Engineer in writing.

10.0 IMPLEMENTATION AND TECHNOLOGY TRANSFER

During the research period the team leader and PI, Dr. George Wang:

Visited the NCDOT Division 1 Office in Elizabeth City, NC, and interacted with Mr. David Otts, Mr. Shawn Mebane (in June 2017); Visited the project site in Moyock, NC (June 2017).

Visited the NCDOT Division 2 Office in Greenville, NC and interacted with Mr. Ed Eatmon, Ms. Maria Rogerson (June 2007), and NCDOT Division 2 Office in Kinston, NC, and interacted with Mr. Jeremy Stoud (in November 2018); visited the project site in Beaufort County (June 2017).

Visited the NCDOT Division 3 project site in Salemburg, NC and interacted with Mr. Nathan Tew, and Kevin Bowen (June 2017).

Attended TRB 2017 and 2018 winter meeting; ADC 60 Meeting; presented a paper, titled, Use Recycled Concrete Aggregate as an Aggregate in Concrete – A Global Review and Current Status in the United States (TRB18-00275).

10.1 Research Products

The research project has produced research products in four major areas: (i) obtained the properties of RCA that was processed from the demolished concrete slab from NCDOT Divisions 1, 2, and 3; (ii) Concrete mix design method, properties of fresh concrete and hardened concrete were obtained; (iii) special properties including RCA's potential alkali-silica reaction, RCA concrete's rapid chloride penetration, brittleness index were obtained; (iv) in the pioneer study of the project, EAF slag, processed scrap tire rubber were tested and used in concrete.

The research products also include a thorough literature review report, literature abstract compilation report, a detailed survey responses, engineering and economic analyses.

10.2 Research Product Users and Applications

The following groups within the NCDOT can apply the research results and products to inform and improve their decisions and policies: Materials and Tests Unit, Construction Unit, and Division and District Engineers. Other groups including ready mix concrete producers, construction companies in North Carolina can used the report as a reference in future effort using RCA in concrete.

Materials and Tests Unit of NCDOT have new reference information and basic information for guidelines to use RCA in nonstructural concrete in Eastern North Carolina. Division and District Resident Engineers will have the guidelines in quality assurance for concrete construction. Contractors and concrete producers will have alternative aggregate sources for nonstructural concrete in East North Carolina.

The NCDOT can use the information to determine the best suitable projects for RCA processing and use as coarse aggregate in nonstructural concrete as an immediate benefit to the projects in the State Transpiration Improvement Plan (STIP). Ultimately, the collected information from the research can be used to develop RCA in other regions in North Carolina in lieu of virgin aggregate. NCDOT can use the data and all technical information of the research study for publication, presentation, and training purposes.

The information in the report can be developed into training materials, or for a workshop, including PowerPoint presentation, addressing the processing, mix design, and concrete batching. The workshop is intended as an initial implementation strategy to help users and agencies advance the routine use of RCA in nonstructural concrete and overcome any barriers encountered.

The information in the report will also give the guidelines for design of nonstructural elements for new pavement projects and rehabilitation projects and guidelines for estimating cost based on the quantitative comparison data.

In addition, the research products can be useful to other departments of transportation, the FHWA, and consultants who are interested in the areas of utilization of recycled materials in concrete and pavements construction. The research products can be interesting to national and international researchers and government agencies.

The significance of this study also includes providing the NCDOT with RCA concrete for comparison with similar results from other states, and for inclusion in a nationwide RCA use in concrete for future comprehensive research.

This study involves a pioneer study including potential recycled materials available in ENC that may be used in future research to develop sustainable concrete materials. The NCDOT can further use the information to determine the best suitable candidate concrete structure demolition project for RCA processing and use in construction. The NCDOT can use the data and all technical information of the research study for publication, presentation, and training purposes.

The research will lead up to the results in implementing the practical use of RCA in concrete: the technical feasibility and the financial benefit for all parties who are involved in the transportation development projects and the citizens in Eastern North Carolina.

11.0 CITED REFERENCES

ACI. (2001). Removal and reuse of hardened concrete. American Concrete Institute (ACI) Report. Detroit, MI, 2001.

Adnan, H.S., Loon, Y.L., Rahman, A.I., Saman, M.H., & Soejos, V.M. (2007). Compressive strength of recycled aggregate concrete with various percentage of recycled aggregate. *Proceedings of National Seminar on Civil Engineering Research* 2007, Skudai.

Ali, S., Zia, U. R., Qasim, K., Shah, R., & Ziad, K. (2014). Performance evaluation of recycled aggregate concrete. *The 1st International Conference on Emerging Trends in Engineering, Management and Sciences*, December 28-30, 2014 (ICETEMS-2014), Peshawar, Pakistan.

Anuar, K.A., Ridzuan, A.R.M., & Ismail S. (2011). Strength characteristic of geopolymer concrete containing recycled concrete aggregate. *International Journal of Civil & Environmental Engineering* (IJCEE-IJENS), 11(1), 81-85.

Arribas, I., Santamaria, A., Ruiz, E., Ortega-Lopez, V., and Manso, J.M. (2015). Electric arc furnace slag and its use in hydraulic concrete. *Construction and Building Materials*, 2015. 90, 68–79.

Breccolotti, M., D'Alessandro, A., Roscini, F., & Bonfigli, F.M. (2015). Investigation of stress-strain behavior of recycled aggregate concrete under cyclic loads. *Environmental Engineering and Management Journal*, 14 (7), 1543-1552.

Caggiano, A., Faella, C., Martinelli, E., Mele, M., Pasqualini, A., Realfonzo, R., & Valente, M. (2012). Mechanical behavior of concrete with recycled aggregate. *Proceedings of the 19th Congress C.T.E.*, Bologna, 8-10 November 2012.

Cavalline, T. (2016). Quantifying the sustainability benefits of concrete pavement recycling. Tech Brief of National Concrete Pavement Technology Center.

CDRA (2018). Recycled Concrete Aggregate Ready Mix Used in Structural Applications. Construction and Demolition Recycling Association (CDRA). http://www.cdrecycling.org/index.php?option=com_content&view=article&id=71:case-histories&catid=20:site-content&Itemid=151. Accessed July. 5, 2018.

Chen, H.J., Yen, T., & Chen, K.H. (2003). Use of building rubbles as recycled aggregates. *Cement and Concrete Research*, 33(2003), 125-132.

Dabhade, A.N., Chaudari, S.R., & Gajbhaye, A.R. (2014). Effect of fly ash on recycle coarse aggregate concrete. *International Journal of Civil Engineering Research*, 5(1), 35-42.

Deshpande, N.K., Kulkarni, S.S., & Pachpande, H. (2012). Strength characteristics of concrete with recycled aggregates and artificial sand, 2(5), 38-42, India.

Eguchi, K., Teranishi, K., Nakagome, A., Kishimoto, H., Shinozaki, K., & Narikawa M. (2007). Application of recycled coarse aggregate by mixture to concrete construction. *Construction and Building Materials*, 21(2007), 1542-1661.

Etxeberria, M., Vazquez, E., Mari, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37(2007), 735-742.

Fronek, B., Bosela, P., and Delatte, N. (2012). Steel slag aggregate used in portland cement concrete U.S. and international perspectives. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2267, 37-42.

Ganiron, T.U. (2015). Recycling concrete debris from construction and demolition waste. *International Journal of Advanced Science and Technology*, 77(2015), 7-24.

Hansen, T.C., & Narud, H. (1983). Strength of recycled concrete made from crushed concrete coarse aggregate. *Concrete International*, 1(1983), 79-83.

Hashim, S.A.H. (2013). Display the results of some researcher about the use of recycled aggregate in new concrete. *International Journal of Science and Research*, 4(9), 1340-1345.

Hawkins, R., & Brown, B. (2010). Recycle aggregates green solution, smart choices. *ASCE Green Streets and Highways Conference*, November 14 - 17, 2010 at the Renaissance Denver Hotel, Denver, CO. Yehualaw, M.D., & Woldesenber, A.K. (2016).

Hole, M.D.S. (2013). Used concrete recycled as aggregate for new concrete. Bachelor thesis, Universitat Politecnica de Valencia.

Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research*, 33(2003), 703-711.

Kim, Y., Sim, J., & Park, C. (2012). Mechanical properties of recycled aggregate concrete with deformed steel re-bar. *Journal of Marine Science and Technology*, 20(3), 274-280.

Kuosa, H. (2012). Reuse of recycled aggregates and other C&D wastes. VTT-R-05984-12.

Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability,* 2010 (2), 1204-1225.

McNeil, K., Thomas H.K., & Kang, T.H.K. (2013). Recycled concrete aggregates: a review. *International Journal of Concrete Structures and Materials*, 7(1), 61–69.

Manzi, S., Mazzotti, C., & Bignozzi, M.C. (2013a). Effect of adhered mortar of recycled concrete aggregates on long-term concrete properties. *3rd International Conference on Sustainable Construction Materials and Technologies*, August 18 – August 21 2013, Kyoto Research Park, Kyoto, Japan.

Manzi, S., Mazzotti, C., Bignozzi, M.C. (2013b). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement & Concrete Composites*, 37 (2013), 312–318.

Murali, G., Vardhan, C.M.V., Rajan, G., Janani, G.J., Jajan, S.N., & Sri, R.R. (2012). Experimental study on recycled aggregate concrete. *International Journal of Engineering Research and Applications (IJERA*). 2(2).

Nelson, S.C. (2004). High-Strength Structural Concrete with Recycled Aggregates. Ph.D. Dissertation. University of Southern Queensland.

Parekh, D.N., & Modhera, C.D. (2011). Assessment of recycled aggregate concrete. *Journal of Engineering Research and Studies*. E-ISSN0976-7916.

Pečur, I.B., Štirmer, N., Milovanović, B., Carević, I., & Alagušić, M. (2014). Energy efficiency aspects of recycled aggregate concrete. *International Symposium on Eco-Crete*, Reykjavik, Iceland, August 2014.

Qasrawi, H. (2014). The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment. *Construction and Building Material*s, 54(2014), 298-304.

Rahman, I.A., Hamdam, H., & Zaidi, A.M.A. (2009). Assessment of recycled aggregate concrete. *Modern Applied Science*, 3(1), 47-53.

Ravindrarajah, R.S., & Tam, C.T. (1985). Properties of concrete made with crushed concrete as coarse aggregate. *Magazine of Concrete Research*, 37(130), 29-38.

Richardson, A.E., Coventry, K., & Graham, S. (2009). Concrete manufacture with un-graded recycled aggregates. Structural Survey, 27(1), 62 – 70. http://dx.doi.org/10.1108/02630800910941692

Sakai, K. (2009). Recycling concrete – The present state and future perspective. TCG-JSCE Joint Seminar. PowerPoint presentation. November 20, Athens.

Snyder, M.B. (2016). Introduction to concrete recycling. Tech Brief of National Concrete Pavement Technology Center.

TxDOT. (1998). Recycled concrete aggregates in Portland cement pavement. http://www.txdot.gov/inside-txdot/forms-publications/consultants-contractors/publications/recycling.html#2

TxDOT. (2008). Recycled concrete aggregates make cents. TxDOT Published as needed by the Construction and Bridge Divisions.

Topçu, I.B., & Şengel, S. (2004). Properties of concretes produced with waste concrete aggregate. *Cement and Concrete Research*, 34(2004), 1307-1312.

Van Dam, T., Harvey, J.T., Muench, S.T., Smith, K.D., Snyder, M.B., Al-Qadi, I.L., Ozer, H., Meier, J., Ram, P.V., Roesler, J.R., and Kendall A. (2015). Towards Sustainable Pavement Systems: A Reference Document. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC.

Wang, G. (2010). Determination of the expansion force of coarse steel slag aggregate. *Construction and Building Materials*, 2010. 24, 1961–1966.

Wang, G. (2016). *The Utilization of Slag in Civil Infrastructure Construction*. Elsevier, London, UK, 2016.

Wijayasundara, M., Mendis, P., Zhang, L., & Sofi, M. (2016). Financial assessment of manufacturing recycled aggregate concrete in ready-mix concrete. *Resources, Conservation and Recycling,* 109 (2016), 187–201.

Yaprak, H., Aruntas, H.Y., Demir, I., Simsek, O., Durmus, G. (2011). Effects of the fine recycled concrete aggregates on the concrete properties. *International Journal of the Physical Sciences*, 6(10), 2455-2461.

12.0 APPENDICES

The appendices for this project are included with the electronic copy of the report located at this web link:

http://www.ncdot.org/doh/

12 APPENDICES

By

George Wang, Ph.D., P.Eng., F.ASCE, Professor
Donna Hollar, Ph.D., P.E., M.ASCE, Associate Professor
At
The Department of Construction Management
The College of Engineering and Technology
East Carolina University
Greenville, North Carolina

And

Robert Poole, Quality Control Manager
At
S.T. Wooten Corporation
Garner, North Carolina

<u>Appendices of the Final Report</u>

Project: RP2017-06

December 2018

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

12.1 Compilation of Abstracts related to the Use of RCA

ACI (2001). Removal and reuse of hardened concrete. American Concrete Institute (ACI) Report, 555R-01.

This report presents information on removal and reuse of hardened concrete. Guidance for assessment of concrete structures for complete or partial demolition is provided. The applicability, advantages, limitations, and safety considerations of various types of concrete removal methods, including hand tools, hand-operated power tools, vehicle-mounted equipment, explosive blasting, drills and saws, nonexplosive demolition agents, mechanical splitters, heating and thermal tools, and hydrodemolition (water-jet blasting), are provided. The available surface removal systems, their probable applications and advantages and disadvantages of various types of surface removal systems are discussed. Consideration for evaluating and processing waste concrete for production of aggregate suitable for reuses in concrete construction are presented.

ACPA. (1998). Rubblization of concrete pavements: A Discussion of its use. American Concrete Pavement Association.

Public agencies have been misusing rubblization and an asphalt overlay of concrete slabs as a rehabilitation technique for the last 10 to 15 years. It has been misused because most of the pavements that have been rubblized did not need rubblization. In most situations, either concrete pavement restoration (CPR) or a concrete overlay is a more appropriate and economical rehabilitation procedure. These procedures directly address why a concrete pavement is deteriorating and minimize further deterioration.

Rubblization is a destructive procedure that breaks an existing concrete slab into small fragments. This destroys the structural integrity of the pavement and reduces its load carrying capacity. Unlike CPR or concrete overlays, rubblization does not address the cause of the existing pavement deterioration and sometimes it can exacerbate the problem. For example, many concrete distresses are a result of poor support conditions. Rubblizing a pavement destroys the concrete slab’s natural bridging action, causing the problems to become more pronounced. This can and has caused early failure of the asphalt overlay.

The only appropriate time to rubblize an existing concrete pavement is when it has severe material durability problems, such as alkali-silica reactivity (ASR), D-cracking, or freeze-thaw damage. These material problems cause the concrete pavement to deteriorate and lose its structural integrity.

Adnan, S.H., Lee, Y.L., Rahman, I.A., Saman, H.M., & Soejoso, M.W. (2007). Compressive strength of recycled aggregate concrete with various percentage of recycled aggregate. Proceedings of National Seminar on Civil Engineering Research 2007, Universiti Teknologi Malaysia, Skudai.

Compressive strength is the basic mechanical properties and one of the indicators to determine the performance of a concrete. In this paper, the effects of various percentages (0%, 25%, 50%, 75%, 100%) of Recycled Aggregate (RA) on compressive strength of Recycled Aggregate Concrete (RAC) were investigated. RA is used to replace natural aggregate (NA) as coarse aggregate in concrete mixes. This research also covered RAC mixtures at different water-cement ratio (0.4, 0.5, 0.6). It was found that RAC had lower compressive strength compared to Natural Aggregate Concrete (NAC). At the age of 28 days, RAC with water-cement ratio of 0.4 had the highest strength.

Ali, S., Zia, U.R., Qasim, K., Shah, R., & Ziad, K. (2014). Performance evaluation of recycled aggregate concrete. The 1st International Conference on Emerging Trends in Engineering, Management and Sciences, December 28-30, 2014 (ICETEMS-2014), Peshawar, Pakistan.

Recycled aggregates are comprised of crushed, graded inorganic particles processed from the materials that have been used in the constructions and demolition debris. The aim for this research was to determine the performance of recycled aggregate in the structural concrete giving a better understanding on the properties of concrete with recycled aggregates, as an alternative material to coarse aggregate in structural concrete. The investigation was carried out using workability test, compressive test and indirect tensile Test.

Test Samples were prepared from the virgin aggregate and workability test, compressive test and indirect tensile test were performed. After testing, samples were recycled to obtain recycled aggregate, a replica of demolished concrete structure in real life. The recycled aggregate samples were prepared in two batches. In the first batch the water cement ratio was kept same (0.55) as that in case of virgin concrete. In the second stage the water cement ratio was increased up to 0.60 to check the variation of concretes specimen in strength and workability.

It was found that at the same water/cement ratios, the workability of virgin concrete are higher than that of recycled concrete. Similarly at water/cement ratio of 0.55, the compressive strength and tensile strength of recycled concrete is appreciably lower than that of virgin concrete. However, at higher w/c ratio of 0.60, the compressive and tensile strength of recycled concrete is very close to that of virgin concrete. Unlike virgin concrete in which compressive strength decreases as water / cement ratio increases, in recycled concrete the contrary is the case, i.e. strength increases with increase in water / cement ratios.

Recycled aggregated can be used with confidence in construction works with increased water cement ratio. The environmental issue can be effectively addressed by avoiding the dumping of the demolished materials associated with the elimination costs pertaining to the disposing operations.

Alqahtani, K.F., Ghataora, G., Khan, M.I., Dirar, S., Kioul, A., & Al-Otaibi, M. (2015). Lightweight concrete containing recycled plastic aggregates. International Conference on Electromechanical Control Technology and Transportation (ICECTT 2015), 527-533.

The concrete industry needs millions of tons of aggregate, comprising natural sands and gravels, each year. In recent years there has been an increasing trend towards use of recycled aggregate to save natural resources and to produce lightweight concrete. In this investigation, an attempt was undertaken to produce recycled plastic aggregate (RPA) using waste plastic and red sand as filler. The physical properties of RPA are reported and an experimental investigation of concrete incorporating RPA as coarse aggregates is presented. It was observed that 100% replacement of conventional lightweight aggregate (LWA) with recycled plastic aggregate (RPA) showed about 13% reduction in chloride penetration. Compressive strength was reduced; however, the achieved strength was between 12 and 15 MPa which is useful for non-structural elements such as low side building, cementations backfill, pavements and others.

Anderson, K.W., Uhlmeyer, J.S., & Russell, M. (2009). Use of recycled concrete aggregate in PCCP: Literature Search. Washington State Department of Transportation Materials Laboratory. WA-RD 726.1 June 2009.

The use of recycled concrete aggregate (RCA) is recommended based on a review of literature that investigated the properties and characteristics of RCA, the physical properties of fresh and hardened concrete containing RCA, the mechanical behavior of concrete containing RCA, and special considerations for concrete pavements using RCA to achieve suitable levels of workability, durability, and strength. The literature also detailed concrete pavement design considerations as well as the successes and failures of trial projects built by other states.

A recommendation is made that RCA be considered for use in Western Washington and that the FHWA Technical Advisory be used as a guide during implementation.

Anuar, K.A., Ridzuan, A.R.M., & Ismail S. (2011). Strength characteristic of geopolymer concrete containing recycled concrete aggregate. *International Journal of Civil & Environmental Engineering (IJCEE-IJENS), 11(1), 59-62.*

Malaysian is one of the develop countries that need to face environmental pollution. Have many ways to reduce environmental pollution that causes by production of Portland cement and cause by the increasing of waste material. Geopolymer concrete incorporating with recycle concrete aggregate (RCA) is one of the method. Waste Paper Sludge Ash (WPSA) and alkaline liquid as a binder are being used to replace the Portland cement to produce geopolymer concrete. The alkaline liquid that been used in geo polymerization is the combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). In the present study, two (2) series of geopolymer concrete specimens composing two (2) different molar of sodium hydroxide (NaOH) which are 8M and 14M were adopted. There are 30 cube specimens at size 100mm x 100mm x 100mm were prepared which is 15 cubes for 8M and another 15 cubes for 14M. The compressive strength of the geopolymer concrete specimens is tested at the age of 3, 7, 14, 21 and 28 days after cured in local laboratory ambient condition. The result shows that the strength of geopolymer concrete based Waste Paper Sludge Ash (WPSA) incorporating with recycle concrete aggregate (RCA) increase by increasing the molarities of sodium hydroxide (NaOH).

Bhanbhro, R., Memon, I., Ansari, A., Shah, A., & Menon, B.A. (2014). Properties evaluation of concrete using local used bricks as coarse aggregate. *Engineering, 6, 211-216.*

With time concrete/reinforced concrete has become the popular material for construction, modern industry utilizes this material a lot and has produced various beautiful, eye catching and amazing structures. Due to modern requirements for living and developed construction industries, the old buildings (usually constructed with brick masonry) are demolished and are replaced with new modern buildings. Demolition of buildings results in waste materials, which can create waste related problems and environmental issues. By using recycled aggregates, weight of concrete can also be reduced, which can also solve problems related to self-weight of concrete. In this paper at- tempt has been made to use local used bricks from vicinity of Nawabshah, Pakistan, as coarse aggregate. Concrete cubes made with local recycled bricks are cast and tested for overall weight of concrete, moisture content, dynamic modulus of elasticity and compressive strength (nondestructive and destructive methods). The results showed that concrete derived from recycled aggregates attained lower strength than regular concrete. More detailed and elaborated work is recommended with different mix ratios and different proportions of recycled aggregates for better conclusion.

Breccolotti, M., D'Alessandro, A., Roscini, F., & Bonfigli, F.M. (2015). Investigation of stress - strain behavior of recycled aggregate concrete under cyclic loads. *Environmental Engineering and Management Journal, 14 (7), 1543-1552.*

The recent awareness about recycling also involves the resources used in civil engineering. The use of Recycled Aggregate Concrete (RAC) has several advantages in terms of conservation of natural resources and of reduction of pollution. Although the interest on the use of structural concrete with recycled aggregates is increasing, extensive studies on the mechanical behavior of such materials that can allow their use in alternative to standard concrete are still lacking. As a consequence most of the structural codes do not provide any information on the mechanical characteristics of RAC while other codes just provide very basic information. This paper presents the results of an experimental investigation about the mechanical behavior of recycled aggregate concrete under uniaxial and cyclical compressive loads. Both monotonic complete stress strain curves and cyclic behavior under high-level compressive loads were analyzed. Stress – strain behavior of RAC is particularly significant for a subsequent analytical investigation of the mechanical behavior of the material. Indeed, the envelope diagram provides the modulus of elasticity, the elastic deformation, the proportional limit, the peak resistance and the total elongation, useful to understand the mechanical capabilities of the material and to plan further experimental tests. The cyclic tests were made with repeated loads with values varying between 25% and 75% and between 25% and 80% of the peak load. The aim of the tests was to evaluate the decay of the mechanical properties over time due to fatigue-induced damage. Three different percentages of recycled coarse aggregate, namely 0%, 50% and 100%, have been investigated in each test. The objective of the experimentation is to provide more information on the mechanical properties of concrete with recycled aggregates in order to better model their behavior and to enhance their use in civil engineering.

Cabral, A.E.B., Schalch, V., Molin D.C.D., & Ribeiro, D.L.J. (2010). Mechanical properties modeling of recycled aggregate concrete. *Construction and Building Materials, 24 (4), 421-430.*

The variability observed in the composition of construction and demolition (C&D) waste is a problem that inhibits the use of recycled aggregates in concrete production. To contribute in this field, a research was carried out varying water/cement ratio and substitution percent of natural aggregates by recycled aggregates. The experimental program used samples of main Brazilian C&D waste sources, which are concrete, mortar and red ceramic bricks as well as tiles. Results of concrete compressive strength and elastic modulus were statistically analyzed and modeled. The study shows that for both concrete properties, recycled coarse aggregate was more influential than recycled fine aggregate. However, the use of fine recycled red ceramic increased concrete strength. Coarse recycled red ceramic aggregate and fine recycled concrete aggregate exercised the largest and the smallest influence, respectively, in concrete properties.

Caggiano, A., Faella, C., Lima, C., Martinelli, E., Mele, M., Pasqualini, A., Realfonzo, R., & Valente, M. (2012). Mechanical behavior of concrete with recycled aggregate. Proceedings of the 19th Congress C.T.E., Bologna, 8-10 November 2012.

This study is aimed at evaluating the mechanical behavior of recycled aggregate concretes (RAC). An extended experimental investigation has been carried out on RAC prepared by replacing variable amounts of “virgin” aggregates with recycled concrete aggregates (RCA) deriving from building demolitions. The mechanical properties measured on RAC specimens are compared to the corresponding ones obtained for a conventional concrete with 100% of natural aggregates. The water-cement ratio (W/C) has been kept constant in all specimens. Some key concrete properties (i.e. strength and permeability) as well as some durability-related parameters have been measured with the aim of assessing feasibility and suitability of a RAC for structural use. Furthermore, the possible replacement of fine sand aggregates with Fly Ash has been also considered and compared. Stress-strain curves and the compressive strength values of both RACs and conventional concretes having different curing ages, have been evaluated and compared.

Cavalline, T. (2016). Quantifying the sustainability benefits of concrete pavement recycling. Tech Brief of National Concrete Pavement Technology Center.

For environmental, economic, and societal reasons, the use of recycled concrete in rehabilitation and new construction is an important step in the development of a more sustainable infrastructure. Much of the existing concrete infrastructure is already comprised of the best available materials, so the reuse and recycling of existing concrete pavements is an important sustainability strategy for highway agencies.

Concrete can be recycled in a variety of ways in pavement applications. Recycled concrete aggregate (RCA) can be used as a substitute for virgin aggregates in new concrete pavements and in foundation layers. Existing concrete pavements can be recycled in place using crack-and-seat, rubblization, on-grade crushing and processing, and as a stabilizer in full depth reclamation (FDR) techniques. The Construction and Demolition Recycling Association estimated that, as of 2014, approximately 140 million tons of concrete is recycled on an annual basis (CDRA 2016).

As state highway agencies increasingly view RCA as an economical, sustainable pavement material that provides satisfactory performance, opportunities exist to increase the volume of concrete repurposed in new infrastructure in the coming decades. Recently, the FHWA has expended considerable effort to advance the application of sustainability principles to pavements through the Sustainable Pavements Program (FHWA 2015). This program maintains a website that provides a clearinghouse of pavement sustainability related information, including references, technical briefs, publications, and recorded webinars.

Several publications exist that describe the tools and techniques that can be utilized to quantify the sustainability benefits (economic, environmental, and societal) of recycling, to assist in weighing alternatives, and to support decision-making. The purpose of this tech brief is to provide guidance concerning the use of these tools in quantifying the sustainability benefits of concrete recycling in pavement applications. Case studies of projects in which concrete recycling was performed and benefits were quantified using these tools are highlighted.

CCAA. (2008). Use of recycled aggregates in construction. Cement Concrete & Aggregates Australia. May 2008, Australia.

There is increasing demand and interest in aggregates from non-traditional sources such as from industrial by-products and recycled construction and demolition (C&D) wastes. The American Concrete Institute (ACI) focuses on the removal and reuse of hardened concrete whereas the Department of the Environment and Water Resources in Australia and CSIRO have developed a guide on the use of recycled concrete and masonry materials.

The Waste & Resources Action Programmed (WRAP) in the UK classified aggregates from primary, recycled and secondary material resources. Recycled aggregates encompass industrial by-products and reused construction products, all of which were once considered wastes and dumped in land ll. The recently introduced European Standards for aggregates do not discriminate between different sources, and are for ‘aggregates from natural, recycled and manufactured materials’. The focus is for purpose rather than origin of the resource.

The purpose of this report is to review the various sources of aggregate and examine their potential use in concrete and/or road construction materials.

Chen, H.J., Yen, T., & Chen, K.H. (2003). Use of building rubbles as recycled aggregates. *Cement and Concrete Research, 33(1), 125-132.*

The application of building rubble collected from damaged and demolished structures is an important issue in every country. After crushing and screening, this material could serve as recycled aggregate in concrete. A series of experiments using recycled aggregate of various compositions from building rubble was conducted. The test results show that the building rubble could be transformed into useful recycled aggregate through proper processing. Using unwashed recycled aggregate in concrete will affect its strength. The effect will be more obvious at lower water/cement ratios. When the recycled aggregate was washed, these negative effects were greatly improved. This is especially true for the flexural strength of the recycled concrete. The recycled coarse aggregate is the weakest phase at a low water/cement ratio. This effect will dominate the strength of recycled concrete. This mechanism does not occur in recycled mortar. The quantity of recycled fine aggregate will govern the mortar strength.

CTC & Associate LLC. (2012). Concrete recycling: reuse of returned plastic concrete and crushed concrete as aggregate. Caltrans Division of Research and Innovation, Rock Products Committee: Materials and QA Sub Task Group of the Concrete Products Task Group.

The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Dabhade, A.N., Chaudari, S.R., & Gajbhaye, A.R. (2014). Effect of fly ash on recycle coarse aggregate concrete. *International Journal of Civil Engineering Research, 5(1), 35-42.*

The rapid growth in construction and depleting natural resources demands the recycling and reusing technology to be adopted in construction field. The recycle coarse aggregate is one of the approaches towards this need. If the recycled coarse aggregate are used in conventional construction work it would saves the cost of materials. In this experimental study, the natural coarse aggregate is replaced with recycled coarse aggregate at different percentage and the mechanical strength of concrete is tested. In addition the fly ash is introduced as replacement of Cement to improve the quality of concrete. The mix designing is done for water cement ratios 0.38. Cylinders and cubes are casted using virgin coarse aggregate and replacing virgin aggregate with 20%, 30%, 40%, 50% and 100% recycle coarse aggregate, total sixteen batches are made. Obtained results are than used for Multi Linear Regression to establish an empirical relationship between the strength of concrete and with percentage of recycle aggregate, with percentage of fly ash and with age of concrete. Results shows that recycle aggregate up to 40% can be used with 10% fly ash for making concrete.

Deshpande, N.K., Kulkarni, S.S., & Pachpande, H. (2012). Strength characteristics of concrete with recycled aggregates and artificial sand. 2(5), 38-42, India.

Growing concern of the planet due to heavy consumption of sand and rock in concrete made it a necessity to find way through sustainable construction practices. A possible solution to these problems is to use of C& D waste in concrete. Recycled concrete can produce an alternative aggregate for structural concrete as partial or total replacement. In this paper an attempt is made to utilize recycled concrete aggregates and artificial sand (machine made sand) in concrete, using IS10262 2009 as guideline for designing the concrete with grade M25. Use of machine made sand will allow replacement to conventional sand. The fresh and hardened properties of new concrete are studied and compared with concrete made using conventional materials. A comparison with control mix mainly their compressive strength, split tensile strength & flexural strength, will allow assessing the suitability of using Recycled aggregate in concrete with replacement to sand with conventional or artificial sand.

Dessy, P., Badalucco, C., Bignami, L., Cantoni, F., Morfini, L., Nironi, L., Palmieri, S., & Strini, A. (1998). Analysis of the performances of concrete components made with recycled aggregates. CNR ICITE, San Giuliano Mil.se, Italy.

The paper presents the first phase of a research programmed that investigates the utilization of recycled aggregates coming from crushed concrete rubble in the production of precast blocks. In particular, the paper reports the results of the characterization of the aggregates and of the performance evaluation of concrete specimens in which different percentages of recycled aggregates are contained. The testing of the precast blocks will be carried out during the second phase of the study. Key words: characterization, concrete performance, recycled aggregates.

DeVenny, S.D.A. (1999). Recycling of demolished masonry rubble. School of the Built Environment, PhD dissertation, Napier University, UK.

The recycling of demolished masonry rubble as the coarse aggregate in new concrete represents an interesting possibility at a time when the cost of dumping such material is on the increase. With growing concerns over the environmental impact of aggregate extraction and the continued rise in aggregate demand in the UK, it is clear that the market is now there for recycled and secondary aggregates.

The present investigation consists of experimental and theoretical studies into the effects of using recycled aggregates to produce concrete instead of virgin aggregates. The aggregates used have been recycled from construction and demolition waste. The recycled aggregates were predominately made up of crushed bricks but the aggregates did contain impurities such as timber and mortar. New bricks were crushed to form an aggregate in order to investigate the properties of brick as a material without impurities.

The physical properties of the various aggregates were firstly examined and compared with granite aggregate, an aggregate proven in the production of good quality concrete. Concrete was then produced with the aggregates and all the physical and mechanical properties of the concretes were examined in some detail. The results showed that recycled masonry aggregates can be used successfully to produce-concrete of an acceptable standard.

New test methods were presented in this investigation to determine brick porosity and water absorption. This involved the testing of broken brick fragments under vacuum, rather than the testing of whole brick units by 5hrs boiling or 24hrs submersion in cold water. The new test methods proved to be easy to perform and provided accurate results.

A new test method for estimating the strength of bricks was presented. This involved point-loading of masonry specimens to obtain strength index values. From the point-load results, equations were presented relating the strength index values of brick fragments to the compressive strength of whole brick units. This involved the development of shape factors for different masonry specimens. The point-load test is easy to perform, presents a cheaper alternative to heavy compression machines and can be used on site to determine the suitability of recycled bricks as the aggregate in new concrete.

Dosho, Y. (2007). Development of a sustainable concrete waste recycling system. *Journal of Advancement Concrete Technology, 5(1), 27-42.*

The generation of huge amounts of construction waste is anticipated due to the demolition of older structures such as power stations built more than 30 years ago. On the other hand, the reuse of construction waste is highly essential from the viewpoint of Life Cycle Assessment (LCA) and effective recycling of construction resources. In order to promote the reuse of construction waste, it is necessary to achieve three basic concepts: (1) assurance of safety and quality, (2) decrease of environmental impact, and (3) increase of cost effectiveness of construction. This paper outlines the development of a recycling system, application of recycled aggregate concrete produced by the aggregate replacing method, which is effective in reducing both cost and environmental impact from the viewpoint of LCA for concrete waste generated by demolition of large-scale buildings such as powerhouses.

Result of this study showed that recycled aggregate concrete using the aggregate replacing method can acquire sufficient quality as structural concrete and/or precast concrete products through material design based on the value of relative quality method. Moreover, with the adoption of the developed recycling system, it was confirmed possible to recycle concrete waste produced from the demolition buildings in a highly effective manner reducing both recycling cost and environmental impact.

Eguchi, K., Teranishi, K., Nakagome, A., Kishimoto, H., Shinozaki, K., & Narikawa M. (2007). Application of recycled coarse aggregate by mixture to concrete construction. *Construction and Building Materials, 21(2007), 1542-1551.*

With regard to the technology for producing aggregate of recycled concrete from concrete blocks, great deals of research and studies have been reported, and the Ministry of Construction of Japan drafted the standard specification in 1996. However, it has hardly been applied to actual structures because of the high cost for production.

The authors have developed a production method for recycled concrete that is different from that of the draft. The recycled coarse aggregate is produced by a simple assembled system of equipment, and is mixed with ordinary coarse aggregate to ensure the quality required of structural concrete. In this research, characteristics of strength, durability, fire-resistant property, structural performance, and workability of the recycled concrete are investigated. The necessary data for establishing a mix proportion design and a quality control method are obtained. In addition, a production method for the recycled concrete, which has no use of a batching plant, is proposed. Eventually, the economics and environmental loads of the developed method are evaluated and its effectiveness is confirmed.

Etxeberria, M., Vázquez, E., Mari, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research, 37 (5), 735-742.*

In this study recycled coarse aggregates obtained by crushed concrete were used for concrete production. Four different recycled aggregate concretes were produced; made with 0%, 25%, 50% and 100% of recycled coarse aggregates, respectively. The mix proportions of the four concretes were designed in order to achieve the same compressive strengths. Recycled aggregates were used in wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The necessity to produce recycled aggregate concrete with low–medium compressive strength was verified due to the requirement of the volume of cement. The influence of the order of materials used in concrete production (made with recycled aggregates) with respect to improving its splitting tensile strength was analyzed. The lower modulus of elasticity of recycled coarse aggregate concretes with respect to conventional concretes was measured verifying the numeral models proposed by several researchers.

Evangelista, L., & de Brito, J. (2007). Mechanical behavior of concrete made with fine recycled concrete aggregates. *Cement & Concrete Composites*, *29 (5), 397-401.*

This paper concerns the use of fine recycled concrete aggregates to partially or globally replace natural fine aggregates (sand) in the production of structural concrete. To evaluate the viability of this process, an experimental campaign was implemented in order to monitor the mechanical behavior of such concrete. The results of the following tests are reported: compressive strength, split tensile strength, modulus of elasticity and abrasion resistance. From these results, it is reasonable to assume that the use of fine recycled concrete aggregates does not jeopardize the mechanical properties of concrete, for replacement ratios up to 30%.

FHWA. (2004). Transportation Applications of Recycled Concrete Aggregate. FHWA State of the Practice National Review. Federal Highway Administration.

The purpose of this review was to capture the most advanced uses of recycled concrete aggregate (RCA) for transportation uses in the United States. This knowledge would then be transferred to all State Transportation Agencies (STA) in the United States through the issuance of this report. The report summarizes the information collected during the review of practices in five states, Texas, Virginia, Michigan, Minnesota and California. These states were selected based on their level of use and supply generated of RCA as an aggregate as well as to obtain a cross-section of the country. This report identifies the applications where the use of RCA can have engineering, economic, and environmental advantages; the barriers related to these RCA applications; and the best practices that allowed State Transportation Agencies, recycled concrete producers and contractors to overcome these barriers. The report is intended to provide the State Transportation Agencies with recommendations, guidelines and specifications for furthering the use of RCA more widely throughout the country.

The overall findings of the review team was that RCA is a valuable resource, and by proper engineering it can be used for PCC pavement, aggregate base, miscellaneous. The material is too valuable to be wasted and landfill. Some of the best aggregates used for highway, bridge, and building construction are already in use in our highways and bridges, effective recycling is a means to re-use these materials.

Florea, M.V.A. & Brouwers, H.J.H. (2012). Recycled concrete fines and aggregates: the composition of various size fractions related to crushing history. The 18th Ibausil International Conference on Building Materials (Internationale Baustofftagung), Bauhaus Universität Weimar, Weimar, Germany. 1034-1041.

Recycling of construction and demolition waste (C&DW) is one of the important topics in concrete research nowadays. Oikonomou gives an extensive comparative review of the C&DW recycling all over the world. For the EU, it is estimated that the annual generation of C&D waste is the largest single waste stream, apart from agricultural waste. Even if the soil and some other wastes were excluded, the annual C&DW generation is computed at almost 500 kg per person within the EU. The recycling goals of most European countries are ambitious- between 50% and 90% of their C&D waste production. In The Netherlands, Germany and Denmark landfilling has become more costly than recycling. The UK went from using only 10% recycled materials in 1989, to 25% in 2001. C&DW in England and Scotland make up about 66% and 50% of recycled aggregates, respectively. The Scottish Executive Development Department (SEDD) found that the total estimated quantity land filled was composed of 44% mixed C&DW, clean soil (34%), contaminated soil (13%), and contaminated C&DW and asphalt (9%). From these, 19% of the mixed C&DW was subsequently reused/recycled.

In its report on "Recycled concrete", WBCSD gives a breakdown of C&DW recycling on individual European countries. Among the total C&DW recovery, recycled aggregates accounts for 6% to 8% of aggregates use in Europe. The greatest users are the United Kingdom, the Netherlands, Belgium, Switzerland and Germany (data from 2005 and 2006, published in 2008, from WBCSD).

Oikonomou also presents data for the US and Japan. In the US, the aggregates used can be divided by use in pavements (10-15%), other road construction and maintenance work (20–30%) and structural concrete (60–70%). Recycled aggregates are produced by natural aggregates producers (50%), contractors (36%) and debris recycling centers (14%). In Japan, the concrete recycling ratio reached 96% in 2006, from only 48% in 1990, and it is mostly used as sub-base material in road construction.

Recycled concrete aggregates (RCA) are mainly used as road-base material, but another interesting application would be their incorporation into concrete mixes. Moreover, through an efficient crushing and milling technique, recycled concrete can be a beneficial addition. This study deals with the mineralogical composition of several recycled concrete fractions, obtained through two crushing methods.

Florea, M.V.A., & Brouwers, H.J.H. (2013). Properties of various size fractions of crushed concrete related to process conditions and re-use. *Cement and Concrete Research*, *52 (2013), 11-21*.

Recycled concrete aggregates are mainly used for road construction, but another interesting application would be their incorporation into concrete mixes. So far, such an application is hindered by the loss of mechanical properties of recycled aggregate concrete. However, through an efficient crushing technique, which is able to generate relatively clean aggregates, recycled concrete can be a beneficial addition. This study deals with properties (particle size distribution, density, thermal treatment reaction, oxide and mineralogical composition) of a large number of recycled concrete fractions, obtained through three crushing methods. The use of recycled concrete sand, i.e. particle sizes between 150 μm and 2 mm, in new concrete is proven to be promising when the right crushing technique is adopted.

Foth, M., Haichert, R. E.I.T., Guenther, D., &Berthelot, C. (2011). Sustainability case study review of using recycled aggregate in road structure. Annual Conference of the Transportation Association of Canada, 14 pages, Edmonton, Canada.

Many transportation agencies are working towards more sustainable infrastructure management practices. One way in which agencies are being sustainable is by using recycled aggregates in road structures. It is important to evaluate the sustainability of these alternative road construction methods compared to the sustainability of traditional road construction methods. This paper reviewed the sustainability of rehabilitated road structures constructed using crushed reclaimed asphalt and cement concrete rubble. Four key aspects of sustainability were considered – economic, social, environmental and technical.

A City of Saskatoon “Green Street” Infrastructure Program case study is presented in this paper. From an economic perspective, significant costs savings are observed compared to the use of traditional virgin road aggregate materials. From a social perspective, residents who use the rehabilitated road will see an equal or improved level of service compared to a traditional structure. This is observed through the use of non-destructive heavy weight deflection (HWD) measurements where the deflection measurements on the recycled structure were less or equal to a traditional structure. The cost savings with the use of recycled materials may also be reinvested into rehabilitating more roadways improving the overall performance of the roadway network for residents.

Environmentally, because recycled materials are typically locally available and aggregate shortages are forcing just editions to haul verging aggregates from further away, fewer emissions are generated due to shorter distances for trucking and less energy is required to be consumed. Less virgin materials are required to be extracted from the earth and recycling construction rubble also generates less waste material. Technically, the mechanistic properties of the recycled materials were found to be equal or superior when compared to conventional road building materials. Laboratory and field measurements indicate that under higher applied stress state field conditions, the recycled materials exhibit performance measures that exceed that of conventional granular materials. This study illustrates that recycled materials can be used effectively in sustainable road construction when applied within a framework of applied engineering computational mechanics for design and analysis.

Ganiron, T.U. (2015). Recycling concrete debris from construction and demolition waste. *International Journal of Advanced Science and Technology, 77(2015), 7-24.*

Recycling of concrete debris can make a contribution to reduce the total environmental impact of the building sector. To increase the scope for recycling in the future, aspects of recycling have to be included in the design phase. Besides, aggregate sources near Metro Manila are almost depleted, so aggregates have to be brought from far quarries. Consequently, reclaiming aggregates from concrete debris would lead to environmental and economic benefits. This experimental study aimed to use crushed concrete debris as alternative fine aggregate in a mortar mixture. A conventional mortar mixture will be compared to concrete debris mixture of the same proportions.

Garber, S., Rasmussen, R., Cackler, T., Taylor, P., Harrington, D., Fick, G., Snyder, M., Van Dam, T., & Lobo, C. (2011). A Technology Deployment Plan for the Use of Recycled Concrete Aggregates in Concrete Paving Mixtures. National Concrete Pavement Technology Center.

The Every Day Counts (EDC) initiative is an FHWA effort that acknowledges the need for sustainable practices. According to the FHWA Administrator, the initiative is "designed to identify and deploy innovation aimed at shortening project delivery, enhancing the safety of our roadways, and protecting the environment". The use of recycled concrete aggregates (RCA) in new concrete paving mixtures is an example of innovation that aligns well the goals of the EDC initiative.

RCA used in new concrete paving mixtures can expedite construction schedules, reduce waste and associated hauling cost, conserve resources of virgin aggregates, and potentially reduce project costs. The Technology Deployment Plan presented herein is aimed at addressing the barriers that limit the use of RCA in new concrete paving mixtures. The Plan recognizes barriers grouped into three primary categories: compliance, quality, and production. In order to overcome these barriers, the Plan includes the creation of a Technical Working Group (TWG) and four programs: Outreach and Communication, Training, Technical Support, and Demonstration Projects. Through coordinated efforts by the TWG, the tasks developed and carried out under each program will mark forward progress towards achieving a future where RCA is used as a commonly accepted alternative to virgin aggregates for new concrete paving mixtures.

Hansen, T.C., & Narud, H. (1983). Strength of recycled concrete made from crushed concrete coarse aggregate. *Concrete International, 1(1983), 79-83.*

Compressive strength of hardened concrete made from recycled concrete coarse aggregates was studied as a function of compressive strength of original concretes from which coarse aggregates were derived. Also studied were properties of fresh concretes made from recycled aggregates, grading's of crusher products, properties of recycled aggregates, and the amount of old mortar, which remained attached to various grades and size fractions of recycled aggregate.

It was found that the compressive strength of recycled concrete is largely controlled by the water-cement ratio of the original concrete when other factors are essentially identical. If the water-cement ratio of the original concrete is the same as or lower than that of the recycled concrete, then the new strengths will be as good as or better than the original strengths or vice versa.

Hashim, S.A.H. (2013). Display the results of some researcher about the use of recycled aggregate in new concrete. *International Journal of Science and Research. 4(9), 1340-1345.*

The utilization of recycled aggregate (RA) as filler in the production of concrete can be detailed in the context of eco- friendliness and costs. Its utilization in construction is prevalent in certain developed European and Asian economies. Waste concrete that are by-products from the destruction of concrete structures represents a potential unending supply for the fabrication of concrete aggregates, while the reception of RA in the production of new concrete is dependent upon their respective qualities. The differences between concrete and natural aggregates are due to the presence of a considerable proportion of mortar being linked to the natural aggregates, consequently affecting the properties and the performance of concrete. This work intends to analyze published work and developmental studies on RA, analyze the latest usage of the aforementioned materials in the context of construction, and suggest approaches that could be useful for a wider range of applications. There are quite a few researchers that have worked on of the utilization of recycled waste material in concrete, and evidence of this is present in literature.

Hawkins, R., & Brown, B. (2010). Recycle aggregates green solution, smart choices. PowerPoint Presentation. American Society of Civil Engineers, Green Streets and Highways Conference, November 14 - 17, 2010 at the Renaissance Denver Hotel, Denver, CO.

An estimated 409 million tons of non-hazardous waste find their way to landfills each year. These statistics don't always include concrete and asphalt. The concrete and asphalt waste streams are nearly half the amount shown above, approximately 190 million tons per year in the United States alone. While this amount is staggering, we can divert over 90% of that into engineered and usable products.

Recycled concrete and asphalt address both the issues of environment and economics. Environment is addressed by diverting a large portion of the waste stream into a reusable product, economics by factoring the economic constant that each project must deal with, into a lower overall cost.

The most common use of recycled concrete is as an aggregate base course. Other uses include:

- Retaining wall fill
- Erosion control
- Soil stabilization
- Slab underlayment
- New concrete production

Asphalt has fewer uses but is recognized as 100% recyclable. Recycled asphalt is used in new asphalt production and as an alternative to paving in areas that can't provide a budget for pavement. With oil costs rising, recycled asphalt is a large contributor in the reduction of the cost of infrastructure improvements.

Recycled concrete and asphalt can reduce our carbon footprint by decreasing the amount of virgin aggregate mined and lowering the quantity of oil used. As aggregates, these benefits generally come at a lower cost than that of virgin sources.

This paper will demonstrate how recycled aggregates are being used in ways that are environmentally responsible, technically sound, commercially competitive, and supportive of a more sustainable society.

Hole, M.D.S. (2013). Used concrete recycled as aggregate for new concrete. Bachelor thesis, Universitat Politecnica de Valencia.

This dissertation has investigated recycled concrete aggregates in bound form. It has given a general overview of what RCA is and the importance of utilizing it. A presentation of the latest research conducted on the material with a special focus on the mechanical properties is given. The new concrete mixture proportioning method called the Equivalent Mortar Volume method is being presented and an Excel worksheet for using the new method is created. This worksheet is more like an example than a program for concrete proportioning. A short investigation of how a reduction of compressive strength reduces the resistance of a beam is also conducted. The reduction of compressive strength is calculated after a proposed equation which takes the amount of RCA into account. At last a study of nonstructural possibilities for RCA has been carried out.

Iqbal, N., Siddiqi, Z.A., Hameed, R., & Riaz, M.R. (2015). Strength prediction of recycled aggregate concrete using accelerated curing method. *Sci. Int. (Lahore), 27(3), 1939-1943.*

Compressive Strength of concrete is one of the most important and useful properties of concrete which is used by the engineer in designing RC structures. Generally, 3-days or 7-days normally cured concrete cylinders specimen are tested to determine the early gain in compressive strength and to predict the 28 day strength at site. However, 28-days compressive strength test is mandatory according to the building code requirements. Currently, research studies all over the world are being carried out on the applications of Recycled Aggregate Concrete (RAC) in real structures. The research work presented in this paper is an attempt to develop a simple mathematical equation based on simple linear regression analysis to estimate the 28-day compressive strength of RAC by employing results of early age (28.5 hr. instead of 3 or 7 days) compressive strength tests. The proposed equation requires the value of 28.5 hr. accelerated curing compressive strength to predict 28-days compressive strength of RAC. The results of 28-days compressive strength obtained using the proposed equation showed good agreement when compared with experimentally obtained 28-days compressive strength values.

Jeong, H. (2011). Processing and properties of recycled aggregate concrete. University of Illinois at Urbana and Champaign. Master thesis.

As interest in sustainable materials such as recycled aggregate concrete (RAC) rises, effort, it is important to understand the properties of RAC that relates to its use in construction. To respond to this need, various tests were performed to investigate the properties of RAC. Properties of RAC are highly affected by processing. Processing variables indeed in this study are two-stage mixing approach (TSMA) and control of RAC initial moisture contents. By two- stage mixing approach, the compressive strength of RAC improved with different initial moisture states of recycled coarse aggregates. However, in case of shrinkage, some previous studies showed that RCA can absorb larger amount of water than natural aggregates because RCA has a higher porosity which leads concrete to increase shrinkage. To make balance strength with shrinkage, our tests were performed by various mixture batches. In addition, ring and dog bone tests were studied when the specimen is restrained and is affected by internal tensile stress. With using 74% initial moisture states of recycled coarse aggregates, the compressive strength was similar to that of normal concrete and the drying shrinkage was less. Furthermore, test with using recycled fine aggregates (RFA) was performed and fly ash was used to reduce shrinkage of RAC. As RFA increases, the shrinkage of the specimen also increased because RFA is composed with mortar, which plays an important role in volume of porosity.

Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research, 33(5), 703-711.*

Concrete having a 28-day compressive strength of 28 MPa was crushed at ages 1, 3 and 28 days to serve as a source of aggregate for new concretes, simulating the situation prevailing in precast concrete plants. The properties of the recycled aggregate and of the new concrete made from it, with nearly 100% of aggregate replacement, were tested. Significant differences were observed between the properties of the recycled aggregates of various particle size groups, while the crushing age had almost no effect. The properties of the concrete made with recycled aggregates were inferior to those of concrete made with virgin aggregates. Effects of crushing age were moderate: concrete made with aggregates crushed at age 3 days exhibited better properties than those made with aggregates of the other crushing ages, when a strong cement matrix was used. An opposite trend was seen when a weaker cement matrix was used. Some latent cementing capacity was seen in the recycled aggregates crushed at an early age.

Kim, Y., Sim, J., & Park, C. (2012). Mechanical properties of recycled aggregate concrete with deformed steel re-bar. *Journal of Marine Science and Technology, 20(3), 274-280.*

This study investigates fundamental properties of the recycled aggregate, which was produced through recent hi-technique of recycling. In addition, the mechanical properties of the concrete that was made by the recycled aggregate were compared to the concrete made of natural aggregate. The primary objective of this study was to characterize the concrete-rebar bonding properties of the recycled aggregate concrete.

The recycled aggregate concrete showed about 18% decreased bond strength as compared to the natural aggregate concrete. The current prediction equation of bond strength suggested by the design specification does not consider this decreased bond strength by the use of the recycled aggregate. Therefore, this study suggests an equation for predicting the bond strength for the recycled aggregate concrete considering the recycled aggregate replacement ratio and consequent compressive strength reduction.

Krezel, Z. A., McManus, K. J., Cumbo, N., Karlie, H., & Cox, C. (2007). There is more to recycled concrete aggregate than just aggregate. Sustainable Development and Planning III, Australia, 981-989.

In Australia, recycled concrete aggregate (RC Aggregate) is produced mainly from two sources, viz. crushed demolition waste concrete and relatively ‘fresh’ crushed construction waste concrete. Apart from standard fine and coarse particles, RC Aggregate consists of a significant amount of very fine dust intrinsic to the crushing process of concrete waste. The amount and characteristics of the very fine particles and presence of cement paste residue (CPR) differentiate RC Aggregate from commonly used crushed natural aggregate. The aggregate fines and CPR impact a number of basic engineering properties of the aggregate and also have potential to influence behavior of the aggregate’s varies applications, including road base and concrete.

This paper reports on an investigation into mineral composition and re-cementing potential of RC Aggregate. Scanning Electron Microscopy with Energy Dispersive X-ray analysis and the X-Ray Diffraction examination were used to determine elemental and compound composition of solid CPR and fines of the aggregate. The re-cementing potential of the fines was assessed by a method, commonly used in determination of cement content in cement treated aggregate used in roads construction.

The results indicate that mineral composition of RC Aggregate is different from that of natural crushed aggregate or commonly used fine concrete sand. Preliminary results also indicate that RC Aggregate contains some anhydrous materials that react with Portland or Blended cements, or undergo a pozzolanic reaction with some hydration products such as calcium hydroxide.

Krizova, K., & Hela, R. (2014). Use of Recycled Aggregates in Current Concretes. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8(10), 1057.*

The paper a summary of the results of concretes with partial substitution of natural aggregates with recycled concrete is solved. Design formulas of the concretes were characterized with 20, 40 and 60% substitution of natural 8-16mm fraction aggregates with a selected recycled concrete of analogous coarse fractions. With the product samples an evaluation of coarse fraction aggregates influence on fresh concrete consistency and concrete strength in time was carried out. The results of concretes with aggregates substitution will be compared to reference formula containing only the fractions of natural aggregates.

Kuosa, H. (2012). Reuse of recycled aggregates and other C&D wastes. VTT-R-05984-12.

This report is a part in NeReMa-project (Advanced Solutions for Recycling of Complex and New Materials, TEKES-project, 2010 - 2012). This report is concentrated on construction and demolition waste (C&D waste) reuse. The main emphasis is in the use of recycled aggregates/concrete aggregates (RA/RCA) in concrete. The use of RA in some other materials and closed cycle reuse is also included.

Information on the effects of RA/RCA on concrete properties, on EN standardization and national specifications are included. Challenges and ways to widen the use, as ways for quality enhancement, are also reviewed.

Some recommendations to widen the use of RCA (RA) in concrete are given. Research is needed to be able to create a classification system applicable to national circumstances. A quality control system is also required. Network to share the experience in using RA will be useful - based on the gained experience, the use of RA and specifications can be modified.

To find novel and value added ways for the use of RA/RCA there should be more researches and innovations. This novel use could include also fine RA and RA-powders. Methods for RA quality enhancement should also be found, as well as novel mix design and mixing methods. Use of RA with other (recycled) materials to produce traditional, novel or low strength materials, as filling materials, including ecological materials without or with minimum amount of cement, use of RA with fly ash (FA)/classified FA/micronized FA, silica fume (SF}, slag (SLG), other (recycled) powder/micronized materials, brick powder, glass powder, rock powders and lime production waste could be possibilities to widen the use of demolished concrete.

The quality of structures for demolition and quality of produced recycled aggregates will decide the potential re-use. A schematic presentation on that is included. It includes a way for RA classification and a way to specify re-use in concrete. End use requirements, which must be based on exposure classes, may be different in different countries because of different climatic circumstances and also because of different national policies and adopted safety levels. Also, structural concrete must always meet the demands presented for concrete in prevailing mandatory standards.

Some possibilities and ideas for the use of other C&D-waste, as gypsum/plasterboard, mineral wool, expanded polystyrene (EPS), polyurethane (PUR), lightweight aggregate concrete, wood, plastics (mainly PVC) and glass are shortly reviewed.

Lauritzen, E.K. (1998). The global challenge of recycled concrete. DEMEX Consulting Engineers A/S, Denmark.

Most of the Construction and Demolition (C&D) waste is concrete and masonry rubble, which could be recycled and reused in the construction industry. At present, very limited quantities of concrete rubble waste are recycled. Experiences and results presented in this paper show very favorable recycling possibilities in this field. From a solely economical point of view, recycling of rubble waste is only attractive when the recycled product is competitive with natural resources in relation to their cost and quality. In addition, recycled materials will be competitive when there is a shortage of both raw materials and suitable disposal sites. This paper presents options and barriers for implementation of integrated recycling of concrete and C&D waste management.

Limbachiya, M.C., Leelawat, T., & Dhir R.K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structure/Materiaux et Constructions*, *33(2000), 574-580.*

The results of a test programmed to study the use of recycled concrete aggregate (RCA) in high-strength, 50 N/mm^2 or greater, concrete are described. The effects of coarse RCA content on the ceiling strength bulk engineering and durability properties of such concretes have been established. The results showed that up to 30% coarse RCA had no effect on concrete strength, but thereafter there was a gradual reduction as the RCA content increased. A method of accommodating the effects of high RCA content, involving simple adjustment to water/cement ratio of the mix is given. It is shown that high-strength RCA concrete will have equivalent engineering and durability performance to concrete made with natural aggregates, for corresponding 28-day design strengths. The practical implications of the study for concrete construction are discussed.

Limbachiya, M.C., Marrocchino, E., & Koulouris, A. (2007). Chemical–mineralogical characterization of coarse recycled concrete aggregate. *Waste Management*, *27(2), 201-208.*

The construction industry is now putting greater emphasis than ever before on increasing recycling and promoting more sustainable waste management practices. In keeping with this approach, many sectors of the industry have actively sought to encourage the use of recycled concrete aggregate (RCA) as an alternative to primary aggregates in concrete production. The results of a laboratory experimental programmed aimed at establishing chemical and mineralogical characteristics of coarse RCA and its likely influence on concrete performance are reported in this paper. Commercially produced coarse RCA and natural aggregates (16–4 mm size fraction) were tested. Results of X-ray fluorescence (XRF) analyses showed that original source of RCA had a negligible effect on the major elements and a comparable chemical composition between recycled and natural aggregates. X-ray diffraction (XRD) analyses results indicated the presence of calcite, portlandite and minor peaks of muscovite/illite in recycled aggregates, although they were directly proportioned to their original composition. The influence of 30%, 50%, and 100% coarse RCA on the chemical composition of equal design strength concrete has been established, and its suitability for use in a concrete application has been assessed. In this work, coarse RCA was used as a direct replacement for natural gravel in concrete production. Test results indicated that up to 30% coarse RCA had no effect on the main three oxides (SiO_2, $Al_2O_3$and CaO) of concrete, but thereafter there was a marginal decrease in $SiO_2$and increase in $Al_2O_3$and CaO contents with increase in RCA content in the mix, reflecting the original constituent's composition.

Limbachiya, M.C., Meddah, M. S., & Ouchagour, Y. (2012). Use of recycled concrete aggregate in fly-ash concrete. *Concrete and Building Materials, 27(1), 439-449.*

Nowadays, environmentally friendly building is becoming a crucial issue in construction industry. The course towards sustainable concrete involves mainly minimizing the environmental impact of concrete production by substituting virgin mineral materials by recycled ones as well as reducing the global CO_2emissions. The approach adopted here includes a large substitution of natural coarse aggregates (NA) by recycled concrete aggregates (RCA) obtained from crushed concrete debris, as well as the use of 30% fly ash (FA) as a partial substitute of Portland cement for FA concrete production.

Previous study by the authors has revealed the potential of using coarse RCA to produce concrete with similar 28-day design strength to that obtained when using natural aggregates. This paper discusses the effect of both partial and full replacement of natural coarse aggregates by coarse RCA in a fly ash concrete. Engineering properties and durability performance have been examined on both concrete types (Portland cement and fly ash) for mixes designed with various proportions of the RCA (0%, 30%, 50% and 100%) by mass. The results obtained showed that while embedding high amount of the RCA could lower the resistance to chloride penetration and carbonation of concrete still comparable design strength to that of the control mix might be achieved.

Lin, Y.H., Tyan, Y.Y., Chang, T.P., & Chang, C.Y. (2004). An assessment of optimal mixture for concrete made with recycled concrete aggregates. *Cement and Concrete Research, 34(8), 1373-1380.*

Due to a wide range of variability of engineering properties for recycled concrete, in general, a large number of experiments are usually required as to decide a suitable mixture for obtaining the desired requirements for concrete made with recycled concrete coarse/fine aggregate. This article adopts Taguchi's approach with an L_{16} (2^{15}) orthogonal array and two-level factor to reduce the numbers of experiment. Five control factors and four responses (slump and compressive strengths at 7, 14, and 28 days) were used. Using analysis of variance (ANOVA) and significance test with F statistic to check the existence of interaction and level of significance, and computed results of total contribution rate, an optimal mixture of concrete qualifying the desired engineering properties with the recycled concrete aggregates can easily be selected among experiments under consideration.

Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability, 2(5), 1204-1225.*

A comparative analysis of the experimental results of the properties of fresh and hardened concrete with different replacement ratios of natural with recycled coarse aggregate is presented in the paper. Crushing the waste made recycled aggregate concrete of laboratory test cubes and precast concrete columns. Three types of concrete mixtures were tested: concrete made entirely with natural aggregate (NAC) as a control concrete and two types of concrete made with natural fine and recycled coarse aggregate (50% and 100% replacement of coarse recycled aggregate). Ninety-nine specimens were made for the testing of the basic properties of hardened concrete. Load testing of reinforced concrete beams made of the investigated concrete types is also presented in the paper. Regardless of the replacement ratio, recycled aggregate concrete (RAC) had a satisfactory performance, which did not differ significantly from the performance of control concrete in this experimental research. However, for this to be fulfilled, it is necessary to use quality recycled concrete coarse aggregate and to follow the specific rules for design and production of this new concrete type.

Manzi, S., Mazzotti, C., & Bignozzi, M.C. (2013). Effect of adhered mortar of recycled concrete aggregates on long-term concrete properties. Third International Conference on Sustainable Construction Materials and Technologies, August 18 – August 21 2013, Kyoto Research Park, Kyoto, Japan.

The scope of the paper is to study and compare the properties of concrete made of coarse recycled concrete aggregates with the properties of conventional concrete made of natural ones. In particular, the effects of recycled concrete aggregates on long-term behavior of concrete (shrinkage and creep) are reported highlighting the correlations between cement paste porosity and mechanical properties. Moreover, the adhered mortar of the recycled concrete aggregates is determined and its influence on the final concrete properties is investigated as its content and porosity can greatly influence the final properties of the new concrete. The obtained results are promising in view of a current use of construction and demolition waste (C&DW) for new sustainable structural concrete.

Manzi, S., Mazzotti, C., & Bignozzi, M.C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement & Concrete Composites*, *37 (2013)*, 312–318.

Recycling concrete construction waste is a promising way towards sustainable construction. Coarse recycled concrete aggregates have been widely studied in recent years, however only few data have been reported on the use of fine recycled aggregates. Moreover, a lack of reliable data on long-term properties of recycled aggregate concrete has to be pointed out. In this paper the effects of both fine and coarse recycled concrete aggregates on short and long-term mechanical and physical properties of new structural concrete are investigated. The studied concrete mixes have been designed by adjusting and selecting the content and grain size distribution of concrete waste with the goal to obtain medium–high compressive strength with high content of recycled aggregates (ranging from 27% to 63.5% of total amount of aggregates). Time-dependent properties, such as shrinkage and creep, combined with porosity measurements and mechanical investigations are reported as fundamental features to assess structural concrete behavior.

Marie, I., & Quiasrawi H. (2012). Closed-loop recycling of recycled concrete aggregates. *Journal of Clean Production, 37(2012), 243-248.*

Reduce, reuse and recycle for environment recovery and respect are the key principles of a sustainable construction material. Much research has been conducted regarding the use of recycled concrete aggregates (RCA) in concrete mixes recycled from parent concrete of natural source aggregates, referred here as first generation. Recycling the RCA forming a second loop of recycling concrete is referred here as the second generation of RCA. This study concentrates on the properties of the second generation concrete. The concrete mixes considered in this study are conventional mixes made of 100% natural aggregates (NA), mixes containing up to 20% replacement of NA with RCA, producing first generation concrete and mixes containing up to 20% replacement of NA with aggregates obtained by recycling the first generation concrete (R-RCA), producing the second generation concrete. Properties that have been studied are workability, absorption, compressive and tensile strengths. The results show that the use of RCA and R-RCA has an adverse effect on concrete properties. Results show that the use of up to 20% replacement of NA by RCA or R-RCA instead of NA is allowed for producing concretes of accepted quality. The second generation RCA performed better than the first generation RCA. It is also shown that the closed-loop recycling is possible and advantages maintaining the sustainability of the natural resources and the environment.

McNeil, K., Thomas H.K., & Kang, T.H.K. (2013). Recycled concrete aggregates: a review. *International Journal of Concrete Structures and Materials, 7(1), 61–69.*

This paper discusses the properties of RCA, the effects of RCA use on concrete material properties, and the large scale impact of RCA on structural members. The review study yielded the following findings in regards to concrete material properties: (1) replacing NA in concrete with RCA decreases the compressive strength, but yields comparable splitting tensile strength; (2) the modulus of rupture for RCA concrete was slightly less than that of conventional concrete, likely due to the weakened the interfacial transition zone from residual mortar; and (3) the modulus of elasticity is also lower than expected, caused by the more ductile aggregate. As far as the structural performance is concerned, beams with RCA did experience greater midspan deflections under a service load and smaller cracking moments. However, structural beams did not seem to be as affected by RCA content as materials tests. Most of all, the ultimate moment was moderately affected by RCA content. All in all, it is confirmed that the use of RCA is likely a viable option for structural use.

Mjelde, D.G. (2013). Evaluation of recycled concrete for use as aggregates in new concrete pavements. Master of Science in Civil Engineering thesis, Washington State University, Department of Civil and Environmental Engineering.

The primary objective of this research is to determine if recycled concrete aggregate (RCA) sourced from demolished pavements in the central region of Washington State can be effectively utilized in new concrete pavements. The effects of two variables on concrete properties were evaluated in this study: the percentage of natural coarse aggregate replaced by RCA, and the incorporation of a 20% substitution of cement with Type F fly ash along with varying percentages of RCA replacement. Eight concrete batches were produced and a series of fresh and hardened concrete samples were created from each batch. The fresh concrete samples were tested for slump, air content, and density, and the hardened concrete samples were tested for compressive strength, modulus of rupture, and coefficient of thermal expansion. Tests were performed on the RCA to determine the absorption, specific gravity, Los Angeles abrasion loss, degradation value, and alkali-silica reactivity.

Incorporating RCA into a concrete mix decreased the workability of the fresh concrete. In contrast, substituting fly ash increased the workability of fresh concrete and could be utilized to counter the slump reduction caused by the addition of RCA. A higher percentage of RCA substitution correlated to a lower fresh concrete density. The percentage of RCA substitution did not have an influence on compressive strength, modulus of rupture, or coefficient of thermal expansion. All of the concrete mixes with RCA investigated in this study, including up to a 45% substitution of RCA, met all Washington State Department of Transportation (WSDOT) requirements for Portland cement concrete pavements.

The conclusions from this study indicate that coarse RCA can be suitable for use as an aggregate source for concrete pavements. Further, the restriction of 30% substitution of RCA recommended in previous studies may be overly restrictive. In order meet the WSDOT minimum degradation value for aggregates, it is recommended that the RCA be washed and fine materials removed prior to use.

Murali, G., Vardhan, C.M.V., Rajan, G., Janani, G.J., Jajan, S.N., & Sri, R.R. (2012). Experimental study on recycled aggregate concrete. International Journal of Engineering Research and Applications (IJERA). 2(2), 407-410.

The recycling of Construction and Demolition Wastes has long been accepted to have the possible to conserve natural resources and to decrease energy used in production. In some nations it is a standard substitute for both construction and maintenance, particularly where there is a scarcity of construction aggregate. The use of recycled aggregate weakens the quality of recycled aggregate concrete, which limits its application. For improving the quality of recycled coarse aggregate, various surface treatment methods such as washing the recycled aggregates with water and diluted acid were investigated. Strength properties of the treated and untreated coarse aggregate were compared. The results indicated that the compressive, flexure and split tensile strength of recycle aggregate is found to be less than the natural aggregate.

Nam, B.H., Behring, Z., Kim, J., & Chopra, M. (2014). Evaluate the Use of Reclaimed Concrete Aggregate in French Drain Applications. Florida Department of Transportation, BDK 78 TWO 977-12.

Recycled concrete aggregate (RCA) is often used as a replacement of virgin aggregate in road foundations (base course), embankments, hot-mix asphalt, and Portland cement concrete; however, the use of RCA in exfiltration drainage systems, such as French drains, is uncommon. The primary concerns with using RCA as a drainage media are the fines content and the precipitation of calcium carbonate to cause a reducing in filter fabric (geotextile) permittivity. RCA was tested for its physical and chemical properties, and aggregate cleaning/washing methods were applied to evaluate the fines removal processes. The use of compressive strength, pH, heat of hydration, and time of setting tests evaluated the potential for RCA rehydration. Permeability testing on RCA was conducted under varied testing conditions, such as, percent fines addition, hydraulic gradient, and tubing and permeameter sizes. In addition, a long-term permeability was monitored to measure the clogging buildup due to RCA fines and calcite precipitation.

Nassar, R.U.D., & Soroushian, P. (2012).Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. Department of Civil and Environmental Engineering, 3546 Engineering Building, Michigan State University, 368-, USA.

Milled waste glass was used as secondary cementations material towards production of recycled aggregate concrete with improved strength and durability attributes. Experimental investigation of the novel concept of using milled waste glass, as partial replacement for cement, to overcome the drawbacks of recycled aggregate and the resulting concrete showed that waste glass, when milled to micro-scale particle size, is estimated to undergo pozzolanic reactions with cement hydrates, forming secondary calcium silicate hydrate (C–S–H). These reactions bring about favorable changes in the structure of the hydrated cement paste and the interfacial transition zones in recycled aggregate concrete.

Use of milled waste glass, as partial replacement of cement, is estimated to produce significant gains in strength and durability of recycled aggregate concrete. Milled waste glass was also found to suppress alkali-silica reactions. The encouraging test results are viewed to facilitate broad-based use of recycled aggregate and diversion of large quantities of landfill-bound mixed-color waste glass for a value-added use to produce recycled aggregate concrete incorporating milled waste glass.

Nelson, S.C. (2004). High-Strength Structural Concrete with Recycled Aggregates. Ph.D. Dissertation. University of Southern Queensland.

Recycled aggregates are comprised of crushed, graded inorganic particles processed from the materials that have been used in the constructions and demolition debris. The aim for this on – going project is to determine the strength characteristic of recycled aggregates for application in high strength structural concrete, which will give a better understanding on the properties of concrete with recycled aggregates, as an alternative material to coarse aggregate in structural concrete. The scope of this project is to determine and compare the high strength concrete by using different percentage of recycled aggregates.

The investigation was carried out using workability test, compressive test, indirect tensile test and modulus of elasticity test. There were total of eight batches of concrete mixes, consists of every 20% increment of recycled aggregate replacement from 0% to 100%. Moreover, 100% of recycled aggregate mix batches included fly ash, water/cement ratio of 0.36 and 0.43. The workability of concrete considerably reduced as the amount of recycled aggregate increased. This was evaluated through standard slump test and compacting factor test. For strength characteristics, the results showed that a gradually decreasing in compressive strength, tensile strength and modulus of elasticity as the percentage of recycled aggregate used in the specimens increased.

Nixon, P.J. (1978). Recycle concrete as aggregate for concrete – a review.37-DRC Committee. Matériaux et Construction, 11(65), 11:371, 371-378.

The present state of knowledge on the use of recycled concrete as an aggregate in new concrete is reviewed and suggestions made as to what further work is necessary before a proper assessment of the material can be made. Where crushed uncontaminated concrete is used the properties of the material as an aggregate and the basic engineering characteristics of the concrete made with it are well established. Much less is known about the type and quantity of impurities which could occur in crushed concrete from general building rubble and the effect these would have on concrete made using such crushed concrete as aggregate.

O'Mahony, M.M. (1990). Recycling of Materials in Civil Engineering. Ph.D. Dissertation, Oxford University.

Although Britain is relatively rich in natural aggregate reserves, planning approvals to develop new quarries are running at about half the rate of aggregate extraction. The use of secondary materials, such as recycled aggregate, might not create a major source of aggregate but if secondary materials were used in less demanding situations, the quantity of natural aggregate required by the construction industry would be reduced.

This dissertation reports mainly on laboratory tests conducted on crushed concrete and demolition debris to examine the potential use of these materials in new construction. Standard aggregate tests were conducted on the materials to check their compliance with the Specification for Highway Works (1986), particularly for use as aggregate in road sub-base layers. A more detailed examination of the aggregates was conducted with regard to CPR, shear strength and frost susceptibility where the influences of moisture content, density and particle packing on these properties were investigated. One part of the study involved examining the use of recycled aggregate as the coarse aggregate fraction in new concrete.

Otoko, G.R. (2014). Use of crushed clay bricks as aggregate in concrete. *International Journal of Engineering and Technology Research 2(4), 1-9.*

The possibility of using crushed clay bricks as aggregate in bituminous mixtures was examined. Two brick aggregates were crushed from unused bricks, one recycled brick aggregate (RBA) and the other, granite aggregate; and the properties compared with each other. Physical and mechanical properties of the aggregates used in the asphalt concrete (AC) were then determined.

Test results showed that AC specimens of unused and recycled brick aggregate outperformed specimens made with granite aggregates, mainly because of the high porosity and roughness of the surface of crushed clay brick aggregates, which can absorb more bitumen and provide better bonding in asphalt concrete (AC). RBA has many environmental benefits that make them suitable alternative aggregates in construction.

Parekh, D.N., & Modhera, C.D. (2011). Assessment of recycled aggregate concrete. Journal of Engineering Research and Studies. E-ISSN0976-7916.

Use of recycled aggregate in concrete can be useful for environmental protection and economical terms. Recycled aggregates are the materials for the future. The application of recycled aggregate has been started in many construction projects in many European, American and Asian countries. Many countries are giving many infrastructural laws relaxation for increase the use of recycled aggregate. Paper reports the basic properties of recycled fine aggregate and recycled coarse aggregate. It also compares these properties with natural aggregates. Basic changes in all aggregate properties were determined and their effects on concreting work were discussed at length. Similarly the properties of recycled aggregate concrete were also determined and explained here. Basic concrete properties like compressive strength, flexural strength, workability etc. are explained here for different combinations of recycled aggregate with natural aggregate. Guidelines of recycled aggregates concrete in various countries were stated here with their effects, on concreting work. In general, present status of recycled aggregate in India with their future need and its successful utilization were discussed here in detail.

Pečur, I.B., Štirmer, N., Milovanović, B., Carević, I., & Alagušić, M. (2014). Energy efficiency aspects of recycled aggregate concrete. International Symposium on Eco-Crete, Reykjavik, Iceland.

One of the basic sustainability targets specified in Agenda 21 for Sustainable Construction is reduction of non-renewable raw material consumption. Since concrete is widely used construction material and has significant impact on the environment, it opens unexplored area of possibilities for improving concrete industry and its reorientation to the sustainability.
Huge potential lies in construction and demolition waste (CDW) which makes 25-30% of all waste generated in the EU. Intensive research activities have been carried out in recycling and reusing of CDW, especially in application of recycled concrete and brick aggregates as replacement of natural aggregates in concrete mixes.

On the other hand, most buildings are 'sub-standard' in terms of energy efficiency, comfort and health. Buildings account for the largest share of the total EU final energy consumption producing about 40% of greenhouse gas emissions during their service life.
This paper shows application of recycled aggregate concrete in energy efficient innovative ventilated prefabricated concrete wall panel with integrated Ecose mineral wool insulation: ECO-SANDWICH. Special emphasis is given on the research conducted regarding thermal properties of sustainable concrete with high inclusion levels of recycled concrete and brick aggregate, together with sound insulation properties of ECO-SANDWICH panels, all with respect to similar products.

Peng, G.F., Huang, Y.Z., Wang, H.S., Zhang, J.F., & Liu, Q.B. (2013). Mechanical properties of recycled aggregate concrete at low and high water/binder ratios. *Advances in Materials Science and Engineering, 2013, 6 pages.*

This paper presents an experimental research on mechanical properties of recycled aggregate concrete (RAC) at low and high water/binder (W/B) ratios. Concrete at two W/B ratios (0.255 and 0.586) was broken into recycled concrete aggregates (RCA). A type of thermal treatment was employed to remove mortar attached to RCA. The RAC at a certain (low or high) W/B ratio was prepared with RCA made from demolished concrete of the same W/B ratio. Tests were conducted on aggregate to measure water absorption and crushing values and on both RAC and natural aggregate concrete (NAC) to measure compressive strength, tensile splitting strength, and fracture energy. The mechanical properties of RAC were lower than those of NAC at an identical mix proportion. Moreover, the heating process caused a decrease in compressive strength and fracture energy in the case of low W/B ratio but caused an increase in those properties in the case of high W/B ratio. The main type of flaw in RCA from concrete at a low W/B ratio should be micro-cracks in gravel, and the main type of flaw in RCA from concrete at a high W/B ratio should be attached mortar.

Poon, C.S., Kou, S.C., & Lam, L. (2016). Use of recycled aggregates in molded concrete bricks and blocks. *Construction and Building Materials*, 16(5), 281-289. DOI: 10.1016/S0950-0618(02)00019-3.

This study aimed to develop a technique for producing concrete bricks and paving blocks using recycled aggregates obtained from construction and demolition waste. Laboratory trials were conducted to investigate the possibility of using recycled aggregates from different sources in Hong Kong, as the replacement of both coarse and fine natural aggregates in molded bricks and blocks. A series of tests were carried out to determine the properties of the bricks and blocks prepared with and without recycled aggregates. The test results showed that the replacement of coarse and fine natural aggregates by recycled aggregates at the levels of 25 and 50% had little effect on the compressive strength of the brick and block specimens, but higher levels of replacement reduced the compressive strength. However, the transverse strength of the specimens increased as the percentage of replacement increased. Using recycled aggregates as the replacement of natural aggregates at the level of up to 100%, concrete paving blocks with a 28-day compressive strength of not less than 49 MPa can be produced without the incorporation of fly ash, while paving blocks for footway uses with a lower compressive strength of 30 MPa and masonry bricks can be produced with the incorporation of fly ashes.

Qasrawi, H., & Marie, I. (2013). Towards better understanding of concrete containing recycled concrete aggregate. *Advances in Materials Science and Engineering, Volume 2013, 8 pages.*

The effect of using recycled concrete aggregates (RCA) on the basic properties of normal concrete is studied. First, recycled aggregate properties have been determined and compared to those of normal aggregates. Except for absorption, there was not between the two. Later, recycled aggregates were introduced in concrete mixes. In these mixes, natural coarse aggregate was partly or totally replaced by recycled aggregates. Results show that the use of recycled aggregates has an adverse on the workability and air content of fresh concrete. Depending on the water/cement ratio and on the percent of the normal aggregate replaced by RCA, the concrete strength is reduced by 5% to 25%, while the tensile strength is reduced by 4% to 14%. All results are compared with previous research. As new in this research, the paper introduces a simple formula for the prediction of the modulus of elasticity of RCA concrete. Furthermore, the paper shows the variation of the air content of RCA.

Qasrawi, H. (2013). The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment. *Construction and Building Materials*, *54(2014), 298-304.*

Waste materials, such as demolished concrete rubbles and steel slag, are dumped in landfills. Such action destroys the environment. Recycling these materials and using them as coarse aggregate in new concrete mixes would eliminate the problem. The paper summarizes a two-stage research conducted to evaluate the use of the two environmentally harmful materials in concrete.

Stage 1 studies the effect of using recycled concrete aggregate (RCA) or steel slag aggregate (SSA) on the properties of normal concrete. First, RCA and SSA properties have been determined and compared with those of normal aggregates. Later, RCA and SSA were introduced in concrete mixes. In these mixes, natural coarse aggregate is partly or totally replaced by RCA or SSA. Results show that the use of RCA or SSA has an adverse effect on the workability and air content of fresh concrete. While RCA resulted in reduction in the mechanical properties of concrete, SSA enhanced these properties.

In order to enhance the properties of RAC so that it can be used safely in structural concrete, the RCA has been partially replaced by SSA in stage 2 of the research. Results show that this is possible.

Qasrawi, H., Marie, I., & Tantawi, H. (2012). Use of recycled concrete rubbles as coarse aggregate in concrete. Proceedings of the 5th Jordanian International Civil Engineering Conference. Amman, Jordan. 281-287.

The use of concrete in structures consumes millions of tons of aggregates. Since earth is the source of the aggregates (either natural or crushed), then obtaining these amounts would have an adverse effect on the environment. Furthermore, demolishing concrete structures and dumping the concrete rubbles would aggravate the problem. Therefore, it becomes necessary to recycle the crushed concrete and use it as course aggregate in new concrete mixes.

The effect of using recycled aggregates concrete (RCA) on the basic properties of normal concrete is studied. First, recycled aggregate properties have been determined and compared to those of normal aggregates. Except for absorption, there was not a significant difference between the two. Later, recycled aggregates were introduced in concrete mixes. In these mixes, natural coarse aggregate was partly or totally replaced by recycled aggregates. Results showed that the use of recycled aggregates has an adverse effect on the workability of concrete. Using plasticizers can easily retain such an effect. Also, concrete strength has been reduced by 5% to 25% depending on the percent of the normal aggregate replaced by recycled aggregate and the water-cement ratio. With respect to the tensile strength, recycled aggregate concrete was slightly lower.

Rahman, I.A., Hamdam, H., & Zaidi, A.M.A. (2009). Assessment of recycled aggregate concrete. *Modern Applied Science, 3(10), 47-54.*

Used of recycled aggregate (RA) in concrete can be described in environmental protection and economical terms. The application of recycled aggregate to use in construction activities has been practice by developed European countries and also of some Asian countries. This paper reports the results of an experimental study on the mechanical properties of recycled aggregate concrete (RAC) as compared to natural aggregate concrete (NAC). The effects of size of RA on compressive strength were discussed in this paper. The 100% of RA used in concrete mix to replace the natural coarse aggregate in concrete with 100 × 100 × 100 cube mm were cast with target compressive strength is 25 MPa. The 28-day compressive strength was crushed at 3, 14, 28 days are reported. It was found the size of 10mm and 14 mm of RA in RAC is quite similar performance with 10mm and 14mm size of natural aggregate (NA) in natural aggregate concrete (NAC).

Rathod, H.A., & Pitroda, J. (2013). A study on recycled aggregate as a substitute to natural aggregate for sustainable development in India. *Global Research Analysis, 2(2)73-75.*

The recycling of Construction and Demolition Wastes has long been accepted to have the possible to conserve natural resources and to decrease energy used in its production. RCAs fit into present day motto of 'Reducing, Reusing, Recycling and Regenerating. In some nations it is a standard substitute for both construction and maintenance, particularly where there is a scarcity of construction aggregate. The use of recycled aggregate weakens the quality of recycled aggregate concrete, which limits its application. This paper deals with the review of the existing literature work for understanding thoroughly about RCAs and the use of recycled concrete as aggregates in concrete and proposes an approach for use of recycled concrete aggregate without compromising the strength in view for better economic growth to pave way for new construction as the old structures brought down.

Ravindrarajh, R.S. (1996). Effects of using recycled as aggregate on the engineering properties of concrete. Proceedings of National Symposium on the Use of Recycled Materials in Engineering Construction. The Institute of Engineers, Sydney, New south Wales, Australia, 147-152.

Waste concrete produced from demolition of concrete structures is an alternative source for the production of concrete aggregates and acceptance of recycled concrete aggregates for the production of new concrete depends on the quality of them. This paper discusses results of a series of investigations into the properties of recycled concrete aggregates and the effects of using them on the properties of concrete. Concrete aggregates differ from the natural aggregates due to the presence of a considerable proportion of mortar attached to the natural aggregates and affecting the properties and performance of concrete. The results showed that for recycled aggregate concrete, compressive and tensile strengths and modulus are reduced, whereas drying shrinkage and creep are increased. The effect of using concrete fine aggregate on the modulus and shrinkage is less than those produced by the use of concrete coarse aggregate. The strength of recycled aggregate concrete can be recovered by making suitable mix all adjustments or by the addition of fly ash or silica fume. Modulus of elasticity, drying shrinkage and creep cannot be fully recovered, by the above methods although improvements were observed.

Ravindrarajh, R.S. (1987). Utilization of waste concrete for new construction. *Conservation & Recycle. 10(2-3), 69-74.*

Recycling of materials used in outdated construction is probably as old as civilization itself. The recycling process can be defined as the recovery and subsequent use of a material for the manufacture and/or fabrication of the same or similar product from which the waste was originated. In many countries, demolition and construction activities generate a significant quantity of waste in which concrete forms a considerable proportion. Construction industry can utilize the waste concrete in many ways. The most common approach is to use the waste concrete with minimum processing as a bulk-fill material. Although this may not seems an intelligent method, sometimes from the economical point of view it may be justifiable.

Waste concrete, when adequately reduced in size, can be used for sub-base or surface material in road construction. Concrete debris with a lower degree of contamination can be used to produce aggregate for new concrete production. Crushed concrete particles retained on 5 mm standard sieve can be used to replace the conventional good quality coarse aggregate in new concrete production. It is also possible to replace the natural fine aggregates' with the crushed concrete fines below the 5 mm size in new concrete.

The need to recycle concrete as a concrete making material arises due to the following reasons: (a) diminishing supplies of good quality natural aggregates; (b) securing ample supply of concrete aggregates to the construction industry: (c) decreasing the available areas for dumping within the urban limits; and (d) avoiding the ecological impact to the marine creatures by limiting the indiscriminate dumping of highly alkaline (pi > 12.5) nature of concrete in sea water.

Ravindrarajah, R.S., & Tam, C.T. (1985). Properties of concrete made with crushed concrete as coarse aggregate. Magazine of Concrete Research, 37(130), 29-38.

Effects of using recycled concrete of different qualities as coarse aggregate upon the strength and deformation of concrete are reported. Tests on the aggregates showed that the recycled concrete aggregates have lower specific gravity and higher absorption capacity than the original crushed granite aggregate. The resistance to mechanical actions such as impact, crushing and abrasion for the recycled concrete aggregates is also lower. The effects of using recycled concrete aggregates instead of natural aggregates in concrete are: reduction in compressive strength up to 25%; reduction in modulus of elasticity up to 30%; improvement in damping capacity up to 30%; and higher amounts of drying shrinkage and creep. Available methods of predicting the modules of elasticity on basis of compressive strength for conventional concrete overestimate the modules of elasticity for recycled-aggregate concretes.

Richardson, A.E., Coventry, K., & Graham, S. (2009). Concrete manufacture with un-graded recycled aggregates. Structural Survey, 27(1), 62 – 70. http://dx.doi.org/10.1108/02630800910941692.

Purpose – The purpose of this paper is to investigate whether concrete that includes un-graded recycled aggregates can be manufactured to a comparable strength to concrete manufactured from virgin aggregates. Design/methodology/approach – A paired comparison test was used to evaluate the difference between concrete made with virgin aggregates (plain control) and concrete including recycled waste. Un-graded construction demolition waste and un-graded ground glass were used as aggregate replacements. With regard to concrete, compressive strength is widely used as a measure of suitability as being fit for purpose. Therefore compressive strength was mainly used to compare the different concrete batches; however density was measured across the range of samples.

Findings – The findings show that a lower average compressive strength is achieved when compared to the plain control sample manufactured with virgin aggregates. Correct particle packing may not be achieved and grading of aggregates is essential prior to mix design. The recycled aggregate was highly variable in terms of the fine particle content, which affected the water demand of the concrete.

Practical implications – This manufacturing practice is considered necessary because of the current trend in using waste products in concrete to replace binders and aggregates; thus reducing the impact on the environment and use of finite natural resources. The research shows the risk of mixing concrete using a simple aggregate replacement without careful aggregate grading and adjustments to the mix design. Originality/value – The paper examines 100 per cent ungraded aggregate replacement with glass and demolition waste.

Safiuddin, M., Alengaram, U.J., Rahman. M., Salam A., & Jumaat, M. Z. (2013). Use of recycled concrete aggregate in concrete: a review. *Journal of Civil Engineering and Management, 19(6), 796-810.*

The use of recycled concrete aggregate (RCA) in concrete as partial and full replacements of natural coarse aggregate is growing interest in the construction industry, as it reduces the demand for virgin aggregate. In addition, the use of RCA leads to a possible solution to the environmental problem caused by concrete waste and reduces the negative environmental impact of the aggregate extraction from natural resources. This paper presents a comprehensive review on the use of RCA in concrete based on the experimental data available in the published research. The most important physical, mechanical, and chemical properties of RCA are discussed in this paper. However, more emphasis has been given to discuss the effects of RCA on the fresh and hardened properties and durability of concrete. This paper also identifies the gaps existing in the present state of knowledge on RCA and RCA concrete and provides some recommendations for future research.

Sagoe-Crentsil, K.K., Brown, T., & Taylor, A.H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research, 31(5), 707-712.*

Performance tests have been carried out for fresh and hardened properties of concrete made with commercially produced coarse recycled concrete aggregate and natural fine sand. Test results indicate that the difference between the characteristics of fresh and hardened recycled aggregate concrete and natural aggregate concrete is perhaps relatively narrower than reported for laboratory-crushed recycled aggregate concrete mixtures. For concrete without blast furnace slag having similar volumetric mixture proportions and workability, there was no difference at the 5% significance level in concrete compressive and tensile strengths of recycled concrete and control normal concrete made from natural basalt aggregate and fine sand. Water absorption rates and carbonation of recycled concrete and reference concrete were comparable for most applications. However, the abrasion loss of recycled aggregate concrete made with ordinary Portland cement increased by about 12% compared to normal concrete, while the corresponding drying shrinkage was about 25% higher at 1 year. The ratio of splitting tensile strength to compressive strength was found to be in good agreement with established values derived for equivalent grade concretes made with normal-weight natural aggregates. One-year test results indicate that incremental improvements in durability characteristics can further be achieved with the use of blast furnace slag cement. Enhanced fresh and hardened concrete properties of the investigated recycled concrete aggregate as compared to aggregate derived from laboratory-crushed concrete arise primarily from improved aggregate grading and quality achievable in plant crushing operations

Sharma, J., & Singla, S. (2014). Study of Recycled Concrete Aggregates. *International Journal of Engineering Trends and Technology (IJETT), 13(3), 123-125.*

This paper describes the introduction and production of recycled concrete aggregates and its various applications in the construction industry. In this paper, properties of recycled aggregates and its comparison with the natural aggregates are also mentioned. Future recommendations about RCA are also included.

Shima, H., Tateyashiki, H., Matsuhashi, R., & Yoshida, Y. (2005). An Advanced Concrete Recycling Technology and its Applicability Assessment through Input-Output Analysis. *Journal of Advanced Concrete Technology, 3(1), 53-67.*

While at present mostly recycled into road subbase, the amount of demolished concrete in Japan is expected to increase rapidly and exceed the demand for road subbase in the near future. To promote the recycling of concrete, a technology to produce high-quality recycled aggregate has been developed. This technology employs the heating and rubbing method. In order to investigate a future concrete recycling system, first of all, a specific model considering indices of economic activity is established to forecast the amount of demolished concrete in the future. Furthermore, an input-output table is extended by a detailed description of concrete-related industries such as construction, aggregate, cement, and ready-mixed concrete, and several concrete recycling processes have been added. The linear programming model connected to the input-output table assume technology will be introduced in 2020. A subsidy for high-quality recycled aggregate and a carbon tax are found to be effective ways to promote the early introduction of the technology. This series of analysis can be widely used in other countries for investigating suitable recycling systems focusing on the cement and concrete industry as well as the applicability of each individual concrete recycling technology.

Snyder, M.B. (2016). Introduction to concrete recycling. Tech Brief of National Concrete Pavement Technology Center.

Concrete pavement recycling is a relatively simple process that involves breaking, removing, and crushing hardened concrete from an acceptable source to produce recycled concrete aggregate (RCA), a granular material that can be produced for any application for which virgin aggregate might be used (ACPA 2009).

Concrete recycling has been used extensively in Europe since the 1940s and in the United States since the 1970s (NHI 1998). Concrete recycling for paving applications is now performed in at least 41 states (FHWA 2004). Annual production of RCA in the United States from all sources (both pavements and demolition debris) was recently reported as about 140 million tons (CDRA 2014).

The recycling of paving materials (including concrete pavement) into new paving applications is supported by the Federal Highway Administration, which states that “reusing the material used to build the original highway system makes sound economic, environmental, and engineering sense” (FHWA 2002, Hall et al. 2007, Van Dam et al. 2015).

Sonawane, T.R., & Pimplikar, S.S. (2013). Use of recycled aggregate concrete. *IOSR Journal of Mechanical and Civil Engineering, 52-59.*

Use of recycled aggregate in concrete can be useful for environmental protection. Recycled aggregates are the materials for the future. The application of recycled aggregate has been started in a large number of construction projects of many European, American, Russian and Asian countries. Many countries are giving infrastructural laws relaxation for increasing the use of recycled aggregate. This paper reports the basic properties of recycled fine aggregate and recycled coarse aggregate & also compares these properties with natural aggregates. Basic changes in all aggregate properties are determined and their effects on concreting work are discussed at length. Similarly the properties of recycled aggregate concrete are also determined. Basic concrete properties like compressive strength, flexural strength, workability etc. are explained here for different combinations of recycled aggregate with natural aggregate. Guidelines of recycled aggregates concrete in various countries are stated here with their effects, on concreting work. In general, present status of recycled aggregate in India along with its future need and its successful utilization are discussed here.

Stein, V. (1987). Recycling of Demolition Waste and its influence on the market of natural mineral building materials. *Conservation and Recycling, 10, 53-57.*

Applications for a new dumping site for building rubble or for new query are treated very often in a similar way in many industrialized countries. The applicants for the dumping site are told to recycle the waste and in the case of the quarry they are told that the recycling of building rubble will produce such a large amount of aggregates that there is no necessity for a new mining site.

These arguments are very often used in public hearings. They could not be correct but for the discussions in the hearings a detailed knowledge based on special investigations seems necessary. The investigations should also include collecting of information on the technical standard of recycling plants and a first assessment of the product quality and the market.

Our investigations have already shown that recycling of demolition rubble is more common on Germany than assumed before. Smaller companies told us of good sales conditions for recycling products. We suppose the reason for this lies mainly in the combination of a recycling plant with a quarry or with a sand/gravel pit, which we found quite often.

Tam, V.W.Y., Gao, X.F., Tam, C.M., & Chan, C.H. (2006). New approach in measuring water absorption of recycled aggregates. *Construction and Building Materials, 3(22), 364-369.*

With the increase in the use of recycled aggregate concrete, the demand on recycled aggregate (RA) is escalating. As such, the behavior and characteristics of RA need to be clearly understood. In practice, the testing procedures of aggregates in Hong Kong follow those laid down in British Standard Institution (BSI) (BS: 812), which provide a good foundation for assessing properties of natural aggregates. As RA may have cement paste attached that may detach from the mass during sample preparation when repetitive soaking in water and drying are employed. Thus, the traditional testing approach for water absorption cannot give accurate results for RA, based upon which, errors in concrete mix designs may result. This paper proposes an innovative method for testing the water absorption of RA named Real-Time Assessment of Water Absorption (RAWA). The detailed testing procedure of the new method is illustrated with examples.

Tiwari, A. (2015). Recycled concrete aggregates. *International Research Journal of Engineering and Technology (IRJET), 2(6), 125-128.*

Structures made up of concrete are when demolished or renovated, concrete recycling is an increasingly common method of utilizing the rubble rather than disposing it in the landfills. Recycling of concrete aggregate is an attractive option in this age of greater environmental awareness. In this rapid industrialized world, recycling construction material plays an important role to preserve the natural resources. Works on recycling have emphasized that if old concrete has to be used in second generation concrete, the product should adhere to the required compressive strength. This paper reports the basic properties of recycled fine aggregate, recycled coarse aggregate and also comparing it with the natural aggregate. Some of the studies have suggested the mix design procedure for recycled aggregates in concrete, yet a simple and cost effective method of using demolished concrete, taking into account % adhered mortar and thus calculating mix composition needs to be developed. In this research concrete waste from demolished structure has been collected and coarse aggregate of different % is used for preparing fresh concrete. Many researchers state that recycled aggregates are only suitable for non-structural concrete application. This study shows that the recycled aggregates that are obtained from concrete specimen make good quality concrete. The slump of recycled aggregate concrete is more than the normal concrete. At the end it can be said that the RCA up to 50-51 % can be used for obtaining good quality concrete.

Topçu, I.B., & Şengel, S. (2004).Properties of concretes produced with waste concrete aggregate. *Cement and Concrete Research, 34(8), 1307-1312.*

An environmentally friendly approach to the disposal of waste materials, a difficult issue to cope with in today's world, would only be possible through a useful recycling process. For this reason, we suggest that clearing the debris from destroyed buildings in such a way as to obtain waste concrete aggregates (WCA) to be reused in concrete production could well be a partial solution to environmental pollution. For this study, the physical and mechanical properties along with their freeze–thaw durability of concrete produced with WCAs were investigated and test results presented. While experimenting with fresh and hardened concrete, mixtures containing recycled concrete aggregates in amounts of 30%, 50%, 70%, and 100% were prepared. Afterward, these mixtures underwent freeze–thaw cycles. As a result, we found out that C16-quality concrete could be produced using less than 30% C14-quality WCA. Moreover, it was observed that the unit weight, workability, and durability of the concretes produced through WCA decreased in inverse proportion to their endurance for freeze-thaw cycle.

TxDOT. (1998). Using recycled concrete aggregates in Portland cement pavement. http://www.txdot.gov/inside-txdot/forms-publications/consultants-contractors/publications/recycling.html#2

Concrete from roads, pavements, airfield runways, buildings, and other sources can be crushed for reuse. After crushing, magnets remove the steel rebar and the resulting aggregates are screened according to planned use. The crushed concrete produces hard, granular aggregates composed of inert mineral materials including sand, gravel, and crushed stone.

The American Concrete Pavement Association estimates that approximately 322 kilometers of concrete pavement is being recycled each year and approximately 5,440 metric tons of crushed concrete can be reclaimed from 1.6 km of concrete pavement with an average thickness. This shows that 2.6 million metric tons of reclaimed concrete is being recycled annually in the United States. TxDOT has specifications that allow crushed concrete to be used in flexbase, cement-stabilized base, and riprap. Additionally, crushed concrete can be used as coarse aggregates in Portland Cement Concrete and as fine aggregates in asphalt stabilized base.

TxDOT. (2008). Recycled concrete aggregates make cents. TxDOT Published as needed by the Construction and Bridge Divisions.

In today's environment of skyrocketing material and transportation costs encountered in road construction, recycled concrete aggregates (RCA) provide substantial savings to TxDOT and taxpayers. Natural resources are conserved, waste disposal is reduced, and air quality is improved due to reduced haul distances and reduced energy consumption. In many cases, allowing the use of RCA can be the most cost effective choice for an aggregate source. This is especially true for those districts that do not have good, native aggregate sources. Using RCA can reduce time and expense of importing aggregates from other parts of the state.

TxDOT has researched and used RCA with good success for about 15 years. In just the last two years alone, TxDOT saved approximately 1.8 million tons of virgin aggregates by incorporating RCA in cement treated base, flexible base, continuously reinforced concrete pavement (CRCP), filter dams, gabion walls, concrete traffic barriers, flow able fill and select backfill for mechanically stabilized earth walls. This equates to an estimated savings of $12.6 million from reduced or eliminated landfill and virgin aggregate associated costs. Savings from using RCA has the potential to increase tenfold based on current availability of RCA.

USGS. (2000). Recycled aggregates profitable resource conservation**.**

The recycling of aggregates from recovered asphalt pavement and demolished concrete debris conserves resources and landfill space, while also generating healthy profits for recyclers. Recycling can take place either at a permanent facility or at the demolition site, using mobile equipment.

A sustainable recycling industry requires numerous factors, including sufficient concrete and asphalt decay and demolition to supply the recycler with raw materials, demand for new infrastructure, favorable transportation distances, product acceptance, and limited landfill space.

Van Dam, T., Smith, K., Truschke, C., & Vitton, S. (2011). Using Recycled Concrete in MDOT's Transportation Infrastructure - Manual of Practice. Michigan Department of Transportation. Final Report.

Crushed concrete aggregate (CCA) is granular material manufactured by removing, crushing, and processing old concrete for reuse as an aggregate source in new construction. Although the Michigan Department of Transportation (MDOT) has used CCA since the 1980s, issues in the performance of some of the early projects currently limit its use to primarily bound and unbound drainable bases beneath concrete pavements. Some of the performance issues on the early projects developed because of the unique characteristics and properties of CCA materials, such as increased absorption, lower specific gravity, and reduced abrasion resistance.

Although there are potentially some limitations associated with the use of CCA, the effective characterization of these materials during their production and throughout the design and construction process can help lead to their successful use and application. This document is intended to help guide MOOT engineers in using CCA in the State's transportation infrastructure, with particular focus on pavement applications. Information is provided by chapter on the processing and production of CCA, on the physical, mechanical, and chemical characteristics of CCA, and on the use of CCA in base layers, asphalt paving layers, and concrete paving layers; these are presented in conjunction with MDOT's standard specifications for construction and special provisions to indicate the Department's current usage policies and recommendations regarding CCA.

Van Dam, T., Harvey, J.T., Muench, S.T., Smith, K.D., Snyder, M.B., Al-Qadi, I.L., Ozer, H., Meier, J., Ram, P.V., Roesler, J.R., & Kendall A. (2015). Towards Sustainable Pavement Systems: A Reference Document. FHWA-HIF-15-002. Federal Highway Administration, Washington, D.C.

All stakeholders in the pavement community—from owner/agencies to designers, and from material suppliers to contractors and consultants—are embracing the need to adopt more sustainable practices in all aspects of their work, and are continually seeking the latest technical information and guidance available to help improve those practices. This reference document has been prepared to provide guidance to the pavement community on sustainability considerations in pavement systems, drawing from and synthesizing the large and diverse body of knowledge that exists on pavement sustainability. As such, it provides the currently available knowledge and information for designing, constructing, and maintaining pavement structures more sustainably, and has been structured so that it can adapt to new findings and new information as sustainability considerations continue to develop and evolve. Key information is presented on pavement sustainability concepts, sustainable materials for paving applications, design of sustainable pavements, sustainable pavement construction practices, use phase considerations, sustainable maintenance and preservation practices, sustainable end-of-life considerations, pavement sustainability and livable communities, and assessment of pavement sustainability.

It is important to recognize that there is no universal definition of a "sustainable" pavement. Sustainability is very much context sensitive in that each project is unique, with specific needs depending on the location, climate, available materials, facility type, and required level of service, as well as on the overall goals of the organization. In essence, sustainability is very much a system characteristic, and pavements represent but one small part of the transportation infrastructure system; consequently, any improvements to the sustainability characteristics of pavement systems cannot be done in isolation from the transportation infrastructure system or from other systems with which pavements interact.

Verian, K.P., Whiting, N.M., Olek, J., Jain, J., & Snyder, M.B. (2013). Using recycled concrete as aggregate in concrete pavements to reduce materials cost. Joint Transportation Research Program (JTRP) Technical Report.

The main objective of this project was to evaluate the effects of using aggregate produced from crushed concrete pavement as a replacement for natural (virgin) coarse aggregate in pavement mixtures. A total of ten different concrete mixtures containing recycled concrete aggregate (RCA) were designed to meet the requirements of Indiana Department of Transportation (INDOT) specifications. These included three different RCA replacement levels (30%, 50% and 100% by weight of the natural coarse aggregate) and two different cementations systems (plain system – Type I Portland cement only and fly ash system – 80% of Type I Portland cement and 20% of ASTM C 618 Class C fly ash). The scope of the project included the evaluation and comparison of several properties of RCA and natural aggregates, evaluation and analysis of the effects of RCA on concrete properties, and modification of aggregate gradations and mixture composition in an attempt to improve the properties of RCA concrete.

All ten mixtures were first produced in the laboratory (trial batches) and were subsequently reproduced in the commercial ready-mixed concrete plant. Each mixture produced in the ready-mixed plant was used to prepare several types of specimens for laboratory testing. The tests performed on fresh concrete included determination of slump and entrained air content. Conducting compressive strength, flexural strength, modulus of elasticity and Poisson's ratio tests assessed the mechanical properties of the hardened concrete.

Concrete durability was assessed using a wide array of measurements, including: rapid chloride permeability (RCP), rapid chloride migration (RCM), electrical impedance spectroscopy (EIS), surface resistivity, free shrinkage, water absorption test, freeze-thaw resistance and scaling resistance.

The test results indicated that the properties of plain (no fly ash) concrete mixtures with 30% RCA as coarse aggregate were very comparable to (in some cases even better than) those of the control concrete (0% RCA). Although mixtures with 50% RCA showed a reduction in durability and mechanical properties of up to 36%, the test results still met INDOT's specifications requirements. The mechanical properties of plain concretes made with 100% RCA were measurably lower (16%-25%) than those of the control concrete. It should be pointed out, however, that these properties were still above the minimums required by INDOT's specifications except for one mixture in which the w/c was increased to 0.47 to achieve workability. The use of fly ash improved the strength and durability of RCA concrete, especially at later ages. In particular, the properties of concrete with 50% RCA coarse aggregate were similar to the properties of control concrete. Similarly, the mechanical and durability properties of the mixture with 100% RCA coarse aggregate and 20% fly ash were better than those of a similar mixture prepared without fly ash. Even though, when compared to the fly ash concrete with 100% virgin aggregate the mechanical and durability properties of the 100% RCA concrete were up to 19% and 35% lower, it still met minimum requirements imposed by INDOT's specifications.

Wen, H., McLean, D., Boyle, S., Spry, T., & Mjelde, D. (2014). Evaluation of recycled concrete as aggregate in new concrete pavements. Washington State Department of Transportation, WSDOT Research Report, WA-RD 826.1, April 2014.

This study evaluated the use of recycled concrete as coarse aggregate in new concrete pavements. Recycled concrete aggregate (RCA) produced from demolished pavements in three geographically-dispersed locations in Washington state were used to perform tests on aggregate characteristics, fresh concrete properties, and hardened concrete properties. Variables included the source of the RCA, percent replacement of coarse natural aggregate with RCA (0% to 45%), and percent replacement of Portland cement with type F fly ash (0% or 20%). RCA from all three sources met WSDOT requirements for aggregates, and all fresh and hardened concrete properties met WSDOT requirements. Replacement of RCA for natural coarse aggregate by up to 45% by volume had no significant effects on any of the properties. These results indicate that high-quality RCA can be used as a replacement for a portion of the coarse natural aggregates in new Portland cement concrete pavements in Washington State.

Yaprak, H., Aruntaş, H.Y., Demir, I., Simsek, O., Durmus, G. (2011). Effects of the fine recycled concrete aggregates on the concrete properties. *International Journal of the Physical Sciences, 6(10), 2455-2461.*

In this experimental study, the effects of the recycled fine recycled concrete aggregate (FRA) that was manufactured from concrete wastes on the concrete properties were investigated. In concrete mixtures, 0, 10, 20, 30, 40, 50 and 100% by weight FRA were used instead of river sand. Afterwards, unit weight and water absorption ratios and 28-day compressive strength were determined. According to the test results obtained, it was seen that FRA can be used up to 10 % ratio for producing C30 concrete, between

20-50% ratios for producing C25 concrete. Thus, environmental impacts and consumption of the natural resources can be significantly reduced by using recycled fine concrete aggregates in concrete applications.

Yehualaw, M.D., & Woldesenbet, A.K. (2016).Economic impacts of recycled concrete aggregate for developing nations: a case study in the Ethiopian construction industry. 2016 Construction Research Congress.

Today, the booming construction industry in Ethiopia is leading to an increased demolition of concrete structures whereby these demolished structures are disposed at landfills. The current practice is now creating a huge amount of construction and demolition waste over large landfills and is becoming the main source of shortage of land for infrastructure development. On the other hand, for the booming construction there is a huge demand of virgin aggregate for new concrete works. This paper discusses the potential use of demolished concrete from site-tested specimens as a recycled concrete aggregate (RCA) material for new concrete production. The study compares the cost of conventional concrete (CC) with recycled aggregate concrete (RAC). The output of this study will highly impact the growing construction industry and communities in Ethiopia thereby reducing waste, saving cost, conserving natural aggregates, building capacity, and setting quality standards.

Zahir, S., Syal, M., LaMore, R., & Berghorn, G. (2016). Approaches and associated costs for removal of abandoned buildings. 2016 Construction Research Congress. http://ascelibrary.org/doi/pdf/10.1061/9780784479827.024#sthash.CLo8760K.dpuf

The life cycle of the built environment consists of new construction, then rehabilitation and, finally, removal. This concept has taken on a unique importance with the widespread property abandonment in certain urban areas such as Detroit, Michigan. Large concentrations of abandoned properties cause blight and lead to social decline which threatens the public health and community welfare. With increases in the amount of structural abandonment comes issues of government intervention, funding of removal operations, and the large-volume of waste stream generated from removal of these structures. A new area of focus, known as “Domicology” is emerging in response to this abandonment crisis. It examines the life-cycle continuum of building and infrastructure abandonment, and studies the policies, practices, and consequences of human structural abandonment with the goal of finding approaches to reduce the negative environmental, social, and economic impacts of such unsustainable abandonment. The objectives of the research include an overview of various approaches and associated costs for demolition and deconstruction, and development of a comparison matrix for demolition and deconstruction. In addition, it discusses parameters related to urban blight removal in Detroit, Michigan. It is hoped that this discussion will help promote environmentally responsible options in the removal of urban abandoned structures.

12.2 Survey List to State Highway Agencies

Table 12.2.1 List of State DOT Engineers Contacted

No.	Last Name	First Name	Email
1	George	Scott	georges@dot.state.al.us
2	Shugart	Robert	shugartr@dot.state.al.us
3	Bell	Frank	bellf@dot.state.al.us
4	Ingram	Steven	ingrams@dot.al.us
5	Angelo	Michael	michael.sanangelo@alaska.gov
6	Giessel	Richard	richard.giessel@alaska.gov
7	Saboundjian	Stephan	steve.saboundjian@alaska.gov
8	Burch	Paul	pburch@azdot.gov
9	Cruz	Maria	mcruz@azdot.gov
10	Sandoval-Gil	Jesus	jsandoval-gil@azdot.gov
11	Little	Shane	slittle@azdot.gov
12	Sullivan	Tony	tony.sullivan@ahtd.ar.gov
13	Benson	Michael	michael.benson@arkansashighway.com
14	Wong	Jacquelyn	jacquelyn.wong@dot.ca.gov
15	Pyle	Tom	tom.pyle@dot.ca.gov
16	Glauz	Doran	doran.glauz@dot.ca.gov
17	Romero	Hector	hector.romero@dot.ca.gov
18	Dayton	Charles	charles.m.dayton@dot.ca.gov
19	Perez	Edwardo	edwardo.perez@dot.ca.gov
20	Jain	Vijay	vijay.jain@dot.ca.gov
21	McCrum	Larry	larry.mccrum@dot.ca.gov
22	Schiebel	Bill	bill.schiebel@state.co.us
23	Prieve	Eric	eric.prieve@state.co.us
24	Henry	Stephen	stephen.henry@state.co.us
25	Goldbaum	Jay	jay.goldbaum@state.co.us
26	Kotzer	David	david.kotzer@state.co.us
27	Connery	James	james.connery@ct.gov
28	Crouthamel	Philip	philip.crouthamel@po.state.ct.us
29	Rodrigues	Nelio	nelio.rodrigues@po.state.ct.us
30	Gardon	Charles	charles.gardon@po.state.ct.us
31	Lauzon	Robert	robert.lauzon@po.state.ct.us
32	Pinkerton	Jennifer	jennifer.pinkerton@state.de.us
33	Thomas	John	john.thomas@state.de.us
34	Balbierer	Mike	mike.balbierer@state.de.us
35	Horhota	David	david.horhota@dot.state.fl.us
36	Shoucair	John	john.shoucair@dot.state.fl.us
37	Jameson	Dino	dino.jameson@dot.state.fl.us
38	Ruelke	Timothy	timothy.ruelke@dot.state.fl.us

(Continued from Table 12.2.1)

39	Bergin	Michael	michael.bergin@dot.state.fl.us
40	Vinik	Paul	paul.vinik@dot.state.fl.us
41	Hasty	Charles	chasty@dot.ga.gov
42	Wu	Peter	pwu@dot.ga.gov
43	Page	Jay	jpage@dot.ga.gov
44	Johnson	Larry	ljohnson@dot.ga.gov
45	Ho	Jamie	jamie.ho@hawaii.gov
46	Pang	Gerald	gerald.pang@hawaii.gov
47	Santi	Michael	mike.santi@itd.idaho.gov
48	Beshears	Sheila	shelia.beshears@illinois.gov
49	Gawedzinski	Mark	mark.gawedzinski@illinois.gov
50	Winkelman	Melinda	melinda.winkelman@illinois.gov
51	Beeson	Matthew	mbeeson@indot.in.gov
52	Walker	Ronald	rwalker@indot.in.gov
53	Musgrove	Wes	wes.musgrove@iowadot.us
54	Ouyang	Cheng	chengsheng.ouyang@iowadot.us
55	Jones	Kevin	kevin.jones@iowadot.us
56	Brakke	Chris	chris.brakke@iowadot.us
57	Schieber	Greg	greg.schieber@ks.gov
58	Bogle	Hugh	hugh.bogle@ks.gov
59	West	Randy	randy.west@ks.gov
60	Stewart	Jeff	jeff.stewart@ks.gov
61	Gudmonson	Wayne	wayne.gudmonson@ks.gov
62	Myers	Allen	allen.myers@ky.gov
63	Semones	Robert	robert.semones@ky.gov
64	Black	Michael	michael.black@ky.gov
65	Dees	Amanda	amanda.dees@ky.gov
66	Glass	Wesley	wesley.glass@ky.gov
67	Owens	Brian	brian.owens@la.gov
68	Davis	Jason	jason.davis@la.gov
69	Caillet	David	david.caillet@la.gov
70	Gudiel	Joaquin	francisco.gudiel@la.gov
71	Charoenpap	Richie	richie.charoenpap@la.gov
72	Fu	Zhengzheng	zhengzheng.fu@la.gov
73	Taylor	Joyce	joyce.taylor@maine.gov
74	Pulver	William	william.pulver@maine.gov
75	Barot	Sejal	sbarot@sha.state.md.us
76	Wolcott	Mark	mwolcott@sha.state.md.us
77	Frempong	Eric	efrempong@sha.state.md.us
78	Pujara	Karuna	kpujara@sha.state.md.us

(Continued from Table 12.2.1)

79	Husain	Azmat	azmat.hussain@dot.gov
80	Hood	Woody	whood@sha.state.md.us
81	Akisetty	Chandra	cakisetty@sha.state.md.us
82	Murkute	Shekhar	smurkute@sha.state.md.us
83	Sajedi	Dan	dsajedi@sha.state.md.us
84	Grieco	John	john.grieco@dot.state.ma.us
85	Fung	Clement	clement.fung@dot.state.ma.us
86	Knox	Wally	wally.knox@dot.state.ma.us
87	Avery	Kim	averyk@michigan.gov
88	Chaput	Mark	chaputm@michigan.gov
89	Papanek	Deanna	papanekd@michigan.gov
90	Engstrom	Gleen	gleen.engstrom@state.mn.us
91	Kochsiek	Jim	jim.kochsiek@state.mn.us
92	Richter	Jason	jason.richter@state.mn.us
93	Masten	Maria	maria.masten@state.mn.us
94	Izvebakhai	Bernard	bernard.izvebakhai@state.mn.us
95	Garver	Rod	rod.garver@state.mn.us
96	Thompson	Darryl	dathompson@mdot.ms.gov
97	Williams	James	jwilliams@mdot.state.ms.us
98	Sullivan	Michael	msullivan@mdot.ms.gov
99	Curtis	Jeff	jcurtis@mdot.ms.gov
100	Hammons	Caleb	jchammons@mdot.ms.gov
101	Ahlvers	David	david.ahlvers@modot.mo.gov
102	Brucks	Dennis	dennis.brucks@modot.mo.gov
103	Trautman	Brett	brett.trautman@modot.mo.gov
104	Strizich	Matt	mstrizich@mt.gov
105	Jagoda	Jean	jjagoda@mt.gov
106	Needham	Matt	maneedham@mt.gov
107	Buchanan	John	jbuchanan@mt.gov
108	Bushnell	Paul	pbushnell@mt.gov
109	Jamshidi	Mostafa	moe.jamshidi@nebraska.gov
110	Syslo	Mick	mick.syslo@nebraska.gov
111	Pan	Changlin	cpan@dot.state.nv.us
112	Tedford	Darin	dtedford@dot.state.nv.us
113	Boisvert	Denis	denis.boisvert@dot.nh.gov
114	Courser	Matt	matthew.courser@dot.nh.gov
115	Amrol	Jim	jim.amrol@dot.nh.gov
116	Black	Beran	beran.black@dot.nh.gov
117	Dearborn	Susan	susan.dearborn@dot.nh.gov
118	Sheehy	Eileen	eileen.sheehy@dot.state.nj.us

(Continued from Table 12.2.1)

119	Patel	Snehal	snehal.patel@dot.state.nj.us
120	Hanczaryk	Paul	paul.hanczaryk@dot.nj.us
121	Gallegos	James	james.gallegos@state.nm.us
122	Anwar	Parveez	parveez.anwar@state.nm.us
123	Mann	Michelle	michelle.mann@state.nm.us
124	Montoya	Kelly	kellyr.montoya@state.nm.us
125	Rondinaro	John	john.rondinaro@dot.ny.gov
126	Fregoe	Daniel	dan.fregoe@dot.ny.gov
127	Bernard	David	david.bernard@dot.ny.gov
128	Stelzer	Michael	mike.stelzer@dot.ny.gov
129	Peoples	Christopher	cpeoples@ncdot.gov
130	Hunter	Brian	bhunter@ncdot.gov
131	Frederick	Samuel	sjfrederick@ncdot.gov
132	Earley	Jessica	jsearley@ncdot.gov
133	Horner	Ron	rhoner@nd.gov
134	Schumaker	Clayton	cschumak@state.nd.us
135	Lisa	Zigmund	lisa.zigmund@dot.state.oh.us
136	Cronin	Mickey	mickey.cronin@dot.state.oh.us
137	Miller	Dan	daniel.miller@dot.state.oh.us
138	Keith	Eblin	keith.eblin@dot.state.oh.us
139	Tim	Jones	tim.jones@dot.state.oh.us
140	Prasad	Kudlapur	prasad.kudlapur@dot.state.oh.us
141	Tony	Vcelka	tony.vcelka@dot.state.oh.us
142	Seiter	Scott	sseiter@odot.org
143	Seward	Kenny	kseward@odot.org
144	Clarke	Christopher	cclarke@odot.org
145	Thomas	John	jthomas@odot.org
146	Romero	Matt	mromero@odot.org
147	Squire	Joe	joe.squire@odot.state.or.us
148	Brophy	Kevin	kevin.j.brophy@odot.state.or.us
149	Cieslak	Jason	jason.cieslak@odot.state.or.us
150	Horwhat	Robert	rhorwhat@pa.gov
151	Ramirez	Timothy	tramirez@pa.gov
152	Kuniega	David	dkuniega@pa.gov
153	Wagner	Matthew	mwagner@paturnpike.com
154	Felag	Mark	mfelag@dot.state.ri.us
155	Lima	Jose	jose.lima@dot.ri.gov
156	Byrne	Michael	michael.byrne@dot.ri.gov
157	Franco	Colin	colin.franco@dot.ri.gov
158	Zwanka	Merrrill	zwankame@scdot.org

(Continued from Table 12.2.1)

159	Short	Temple	shorttk@scdot.org
160	Feller	Joe	joe.feller@state.sd.us
161	Grannes	Tom	tom.grannes@state.sd.us
162	Lane	Danny	danny.lane@tn.gov
163	Egan	Brian	brian.egan@tn.gov
164	Doran	Mike	michael.doran@tn.gov
165	Anderson	Bob	bob.anderson@tn.gov
166	Sanders	Mike	mike.sanders@tn.gov
167	Hall	Heather	heather.purdy.hall@tn.gov
168	Waller	Jamei	jamie.waller@tn.gov
169	Cain	Tracy	tracy.cain@txdot.gov
170	Hazlett	Darren	darren.hazlett@txdot.gov
171	Andrus	Scott	scottandrus@utah.gov
172	Anderson	Steve	stevenanderson@utah.gov
173	Saddler	Jeff	jsaddler@utah.gov
174	Hoyne	David	david.hoyne@vermont.gov
175	Gagulic	Mladen	mladen.gagulic@vermont.gov
176	Willette	Andy	andy.willette@vermont.gov
177	Van Den Berg	Nick	nick.vandenberg@vermont.gov
178	Wu	Chung	chung.wu@vdot.virginia.gove
179	Schuler	John	john.schuler@vdot.virginia.gov
180	Babish	Charles	andy.babish@vdot.virginia.gov
181	Bailey	William (Bill)	bill.bailey@vdot.virginia.gov
182	Crandol	Robert	robert.crandol@vdot.virginia.gov
183	Uhlmeyer	Jeff	uhlmeyj@wsdot.wa.gov
184	Williams	Kurt	willikr@wsdot.wa.gov
185	Stanevich	Ron	ron.l.stanevich@wv.gov
186	Farley	Paul	paul.m.farley@wv.gov
187	Chapman	Kelly	kelly.a.chapman@wv.gov
188	Paye	Barry	barry.paye@dot.wi.gov
189	Milburn	Greg	greg.milburn@wyo.gov
190	Rothwell	Bob	bob.rothwell@dot.state.wy.us
191	Romo	Chris	chris.romo@dot.state.wy.us
192	Quinn	Tracy	tracy.quinn@dot.state.wy.us

12.3 Survey Results - Responses from State Highway Agencies

Table 12.3.1 Survey Questions to State Highway Agencies

No.	Question
1	Does you agency allow the use of crushed recycled concrete aggregate (RCA) as an aggregate in new concrete for transportation infrastructure construction?
2	Please describe how your agency's practices or specifications differ for the use of RCA compared to virgin aggregate in concrete.
3	Which application(s) RCA is commonly (often) used?
4	What are your agency's limitations of RCA, by percent weight of total aggregate, to a new concrete mix?
5	What are your agency's testing requirements or quality control procedures for using RCA as an aggregate in concrete?
6	Has your agency encountered any problems of using RCA as an aggregate in concrete for transportation infrastructure construction?
7	Has your agency considered expanding the use of RCA as an aggregate in concrete (higher allowed percentages or for more applications)?
8	If your agency allows (or requires) using admixtures to modify any properties of concrete containing RCA, please provide details: What type of admixtures? When are they used or required?

Table 12.3.2 Responses to Question 1

Does you agency allow the use of crushed recycled RCA as an aggregate in new concrete for transportation infrastructure construction?

State	Responses (Yes/No)
Alaska	Yes
Arizona	No
California	Yes
Colorado	Yes
Connecticut	No
Florida	Yes
Hawaii	No
Illinois	Yes
Indiana	Yes
Iowa	No
Kansas	No
Kentucky	No
Louisianan	Yes
Maine	No
Maryland	No
Michigan	Yes
Minnesota	Yes
Montana	Yes
Nevada	No
New Mexico	No
New York	No
North Carolina	Yes
Ohio	Yes
Oklahoma	Yes
Oregon	Yes
Pennsylvania	No
Rhode Island	No
South Carolina	Yes
South Dakoda	No
Tennessee	No
Texas	Yes
Utah	No
Vermont	No
Virginia	Yes
Washington	Yes
Wisconsin	Yes

Table 12.3.3. Responses to Question 2

Please describe how your agency's practices or specifications differ for the use of RCA compared to virgin aggregate in concrete.

State	Responses
Alaska	RCA is a very small component of the Alaska aggregate market. It is mostly used in concrete for building foundations where the building owner is pursuing LEED or Green Building points. Alaska DOT could allow RCA mixes in similar applications on a project basis.
California	It is allowed in minor concrete not structural concrete. Minor concrete is used for curbs, gutters and sidewalks, drainage inlets, drainage end walls, median barrier and small sign foundations. Allowed 15% coarse aggregate replacement in bottom lift in two-lift concrete pavement. Also allowed use in minor concrete.
Colorado	No differences. RCA has to meet standard specifications for aggregates. Otherwise CDOT does not have a RCA spec.
Florida	RCA is allowed only in non-structural mixes.
Illinois	Concrete from a location can be utilized back into new concrete for the same location. Freeze-thaw, ASR and chloride testing has to be conducted prior to use. Although IDOT allows this use, there has been only one construction contract that has used RCA in new concrete.
Indiana	We require the use of the Hydraulic Fracture test in lieu of standard freeze-thaw aggregate testing.
Kansas	Specifications do not allow the use of RCA in concrete. The use of RCA is allowed in cement treated bases and bound drainable bases, and occasionally in aggregate bases.
Louisiana	RCA has to meet the same requirements of virgin materials.
Maryland	We use RCA for CR6 replacement for shoulder aggregate. Most RCA will not meet the ASR requirements for our mixes and we do not have a steady supply of RCA aggregate to be named as a source.
Michigan	RCA has to be freeze thaw tested along with the other physical property testing per project compared to aggregate source qualification of virgin materials. Hence, the contractors opt to not consider RCA for concrete aggregate.
Minnesota	RCA is required to be washed. RCA is allowed on a case by case basis. Concrete Engineer makes approval of use based upon past history of the specific RCA pile. We do not allow stockpiles of multi-sourced RCA to be used in concrete. Information is available on-line at the MnDOT web site under Construction Specifications.
Montana	Currently our specifications allow for any aggregates, including recycled aggregates, to be used provided they meet our overall requirements of aggregate used in concrete. We have not had a project to-date that has utilized recycled concrete.
Nevada	The mineral aggregate shall be the product of approved deposits.
New York	RCA is not allowed in new concrete. RCA is only allowed as a granular material (embankment, subbase, etc.).
North Carolina	Class B concrete only.

(Continued-1 from Table 12.3.3)

Ohio	For Structural Backfill some quality specifications are waived if it can be proven that the aggregate met specification at the time of concrete production. For Embankment use this material is required to be blended with a minimum of 30% natural material. http://www.dot.state.oh.us/Divisions/ConstructionMgt/Specification%20Files/1117_01152016_for_2016.pdf Supplement 1117 describes the aggregate requirements along with the other special testing that is required when RCA is to be reclaimed and used in a concrete pavement.
Oklahoma	Our specifications for RCA or virgin aggregate don't differ. It can used in bases, but currently not in concrete. We did a couple of projects in the early 80's but none since then. Our specifications don't mention RCA, but it is allowed under our reference to AASHTO M80.
Oregon	If a contractor would like to use RCA, they have to have the material pre-approved and the same tests of the materials must pass the same specifications as virgin aggregate.
Pennsylvania	RCA can only be used as subbase. It must be recycled concrete from a Department, county or municipal project. We run quality test on it - except for sodium sulfate.
Rhode Island	RIDOT's specifications states that coarse aggregate for concrete must be either screened gravel, crushed gravel, or crushed quarry rock all from a single source location. The specifications do not mention RCA. RCA is not used in Rhode Island.
South Carolina	The use of recycled PCC pavement as coarse aggregate in the new PCC pavement mixture will be allowed at the option of the contractor with the following qualifications. Only aggregate derived from this project existing pavement is permitted. Recycled PCC pavement fine aggregate will not be allowed. Coarse Aggregate must meet the requirements of Subsection 701.2.10, except that the LA Abrasion and Sulfate Soundness requirements do not apply. All joint sealant and backer rod material must be removed from the existing pavement prior to removal for recycling. Ensure that the resulting recycled aggregate is free from steel reinforcement and other contaminants. Aggregates derived from limestone or slag are not allowed. Absorption of Coarse Aggregate shall not exceed 10 percent. A quality control plan for the production of recycled aggregates must be approved by SCDOT prior to beginning production. This plan must include consideration for controlling moisture content, stockpile management, and trial batching.
Tennessee	TDOT has recently performed research of multiple suppliers throughout the state on various recycled concrete aggregate for use as 100% base material. We have a proposed specification that has not been approved for full acceptance in the TDOT specifications. It is up for vote in the next few weeks. We do not allow RCA at all in concrete for TDOT projects.
Texas	RCA is not subject to magnesium soundness testing and requirements.
Vermont	We currently do not have a specification for use of RCA, and the use of RCA has not been a priority of industry.

(Continued-2 from Table 12.3.3)

Virginia	Crushed hydraulic cement concrete will be permitted for use as a coarse aggregate provided it conforms to the physical requirements specified in the Virginia DOT Road and Bridge Specifications, Section 203 and shows no adverse chemical reaction. Crushed hydraulic cement concrete will not be permitted in the following: (1) reinforced cement concrete, (2) in combination with other materials in contact with geotextile fabric when such fabric is used as a drainage item, and (3) in backfill or bedding for perforated pipe. Our Spec 203 allows CHCC (RCA) as coarse aggregate provided it conforms to the physical requirements of the spec and shows no adverse chemical effect, and it is not permitted in reinforced concrete, or as aggregate where there is textile wrapped underdrain in contact with it, or in backfill or bedding of perforated pipe. We are completing a research study which may allow CHCC use up to 40% in a blend with virgin aggregate in base course even with textile wrapped underdrain in contact with it.
Washington	Recycled concrete aggregates are coarse aggregates manufactured from hardened concrete mixtures. 9-03.21(1) B Recycled Concrete Aggregate Recycled concrete aggregates are coarse aggregates manufactured from hardened concrete mixtures. Recycled concrete aggregate may be used as coarse aggregate or blended with coarse aggregate for Commercial Concrete and Controlled Density Fill.
Wisconsin	Use of RCA is not allowed in open graded base course. RCA must originate from a previous pavements/structures on WisDOT projects with known satisfactory properties and service record. RCA from mixed source recycling centers is not allowed.

Table 12.3.4. Responses to Question 3

Which application(s) RCA is commonly (often) used?

	Usage												
State	Sidewalks	Curb &gutter or slopes	Footings for lighting, signs or fences	Median barriers	Pipe or pull box filler	Lean concrete base	Controlled low strength material	Culvert backfill	Low volume roads	High volume roads/ highways	Bridge substructures	Bridge superstructures	Other applications
Alaska					x	x	x	x					
California	x	x	x	x	x	x	x	x					
Colorado	x	x	x	x	x	x	x	x	x	x	x	x	Lean concrete base
Florida								x					
Illinois										x			
Indiana													(Not indicated)
Kansas						x		x					Cement treated base
Louisiana													(Not indicated)
Minnesota	x	x	x		x				x	x			
Montana													(Not indicated)
North Carolina													Class B concrete
Ohio	x	x						x	x	x			Dump rock
Oklahoma	x	x	x							x			
Pennsylvania													(Not indicated)
South Carolina										x			
Tennessee							x	x					
Texas										x	x	x	
Virginia	x					x	x	x	x				roller compacted concrete
Washington	x	x					x						
Wisconsin	x	x		x		x				x			

Table 12.3.5. Responses to Question 4

What are your agency's limitations of RCA, by percent weight of total aggregate, to a new concrete mix?

State	Responses
Alaska	Agency has not established criteria. Only one concrete supplier in Alaska makes a RCA mix. This supplier uses RCA at a 50% substitution rate for the Coarse Aggregate.
California	There is not a prescriptive limitation or requirement for use. Maximum 15 percent replacement of coarse aggregate in bottom lift in two-lift concrete pavement. Fine RCA is not allowed. Mo limitation in minor concrete.
Colorado	Coarse aggregate applications only. Concrete fines not used in mixes. The contractor sets the target values.
Florida	No limit if used in nonstructural mix. Otherwise no usage allowed.
Illinois	No limit on coarse aggregate manufactured sand is limited to 50% of total fine aggregate.
Indiana	50%.
Louisiana	None.
Michigan	No limitations. However, contractors do not propose its use in concrete.
Minnesota	There is no current limit. RCA would be expected to meet all of the same quality requirements that a virgin aggregate would meet. Information is available on-line at the MnDOT web site under Construction Specifications.
Montana	No limit established at this point.
Nevada	No limitation.
New Mexico	0%.
North Carolina	None.
Ohio	The coarse aggregate portion may be replaced up to 100% with RCA. Supplement 1117.05 describes the requirements for mix design submittals.
Oklahoma	Limitations are not mentioned in our specifications.
Oregon	0%.
South Carolina	We do not limit by weight, but only allow use as coarse aggregate.
Texas	100% for coarse aggregate and 20% maximum for fine aggregate.
Virginia	VDOT has no limitations provided the following criteria are met: Crushed hydraulic cement concrete will be permitted for use as a coarse aggregate provided it conforms to the physical requirements specified in the VDOT Road and Bridge Specifications, Section 203 and shows no adverse chemical reaction. Crushed hydraulic cement concrete will not be permitted in the following: (1) reinforced cement concrete, (2) in combination with other materials in contact with geotextile fabric when such fabric is used as a drainage item, and (3) in backfill or bedding for perforated pipe.
Washington	No limit for the application listed in Question 3.
Wisconsin	Coarse aggregate = 100%; Fine aggregate = 0%.

Table 12.3.6. Responses to Question 5

What are your agency's testing requirements or quality control procedures for using RCA as an aggregate in concrete?

State	Responses
Alaska	Same as for regular concrete.
California	It is treated as aggregate. All property requirements for aggregate must be met. RCA should be from concrete pavement gradation, sand equivalent.
Colorado	Must meet specification applicable to virgin aggregates. 28-day flexural strength, 28-day compressive strength, moisture content, air content, unit weight, yield, slump, temperature, water/cementitious ratio, sand equivalent.
Florida	Gradation, minus 200, LA Abrasion, various deleterious materials.
Illinois	Prior to use, Freeze-thaw, ASR and Chloride testing.
Louisiana	Meet AASHTO T96, T104, and meet gradation.
Maryland	ASR TCLP
Michigan	All properties associated with virgin, LA Abrasion, deleterious, freeze thaw, LBW, gradation, etc.
Minnesota	No additional procedures currently established for RCA. I would anticipate additional testing on the % absorption of the material would be expected. Info is available on-line at the MnDOT web site under Construction Specifications.
Montana	No established qc pertinent to RCA at this point in time.
North Carolina	Same as for virgin aggregate with the exception of sodium sulfate soundness.
Ohio	Supplement 1117.07 Controls Develop and implement a quality control plan for aggregate production that details the production procedures, testing methods and testing frequencies that will ensure consistent material and that the recycled concrete aggregate meets the requirements of this specification. Provide the following controls on the RCA and the concrete during construction: 1. Stockpile the RCA in increments of no more than 5000 tons (4500 metric tons) and test the absorption and specific gravity of the RCA prior to use. Use the information to make batch adjustments as necessary and do not use RCA with an absorption exceeding 7%. 2. Maintain all coarse aggregate above SSD moisture during concrete production by stockpile watering. a. Test the moisture content of all aggregates at the beginning of each day's production and retest at least every for 1000 yd3 (765 m^3) of concrete thereafter. 3. Test gradation of all aggregates daily to maintain gradation within specification limits and adjust mix proportions if necessary to stay within the original gradation. 4. Establish a slump range for the mix for each method of placement, and control the mixes within the established range. Submit the slump range to the Engineer for acceptance. 5. Remove wash water from the mixer prior to batching concrete. 6. If during the work, the specific gravity changes by more than 0.02 from the original design, adjust the design weight to conform to the new specific gravity.

(Continued from Table 12.3.6)

Ohio (cont'd)	7. Adjust the amount of water added at the mixer based on the moisture in the aggregate and the moisture the aggregate will absorb. Do not exceed maximum established water/cementitious ratio. 8. Use an approved set-retarding admixture conforming to 705.12, type B or D when the concrete temperature exceeds 75 ^oF (24 ^oC). 9. Test the air content, slump, unit weight and temperature on the first 3 loads. If consistent to the Engineers satisfaction, extend testing to every 5 loads of concrete or as directed by the Engineer. a. Maintain the air, yield and temperature within the specification requirements and slump within the established range. 10. Make beams for strength specimens twice a day at the Engineer's direction. Perform air, slump, yield and temperature tests when strength specimens are made. Ensure that the pavement obtains 600 psi (4.1 MPa) modulus of rupture before subjecting the pavement to traffic. Do not allow moisture runoff from RCA stockpiles to enter streams or groundwater.
Oklahoma	Not specifically mentioned in our specifications.
Oregon	They must meet the same specification requirements as virgin aggregate. Sulfate soundness, LAR, gradation, Oregon Air Degrade, light weight particles, organics.
South Carolina	We require a contractor QC plan for production, it must come from one source. Usually a pavement that is being removed and replaced. We have only utilized it on one large scale project due to issues with absorption. We do limit to 10% absorption.
Virginia	Same as virgin aggregate, plus ensure no chemically adverse effects. The testing requirements are found at the following link in Section 203: http://www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf
Washington	Deleterious material, LA wear, degradation factor and gradation.
Wisconsin	Gradation testing Source must come from WisDOT project with known properties/service record.

Table 12.3.7. Responses to Question 6

Has your agency encountered any problems of using RCA as an aggregate in concrete for transportation infrastructure construction?

State	Responses
Alaska	No
Arizona	No
California	No
Colorado	No
Florida	No
Illinois	No
Indiana	Yes
Kansas	No
Kentucky	No
Louisiana	Yes
Maryland	No
Michigan	Yes
Minnesota	No
Montana	No
Nevada	No
New Mexico	No
North Carolina	No
Ohio	No
Oklahoma	No
Oregon	No
Pennsylvania	No
Rhode Island	No
South Carolina	Yes
Tennessee	No
Texas	No
Utah	No
Vermont	No
Virginia	No
Washington	No
Wisconsin	Yes

Table 12.3.8 Responses to Question 7

Has your agency considered expanding the use of RCA as an aggregate in concrete (higher allowed percentages or for more applications)?

State	Responses
Alaska	No
Arizona	No
California	Yes
Colorado	No
Florida	No
Illinois	Yes
Indiana	No
Kansas	No
Kentucky	No
Louisiana	No
Maryland	No
Michigan	No
Minnesota*	Yes/No
Montana	No
Nevada	No
New Mexico	No
North Carolina	No
Ohio*	Yes/No
Oklahoma	Yes
Oregon	No
Pennsylvania	No
Rhode Island	No
South Carolina	Yes
Tennessee	No
Texas	Yes
Utah	No
Vermont	No
Virginia	Yes
Washington	Yes
Wisconsin	No

**Two persons from each of the Minnesota and Ohio state responded, one responded "Yes" and one responded "No".*

Table 12.3.9. Responses to Question 8

If your agency allows (or requires) using admixtures to modify any properties of concrete containing RCA, please provide details: What type of admixtures? When are they used or required?

State	Responses
Alaska	Water reducers and air entrainment are commonly used but not required.
Colorado	No difference from virgin mixes. Ready Mixed suppliers follow industry standards and make mixes containing RCA comply with specs and contractor demands. The main problem encountered in production is the higher absorption (2+ to 6%) which requires the contractor to keep the stockpiles watered during production.
Illinois	IDOT has not researched this.
Michigan	Not considered, to date
Montana	We don't use RCA
Montana	Allow all types of admixtures A-F. Require Concrete Engineer approval to use C & E in concrete. We also allow Type S - VMAs. Have discussed Type S - SRA - but not used to this point.
North Carolina	Same process as for virgin aggregates.
Ohio	See Supplement 1117 with regards to air content requirements and the use of chemical admixtures in concrete with RCA.
Oklahoma	No experience with this issue. The last use of RCA in concrete was in the 1990's.
Texas	Water reducing admixtures/plasticizers are commonly used in all concrete including mixes containing RCA.
Utah	Don't allow use of RCA in concrete
Virginia	The chemical and mineral admixtures are the same as used in concrete containing virgin aggregate.
Virginia	We know CHCC will not pass LL test, so waive that requirement.
Washington	Contractor provided mix designs.
Wisconsin	None different than standard concrete mixtures

Table 12.3.10. Website links of your agency uses for RCA as an aggregate in concrete

State	Responses
Alaska	Agency has not written any standards for use of RCA, but we would allow use of the only RCA mix made by one supplier on a case by case basis in the four applications noted earlier.
California	See Section 90-2.02C http://www.dot.ca.gov/hq/esc/oe/construction_contract_standards/std_specs/2015_StdSpecs/2015_StdSpecs.pdf
Colorado	https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/standard-special-provisions/section-700-revisions/703ca/view
Florida	No specific differences. Section 347 Portland Cement Concrete - Class NS at http://www.fdot.gov/programmanagement/Implemented/SpecBooks/July2017/Files/717eBook.pdf
Illinois	http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Materials/Aggregate/7-08.2recyclingportlandcementconcrete.pdf
Kansas	http://www.ksdot.org/Assets/wwwksdotorg/bureaus/burConsMain/specprov/2015/1105.pdf
Maryland	www.marylandroads.com section 902 for ASR requirements
Michigan	www.michigan.gov/specbook. Section 902.
Minnesota	http://www.dot.state.mn.us/pre-letting/spec/2016/2016specbook.pdf Spec 3137 is the Coarse Aggregate Specification for Portland Cement Concrete.
Montana	No specific standards pertaining to RCA at this time. Our Standard Specifications can be found at: http://www.mdt.mt.gov/other/webdata/external/const/specifications/2014/2014_stand_specs.pdf current changes to our standard specifications can be found at: http://www.mdt.mt.gov/other/webdata/external/const/specifications/2014/2014_supplemental_specs/SUPPLEMENTAL_SPECIFICATIONS_Let_2017-01-19.pdf
North Carolina	https://connect.ncdot.gov/resources/Specifications/Pages/2012StandSpecsMan.aspx?Order=SM-10-1043
Ohio	http://www.dot.state.oh.us/Divisions/ConstructionMgt/Specification%20Files/1117_01152016_for_2016.pdf http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Specifications/2016CMS/2016_CMS_01202017_for_web_letter_size_with_SS800_Included.pdf
Oklahoma	Not available. The last use of RCA in concrete was in the 1990's.
Oregon	http://www.oregon.gov/ODOT/HWY/SPECS/pages/standard_specifications.aspx
Pennsylvania	I can send the standard for RCA used as a subbase. We do not allow its use anywhere else.
Tennessee	TDOT has a proposed specification that is up for vote very soon. Currently we only allow it for a percentage of aggregate base material. TDOT Specification included below. Section 903.05: Aggregate for Mineral Aggregate Base and Surface Course and 903.15: Aggregate for Aggregate-Cement Base Course http://www.tn.gov/assets/entities/tdot/attachments/TDOT_2015_Spec_Book_FINAL_pdf.pdf
Texas	Refer to Item 421 of the 2014 Standard Specifications Book at the following link: http://www.txdot.gov/inside-txdot/division/construction/txdot-specifications.html
Virginia	http://www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf (S. 217)
Washington	WSDOT Standard Specification 6-02.3(2)A Commercial Concrete 6-02.3(2)B http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS2016.pdf

Table 12.3.11. Additional comments on use of RCA in concrete

State	Responses
Alaska	While we would allow RCA mixes for some applications, so little of it is produced in Alaska that I do not think any has been placed on a DOT project to date.
Arizona	Not Allowed
California	It has been permitted in lean concrete base for decades. It has also been permitted as aggregate base for decades. Its use in minor concrete has only been permitted for a few years and it is probably not done much because a producer would need to have another stockpile and weigh hopper. Caltrans allow use of returned plastic concrete replacing 15 percent of new plastic concrete for minor concrete for gutters and sidewalks. Caltrans is working with Industry to maximize utilization of RCA in concrete pavement.
Colorado	Please see Subsection 601.05 from the attached link on CDOT's specifications for mix designs: https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/2011-specs-book/section_600.pdf/view Please see the attached link for workability specifications: https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/standard-special-provisions/section-600-revisions/601cbbz/view
Florida	Although our Specifications allow its use in non-structural concrete, all our facilities choose to crush and sell as an unbound base material.
Indiana	We allowed the use of RCA in concrete two years ago. To date, no Contractors have elected to use the material. Due to the lack of interest, we are planning on removing the provisions allowing RCA in concrete in the near future.
Louisiana	Louisiana DOTD does not prohibits the use of RCA in concrete mixes but it is not used by the concrete producers because its high degree of absorption.
Maryland	MD-SHA is using the RCA to replace with the virgin Graded aggregate base in the pavement system.
Minnesota	With the low w/c ratio specifications for our concrete pavements, use of recycled has been very difficult to produce to the great variability in water demand.
Ohio	Currently we do not have any mixes where the Supplement has been used. Most of our RCA materials are dump rock and other erosion control protection items. We do not allow RCA as an aggregate base due to research that found tufa in under drains that caused extensive clogging and allowed for high pH water to runoff and into streams and farm land (not well received by EPA).
Oklahoma	The availability of good quality RCA is limited. In our experience, RCA of suitable quality is only available from the removal of existing pavements on ODOT projects. Projects involving the total removal and replacement of concrete pavements are not all that common. When it does occur, the RCA is incorporated in the unbound aggregate base layer.
Oregon	Industry has not requested the use of RCA in ODOT structural concrete very often. We allowed its use as a pilot project a couple years ago on some mass footings; the contractor was able to salvage the RCA from the bridge they were replacing. The performance was satisfactory and we would certainly consider its use again, however the demand for it hasn't been there.
South Carolina	We include it as an option for the contractor rather than requiring it. We have found that material properties sometimes may not be favorable for use as a recycled aggregate and can vary.

(Continued from Table 12.3.11)

Tennessee	New specification for the use of 100% RCA should be included in the supplemental specifications in the summer of 2017.
Texas	RCA was used as 100% of the fine aggregate early on however we had workability issues and therefore reduced the max allowable RCA fine aggregate to 20%.
Virginia	VDOT does not use RCA in new concrete. However, VDOT does allow the use of crushed concrete as coarse aggregate doe aggregate base, cement treated aggregate base, shoulder stone, etc. Trying to determine the amount of cement added using a titration method has been problematic. VDOT "2016 Road and Bridge Specification Book" Section 203.02(a) details the requirement. see the link below: http://www.virginiadot.org/business/const/spec-default.asp

12.4 Survey List to Ready Mix Concrete Producers

Table 12.4.1 List of Ready Mix Concrete Companies Contacted

No.	Company Name	Address	Email Address
1	Chandler Concrete Co.	P. O. Box 131, Burlington NC 27216-0131	bob.chandler@chandlerconcrete.com
2	Chandler Concrete Co.	P. O. Box 131, Burlington, NC 27216-0131	tom.chandler@chandlerconcrete.com
3	Chandler Concrete Co.	P. O. Box 131, Burlington , NC 27216-0131	jeff.hinkle@chandlerconcrete.com
4	Chandler Concrete Co.	P. O. Box 131, Burlington, NC 27216-0131	ken.waegerle@ChandlerConcrete.com
5	RALEIGH Ready Mixed concrete Company	P. O. Box 27326, Raleigh, NC 27611	Don.Bennett@rmcc.corn
6	WINTON Commercial Ready Mixed Products Inc.	P. O. Box 189, Winton, NC 27986	tommyc@crmpinc.com
7	Commercial Ready Mixed Products Inc.	P. O. Box 189, Winton, NC 27986	charlesh@crmpinc.com
8	Commercial Ready Mixed Products Inc.	P. O. Box 189, Winton, NC 27986	timn@crmpinc.com
9	Essroc Ready Mix	P. O. Box 4336, Pakersburg, WV 26104	doug.rexroad@essroc.com
10	Lakeside Ready Mix	P. O. Box 1144, Abingdon, VA 24212-1144	debbie@lakesidereadymix.com
11	Wright's Ready-Mix	P. O. Box 401, Amelia, VA 23002	info@wrightsreadymix.com
12	Lynchburg Ready Mix Concrete Co., Inc.	897 Amherst Highway, Amherst, VA 24521	jblueoystercult@aol.com
13	Green Rock Materials, LLC	11340 Virginia Crane Drive, Ashland, VA 23005	skerr@greenrock.net
14	Essex Concrete Corporation	15700 Richmond-Tappahannock Hwy Aylett, VA 23009	rdarby@essexconcrete.com
15	Bedford Ready Mix Concrete Co., Inc.	805 Railroad Avenue, Bedford, VA 24523	sburns@Irmcc.com
16	S.B. Cox Ready-Mix, Inc.	800 Dearing Avenue, Blackstone, VA 23824	kgarrett@coxreadymix.com
17	Boxley	139 Healing Springs Road, Blue Ridge, VA 24064	trussell@boxley.com
18	Boxley	191 St. Claires Crossing, Bluefield, VA 24605	sgeso@boxley.com
19	R. R. Beasley, Inc.	P. O. Box 719, Callao, VA 22435	BeasleyConcrete@VABB.com
20	Titan Virginia Ready-Mix LLC	15700 Lee Highway, Centreville, VA 20120	dacott@titanamerica.com

(Continued from Table 12.4.1)

21	DuBrook Concrete Inc.	4215 Lafayette Center Drive, #1 Chantilly, VA 20151	tjones@dubrookconcrete.com
22	DuBrook Concrete Inc.	4215 Lafayette Center Drive, #1 Chantilly, VA 20151	togorchock@dubrooklIc.com
23	DuBrook Concrete Inc.	4215 Lafayette Center Drive, #1 Chantilly, VA 20151	craggio@dubrookconcrete.com
24	Allied Concrete Company	P. O. Box 1648, Charlottesville, VA 22902	vbush@eaglecorpusa.com
25	Allied Concrete Company	P. O. Box 1647, Charlottesville, VA 22903	tcobb@allied-concrete.com
26	Allied Concrete Company	1000 Harris Street, Charlottesville, VA 22902	phawes@allied-concrete.com
27	Allied Concrete Company	P. O. Box 1648, Charlottesville, VA 22902	tknight@allied-concrete.com
28	Allied Concrete Company	977 Seminole Trail, #177 Charlottesville, VA 22901	pjm@eagle-corp.com
29	Allied Concrete Company	1000 Harris Street, Charlottesville, VA 22903	bmotuk@allied-concrete.com
30	Allied Ready-Mix	P. O. Box 1647, Charlottesville, VA 22902-1647	dpettit@allied-concrete.com
31	Allied Concrete Company	P. O. Box 1647, Charlottesville, VA 22902-1647	rwatkins@allied-concrete.com
32	Wilson Ready Mix LLC	3906 Seminole Trail, Charlottesville, VA 22911	bryan@wilsonreadymix.com
33	Wilson Ready Mix LLC	3906 Seminole Trail, Charlottesville, VA 22911	rodney@wilsonreadymix.com
34	Commercial Ready Mixed Products Inc.	1888 S Military Highway, Cheapeake, VA 23322	dano@crmpinc.com
35	Vulcan Construction Materials LP	5601 lronbridge Parkway, Suite 201, Chester, VA 23831	mearsw@vmcmail.com
36	Vulcan Construction Materials LP	5601 Ironbridge Parkway, Suite 201, Chester, VA 23831	adamsonb@vmcmail.com
37	Vulcan Construction Materials LP	5601 lronbridge Parkway, Suite 201, Chester, VA 23831	beckw@vmcmail.com
38	CEVA Ready Mix	5601 lronbridge Parkway, Suite 201, Chester, VA 23831	millerto@vmcmail.com
39	Vulcan Construction Materials LP	5601 lronbridge Parkway, Suite 201, Chester, VA 23831	pearcep@vmcmail.com
40	Chandler Concrete Co.	700 Block Lane, Christiansburg, VA 24073	junior.adkins@chandlerconcrete.com
41	Chandler Concrete Co.	700 Block Lane, Christiansburg, VA 24073	george.kuhn@chandlerconcrete.com
42	Chandler Concrete Co.	700 Block Lane, Christiansburg, VA 24073	bret.queen@chandlerconcrete.com
43	Titan Virginia Ready-Mix LLC	1383 Brucetown Road, Clear Brook, VA 22624	bcutright@titanamerica.com

(Continued from Table 12.4.1)

44	Chandler Concrete Co.	1503 Main Street, Altavista, VA 24517	aubrey.owen@chandlerconcrete.com
45	Essex Concrete Corporation	12068 Stone Quarry Drive Doswell, VA 23047	tpenny@essexconcrete.com
46	Chandler Concrete Co	5488 Bagging Plant Road, Dublin, VA 24084	mike.edwards@chandlerconcrete.com
47	Rockingham Redi-Mix Inc.	15884 Old Spotswood Trail, Elkton, VA 22827	todd.mccoy@conmatgroup.com
48	Titan Virginia Ready-Mix LLC	48 Powell Lane, Falmouth, VA 22405	cgillis@titanamerica.com
49	Wilson Ready Mix LLC	46 Wilshire, Fishersville, VA 22939	todd@wilsonreadymix.com
50	Chaney Enterprises	8520 Indian Hills Court, Fredericksburg, VA 22407	bdunigan@chaneyenterprises.com
51	Rappahannock Concrete Corporation	P. O. Box 520, Gloucester, VA 23061	sfinney@raperete.com
52	Rappahannock Concrete Corporation	P. O. Box 520, Gloucester, VA 23061	tjohnson@raperete.com
53	Vulcan Materials Company	808 Kiwanis Street, Hampton, VA 23661	goldenb@vmcmail.com
54	Rockingham Redi-Mix Inc.	P. O. Box 1347, Harrisonburg, VA 22803	buddy.murtaugh@conmatgroup.com
55	Rockingham Redi-Mix Inc.	P. O. Box 1347, Harrisonburg, VA 22803	roy.simmons@conmatgroup.com
56	Superior Concrete Inc.	P.O. Box 1147, Harrisonburg, VA 22803	sboshart@superiorconcreteinc.com
57	Superior Concrete Inc.	P. O. Box 1147, Harrisonburg, VA 22803	kwilt@superiorconcreteinc.com
58	Vulcan Materials Company Diggs Bishop	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	bishopd@vmcmail.com
59	Vulcan Materials Company	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	bishopm@vmcmail.com
60	Vulcan Materials Company	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	foleyt@vmcmail.com
61	Vulcan Materials Company	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	scotte@vmcmail.com
62	Vulcan Materials Company	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	sniderd@vmcmail.com
63	Vulcan Materials Company	13880 Dulles Corner Lane, Suite 450, Herndon, VA 20171	terryk@vmcmail.com
64	Titan Virginia Ready-Mix LLC	42105 Cochran Mill Road, Leesburg, VA 20175	clunsford@titanamerica.com
65	Charles W. Barger & Son Cons. Co. Inc.	10 Bordens School Lane, Lexington, VA 24450	cbarger@cwbarger.com
66	Vulcan Materials Company	8115 Mims Street, Lorton, VA 22079	meetred@vmcrnail.com

(Continued from Table 12.4.1)

67	Lynchburg Ready Mix Concrete Co., Inc.	P. O. Box 10066, Lynchburg, VA 24506	hatrick893@aol.com
68	Lynchburg Ready Mix Concrete Co., Inc.	P. O. Box 10066, Lynchburg, VA 24506	jlandes@Irmcc.com
69	Lakeside Ready Mix, Inc.	5055 Lee Highway, Marion, VA 24354	rusty@lakesidereadymix.com
70	Boxley	201 Koehler Road, Martinsville, VA 24112	dkirks@boxley.com
71	Powhatan Ready Mix	3501 Warbro Road, Midlothian, VA 23112	flusby@powmix.com
72	Powhatan Ready Mix	3501 Warbro Road, Midlothian, VA 23112	dreed@powmix.com
73	Powhatan Ready Mix	3501 Warbro Road, Midlothian, VA 23112	jwallis@powmix.com
74	Titan Virginia Ready-Mix LLC	3501 Warbro Road, Midlothian, VA 23112	jdetmer@titanamerica.com
75	MILFORD R. R. Beasley, Inc.	P. O. Box 322, Milford, VA 22514	BeasleyConcretelnc@hotmail.com
76	Vulcan Materials Company	700 Shields Road, Newport News, VA 23608	wrightsh@vmcmail.com
77	Capital Concrete Inc.	P. O. Box 1137, Norfolk, VA 23501	sarah@capitalconcreteinc.com
78	Capital Concrete Inc.	P. O. Box 1137, Norfolk, VA 23501	jim@capitalconcreteinc.com
79	Capital Concrete Inc.	P. O. Box 1137, Norfolk, VA 23501	boo@capitalconcreteinc.com
80	Capital Concrete Inc.	P. O. Box 1137, Norfolk, VA 23501	helen@capitalconcreteinc.com
81	Titan Virginia Ready-Mix LLC	2125 Kimball Terrace, Norfolk, VA 23504	jconnolly@titanamerica.com
82	Titan Virginia Ready-Mix LLC	2125 Kimball Terrace, Norfolk, VA 23504	jtrefry@titanamerica.com
83	T & W Block Inc. www.twblock.com	P. O. Box 487 Onley, VA 23418	tammyhill@twblock.com
84	T & W Block Inc.	P. O. Box 487 Onley, VA 23418	gwalker@twblock.com
85	Essex Concrete Corporation	2315 Pocahontas Trail, Quinton, VA 23141	asidell@essexconcrete.com
86	Ready-Mix Operations	P. O. Box 810, Quinton, VA 23141	Ilamb@greenrock.net
87	Powhatan Ready Mix	111 Nicholson Street, Richmond, VA 23231	barrington@powmix.com
88	Ready Mixed Concrete Company	P. O. Box 11063, Richmond, VA 23230	wayne.bracey@rmcc.com
89	Ready Mixed Concrete Company	Old Stage Road, P. O. Box 11063, Richmond, VA 23230	david.cayton@rmcc.com

(Continued from Table 12.4.1)

90	Ready Mixed Concrete Company	Warbro Road, P. O. Box 11063 Richmond, VA 23230	sterling.durham@rmcc.com
91	Ready Mixed Concrete Company	Bryan Park, P. O. Box 11063, Richmond, VA 23230	robert.ehrlick@rmcc.com
92	Ready Mixed Concrete Company	P. O. Box 11063, Richmond, VA 23230	troy.ferdinand@rmcc.com
93	Ready Mixed Concrete Company	P. O. Box 11063, Richmond, VA 23230	matthew.jones@rmcc.com
94	Ready Mixed Concrete Company	P.O. Box 11063, Richmond, VA 23230	scott.mogel@rmcc.com
95	S.B. Cox Ready-Mix, Inc.	12554 West Broad Street, Richmond, VA 23233	kgoode@coxreadymix.com
96	S.B. Cox Ready-Mix, Inc.	12554 West Broad Street, Richmond, VA 23233	cparker@coxreadymix.com
97	S.B. Cox Ready-Mix, Inc.	12554 West Broad Street, Richmond, VA 23233	dzabrosky@coxreadymix.com
98	Boxley	P. O. Box 13527, Roanoke, VA 24035	aboxley@boxley.com
99	Boxley	P. O. Box 13527, Roanoke, VA 24035	Ibullock@boxley.com
100	Boxley	P. O. Box 13527, Roanoke, VA 24035	swoolwine@boxley.com
101	Boxley	P. O. Box 13527, Roanoke, VA 24035	jperkins@boxley.com
102	Chandler Concrete Co.	P. O. Box 12462 Roanoke, VA 24025	kevin.smith@chandlerconcrete.com
103	Titan America Mid-Atlantic Business Unit	188 Summerfield Court, Suite 201, Roanoke, VA 24019	rsells@titanamerica.com
104	Essex Concrete Corporation	2391 Lanier Road, Rockville, VA 23146	blarochelle@essexconcrete.com
105	Turner's Ready Mix	150 Cliff Street, Rocky Mount, VA 24151	concretemx@gmail.com
106	Chandler Concrete Co.	22 Seventh Street, Salem, VA 24153	steve.bernard@chandlerconcrete.com
107	SPRINGFIELD Titan Virginia Ready-Mix LLC	6600 Electronic Drive, Springfield, VA 22151	bdulaney@titanamerica.com
108	Titan Virginia Ready-Mix LLC	22963 Concrete Plaza, Sterling, VA 20166	mfullilove@titanamerica.com
109	Farmer's Service Company, Inc.	865 Main Street, Smithfield, VA 23430	gholloway@farmerserv.com
110	Farmer's Service Company, Inc.	865 Main Street, Smithfield, VA 23430	Ignieski@farmserv.com
111	Felton Brothers Transit Mix	P. O. Box 463 South, Boston, VA 24592	feltonbr@embarqmail.com

(Continued from Table 12.4.1)

112	Titan Virginia Ready-Mix LLC	22963 Concrete Plaza, Sterling, VA 20166	bhorton@titanamerica.com
113	Titan Virginia Ready-Mix LLC	22963 Concrete Plaza, Sterling, VA 20166	ttichacek@titanamerica.com
114	Titan Virginia Ready-Mix LLC	22963 Concrete Plaza, Sterling, VA 20166	jwoerl@titanamerica.com
115	Essex Concrete Corporation	P. O. Box 127, Tappahannock, VA 22560	mainoffice@essexconcrete.com
116	Essex Concrete Corporation	P. O. Box 127, Tappahannock, VA 22560	markt@essexconcrete.com
117	Branscome Inc.	21266 Fairgrounds Road, Tasley, VA 23441	hubbards@branscome.com
118	Rappahannock Concrete Corporation	7480 Ready Mix Drive, West Point, VA 23181	ppetke@raperete.com
119	Branscome Inc.	432 McLaws Circle, Williamsburg, VA 23185	bundym@branscome.com
120	Branscome Inc.	432 McLaws Circle, Williamsburg, VA 23185	kowalskij@branscome.com
121	Branscome Inc.	432 McLaws Circle, Williamsburg, VA 23185	lipscombj@branscome.com
122	WINCHESTER Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	john.carter@essroc.com
123	Construction Materials-US Region	P. O. Box 4099, Winchester, VA 22604	brent.edwards@essroc.com
124	Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	leann.hamman@essroc.com
125	Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	duane.laughlin@essroc.com
126	Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	larry.rudy@essroc.com
127	Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	marty.shurina@essroc.com
128	Essroc Ready Mix	P. O. Box 4099, Winchester, VA 22604	tommy.tilling@essroc.com
129	Boxley	1050 Church Street, Wytheville, VA 24382	tbass@boxley.com
130	A-1 Ready Mix	111 Industrial Pkwy., West Hayward, CA 94544	jack@a1readymix.net
131	ABC Ready Mix	P. O Box 99, Elverta, CA 95626	kholzmeister@abcreadymix.com
132	Ace Ready Mix, Inc.	2001 North Bahnson Avenue, Sioux Falls, SD 57103-6160	owen.matson@acereadymix.com
133	Acme Readymix Ltd., LLP	2705 CR 342, Alice, TX 78332	acmereadymix@gmail.com
134	Advance Ready Mix Concrete, Inc.	161 N. Shelby Street, Louisville, KY 40202	camilla@advancereadymix.com

(Continued from Table 12.4.1)

135	Advanced Ready Mix, Inc.	5720 Observation Court, Colorado Springs, CO 80916	larryarmi@aol.com
136	Aggregates USAA Ready Mix USA Company	2209 Blount Avenue, Knoxville, TN 37920	buckp@aggregatesusa.com
137	All American Redi-Mix, LLC	4950 E. Bannnister Road, Kansas City, MO 64134	allamericanredimix@msn.com
138	All Ohio Ready Mix A Division of the Shelly Company	7901 Sylvania Avenue, Sylvania, OH 43560	bperry@shellyco.com
139	Alpha Ready Mix LLC	212 Investment Loop, Hutto, TX 78634	tatiana@alphareadymixaustin.com
140	American Ready Mix, Inc.	1475 E Greg Street, Sparks, NV 89431	therschbach@pyramidmaterialsinc.com
141	Austin Ready Mix, LLC	P. O. Box 579, Del Valle, TX 78617	jenny@armtexas.com
142	B.H. Hall Ready-Mix Concrete Co.	305 South Washington Street, P. O. Box 870, Dublin, GA 31040-0870	Gboatright@dublinconstruction.com
143	Baldwin Redi Mix Co., Inc.	P. O. Box 670, Baldwin, LA 70514	sbishop@cox.net
144	Barry County Ready Mix, LLC	P. O. Box 542, 601 West 14th Street, Cassville, MO 65625	breadymix@hchsi.com
145	Bay Ready Mix Concrete LLC	2124 Priest Bridge Drive, Suite 18 Crofton, MD 21114	salesinfo@bayreadymix.com
146	Bender Ready Mix, Inc.	516 S. Santa Fe Street, Santa Ana, CA 92705	benderreadymix@sbcglobal.ne
147	Blue Grass Ready Mix LLC	P. O. Box 4162, Waynesville, MO 65583	bluegrass@jobe.net
148	Boulder Ready Mix Concrete, Inc.	3180 61st Street, Boulder, CO 80308	boulderreadymix@msn.com
149	Buckeye Ready-Mix, LLC	7657 Taylor Road, Reynoldsburg, OH 43068	jyoung@buckeyereadymix.com
150	Cajun Ready Mix Concrete LLC	15473 Old Perkins Road, W Baton Rouge, LA 70810	kathie.mckinney@cajunrmc.com
151	Cajun Ready Mix, Ltd.	12691 FM 149 Road, Montgomery, TX 77316	crm-robby@consolidated.net
152	Cape Cod Ready Mix, Inc.	300 Cranberry Hwy., Orleans, MA 02653-3114	peterzoni@capecodreadymix.com
153	Carl's Ready Mix	3660 Copperhill Lane, Santa Rosa, CA 95403	Davis1171@aol.com
154	Carolina Ready Mix & Builders Supply, Inc.	606 Old US 70, Swannanoa, NC 28778	bjones@carolinareadymixinc.com
155	Coastal Ready Mix LLC	P. O. Box 140, Coden, AL 36523	awigley@esfellerconstruction.com

(Continued from Table 12.4.1)

156	Commercial Ready Mix Products, Inc.	P. O. Box 189, Winton, NC 27986-0189	bobn@crmpinc.com
157	Conewago Enterprises, Inc. dba Conewago Ready Mix	576 Edgegrove Road, P. O. Box 461 Hanover, PA 17331	drummel@conewago.com
158	Consolidated Ready Mix, Inc.	P. O. Box 786, 1510 Western Avenue Brookings, SD 57006-0786	bandbinc@brookings.net
159	Corona Ready Mix, Inc.	50-25 97th Place, Corona, NY 11368	paul@coronareadymix.com
160	Coston & Son Ready Mix	155 East Oak Avenue, Paris, TX 75460-2663	travaables@suddenlinkmail.com
161	Crete Ready Mixed Concrete Co., Subsidiary of Beatrice Concrete Co.	P. O. Box 246, Crete, NE 68333-0246	tombusboom@yahoo.com
162	Darby Ready Mix	11200 Herold Hwy., Addison, MI 49220-9301	mcomstock@darbyreadymix.com
163	Detroit Ready Mix Concrete, Inc.	9189 Central Street, Detroit, MI 48204-4323	detroitreadymix@sbcglobal.net
164	Dickinson Ready Mix Co.	P. O. Box 726 Dickinson, ND 58602-0726	scott.olin@dickinsonreadymix.com
165	Dillon Bros. Ready Mix Concrete	11100 Almonaster Ave., New Orleans, LA 70129	gpdf1@aol.com
166	DKN Ready Mix LLC	25-50 Borden Avenue, Long Island City, NY 11101	tommy@dknreadymix.com
167	Drake Ready Mix Inc.	15460 Alico Road Fort, Myers, FL 33913	tdrake@drakereadymix.com
168	Eddystone Rock & Ready Mix, LLC	P. O. Box 5831, Ketchikan, AK 99901	cliffskillz@gci.net
169	Elite Ready Mix LLC	6790 Bradshaw Road, Sacramento, CA 95829	jlacombe@vc-inc.net
170	Essroc Ready Mix Mid-Atlantic Corporate Office	150 Lee Avenue, Winchester, VA 22601	doug.shaffer@essroc.com
171	Eureka Ready Mix Concrete Co., Inc.	4945 Boyd Road, Arcata, CA 95521	robm@eurekareadymix.com
172	Folsom Ready Mix, Inc.	3401 Fitzgerald Road, Rancho Cordova, CA 95742-6815	rbarnes@folsomreadymix.com
173	GCC Ready Mix	P. O. Box 656, Fort Smith, AR 72902	bill.lincks@gcc.com
174	Geiger Ready-Mix Co., Inc.	1333 South 2nd Street, Leavenworth, KS 66048	billgeiger@geigerreadymix.com
175	Greco Bros. Ready Mix Concrete Co	8713 Rockaway Blvd., Ozone Park, NY 11416-2113	jgreco@grecoreadymix.com
176	Green Ready Mix	183-30 Jamaica Avenue, Hollis, NY 11423	sam@royalgroupny.com
177	Gulf States Ready Mix	1540 Schillinger Road, Semmes, AL 36575	sethered@hotmail.com

(Continued from Table 12.4.1)

178	H.S.I Ready Mix	P. O. Box 758, Picayune, MS 39466	feeleyfrank@hueystockstill.com
179	Hawkeye Ready Mix, Inc.	1340 Hawkeye Drive, Hiawatha, IA 52233-1108	jsauter@hawkeyeready.com
180	Hood River Sand Gravel & Ready Mix Inc.	2630 Old Columbia River Drive, Hood River, OR 97031-9523	dubber@hrsand.com
181	Humboldt Readymix, Inc.	P. O. Box 2188, Winnemucca, NV 89446	cheri_maynick@sbcglobal.net
182	Independence Ready Mix	920 North 10th Street Independence, KS 67301-0528	markprestonwoods@yahoo.com
183	Isbell Ready Mix,	6158 Moores Mill Road, Huntsville, AL 35811	isbellrm@att.net
184	Island Ready-Mix Concrete, Inc.	P. O. Box 2230, 91-047 Hanua, Street Pearl City, HI 96782	skuhn@islandrm.com
185	Jackson Ready Mix	P. O. Box 1292, Jackson, MS 39215	dstrong@delta-ind.com
186	Jones Ready Mix, LLC	236 Herring Road, Sandy Hook, MS 39478	jason.stringer@jonescompanies.net
187	Kenyon Noble - Ready Mix & Portable, Inc.	P. O. Box 1310, Bozeman, MT 59771-1310	scottm@kenyonnoble.com
188	Ketchikan Ready Mix & Quarry, Inc.	8860 N. Tongass Hwy., Ketchikan, AK 99901-9112	hopeenright@mail.com
189	Kincaid Ready Mix	P. O. Box 520, Olathe, KS 66051	spearl@kincaidreadymix.com
190	Kings Ready Mix, Inc.	692 McDonald Avenue, Brooklyn, NY 10472-1001	phil@kingsny.com
191	Kobyluck Ready Mix, Inc.	24 Industrial Drive, Waterford, CT 06385-4026	matt@Kobyluckinc.com
192	Landvatter Ready Mix, Inc.	3000 Barrett Station Road, Saint Louis, MO 63122-3397	rogerl@landvatter.net
193	Lopez Ready Mix	600 N West Street, Rio Grande City, TX 78582	lopezreadymix@gmail.com
194	Lynchburg Ready Mix Concrete Co., Inc.	100 Halsey Road, P. O. Box 10066 Lynchburg, VA 24501-2540	redimixer@comcast.net
195	Machado Ready Mix	2930 Hammonds Ferry Road, Baltimore, MD 21227-3142	info@machadoconstruction.com
196	Mathews Readymix LLC	4711 Hammonton Road, Marysville, CA 95901	brianphillipe@hotmail.com
197	Molalla Ready Mix & Rock Products, Inc.	P. O. Box 555, Molalla, OR 97038	mjj@molalla.net
198	National Ready Mixed Concrete Co.	15821 Ventura Blvd., Suite 475, Encino, CA 91436-2915	ttoland@natcem.com
199	National Ready-Mix, Inc.	39000 Ford Road, Westland, MI 48185-1964	martyeise@yahoo.com
200	Nex-Gen Ready Mix Corp.	530 Faile Street, Bronx, NY 10474-6908	nexgenreadymix@gmail.com

(Continued from Table 12.4.1)

201	Northern Ready Mix	2809 State Route 3, Fulton, NY 13069	l.okoniewski@northernco mpanies.com
202	Northgate Ready Mix	5922 Pruitt Avenue, Windsor, CA 95492	troy@northgatereadymix. com
203	Northland Ready Mix	8607 Schell Road, Liberty, MO 64068-8609	challey3@live.com
204	Ohio Ready Mix, Inc.	P. O. Box 305, Huntsville, OH 43324-9617	JeremySloan@ohioready mix.com
205	On Time Ready Mix, Inc.	34-16 College Point Blvd., Flushing, NY 11354	info@ontimereadymix.co m
206	Orgain Ready Mix	240 Kraft Street, Clarksville, TN 37041-0561	dina@orgainreadymix.co m
207	Overland Ready Mixed Concrete Company	3rd & Division Avenue, York, NE 68647	merlynh@overlandready mixed.com
208	Ozinga Ready Mix Concrete, Inc	400 Blaine Street, Gary, IN 46406-1252	donrapley@ozinga.com
209	Patriot Ready Mixed Concrete LLC	P. O. Box 15177, Alexandria, VA 22315	roy.eller@patriotreadymi x.com
210	Prefer Ready Mix Inc.	P. O. Box 709, Rush City, MN 55069	preferpaving@youbetnet. net
211	Quality Ready Mix Co, Inc.	1824 Gilford Avenue, New Hyde Park, NY 11040	qreadymix@aol.com
212	Queens Ready Mix Inc.	149-01 95th Avenue, Jamaica, NY 11435	mike.queensreadymix@y ahoo.com
213	R&R Ready Mix, Inc.	6050 Melbourne Road, Saginaw, MI 48604	russ@r-rreadymix.com
214	Ready Mix Company, Inc.	P. O. Box 2604, Savannah, GA 31402	wanewkirk@hotmail.com
215	Ready Mix USA, LLC	106 Bell Parkway, Woodstock, GA 30188	rchandley@cemex-usa.com
216	Ready Mix USA, LLC	Box 101868, Birmingham, AL 35210-6868	marct@readymixusa.com
217	Ready Mixed Concrete Boral Construction Materials	4395 Washington Street, Denver, CO 80216	Bob.Haun@boral.com
218	Ready Mixed Concrete Company Division of Lyman-Richey Corp.	4315 Cuming Street, Omaha, NE 68131-1014	mark.deetz@lymanrichey. com
219	Rhode Island Ready Mix	35 Stilson Road, Richmond, RI 02898-1027	mattrrmix@aol.com
220	Riccelli Ready Mix, Inc.	P. O. Box 6418, Syracuse, NY 13217	samc@riccellienterprises. com
221	Richmond Ready Mix	291 Chelsea Road, Staten Island, NY 10314	richmondreadymix@gmai l.com
222	Robertson’s Ready Mix, Ltd.	P. O. Box 3600, Corona, CA 92878-1659	jon@rrmca.com

(Continued from Table 12.4.1)

223	Rockport Ready Mix	3092 Rockefeller Avenue, Cleveland, OH 44115	amnock@rockportreadymix.com
224	Rocky Mountain Ready Mix Concrete, Inc.	9605 South Kingston Court, Suite 240, Englewood, CO 80112	jerald_schnabel@transitmix.com
225	Roswell Ready Mix Co.	P. O. Box 448, Roswell, NM 88202-0448	rrmrock@dfn.com
226	Sagamore Ready Mix LLC	9170 East 131st Street, Fishers, IN 46038-3545	bnuckols@sagamorereadymix.com
227	Savannah Ready Mix	P. O. Box 16387, Savannah, GA 31416	marketurner@me.com
228	Shafer Ready Mix	29150 C Drive, North Albion, MI 49224-9410	doug@shaferbros.com
229	Show Me Ready Mix LLC	1271 NE Delta School Road, Lees Summit, MO 64064	stevem@showmereadymix.com
230	Smith Ready Mix, Inc.	251 Lincolnway, Valparaiso, IN 46383-5525	dougsmith@smithreadymix.com
231	Smith’s Ready Mix, Inc.	9268 Hwy. 278 W., P. O. Box 146 Nashville, AR 71852	hix@smithreadymix.net
232	Smith’s Ready Mix, Inc. - Ashdown	248 Hwy. 7 S. Ashdown, AR 71822	john@smithreadymix.net
233	Smyrna Ready Mix Concrete, LLC	1136 Second Avenue , North Nashville, TN 37208-1702	mzagula@smyrnareadymix.com
234	Souris Valley Ready Mix,	P. O. Box 1947, Minot, ND 58702	svradmin@srt.com
235	South-Central Ready Mix	1341 Fred Street, Prentiss, MS 39474	rboyd@delta-ind.com
236	Spragues’ Ready Mix	230 E. Longden Avenue, Irwindale, CA 91706-1328	mtoland@srmconcrete.com
237	Springfield Ready Mix Company	2836 West Division, Springfield, MO 65802	srm2836@sbcglobal.net
238	Standard Ready Mix Concrete, LLC	P. O. Box 325, Sioux City, IA 51102-0064	eric.sieh@siouxlandconcrete.com
239	Stillwell Ready Mix, LLC	2543 Stillwell Avenue, Brooklyn, NY 11223	stillwell2608@hotmail.com
240	Tech Ready Mix	5000 Crayton Avenue, Cleveland, OH 44104	dzupancic@techreadymix.com
241	The Shelly Company Ready Mix Division	2301 Progress Street, Dover, OH 44622	dwilson@shellyco.com
242	Titan Virginia Ready-Mix, LLC	2025 Oakton Dr., Raleigh, NC 27606	dingerson@titanamerica.com
243	Tri County Ready Mix, Inc.	P. O. Box 148, Stringer, MS 39481	tricomix@g-gate.net
244	Triple J Ready Mix	301 Enterprise Parkway, Coalinga, CA 93210	jdilworth@triplejreadymix.com

(Continued from Table 12.4.1)

245	Tuskegee Ready-Mix, Inc.	900 County Road 49, P. O. Box 830428, Tuskegee, AL 36083-5502	TuskegeeReadyMix@gmail.com
246	Universal Ready Mix, Inc.	197 Atlantic Avenue, Garden City Park, NY 11040	universalrmix@hotmail.com
247	Vicksburg Ready Mix	1730 Hwy. 80 W., Vicksburg, MS 39180	drosamond@delta-ind.com
248	Warden & Smith, Inc. Ready Mixed Concrete	P. O. Box 130 Cheraw, SC 29520-0130	burchell@wardenandsmith.com
249	Welsch Ready Mix, Inc.	4243 W 166th St., Oak Forest, IL 60452	mdejong@welschrm.com
250	S.T. Wooten Corp.	104 High Hope Lane, Garner, NC 27529	jason@stwcorp.com

12.5 Survey Results - Responses from Ready-Mix Suppliers

Table 12.5.1 Survey Questions to Ready-Mix Companies

No.	Question
1	Has your company or plant ever used RCA as an aggregate to make new concrete? If yes, what are the applications?
2	Is the RCA provided to your ready mix facility by a supplier in a ready-to-use format or your ready mix facility processes its own RCA on-site.
3	Is the fresh concrete containing RCA mixed at your mixing plant or at a construction site?
4	How does your practice, including mix design, differ for the use of RCA compared to virgin aggregates?
5	What are your company's testing requirements or quality control procedures for using RCA as aggregate in concrete?
6	Has your plant ever encountered any problems in using RCA as an aggregate?
7	Do you think the use of RCA as an aggregate in concrete will expand if the specifying agency allows using RCA in concrete?
8	Please provide any additional comments you may have about your company's use of RCA in concrete.

Table 12.5.2. Responses to Question 1

Has your company or plant ever used crushed recycled concrete aggregate (RCA) as an aggregate to make new concrete? If yes, what are the applications?

Company	Location	Responses
1	Alabama	N/A
2	California	Yes, aggregate replacement for 4000 psi post tensioned, slab on grade mix designs. 30% aggregate replacement for 3000 psi foundation mix designs. 100% aggregate replacement in 150 psi trench slurry mix designs.
3	California	Yes, RCA is used in our Northern California operations in all classes of concrete except high strength (up to 6000 psi), architectural, and some special applications.
4	California	N/A
5	Hawaii	Yes, crushed to 3/8 minus to make controlled low strength fills.
6	Louisiana	No
7	Michigan	Yes, Michigan utilized RCA in concrete pavement in the 1980's, as a result of some early failures it was concluded that RCA should only be allowed in the subbase layers of the pavement.
8	Minnesota	N/A
9	National	Yes, on a trial basis only.
10	North Carolina	No
11	North Dakota	No
12	Oregon	No
13	Oregon	No
14	Virginia	No
15	Virginia	Yes, residential concrete (footings, slabs, walls, etc.).
16	Virginia	No
17	Virginia	No
18	Virginia	No, we do not have concrete plants in this area.

Table 12.5.3. Responses to Question 2

Is the RCA provided to your ready mix facility by a supplier in a ready-to-use format or your ready mix facility processes its own RCA on-site?

Company	Location	Responses
1	Alabama	Mixing plant
2	California	Mixing plant
3	California	Both
4	California	Mixing plant
5	Hawaii	Mixing plant
6	Louisiana	N/A
7	Michigan	N/A
8	Minnesota	N/A
9	National	Mixing plant
10	North Carolina	N/A
11	North Dakota	N/A
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	N/A
15	Virginia	Mixing plant
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.4. Responses to Question 3

Is the fresh concrete containing RCA mixed at your mixing plant or at a construction site?

Company	Location	Responses
1	Alabama	N/A
2	California	Mixing plant
3	California	Mixing plant
4	California	Mixing plant
5	Hawaii	Mixing plant
6	Louisiana	N/A
7	Michigan	N/A
8	Minnesota	N/A
9	National	Mixing plant
10	North Carolina	N/A
11	North Dakota	N/A
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	N/A
15	Virginia	Mixing plant
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.5. Responses to Question 4

How does your practice, including mix design, differ for the use of RCA compared to virgin aggregates?

Company	Location	Responses
1	Alabama	N/A
2	California	No difference.
3	California	We do not use RCA in normal concrete mixes. RCA has too many "unknowns" as to the original aggregate quality.
4	California	N/A
5	Hawaii	RCA is only used in one mix and this mix is not set up to use virgin materials.
6	Louisiana	N/A
7	Michigan	If we were to utilize RCA in concrete the moisture conditioning of the RCA is a critical factor, it needs to be at SSD, adding water during stockpiling is a critical step along with sprinklers on the pile.
8	Minnesota	Decrease strength Decrease in slump Only able to use coarse.
9	National	More water and/or admixtures are needed to get comparable slumps, workability, etc.
10	North Carolina	N/A
11	North Dakota	N/A
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	We don’t use RCA
15	Virginia	Requires higher water demand.
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.6. Responses to Question 5

What are your company's testing requirements or quality control procedures for using RCA as aggregate in concrete?

Company	Location	Responses
1	Alabama	N/A
2	California	Monthly gradations on the 1" minus RCA to confirm our mix designs remain in specification.
3	California	We do not use RCA in standard ready mix concrete designs. We are not willing to accept the risk of RCA in concrete.
4	California	N/A
5	Hawaii	The same as testing any other concrete that we manufacture.
6	Louisiana	N/A
7	Michigan	N/A
8	Minnesota	Just research, did not use in production.
9	National	Has to meet all ASTM and ACI specifications.
10	North Carolina	N/A
11	North Dakota	N/A
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	We don’t use RCA.
15	Virginia	Air, slump, temperature, cylinders.
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.7. Responses to Question 6

Has your plant ever encountered any problems in using RCA as an aggregate?

Company	Location	Responses
1	Alabama	N/A
2	California	No
3	California	No
4	California	No
5	Hawaii	No
6	Louisiana	N/A
7	Michigan	Yes
8	Minnesota	N/A
9	National	No
10	North Carolina	N/A
11	North Dakota	N/A
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	N/A
15	Virginia	No
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.8. Responses to Question 7

Do you think the use of RCA as an aggregate in concrete will expand if the specifying agency allows using RCA in concrete?

Company	Location	Responses
1	Alabama	N/A
2	California	Yes
3	California	No
4	California	N/A
5	Hawaii	Maybe
6	Louisiana	N/A
7	Michigan	Yes
8	Minnesota	Yes
9	National	Yes
10	North Carolina	N/A
11	North Dakota	Yes
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	Maybe
15	Virginia	Yes
16	Virginia	Yes
17	Virginia	N/A
18	Virginia	N/A

Table 12.5.9. Survey Results - Responses to Question 8

Please provide any additional comments you may have about your company's use of RCA in concrete.

Company	Location	Responses
1	Alabama	N/A
2	California	We've experiences tremendous success using 30% aggregate replacement in our mix designs. No strength deficiency issues. We typically increase the amount of WRA in a RCA mix design about 20% to account for slightly higher absorption and subsequent water demand. We've not experienced any shrinkage issues or cracking issues on the slab on grade projects thus far. The quality of our RCA is high as it is nearly 100% of our own returned concrete processed again.
3	California	The "Green Movement" looks the way in truly understanding the quality of a recycled aggregate for concrete. There will be lawsuits in the future in regard to using RCA in a situation where the concrete fails. The testing criteria in understanding the quality of the original aggregate in recycled concrete is nonexistent. An aggregate that would not be allowed in spec work could then be used in non spec concrete work and just because it is "recycled concrete" will be allowed in spec concrete work? This is a problem that the "Green Movement" is not addressing.
4	California	N/A
5	Hawaii	It is a cost effective way of disposing returned concrete.
6	Louisiana	N/A
7	Michigan	Another key issue is the source material of the RCA. Yards that accept all kinds of broken concrete can have significant inconsistencies in aggregate quality.
8	Minnesota	N/A
9	National	Would very much welcome the specification for the use of a % of RCA in non-structural concrete as returned concrete is becoming more difficult (and expensive) to process and real estate in our urban environment (New York City) is extremely scarce.
10	North Carolina	N/A
11	North Dakota	We have not used recycled concrete as aggregate in new batched concrete but as regional aggregate shortages get more and more acute I believe interest in utilizing recycled concrete as coarse aggregate in concrete will continue to grow. FYI, because of the lack of quality aggregate in our area we already have to ship our concrete aggregate from hundreds of miles away in Montana.
12	Oregon	N/A
13	Oregon	N/A
14	Virginia	N/A
15	Virginia	N/A
16	Virginia	N/A
17	Virginia	N/A
18	Virginia	N/A

12.6 Survey List to Construction Companies

Table 12.6.1 List of Construction Companies Contacted

No.	Company Name	Address	Email Address
1	AAA Concrete Product Corp.	1224 E. Broad Avenue, Albany, GA 31705	SteveWilliams@aaaconcrete.biz
2	Abhw Concrete	347 S. Wharton Station Road Washington, NC 27889	abhwconcrete@embarqmail.com
3	Allied Concrete Company	1000 Harris Street, Charlottesville, VA 22903	glorber@allied-concrete.com
4	Altaview Concrete	7057 W. 2100 S., Salt Lake City, UT 84044	Scott.Reynolds@altaviewconcrete.com
5	Anderson/Vanguard Homes	201 Shannon Oaks Circle, Suite 120 Cary, NC 27511	kguyon@ahihomes.com
6	APAC – Atlantic Inc. Harrison Div.	4817 Rutledge Pike, Knoxville, TN 37914	dbrown@harrisoncc.com
7	Argos USA	P. O. Box 6388, Statesville, NC 28687	andy.stankwytch@rmcc.com
8	Argos USA	3015 Windward Plaza, Suite 300, Alpharetta, GA 30005	bwagner@argos-us.com
9	Austin ServAll Concrete	1919 Reed Street, Erie, PA 16503	CKohler@austinservallconcrete.com
10	Barnhill Contracting Co, Human Resources	P. O. Box 1529, Tarboro, NC 27886	jhughes@barnhillcontracting.com
11	Berks Products	167 Berks Products Drive, Leesport, PA 19533	andrew.davis@berksproducts.com
12	Black Concrete, Inc.	705 Cotton Grove Road, Lexington, NC 27292-3823	scottblack@lexcominc.net
13	Blalock Ready Mix	P. O. Box 4750, Sevierville, TN 37862-2841	wesblalock@blalockandsons.com
14	Boxley Concrete Products of VA, Inc.	P. O. Box 13527, Roanoke, VA 24035-3527	aboxley@boxley.com
15	Callahan Concrete Company	3545 W US Highway 64, Lexington, NC 27295	jake.callahan@callahan-concrete.com
16	Capital Concrete Co.	P. O. Box 2494, Lexington, SC 29071	rshealy@capitalconcreteco.com
17	Carolina Concrete Company	P. O. Box 389, Clinton, SC 29325-0389	mhartsell@carolinaconcrete.net
18	Carolina Sunrock LLC	200 Horizon Drive, Suite 100, Raleigh, NC 27615	epfohlsasser@thesunrockgroup.com
19	Carruth & Son, Inc.	P. O. Box 870, Bryantown, MD 20617-0870	carruthandson@gmail.com
20	CEMEX	PO Box 2389 Knoxville, TN 37901-2389	Dphillips@cemex-usa.com
21	Central Builders Supply Co.	P. O. Box 152, Sunbury, PA 17801-0152	cbsc@ptd.net

(Continued from Table 12.6.1)

22	Centre Concrete Company	P. O. Box 859, State College, PA 16804-0859	enicholson@centreconcrete.com
23	Chandler Concrete & Building Supply Co., Inc.	400 N. Long Street, Burlington, NC 27216-0131	bob.cartner@chandlerconcrete.com
24	Chandler Concrete Co., Inc.	400 N. Long Street, Burlington, NC 27216-0131	ted.chandler@chandlerconcrete.com
25	Chaney Enterprises	2410 Evergreen Road, Suite 201, Gambrills, MD 21054-1848	bchilds@chaneyenterprises.com
26	CHE Mid-Atlantic, Inc.	P. O. Box 586, Greenville, NC 27835	cliftonedwards@chemidatlantic.com
27	CMS Construction Company, Inc.	16855 Woodinville-Redmond Road NE, Woodinville, Washington 98072	wea@isomedia.com
28	Coakley & Williams Construction, Inc.	16 South Summit Ave., Suite 300, Gaithersburg, MD 20877	tcoakley@coakleywilliams.com
29	Concrete Enterprises, Inc.	801 Turner Field Road, Albany, GA 31705-1534	rgarcia@ConcreteEnterprisesInc.net
30	Concrete Materials, Inc.	P. O. Box 1051, Morristown, TN 37816-1051	carlbstorms@aol.com
31	Concrete Restoration, Inc.	P. O. Box 521, Macungie, PA 18062	sales@concrete-restoration-inc.com
32	Construction Managers, LLC	2900 Hillsboro, Road Fremont, NC 27830	sam.sasser@gmail.com
33	Cornerstone Ready Mix Concrete LLC	1502 Stephens Road, North Augusta, SC 29860	cornerstoneconcrete@live.com
34	D. S. Simmons	P. O. Drawer 287, Goldsboro, NC 27560-0919	cleve.paul@dssimmons.com
35	Daniel G. Schuster, LLC	P. O. Box 604, Owings Mills, MD 21117-0604	dschuster@schusterconcrete.com
36	Delaware Valley Concrete Co., Inc.	248 E County Line Road, Hatboro, PA 19040-045	mdiliberto@delvalconcrete.com
37	Denfeld Concrete Construction	6702 Clover Road, Wausau, WI 54401	medenfeld@msn.com
38	DSG Concrete Contractors	222 Westinghouse Blvd., Charlotte, NC 28273	DSG-Estimating@dsgconst.com
39	DuBrook Inc.	P. O. Box 376, Falls Creek, PA 15840	ro.barber@dubrookinc.com
40	Eagle Rock Concrete Company	8310 Brandford Way, Raleigh, NC 27615	adam@eaglerockconcrete.com
41	Elite Concrete	P. O. Box 1696, Hardeeville, SC 29927	mike.smith@eliteconcrete.biz
42	Ernest Maier, Inc.	4700 Annapolis Road, Bladensburg, MD 20710	nryan@emcoblock.com
43	Essroc Cement Corp.	3251 Bath Pike, Nazareth, PA 18064	brent.edwards@essroc.com
44	Farrior & Sons, Inc.	P. O. Box 127, Farmville, NC 27828	billjr@farriorandsons.com

(Continued from Table 12.6.1)

45	FMB Masonry, Inc.	1048 Lewis Street, Santa Clara, CA 95050	fernando@fmbmasonryinc.com
46	Forrester Construction Co, PreConstructionSvce	12231 Parklawn Drive, Rockville, MD 20852	rforrester@forresterconstruction.com
47	Forsyth Redi Mix, Inc.	P. O. Box 95, Rural Hall, NC 27045	frmx@windstream.net
48	Garrott Brothers Continuous Mix, Inc.	375 Red River Road, Gallatin, TN 37066-0419	jgarrott@garrottbros.com
49	Gillespie & Son, Inc.	P. O. Box 450, Chestertown, MD 21620-0450	jimg@gillespieandson.com
50	Glasscock Company, Inc.	5378 Broad Street, Extension Sumter, SC 29154	jamesglasscock@glasscockco.com
51	Goldsboro Builders Supply Co., Inc.	P. O. Drawer E, Goldsboro, NC 27533	DPerry6961@aol.com
52	Haley Construction, Inc.	P. O. Box 339, 165 Main Street, Sangerville, ME 04479	concrete@haleyconstructioninc.com
53	Hamlin Roofing Company, Inc.	P. O. Box 465, 1411 W. Garner Road, Garner, NC 27529	jeffreys@hamlincos.com
54	Hardin Construction Company	530 Medley Street, Greensboro, NC 24401	jpike@hardingconstruction.com
55	Harrison Construction Company	4817 Rutledge Pike, Knoxville, TN 37914	dchildress@harrisoncc.com
56	Home Builders Supply, Inc.	2045 Eastgate Drive, Greenville, NC 27834	hunterblount@gmail.com
57	Interlocking Concrete Pavement Institute	13921 Park Center Road, Suite 270, Herndon, VA 20171	cmcgrath@icpi.org
58	Irving Materials, Inc. Tennessee Region	2617 Grandview Avenue, Nashville, TN 37211	john.curtis@irvmat.com
59	James G. Davis Construction Corporation	12530 Park Lawn Drive, Rockville, MA 20875	chirrlinger@davisconstruction.com
60	KBE Building Corporation	30 Batterson Park Road, Farmington, CT 06032	mkolakowski@kbebuilding.com
61	Kerr's HRM Concrete	P. O. Box 1924, Hickory, NC 28603	rskerr@kerrsconcrete.com
62	LafargeHolcim	6401 Golden Triangle Drive, Suite 400, Greenbelt, MD 20770-3202	don.delano@aggregate.com
63	LafargeHolcim	1049 Willeo Ct., Marietta, GA 30068	fred.kemph@lafarge-na.com
64	Larco Construction	2755 Hartland Road, Winston-Salem, NC 27115	rponton@barrettpaving.com
65	Lomas Construction Company	P. O. Box 35169, Greensboro, NC 27425	jlomax@lomaxconstruction.com
66	Martin Marietta Materials, Inc.	2710 Wycliff Road, Raleigh, NC 27607	ward.nye@martinmarietta.com

(Continued from Table 12.6.1)

67	Mechanicsville Concrete, Inc. dba Powhattan Ready Mix	3501 Warbrod Road, Midlothian, VA 23112	vaslate@aol.com
68	MF Concrete Contractors	7106 West Frier Drive, Suit, Glendale, Arizona 85303	mitch@mf-concrete.com
69	MFI Concrete LLC	7860 Kabik Court, Woodbine, MD 21797	mneale@mficoncrete.com
70	National Concrete Masonry Association	13750 Sunrise Valley Dr. Herndon, VA 20171	jgaidry@ncma.org
71	National Stone Sand & Gravel Association	1605 King Street, Alexandria, VA 22314-2726	mjohnson@nssga.org
72	Newland Communities, Houston Division	10235 W. Little York, Suite 300, Houston, TX 77040	tstone@newlandcommunities .com
73	Newrock Materials, Subsidiary of Newington Concrete Corp	11454 Quarry Drive, Mitchells, VA 22729	newcon1@aol.com
74	Oldcastle Materials, Inc.	900 Ashwood Pkwy., Suite 700, Atlanta, GA 30338	randy.lake@oldcastlematerial s.com
75	Patriot Ready Mixed Concrete LLC	P. O. Box 151777, Alexandria, VA 22315	roy.eller@patriotreadymix.co m
76	Pavement Corporation	10903 Indian Head Hwy., Fort Washington, MD 20744	info@pavementcorp.com
77	PCA Southeast Region	2180 Satelite Blvd., Suite 300, Duluth, GA 30097	rfaulkner@cement.org
78	PCS	P. O. Box 265, Annapolis Junction, MD 20701-0265	tpittman@myconcretesupply. com
79	PLT Concrete Services, Inc.	3214 Turnage Road, Wilson, NC 27893-7580	rickproctor@pltconcrete.com
80	Port City Concrete, Inc.	9530 William Aiken Avenue, Ladson, SC 29456	russ@portcityconcrete.com
81	R. H. Loven Company	P. O. Box 155, 251 Jonas Ridge Hwy., Pineola, NC 28662-0155	bloven@skybest.com
82	Riverstone Concrete, Inc.	1384 North Carol Street, Meridian, Idaho 83680	jay@riverstoneconcrete.com
83	RMC Research & Education Foundation	900 Spring Street, Silver Spring, MD 20910	jgarbini@rmc-foundation.org
84	Rockville Fuel & Feed Co., Inc.	14901 Southlawn Ln., Rockville, MD 20850-1322	steve@rockvilleconcrete.com
85	Rogers Builders, Inc.	5701 North Sharon Amity Road, Charlotte, NC 28215	RCohn@RodgersBuilders.co m
86	Rowe Materials LLC	P. O. Box 2217, Waldorf, MD 20604	rgraf@rowematerials.com
87	Rutherfoord, Inc.	3101 Glenwood Avenue, Suite 105, Raleigh, NC 27612	William.moore@rutherfoord. com

(Continued from Table 12.6.1)

88	S & G Concrete Co.	2110 Philadelphia Road, Edgewood, MD 21040-1108	chapmans@vmcmail.com
89	S&W Ready Mix Concrete Co., Inc.	P. O. Box 872, Clinton, NC 28329	billwest@snwreadymix.com
90	S.T. Wooten Corporation	P. O. Box 2408, Wilson, NC 27894-2408	hank.butts@stwcorp.com
91	S.T. Wooten Corporation	3931 Highway 24, Newport, NC 28570	taylor.car@stwcorp.com
92	Sanford Contractors, Inc.	8540 Colonnade Center Drive, Sanford, NC 27330	Dstike@sanfordcontractors.c om
93	Satterfield & Pontikes Construction, Inc.	6220 N. Beltline Road, Suite 200, Irving, TX 75063	jharalson@satpon.com
94	Sequatchie Concrete Service, Inc.	P. O. Box 129, South Pittsburg, TN 37380-0129	cblevins@seqconcrete.com
95	South Carolina Prestress Corp.	P. O. Box 160, Lake City, SC 29560	wetconcrete33@yahoo.com
96	Southern Concrete Materials, Inc.	P. O. Box 5395, Asheville, NC 28813	jcombest@scmusa.com
97	Stevenson-Weir, Inc.	1523 South Anderson Road, Rock Hill, SC 29730	kendrick@stevenson- weir.com
98	Superior Concrete Materials, Inc. A U.S. Concrete Company	1601 S. Capitol Street, SW Lanham, MD 200003	tmartineau@us-concrete.com
99	Swederski Concrete & Paving Company	4221 Golf Acres Drive, Charlotte, NC 28208	len@swederski.com
100	T. A. Loving Company	P. O. Drawer 919, Goldsboro, NC 27533-0287	shunter@taloving.com
101	Tennessee Concrete Association	705 Fort Negley Court, Nashville, TN 37203	asparkman@tnconcrete.org
102	Thomas Bennett & Hunter, Inc.	70 John Street, Westminster, MD 21157-4835	john.alexander@tbhconcrete. com
103	Thomas Concrete of Carolina Raleigh	P. O. Box 12544, Raleigh, NC 27605-2544	Gregg.Clark@thomasconcret e.com
104	Thomas Concrete, Inc.	2500 Cumberland Parkway SE, Suite 200, Atlanta, GA 30339-3932	alan.wessel@thomasconcrete. com
105	Tipton Builders, Inc.	628 Rocky Fork Church Road, Greenville, NC 27858	edtipton2@embarqmail.com
106	Toxaway Concrete, Inc.	P. O. Box 40, Lake Toxaway, NC 28747-0040	WMcNeely@McNeelyComp anies.com
107	Transit-Mix Concrete Company, Inc.	P. O. Box 1275, Johnson City, TN 37605-1275	eewalker@tmix.com
108	U.S. Concrete On-Site, Inc.	4600 Forbes Blvd., Suite 105, Lanham, MD 20706-4359	RMiller@us-concrete.com
109	USI DC Metro	530 Medley Street, Falls Church, VA 22043	Skip.Plate@usi.biz

(Continued from Table 12.6.1)

110	VanHooseCo Ready Mix 244	Blair Bend Road, Loudon, TN 37774	ltrent@vanhooseco.com
111	Vulcan Materials Co. Mideast Division	4401 N. Patterson Avenue, Winston Salem, NC 27107	dukek@vmcmail.com
112	Vulcan Materials Company, Southern Division	P. O. Box 467279, Atlanta, GA 31146	shepherdd@vmcmail.com
113	Vulcan Materials Company Central Division	121 Bush Road, Nashville, TN 37217	bschmidt@vmcmail.com
114	Walker Concrete Company	P. O. Box 2637, Stockbridge, GA 30281	jdickinson@walkerconcrete.com
115	Wando Redimix, LLC	P. O. Box 61389, Charleston, SC 29419-1389	EParrin@oltc.com
116	Wayne Brothers Inc.	357 Concrescere Parkway, Davidson, NC 28036	alang@waynebrothers.com
117	Wellington Hamrick, Inc.	P. O. Box 755, Boiling Springs, NC 28017-0755	kittyhoyle@wellingtonhamrick.com
118	Wiggins Concrete Co., Inc.	P. O. Box 9, Estill, SC 29918	wigginsandson@yahoo.com
119	Wimco Corporation	4130 N. Glenn Avenue, Washington, NC 27889	kevin@wimcocorp.com
120	Woolems Incorporated	P. O. Box 121, West Palm Beach, FL 33405	jrogers@woolemsinc.com
121	Bama Concrete Products Company	1608 17th Street, Tuscaloosa, AL 35401	timk@bamaconcrete.com
122	Bayou Concrete LLC	P. O. Box 1529, Theodore, AL 36590-1529	wverneuille@bayouconcretellc.com
123	Hodgson Concrete Co. Inc.	P. O. Box 9868, Montgomery, AL 36108-0017	whodgson@natcem.com
124	Kirkpatrick Concrete, Inc.	2000 A Southbridge Pkwy, Suite 610, Birmingham, AL 35209	bmoore@natcem.com
125	LafargeHolcim	6781 Rester Road, Theodore, AL 36582	doug.berger@lafarge-na.com
126	Reed Contracting Services, Inc.	2512 Triana Blvd., Huntsville, AL 35805	miker@reedalabama.com
127	Vulcan Materials Company	P. O. Box 385014, Birmingham, AL 35238-5014	jamesd@vmcmail.com
128	Aggpro	P. O. Box 32159, Juneau, AK 99803	blupro@colaska.com
129	Best Transit Mix Inc.	35482 K-B Drive, Soldotna, AK 99669	bestmix@alaska.net
130	Delta Concrete Products	P. O. Box 289, Delta Junction, AK 99737-0289	mj.walker@deltaconcrete.u
131	Fairbanks Sand & Gravel, Inc.	P. O. Box 80430, Fairbanks, AK 99708	lbishop@fsgrm.com
132	Arizona Materials, LLC	3636 S. 43rd Avenue Phoenix, AZ 85009	patm@azmatl.com

(Continued from Table 12.6.1)

133	Arizona Metro Mix LLC	P. O. Box 1300, Higley, AZ 85236	ddopson@azmetromix.com
134	California Portland Cement Co.	3755 N. Business Center Drive #3, Tucson, AZ 85705	enappa@calportland.com
135	Drake Materials	5745 North Scottsdale Rd., Suite B110, Scottsdale, AZ 85250-5902	dleazier@drakeus.com
136	Fort McDowell Yavapai Materials	P. O. Box 19120, Fountain Hills, AZ 85269	sbrunson@fmym.com
137	Lehigh Hanson, Inc.	4127 E. Van Buren Street, Phoenix, AZ 85008	sdickson@lehighcement.com
138	Oremus Materials Inc.	10100 W. Avra Valley Road, Marana, AZ 85653	mjoremus@aol.com
139	S&S Concrete & Materials, LLC	P. O. Box 23283, Bullhead City, AZ 86439-3283	snsconcrete@yahoo.com
140	Smith Precast	2410 West Broadway Road, Phoenix, AZ 85041-2408	bwasson@us-concrete.com
141	Staker Parson Companies	5400 W. Massingale Road, Tucson, AZ 85741	randy.anderson@stakerparson.com
142	Beaver Lake Concrete	P. O. Box 307, Springdale, AR 72765-0307	fred.vernor@beaverlakeconcrete.com
143	GCC	900 South O Street, Fort Smith, AR 79202	daniel.martin@gcc.com
144	Martin Marietta Materials (MidSouth Division)	7 Collins Industrial Place, North Little Rock, AR 72113	jim.hall@martinmarietta.com
145	Mobley Concrete Company	106 S West Street, P. O. Box 11630 Russellville, AR 72812	bryce.mobley@mobleyconcrete.com
146	Pine Bluff Sand & Gravel Co.	1501 Port Road, P. O. Box 7008, Pine Bluff, AR 71611-7008	mark.oliger@pbsgc.com
147	Razorback Concrete Company	P. O. Box 1028, West Memphis, AR 72303-1028	kwetsell@razorbackconcrete.com
148	A. Teichert & Son, Inc.	3500 American River Drive, Sacramento, CA 95864	mrotelli@teichert.com
149	AgCon Inc.	17671 Bear Valley Road, Hesperia, CA 92345-4902	jhove@robarenterprises.com
150	Arrow Transit Mix, Inc.	507 East Avenue, L-12, Lancaster, CA 93535-5417	cfollendore@dslextreme.com
151	Bode Gravel Company	P. O. Box 880130, San Francisco, CA 94188	danboardman@bodegravel.com
152	Bonanza Concrete, Inc.	15115 Oxnard Street, Van Nuys, CA 91411	john@bonanzaconcrete.com
153	Builders Concrete Inc.	P. O. Box 9129, Fresno, CA 93790-9129	cwensley@natcem.com
154	Calavaras Standard Materials	P. O. Box 26240, Fresno, CA 93729-6240	bgilpin@lehighcement.com
155	Catalina Pacific A CalPortland Company	2025 East Financial Way, Glendora, CA 91741-4692	ckerzic@calportland.com

(Continued from Table 12.6.1)

156	CEMEX	16 Downfield Way, Coto de Caza, CA 92679	peterbrewin@cemex.com
157	Central Concrete Supply Company, Inc. A US Concrete Company	755 Stockton Avenue, San Jose, CA 95126-1839	jdavis@us-concrete.com
158	Don Chapin Company	560 Crazy Horse Canyon Road, Salinas, CA 93907	dchapin@donchapin.com
159	Engineered Concrete Placement, Inc.	18903 North Shore Drive, Hidden Valley Lake, CA 95467	hbarradas@mchsi.com
160	Graniterock	P. O. Box 50001, Watsonville, CA 95077-5001	tsqueri@graniterock.com
161	Hansen Bros. Enterprises	P. O. Box 1599, Grass Valley, CA 95945-1599	nmaffucci@gohbe.com
162	Hanson Aggregates North America	699 Virginia St, Suite 225, Berkeley, CA 94710	bill.butler@hanson.com
163	Harold Smith & Son, Inc.	P. O. Box 232, Saint Helena, CA 94574	hs_praybould@sbcglobal.net
164	Holliday Rock Company	1401 North Benson Avenue Upland, CA 91786	jfhhrc@hollidayrock.com
165	Livingston's Concrete Service, Inc.	5416 Roseville Road, North Highlands, CA 95660-5037	patti@livingstonsconcrete.com
166	Outback Materials, Inc.	P. O. Box 440, Coarsegold, CA 93614	clovett@outbackmaterials.com
167	Shamrock Materials, Inc.	P. O. Box 808044, Petaluma, CA 94975	donomadi@shamrockmaterials.com
168	Star Concrete	1404 S. 7th Street, San Jose, CA 95112	jerryblatt@sbcglobal.net
169	Teichert Materials Division of A. Teichert& Son	3500 American River Drive, Sacramento, CA 95864	ddavis@teichert.com
170	Truckee North Tahoe Materials	10642 Pioneer Trail, Truckee, CA 96161-0218	rodarte@tnt-materials.com
171	Vulcan Materials Company Western Division	500 N Brand Blvd., Suite 200, Glendale, CA 91203	LuceE@VMCMAIL.com
172	B & B Excavating, Inc.	P. O. Box 1729, Edwards, CO 81632-1729	vpack@bbexcavating.com
173	Bestway Concrete Co.	301 Centennial Drive, Milliken, CO 80543	rvan@bestwayconcrete.com
174	GCC America	Cherry Creek Plaza 1, 600 S. Cherry Street, Suite 1000, Denver, CO 80246	rhenley@gcc.com
175	Martin Marietta	10170 Church Ranch Way, Suite 201, Broomfield, CO 80021	abbott.lawrence@martinmarietta.com
176	Oldcastle SW Group, Inc.	P. O. Box 4870, Eagle, CO 81631	thomas.lyons@oldcastlematerials.com

(Continued from Table 12.6.1)

177	Rocky Mountain Premix, Inc.	1910 Rand Avenue, Colorado Springs, CO 80905	rissy@rockymountainpremix.com
178	Rocky Mountain Premix, Inc.	2895 Capital Drive, Colorado Springs, CO 80915	roger@rockymountainpremix.com
179	Summit Materials LLC	1550 Wunkoop Street, 3rd Floor, Denver, CO 80202	thill@summit-materials.com
180	Telluride Gravel, An Oldcastle Company	270 Hwy. 625, Telluride, CO 81435	ghoman@telluridegravel.com
181	Trans-Colorado Concrete, Inc. Division of Pete Lien and Son’s	3370 Drennan Industrial Loop N. Colorado, Springs, CO 80910-1077	hrivera@petelien.com
182	Transit Mix of Pueblo	444 E Costilla Street, Colorado Springs, CO 80903	jerry_schnabel@transitmix.com
183	Aiudi Concrete Inc.	P. O. Box 361, 129 Essex Road Westbrook, CT 06498	aiudiconcrete@live.com
184	Joseph J. Mottes Co.	10 Meadow Lane, Stafford Springs, CT 06076-1613	dcharette@jjmottes.com
185	Mohican Valley Concrete Corp.	195 Ardmore Street, Fairfield, CT 06824	markg@mohicanvalleyconcrete.com
186	O&G Industries, Inc.	112 Wall Street, Tornington, CT 06790	jimmaher@ogind.com
187	The F & F Concrete Corp.	110 West Main Street, Plantsville, CT 06479-1130	gradocchio@ffconcrete.com
188	The L. Suzio Concrete Co., Inc.	P. O. Box 748, Meriden, CT 06450-0748	lhsuzio@suzioyorkhill.com
189	Heritage Concrete	307 A Street, Wilmington, DE 19801	mpetrillo@heritageconcrete.net
190	HD&D, LLC	P. O. Box 29968, Honolulu, HI 96820-2368	ameronhawaii@yahoo.com
191	Jas. W. Glover, Ltd	248 Sand Island Access Road, Honolulu, HI 96819	johnr@gloverltd.com
192	Atlas Concrete	4341 Snake River Avenue, Lewiston, ID 83501-5195	brien@atlassandandrock.com
193	Atlas Sand & Rock, Inc.	4341 Snake River Avenue, Lewiston, ID 83501	angela@atlassandandrock.com
194	Burns Concrete, Inc.	P. O. Box 1864, 2385 Gallatin Avenue, Idaho Falls, ID 83402-1864	kirk@burnsconcrete.com
195	Clearwater Concrete Inc.	212 Industrial Loop, McCall, ID 83638	clearwaterconcrete@hotmail.com
196	Idaho Materials & Construction	924 North Sugar Street, Nampa, ID 83653	grunenwald@idahoconcrete.com
197	Sunroc Corp. dba Clements Concrete Co.	P. O. Box 8124, Boise, ID 83707-2124	sclements@sunroc.com
198	Elmhurst-Chicago Stone Co.	400 West 1st Street, Elmhurst, IL 60126-0057	mkroeger@ecstone.com
199	Kienstra-Illinois	201 West Ferguson Avenue, Wood River, IL 62095-1408	smaberry@kienstra-illinois.com

(Continued from Table 12.6.1)

200	LCI Concrete, Inc.	4055 W. Jackson Street, Macomb, IL 61455	rhs@lciconcrete.net
201	Lincolnland Concrete Inc.	P. O. Box 110, New Berlin, IL 62670	redimix910@aol.com
202	Odum Concrete Products, Inc.	P. O. Box 248, Marion, IL 62959	tim@odumcp.com
203	Ozinga Bros., Inc.	19001 Old LaGrange Rd., Mokena, IL 60448	martinozingaiv@ozinga.com
204	Prairie Material Sales, Inc.	9S753 Lorraine Drive, Hinsdale, IL 60527	gkrozel@mstli.com
205	VotarantimCimentosPrairie Materials	7601 West 79th Street, Bridgeview, IL 60455-1400	james.munro@vcimentos.com
206	Irving Materials, Inc.	8032 N. State Road 9, Greenfield, IN 46140-9017	earl.brinker@irvmat.co
207	JJ’s Concrete Construction, LLC	9149 E 800, North Montgomery, IN 47558	jwagler@jjsconcrete.com
208	Kuert Concrete Inc.	3402 Lincoln Way, West South Bend, IN 46628-1455	steve@kuert.com
209	Shelby Materials	P. O. Box 280, 157 East Rampart, Shelbyville, IN 46176-0280	phaehl@shelbymaterials.com
210	Tell City Concrete Supply	P. O. Box 249, Tell City, IN 47586-0249	bartmulzer@mulzer.com
211	Bard Materials	P. O. Box 246, Dyersville, IA 52040	dennist@bardmaterials.com
212	King’s Material Inc.	355 50th NE DR SW, Cedar Rapids, IA 52404	carohde@kingsmaterial.com
213	Manatt’s Inc.	1775 Old 6 Road, Box 535, Brooklyn, IA 52211-0535	adamm@manatts.com
214	Mohr Concrete	P. O. Box 232, Lohrville, IA 51453	mohrexcavating@gmail.com
215	Oldcastle Materials, Inc. Midwest Region	2401 SE Tones Drive, Suite 13, Ankeny, IA 50021	clamberty@omgmidwest.com
216	Ash Grove Materials Corp	11011 Cody St., Overland Park, KS 66210	rob.henning@ashgrove.com
217	Builders Concrete & Supply, Inc.	P. O. Box 225 Newton, KS 67114-3301	buildersconcrete@sbcglobal.net
218	Midwest Concrete Materials	701 S. 4th Street, Manhattan, KS 66502-6426	richards@4mcm.com
219	Monarch Cement Company	P. O. Box 1000, Humboldt, KS 66748-0900	walter.wulf@monarchcement.com
220	Penny’s Concrete, Inc.	23400 West 82nd Street, Shawnee Mission, KS 66227-2705	cclaxton@pennysconcrete.com
221	S.T. Wooten Corp.	104 High Hope Lane, Garner, NC 27529	jason@stwcorp.com

12.7 Survey Results - Responses from Construction Companies

Table 12.7.1 Survey question to Construction Companies

No.	Question
1	Has your company ever used crushed recycled concrete aggregate (RCA) as an aggregate in new concrete?
2	Please describe how your company's practices differ for the use of RCA compared to virgin aggregate in concrete.
3	For which application(s) RCA is used as an aggregate in new concrete? For which application(s) RCA is commonly (often) used?
4	What are your company's testing requirements or quality control procedures for using RCA as an aggregate in concrete?
5	Has your company encountered any problems in using concrete containing RCA?
6	If DOT allows using RCA in concrete in transportation applications would your company select RCA as an alternative aggregate or concrete containing RCA?
7	Please provide any additional comments you may have about your company's use of RCA in concrete.

Table 12.7.2. Responses to Question 1

Has your company ever used crushed recycled concrete aggregate (RCA) as an aggregate in new concrete?

Firm	Location	Responses
1	Alabama	No
2	Arizona	No
3	California	No
4	California	No
5	California	Yes
6	California	Yes
7	Maryland	Yes
8	Massachusetts	No
9	North Carolina	Yes
10	North Carolina	No
11	North Carolina	No
12	North Carolina	No
13	North Carolina	No
14	Pennsylvania	No
15	Pennsylvania	Not crushed recycled, but have used reclaimed.
16	South Carolina	No
17	Tennessee	Yes
18	Texas	No

Table 12.7.3. Responses to Question 2

Please describe how your company's practices differ for the use of RCA compared to virgin aggregate in concrete

Firm	Location	Responses
1	Alabama	N/A
2	Arizona	No not use RCA. Generally not allowed by specification other than as an alternate design.
3	California	Never use crushed recycled aggregates.
4	California	We only use aggregates that satisfy ASTM C33.
5	California	Handling in plant can be a challenge Water demand can be higher.
6	California	We replace 15% of the virgin aggregate both coarse and fine with RCA across most all of our concrete mixes except architectural and ultra-high strength +10,000 psi.
7	Maryland	Blend aggregates with virgin. Very careful to watch air entrainment and yield.
8	Massachusetts	Not used.
9	North Carolina	N/A
10	North Carolina	I have no knowledge of our Company utilizing RCA.
11	North Carolina	N/A
12	North Carolina	N/A
13	North Carolina	I really don't know since we have never used it.
14	Pennsylvania	N/A
15	Pennsylvania	Use it only in flowfill.
16	South Carolina	None at this time.
17	Tennessee	Increased water demand and material didn't come out of bins very well.
18	Texas	Engineers do not design new concrete structures or flatwork with it specified. We have on many occasions used RCA as a base course for paving.

Table 12.7.4. Responses to Question 3

For which application(s) RCA is used as an aggregate in new concrete? For which application(s) RCA is commonly (often) used?

		Usage												
Firm	**Location**	Sidewalks	Curb &gutter or slopes	Footings for lighting, signs or fences	Median barriers	Pipe or pull box filler	Lean concrete base	Controlled low strength material	Culvert backfill	Low volume roads	High volume roads/ highways	Bridge substructures	Bridge superstructures	Other applications
1	Alabama													
2	Arizona													
3	California	x	x	x		x	x	x	x					
4	California													
5	California	x	x	x		x	x	x	x	x				
6	California	x	x	x	x	x	x	x	x	x	x	x	x	
7	Maryland	x					x	x						
8	Massachusetts													
9	North Carolina													
10	North Carolina													
11	North Carolina													
12	North Carolina													Subgrade application only
13	North Carolina													

(Continued from Table 12.7.4.)

14	Pennsylvania													
15	Pennsylvania							x						
16	South Carolina													
17	Tennessee													
18	Texas													Base courses for paving

Table 12.7.5. Responses to Question 4

What are your company's testing requirements or quality control procedures for using RCA as an aggregate in concrete?

Firm	Location	Responses
1	Alabama	N/A
2	Arizona	N/A
3	California	Checking gradations, cleanliness, test water used to wash aggregates, checking of set times, compressive strengths often checked.
4	California	N/A
5	California	Air content, water demand, follow up psi testing Gradations.
6	California	Conditioned to assure SSD, combined aggregate RCA + virgin to meet ASTM C-33, Caltrans grading, durability, ASR, SE, ASTM 157, LA Abrasion.
7	Maryland	It is a case by case basis, typically standard base tests such as gradation and specific gravity.
8	Massachusetts	N/A, not used.
9	North Carolina	N/A
10	North Carolina	N/A
11	North Carolina	N/A
12	North Carolina	N/A
13	North Carolina	We don't use RCA so we don't have any specific quality control procedures.
14	Pennsylvania	N/A
15	Pennsylvania	We run strength tests.
16	South Carolina	We don’t use.
17	Tennessee	N/A
18	Texas	N/A

Table 12.7.6. Responses to Question 5

Has your company encountered any problems in using concrete containing RCA?

Firm	Location	Responses
1	Alabama	N/A
2	Arizona	N/A
3	California	Yes
4	California	No
5	California	Yes
6	California	No
7	Maryland	Yes
8	Massachusetts	No
9	North Carolina	N/A
10	North Carolina	N/A
11	North Carolina	N/A
12	North Carolina	N/A
13	North Carolina	No
14	Pennsylvania	N/A
15	Pennsylvania	No
16	South Carolina	No
17	Tennessee	N/A
18	Texas	No

Table 12.7.7. Responses to Question 6

If DOT allows using RCA in concrete in transportation applications would your company select RCA as an alternative aggregate or concrete containing RCA?

Firm	Location	Responses
1	Alabama	N/A
2	Arizona	N/A
3	California	Yes
4	California	Maybe
5	California	Yes
6	California	Yes
7	Maryland	Yes
8	Massachusetts	Maybe
9	North Carolina	N/A
10	North Carolina	Yes
11	North Carolina	N/A
12	North Carolina	N/A
13	North Carolina	Yes
14	Pennsylvania	N/A
15	Pennsylvania	Maybe
16	South Carolina	Maybe
17	Tennessee	N/A
18	Texas	Maybe

Table 12.7.8. Responses to Question 7

Please provide any additional comments you may have about your company's use of RCA in concrete.

Firm	Location	Responses
1	Alabama	N/A
2	Arizona	N/A
3	California	Special precautions and use of admixtures need to be administered during warm weather concreting. RCA need to be managed correctly.
4	California	N/A
5	California	N/A
6	California	We produce a number of mixed for street base application that use 100% coarse RCA and 50% fine RCA. We have produced 6000 PSI structural concrete with 100% coarse RCA. The use of coarse RCA is fairly straightforward the use of fine RCA has more challenges specific to handling through production and increased water demand in the mix.
7	Maryland	As of now only used where all parties are ok with the use and where mix failure is limited and will not affect constructed product.
8	Massachusetts	My responses are based on the market place in the greater Washington DC area. Recycled concrete is only used to my knowledge for fill and structural fill.
9	North Carolina	N/A
10	North Carolina	N/A
11	North Carolina	N/A
12	North Carolina	N/A
13	North Carolina	Since we don't use it we really don't have much to offer. We wouldn't be opposed to using it we just haven't in the past.
14	Pennsylvania	N/A
15	Pennsylvania	N/A
16	South Carolina	N/A
17	Tennessee	N/A
18	Texas	N/A

12.8 Concrete Mix Design

Table 12.8.1 Conrol Mix – 0% RCA

Control mix														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			Metric Conversion						
Test No.	Lab 1							0.006895	17.2375	MPA	COST/TON	COST/LB	TOTAL	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1749	2.63	10.66	26.24	131.50	lbs.		0.5933	1038	kg	15.75	0.00788	13.7734	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	0	2.27	0.00	0.00	0.00	lbs.		0.5933	0		16.25	0.00813	0.0000	
2S	1193	2.63	7.27	23.87	90.16	lbs.		0.5933	708	kg	9.35	0.00468	5.5788	
Water	267	1.00	4.28	217	16.07	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3776		27.0		4 stone	0.05						TOTAL	58.91	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			139.9	pcf		Theoritical Unit Wt. (wet)			2241	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.59	0.41			Age	PSI	MPA								
Mortar Ratio:	16.34			8 Day	**7070**	48.75		Mortar Ratio:	0.46					
Sand/Rock	0.682			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.2 15% RCA + 85% CA, Division 1

Div1_15%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1487	2.63	9.06	22.31	111.80	lbs.		0.5933	882	kg	15.75	0.00788	11.7101	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	225	2.25	1.60	11.25	17.50	lbs.		0.5933	133		16.25	0.00813	1.8281	
2S	1192	2.63	7.27	23.85	90.09	lbs.		0.5933	707	kg	9.35	0.00468	5.5741	
Water	267	1.00	4.28	210	15.53	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3738		27.0		4 stone	0.05						TOTAL	58.67	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			138.5	pcf		Theoritical Unit Wt. (wet)			2218	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.55	0.45			Age	PSI	MPA								
Mortar Ratio:	17.94			8 Day	**7070**	48.75		Mortar Ratio:	0.51					
Sand/Rock	0.696			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.3 30% RCA + 70% CA, Division 1

Div1_30%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1224	2.63	7.46	18.36	92.03	lbs.		0.5933	726	kg	15.75	0.00788	9.6390	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	453	2.27	3.20	22.65	35.23	lbs.		0.5933	269		16.25	0.00813	3.6806	
2S	1193	2.63	7.27	23.87	90.17	lbs.		0.5933	708	kg	9.35	0.00468	5.5795	
Water	267	1.00	4.28	202	14.97	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3704		27.0		4 stone	0.05						TOTAL	58.45	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	6.00	inches			Slump:		25.4	152	mm				
% Air :	6.0	4.9	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			137.2	pcf		Theoritical Unit Wt. (wet)			2198	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.51	0.49			Age	PSI	MPA								
Mortar Ratio:	19.54			8 Day	**7070**	48.75		Mortar Ratio:	0.55					
Sand/Rock	0.712			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.4 50% RCA + 50% CA, Division 1

Div1_50%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			Metric Conversion						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	431	3.15	2.19		31.93	lbs.		0.5933	256	kg	141.42	0.07071	30.4760	
Fly Ash	136	2.20	0.99		10.07	lbs.	23.99	0.5933	81	kg	61.20	0.03060	4.1616	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	875	2.63	5.33	13.13	65.79	lbs.		0.5933	519	kg	15.75	0.00788	6.8906	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	754	2.27	5.32	37.70	58.64	lbs.		0.5933	447		16.25	0.00813	6.1263	
2S	1192	2.63	7.26	23.84	90.06	lbs.		0.5933	707	kg	9.35	0.00468	5.5723	
Water	267	1.00	4.28	192	14.25	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3655		27.0		4 stone	0.05						TOTAL	57.94	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			135.4	pcf		Theoritical Unit Wt. (wet)			2169	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.42	0.58			Age	PSI	MPA								
Mortar Ratio:	21.67			8 Day	**7070**	48.75		Mortar Ratio:	0.61					
Sand/Rock	0.732			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.5 100% RCA + 0% CA, Division 1

Div1_100%														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	0	2.63	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	1510	2.27	10.66	75.50	117.44	lbs.		0.5933	896		16.25	0.00813	12.2688	
2S	1193	2.63	7.27	23.86	90.13	lbs.		0.5933	708	kg	9.35	0.00468	5.5766	
Water	267	1.00	4.28	168	12.42	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3537		27.0		4 stone	0.05						TOTAL	57.40	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			131.0	pcf		Theoritical Unit Wt. (wet)			2099	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.00	1.00			Age	PSI	MPA								
Mortar Ratio:	27.00			8 Day	**7070**	48.75		Mortar Ratio:	0.77					
Sand/Rock	0.790			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.6 15% RCA + 85% CA, Division 2

Div2_15%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1487	2.63	9.06	22.31	111.80	lbs.		0.5933	882	kg	15.75	0.00788	11.7101	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	225	2.25	1.60	11.25	17.50	lbs.		0.5933	133		16.25	0.00813	1.8281	
2S	1192	2.63	7.27	23.85	90.09	lbs.		0.5933	707	kg	9.35	0.00468	5.5741	
Water	267	1.00	4.28	210	15.53	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3738		27.0		4 stone	0.05						TOTAL	58.67	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			138.5	pcf		Theoritical Unit Wt. (wet)			2218	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.55	0.45			Age	PSI	MPA								
Mortar Ratio:	17.94			8 Day	**7070**	48.75		Mortar Ratio:	0.51					
Sand/Rock	0.696			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.7 30% RCA + 70% CA, Division 2

Div2_30%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1225	2.63	7.46	18.38	92.10	lbs.		0.5933	727	kg	15.75	0.00788	9.6469	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	449	2.25	3.20	22.45	34.92	lbs.		0.5933	266		16.25	0.00813	3.6481	
2S	1192	2.63	7.27	23.85	90.10	lbs.		0.5933	708	kg	9.35	0.00468	5.5749	
Water	267	1.00	4.28	202	14.99	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3700		27.0		4 stone	0.05						TOTAL	58.43	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			137.1	pcf		Theoritical Unit Wt. (wet)			2196	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.51	0.49			Age	PSI	MPA								
Mortar Ratio:	19.54			8 Day	**7070**	48.75		Mortar Ratio:	0.55					
Sand/Rock	0.712			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.8 50% RCA + 50% CA, Division 2

Div2_50%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	875	2.63	5.33	13.13	65.79	lbs.		0.5933	519	kg	15.75	0.00788	6.8906	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	748	2.25	5.33	37.40	58.18	lbs.		0.5933	444		16.25	0.00813	6.0775	
2S	1193	2.63	7.27	23.86	90.14	lbs.		0.5933	708	kg	9.35	0.00468	5.5772	
Water	267	1.00	4.28	193	14.27	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3650		27.0		4 stone	0.05						TOTAL	58.10	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			135.2	pcf		Theoritical Unit Wt. (wet)			2166	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.42	0.58			Age	PSI	MPA								
Mortar Ratio:	21.67			8 Day	**7070**	48.75		Mortar Ratio:	0.61					
Sand/Rock	0.735			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.9 100% RCA + 0% CA, Division 2

Div2_100%														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	0	2.63	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	1496	2.25	10.66	74.80	116.36	lbs.		0.5933	888		16.25	0.00813	12.1550	
2S	1194	2.63	7.27	23.87	90.19	lbs.		0.5933	708	kg	9.35	0.00468	5.5804	
Water	267	1.00	4.28	168	12.47	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3524		27.0		4 stone	0.05						TOTAL	57.29	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			130.5	pcf		Theoritical Unit Wt. (wet)			2091	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.00	1.00			Age	PSI	MPA								
Mortar Ratio:	27.00			8 Day	**7070**	48.75		Mortar Ratio:	0.77					
Sand/Rock	0.798			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.10 15% RCA + 85% CA, Division 3

Div3_15%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1487	2.63	9.06	22.31	111.80	lbs.		0.5933	882	kg	15.75	0.00788	11.7101	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	228	2.29	1.60	11.40	17.73	lbs.		0.5933	135		16.25	0.00813	1.8525	
2S	1193	2.63	7.27	23.87	90.17	lbs.		0.5933	708	kg	9.35	0.00468	5.5795	
Water	267	1.00	4.28	209	15.51	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3742		27.0		4 stone	0.05						TOTAL	58.70	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	6.00	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	4.9	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			138.6	pcf		Theoritical Unit Wt. (wet)			2221	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.55	0.45			Age	PSI	MPA								
Mortar Ratio:	17.94			8 Day	**7070**	48.75		Mortar Ratio:	0.51					
Sand/Rock	0.696			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.11 30% RCA + 70% CA, Division 3

Div3_30%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	1225	2.63	7.46	18.38	92.10	lbs.		0.5933	727	kg	15.75	0.00788	9.6469	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	457	2.29	3.20	22.85	35.54	lbs.		0.5933	271		16.25	0.00813	3.7131	
2S	1192	2.63	7.27	23.85	90.10	lbs.		0.5933	707	kg	9.35	0.00468	5.5748	
Water	267	1.00	4.28	202	14.96	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3708		27.0		4 stone	0.05						TOTAL	58.49	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			137.4	pcf		Theoritical Unit Wt. (wet)			2201	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.51	0.49			Age	PSI	MPA								
Mortar Ratio:	19.54			8 Day	**7070**	48.75		Mortar Ratio:	0.55					
Sand/Rock	0.709			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.12 50% RCA + 50% CA, Division 3

Div3_50%_by volume														
Date: 06/30/2018														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	874	2.63	5.33	13.11	65.71	lbs.		0.5933	519	kg	15.75	0.00788	6.8828	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	762	2.29	5.33	38.10	59.27	lbs.		0.5933	452		16.25	0.00813	6.1913	
2S	1193	2.63	7.27	23.86	90.15	lbs.		0.5933	708	kg	9.35	0.00468	5.5782	
Water	267	1.00	4.28	192	14.22	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3663		27.0		4 stone	0.05						TOTAL	58.21	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			135.7	pcf		Theoritical Unit Wt. (wet)			2174	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.42	0.58			Age	PSI	MPA								
Mortar Ratio:	21.67			8 Day	**7070**	48.75		Mortar Ratio:	0.61					
Sand/Rock	0.729			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.13 100% RCA + 0% CA, Division 3

Div3_100%														
Date: 06/30/2018														
		NCDOT RECYCLE MIX		2500	PSI			**Metric Conversion**						
Test No.	Lab 1							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**2.00**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		32.30	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		9.70	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
67 Stone	0	2.63	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	1523	2.29	10.66	76.15	118.46	lbs.		0.5933	904		16.25	0.00813	12.3744	
2S	1193	2.63	7.27	23.86	90.15	lbs.		0.5933	708	kg	9.35	0.00468	5.5782	
Water	267	1.00	4.28	167	12.37	lbs.	32.1	4.951	159	L	0.05	1.60264	1.6026	
Darex II	0.00	CWT	1.62		0.0	ml		38.7	0	ml	2.86	0.02234	0.0000	
Mira 85	68.0	12.00			149.0	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			Rock %M	0.015		38.7	0		0.00	0.00000	0.0000	
Total:	3550		27.0		4 stone	0.05						TOTAL	57.51	
		ACTUAL RESULTS			2S %M	0.02								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.9**	%			% Air :			4.9	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	144.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			131.5	pcf		Theoritical Unit Wt. (wet)			2107	kg/m3				
W/C Ratio			0.47											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.00	1.00			Age	PSI	MPA								
Mortar Ratio:	27.00			8 Day	**7070**	48.75		Mortar Ratio:	0.77					
Sand/Rock	0.783			8 Day	**7190**	49.58								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.14 20 EAF Slag + 80% RCA

20% Slag - 80% RCA														
27-Jul-18														
		NCDOT RECYCLE MIX		2500	PSI			**Metric Conversion**						
Test No.	Lab 2							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**1.50**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		24.22	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		7.28	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
Slag	473	3.22	2.35	2.37	26.41	lbs.		0.5933	281	kg	15.75	0.00788	3.7249	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	1078	2.27	7.61	5.39	60.19	lbs.		0.5933	640		16.25	0.00813	8.7588	
2S	1331	2.63	8.11	48.70	76.63	lbs.		0.5933	790	kg	9.35	0.00468	6.2210	
Water	258	1.00	4.13	202	11.20	lbs.	31.0	4.951	153	L	0.05	1.54862	1.5486	
Darex II	12.00	CWT	1.62		19.7	ml		38.7	464	ml	2.86	0.02234	0.5494	
Mira 85	68.0	12.00			111.8	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			A 11	0.005		38.7	0		0.00	0.00000	0.0000	
Total:	3707		27.0		A 13	0.005						TOTAL	58.76	
		ACTUAL RESULTS			2S %M	0.037								
Slump:	5.0	**5.25**	inches			Slump:		25.4	133	mm				
% Air :	**6.0**	**5.8**	%			% Air :			5.8	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	137.54		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			137.3	pcf		Theoritical Unit Wt. (wet)			2199	kg/m3				
W/C Ratio			0.46											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.23	0.77			Age	PSI	MPA								
Mortar Ratio:	24.65			8 Day	**0**	0		Mortar Ratio:	0.70					
Sand/Rock	0.858			8 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

Table 12.8.15 50 EAF Slag + 50% RCA

50% Slag - 50% RCA														
27-Jul-18														
	NCDOT RECYCLE MIX			2500	PSI			**Metric Conversion**						
Test No.	Lab 2							0.006895	17.2375	MPA	**COST/TON**	**COST/LB**	**TOTAL**	
Mix Design		**S.Gravity**	**Volume**	**Moisture**	**1.50**	**cu.ft.**								
							% Ash							
Giant	436	3.15	2.22		24.22	lbs.		0.5933	259	kg	141.42	0.07071	30.8296	
Fly Ash	131	2.20	0.95		7.28	lbs.	23.10	0.5933	78	kg	61.20	0.03060	4.0086	
Slag	0	2.90	0.00		0.00	lbs.		0.5933	0	kg	110.00	0.05500	0.0000	
Microsilica	0	2.25	0.00		0.00	lbs.		0.5933	0	kg	0.00	0.00000	0.0000	
Slag	1101	3.22	5.48	5.51	61.47	lbs.		0.5933	653	kg	15.75	0.00788	8.6704	
	0	2.43	0.00	0.00	0.00	lbs.		0.5933	0	kg	15.75	0.00788	0.0000	
RCA	776	2.27	5.48	3.88	43.33	lbs.		0.5933	460		16.25	0.00813	6.3050	
2S	1168	2.63	7.12	42.74	67.24	lbs.		0.5933	693	kg	9.35	0.00468	5.4588	
Water	258	1.00	4.13	206	11.44	lbs.	31.0	4.951	153	L	0.05	1.54862	1.5486	
Darex II	12.00	CWT	1.62		19.7	ml		38.7	464	ml	2.86	0.02234	0.5494	
Mira 85	68.0	12.00			111.8	ml		38.7	2633	ml	5.86	0.04578	3.1150	
Recover	0.0	0.00			0.0	ml		38.7	0	ml	12.00	0.09375	0.0000	
EXP 950	0.0	0.00			0.0	ml		38.7	0	ml	13.00	0.10156	0.0000	
	0.0	0.00			A 11	0.005		38.7	0		0.00	0.00000	0.0000	
Total:	3870		27.0		A 13	0.005						TOTAL	60.49	
		ACTUAL RESULTS			2S %M	0.037								
Slump:	5.0	**6.00**	inches			Slump:		25.4	152	mm				
% Air :	**6.0**	**4.3**	%			% Air :			4.3	%				
Concrete Temp.:			60			Concrete Temp.:			15.6	C				
Air Temp. :			65	145.8		Air Temp. :			18.3	C				
Theoritical Unit Wt. (wet)			143.3	pcf		Theoritical Unit Wt. (wet)			2296	kg/m3				
W/C Ratio			0.46											
ROCK :	**SAND RATIO**			**Cylinder Results**										
0.44	0.56			Age	PSI	MPA								
Mortar Ratio:	21.52			8 Day	**0**	0		Mortar Ratio:	0.61					
Sand/Rock	0.622			8 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								
				28 Day	**0**	0								

12.9 Concrete Strength Test Results

S.T. WOOTEN

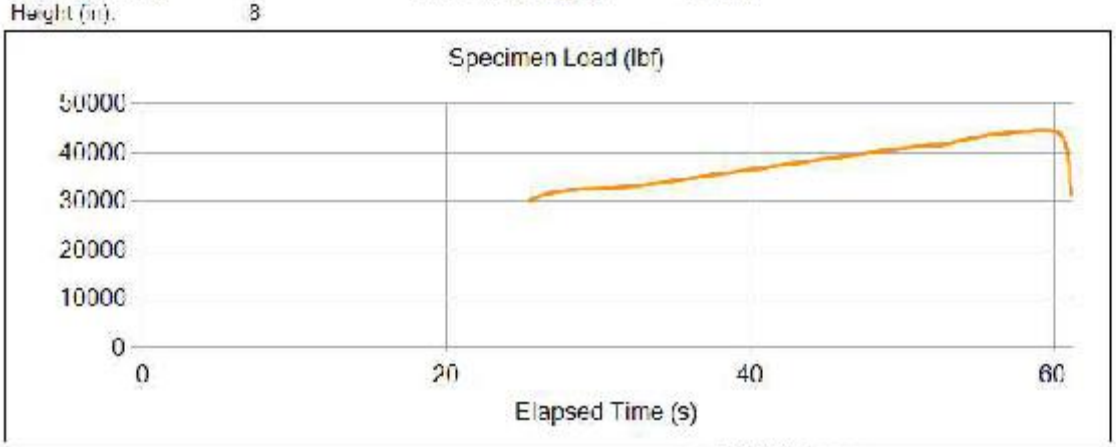
Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
3104 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Control Mix

Test ID:	66	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	09:58	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	44602
Cyl. Corr. Factor:	1	Stress at Break (psi):	3549.32
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.1 Control Concrete – 7-day Compressive Strength

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
304 High Hope Ln www.stwcorp.com
Garner, NC 27529

Control Mix

Test ID:	67	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:00	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	41810
Cyl. Corr. Factor:	1	Stress at Break (psi):	3327.14
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.2 Control Concrete – 7-day Compressive Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-5380
204 High Hope Ln www.stwcorp.com
Garner, NC 27529

Control Mix

Test ID:	68	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:03	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	42130
Cyl. Corr. Factor:	1	Stress at Break (psi):	3352.63
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.3 Control Concrete – 7-day Compressive Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-5380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 1 -15%

Test ID:	60	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:08	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	28
Diameter (in):	4	Load at Break (lbf):	40417
Cyl. Corr. Factor:	1	Stress at Break (psi):	3216.26
Height (in):	8		

www.FORNEYonline.com

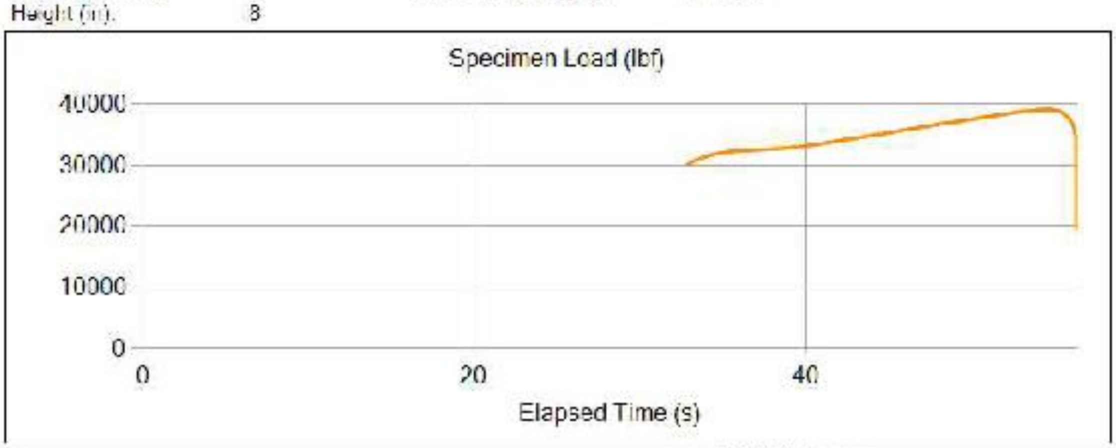
Figure 12.9.4 15% RCA +85% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3'14 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 1 - 15%

Test ID:	70	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:08	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	32
Diameter (in):	4	Load at Break (lbf):	39101
Cyl. Corr. Factor:	1	Stress at Break (psi):	3111.56
Height (in):	8		



www.FORNEYonline.com

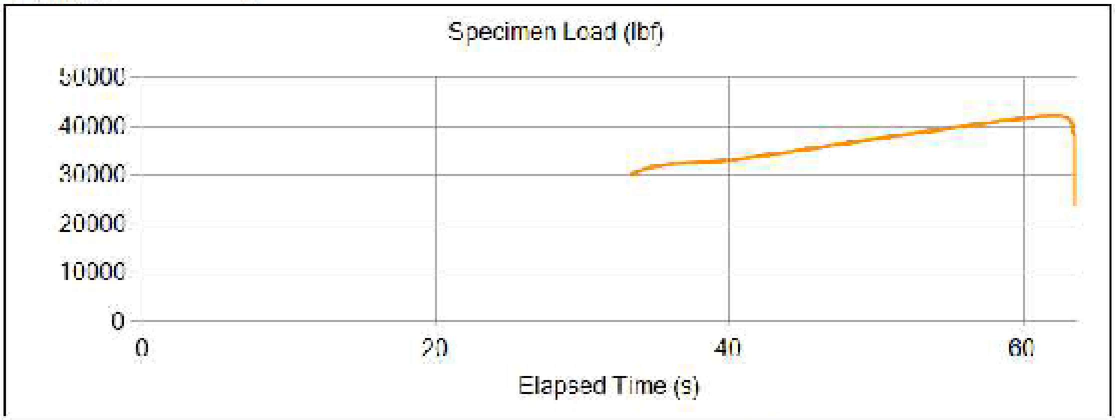
Figure 12.9.5 15% RCA +85% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 2 - 15%

Test ID:	71	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:12	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	42226
Cyl. Corr. Factor:	1	Stress at Break (psi):	3360.21
Height (in):	8		



www.FORNEYonline.com

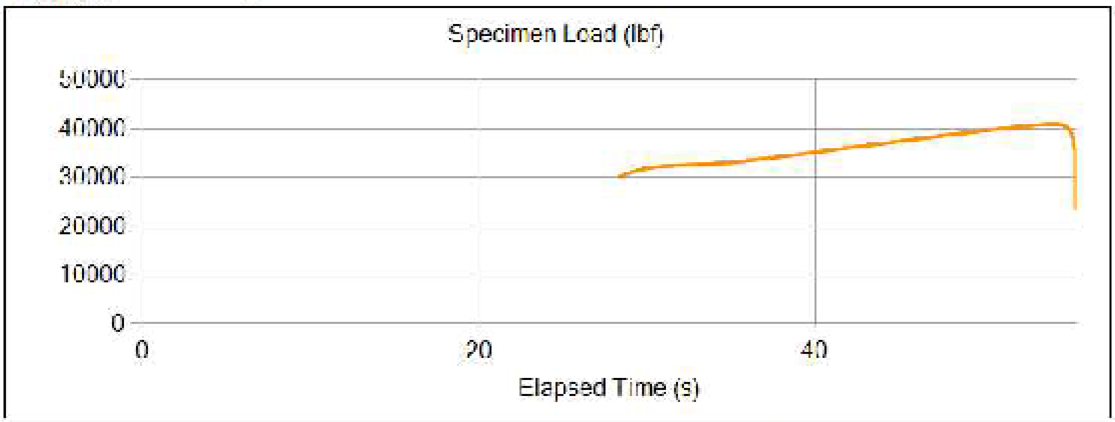
Figure 12.9.6 15% RCA +85% CA – 7-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-5380
www.stwcorp.com

Division 2 - 15%

Test ID:	72	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10.15	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	40908
Cyl. Corr. Factor:	1	Stress at Break (psi):	3255.33
Height (in):	8		



www.FORNEYonline.com

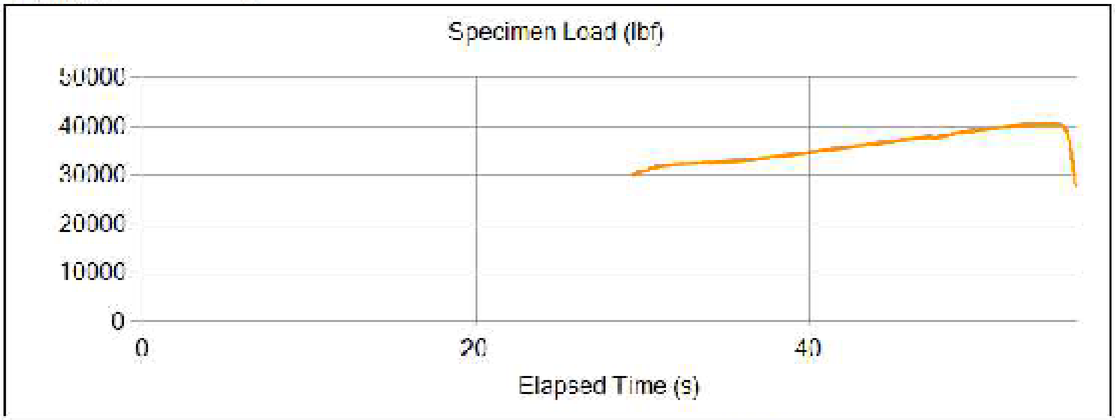
Figure 12.9.7 15% RCA +85% CA – 7-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 3 - 15%

Test ID:	73	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:17	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	32
Diameter (in):	4	Load at Break (lbf):	40588
Cyl. Corr. Factor:	1	Stress at Break (psi):	3229.88
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.8 15% RCA +85% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten (919) 773-5380

204 High Hope Ln www.stwcorp.com

Garner, NC 27529

Division 3 - 15%

Test ID:	74	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:20	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	43084
Cyl. Corr. Factor:	1	Stress at Break (psi):	3428.5
Height (in):	8		

www.FORNEYonline.com

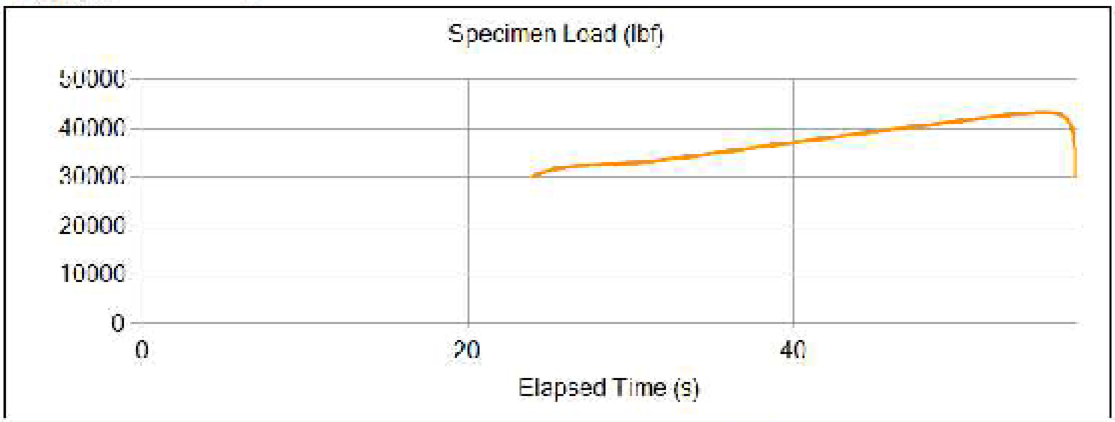
Figure 12.9.9 15% RCA +85% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 1 - 30%

Test ID:	75	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:23	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	43329
Cyl. Corr. Factor:	1	Stress at Break (psi):	3447.98
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.10 30% RCA +70% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-5380
204 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 1 - 30%

Test ID:	76	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:25	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	44324
Cyl. Corr. Factor:	1	Stress at Break (psi):	3527.22
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.11 30% RCA +70% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-5380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 2 - 30%

Test ID:	78	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:32	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	45173
Cyl. Corr. Factor:	1	Stress at Break (psi):	3594.75
Height (in):	8		

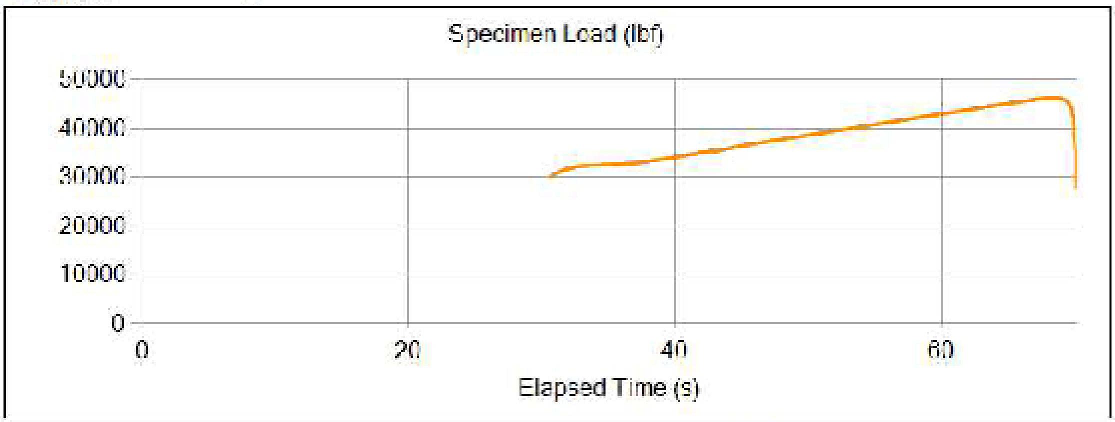
www.FORNEYonline.com

Figure 12.9.12 30% RCA +70% CA – 7-day Compressive Strength, Division 2

Forney CA-0397VLD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-5380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 2 - 30%

Test ID:	79	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:35	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	46183
Cyl. Corr. Factor:	1	Stress at Break (psi):	3675.14
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.13 30% RCA +70% CA – 7-day Compressive Strength, Division 2

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
104 High Hope Ln
Garner, NC 27529
(919) 773-5380
www.stwcorp.com

S.T. WOOTEN

Division 3 - 30%

Test ID:	80	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:37	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	45315
Cyl. Corr. Factor:	1	Stress at Break (psi):	3606.07
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.14 30% RCA +70% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten (919) 773-5380

104 High Hope Ln www.stwcorp.com

Garner, NC 27529

Division 3 - 30%

Test ID:	8L	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:39	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	46022
Cyl. Corr. Factor:	1	Stress at Break (psi):	3662.3
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.15 30% RCA +70% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

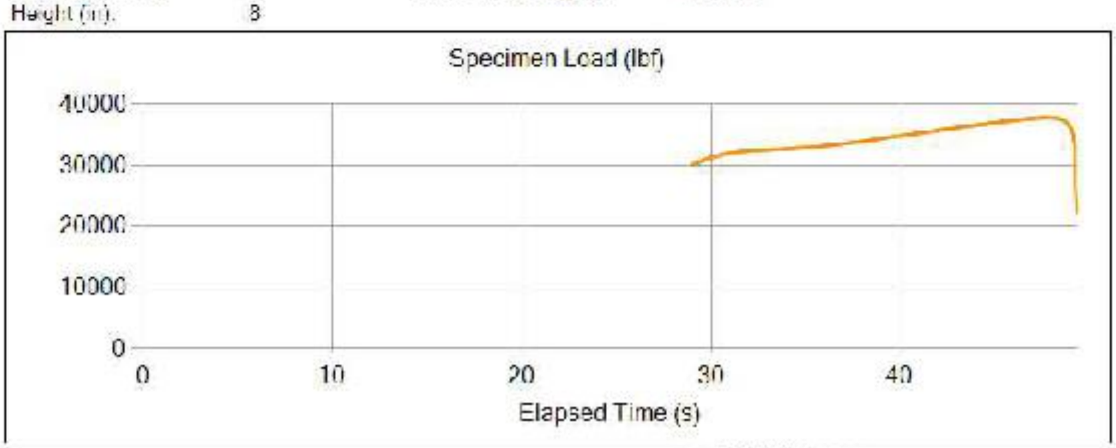
Forney CA-0397-VI-D Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Division 1 -50%

Test ID:	82	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:41	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	32
Diameter (in):	4	Load at Break (lbf):	37805
Cyl. Corr. Factor:	1	Stress at Break (psi):	3008.46
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.16 50% RCA +50% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VLD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten

104 High Hope Ln

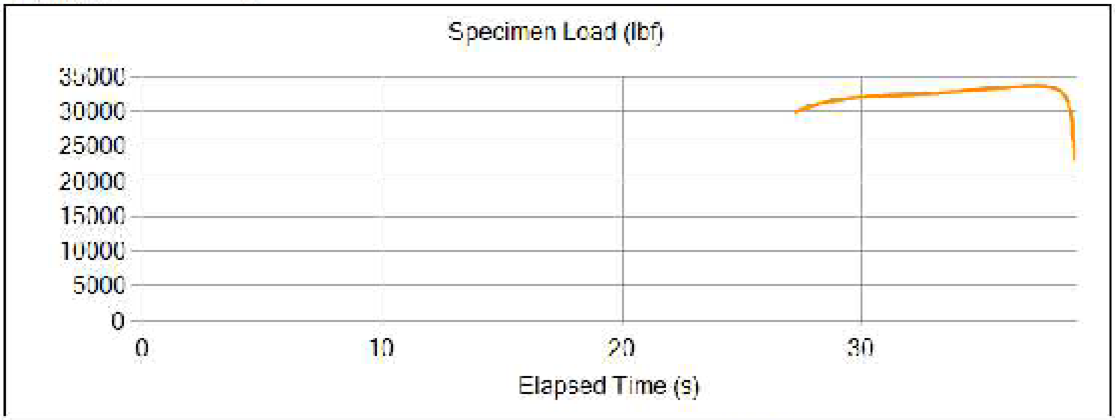
Garner, NC 27529

(919) 773-5380

www.stwcorp.com

Division 1 -50%

Test ID:	83	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:43	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	33843
Cyl. Corr. Factor:	1	Stress at Break (psi):	2693.13
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.17 50% RCA +50% CA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-039/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 2 -50%

Test ID:	84	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:45	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	37297
Cyl. Corr. Factor:	1	Stress at Break (psi):	2967.98
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.18 50% RCA +50% CA – 7-day Compressive Strength, Division 2

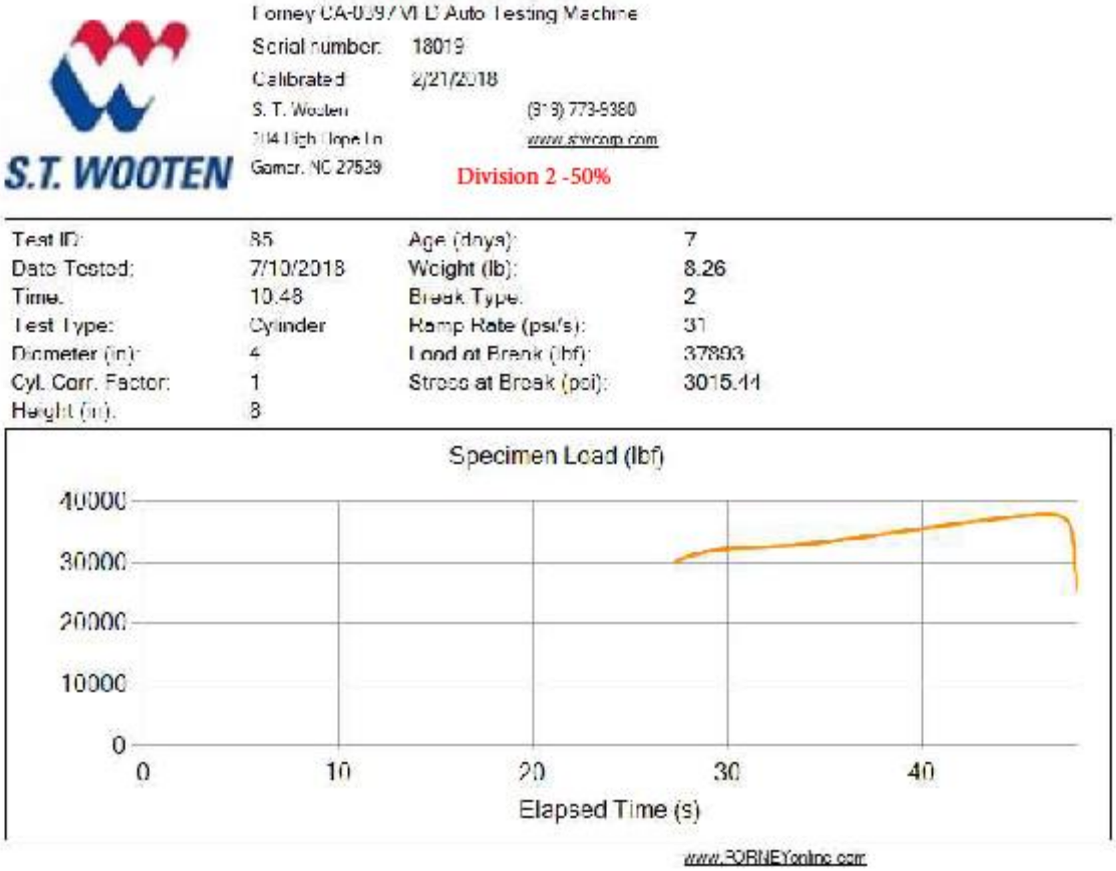


Figure 12.9.19 50% RCA +50% CA – 7-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten
214 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Division 3 -50%

Test ID:	86	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:48	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	14
Diameter (in):	4	Load at Break (lbf):	37343
Cyl. Corr. Factor:	1	Stress at Break (psi):	2971.66
Height (in):	8		

www.FORNEYonline.com

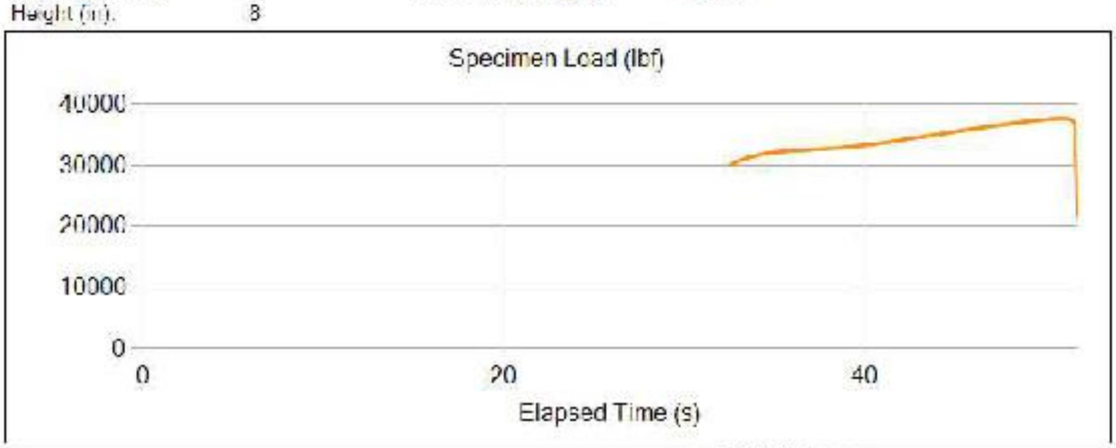
Figure 12.9.20 50% RCA +50% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397-VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 3 -50%

Test ID:	87	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:50	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	37705
Cyl. Corr. Factor:	1	Stress at Break (psi):	3000.5
Height (in):	8		



www.FORNEYonline.com

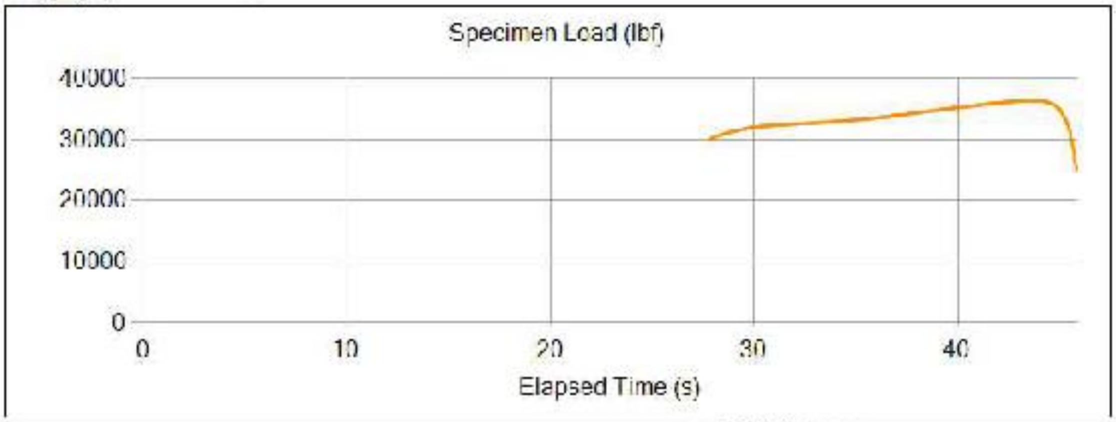
Figure 12.9.21 50% RCA +50% CA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 1 -100%

Test ID:	88	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:52	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	25
Diameter (in):	4	Load at Break (lbf):	36393
Cyl. Corr. Factor:	1	Stress at Break (psi):	2896.07
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.22 100% RCA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

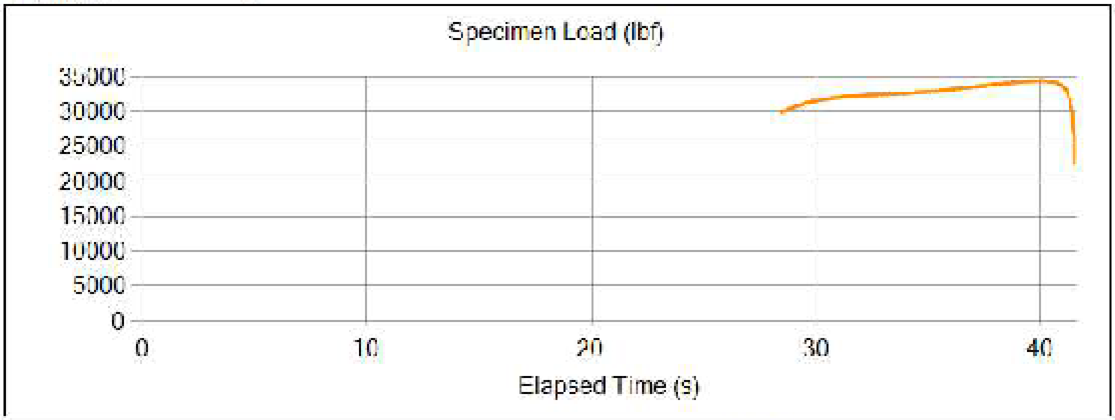
Calibrated: 2/21/2018

S. T. Wooten
304 High Hope Ln
Garner, NC 27529

(919) 773-5380
www.stwcorp.com

Division 1 -100%

Test ID:	80	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:53	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	34599
Cyl. Corr. Factor:	1	Stress at Break (psi):	2753.3
Height (in):	8		



www.FORNEYonline.com

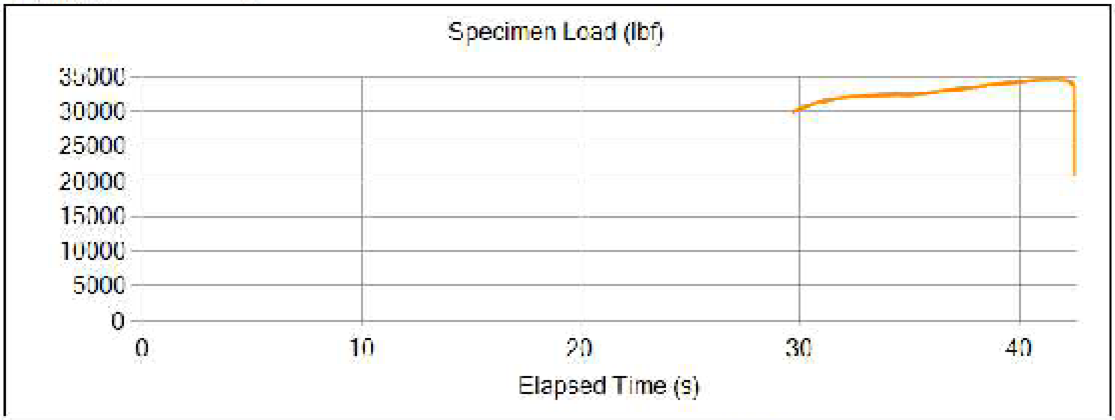
Figure 12.9.23 100% RCA – 7-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Division 2 -100%

Test ID:	90	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:55	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	34768
Cyl. Corr. Factor:	1	Stress at Break (psi):	2766.75
Height (in):	8		



www.FORNEYonline.com

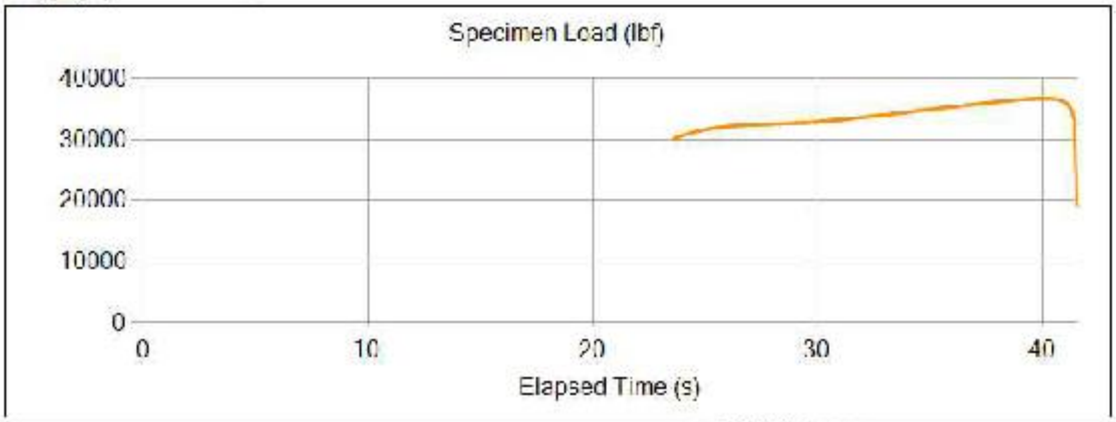
Figure 12.9.24 100% RCA – 7-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 2 -100%

Test ID:	01	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:58	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	32
Diameter (in):	4	Load at Break (lbf):	36733
Cyl. Corr. Factor:	1	Stress at Break (psi):	2923.13
Height (in):	8		



www.FORNEYonline.com

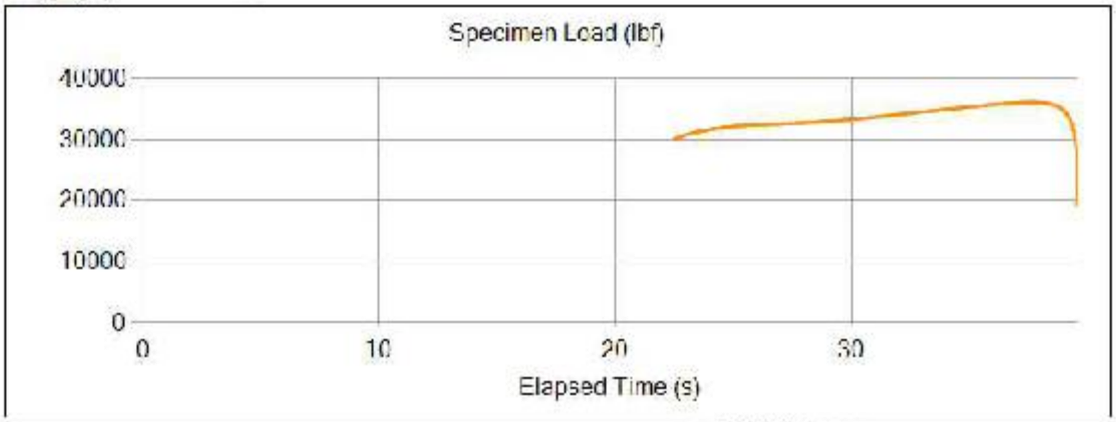
Figure 12.9.25 100% RCA – 7-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 3 -100%

Test ID:	02	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	10:59	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	31
Diameter (in):	4	Load at Break (lbf):	36135
Cyl. Corr. Factor:	1	Stress at Break (psi):	2875.5
Height (in):	8		



www.FORNEYonline.com

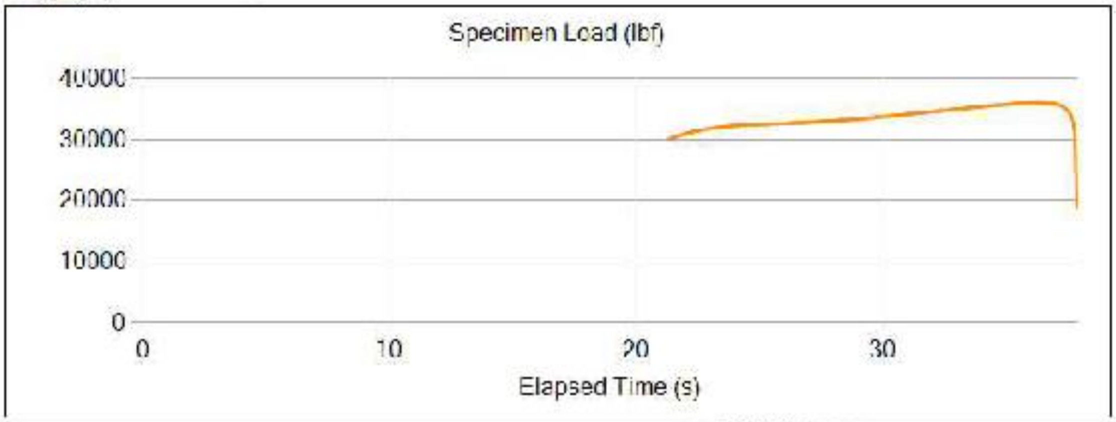
Figure 12.9.26 100% RCA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Division 3 - 100%

Test ID:	03	Age (days):	7
Date Tested:	7/10/2018	Weight (lb):	8.26
Time:	11:01	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	30
Diameter (in):	4	Load at Break (lbf):	36062
Cyl. Corr. Factor:	1	Stress at Break (psi):	2869.72
Height (in):	8		



www.FORNEYonline.com

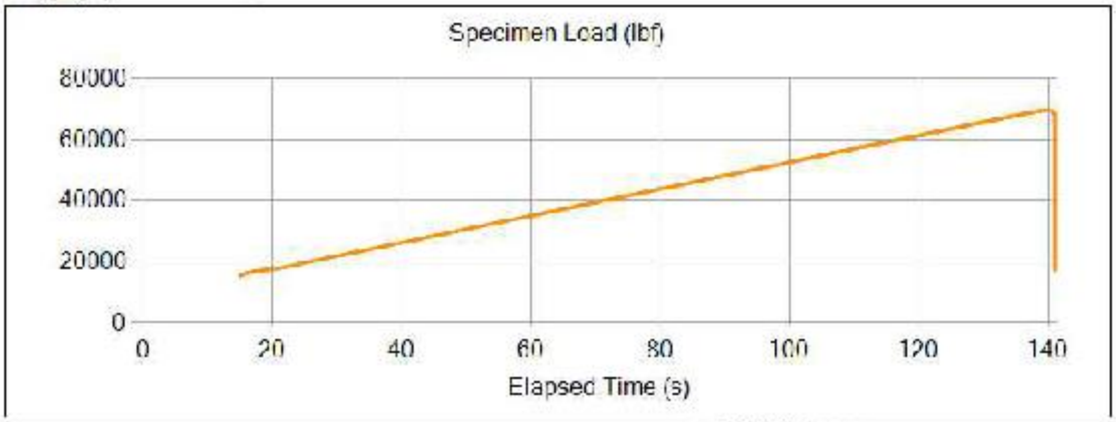
Figure 12.9.27 100% RCA – 7-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	118	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:09	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	69637
Cyl. Corr. Factor:	1	Stress at Break (psi):	5541.57
Height (in):	8		



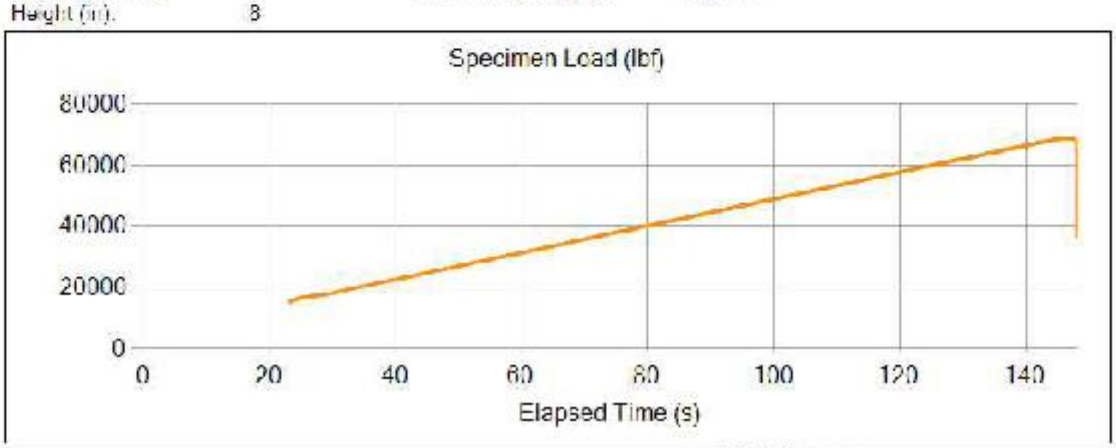
www.FORNEYonline.com

Figure 12.9.28 Control Concrete – 28-day Compressive Strength

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3?4 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	119	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:12	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	69062
Cyl. Corr. Factor:	1	Stress at Break (psi):	5495.79
Height (in):	8		



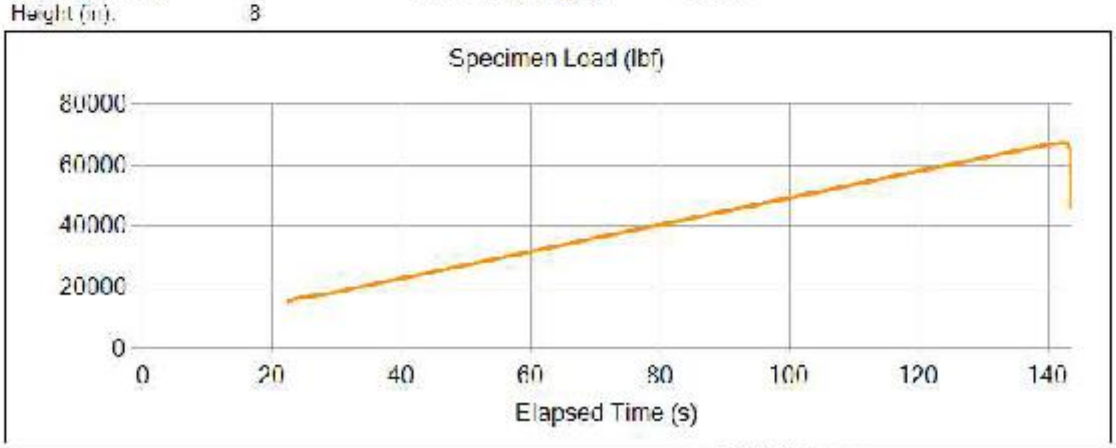
www.FORNEYonline.com

Figure 12.9.29 Control Concrete – 28-day Compressive Strength

S.T. WOOTEN

Forney CA-039?/VFD Auto Testing Machine
Serial number: 18019
Calibrated 2/21/2018
S. T. Wooten (919) 773-5380
[illegible]14 High Hope Ln www.stwcorp.com
Garner, NC 27529

Test ID:	120	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:18	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	67373
Cyl. Corr. Factor:	1	Stress at Break (psi):	5361.41
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.30 Control Concrete – 28-day Compressive Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
[illegible] High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	121	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:19	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	62967
Cyl. Corr. Factor:	1	Stress at Break (psi):	5010.72
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.31 15%RCA +85% CA – 28-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
3104 High Hope Ln www.stwcorp.com
Garner, NC 27529

Test ID:	122	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:22	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	60292
Cyl. Corr. Factor:	1	Stress at Break (psi):	4797.92
Height (in):	8		

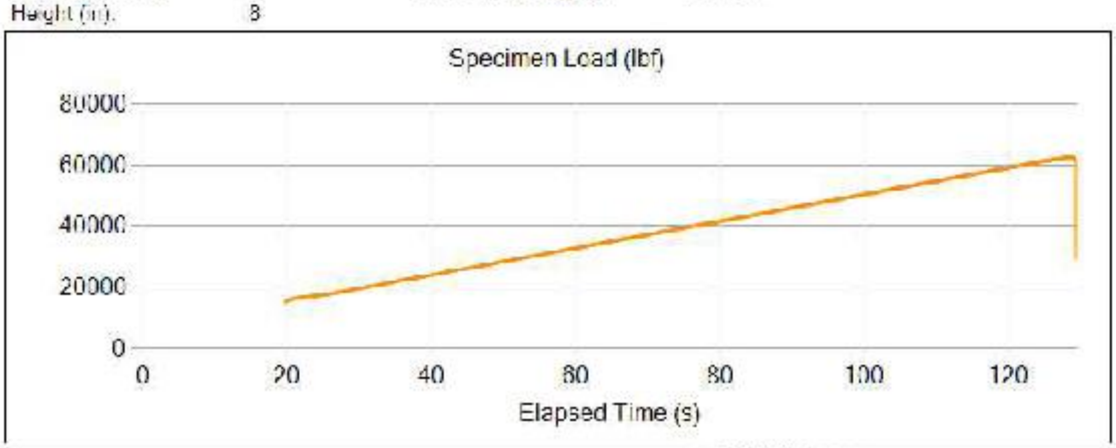
www.FORNEYonline.com

Figure 12.9.32 15%RCA +85% CA – 28-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	123	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10.25	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	62727
Cyl. Corr. Factor:	1	Stress at Break (psi):	4991.69
Height (in):	8		



www.FORNEYonline.com

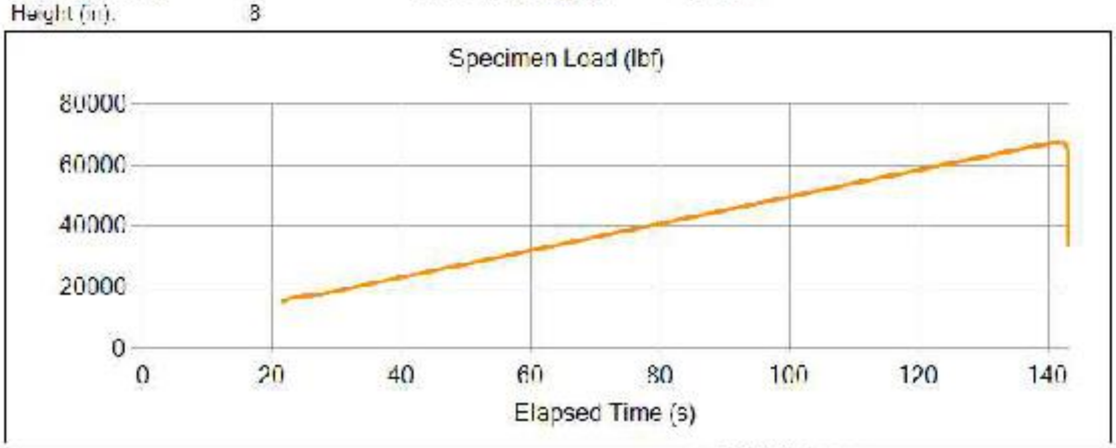
Figure 12.9.33 15%RCA +85% CA – 28-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

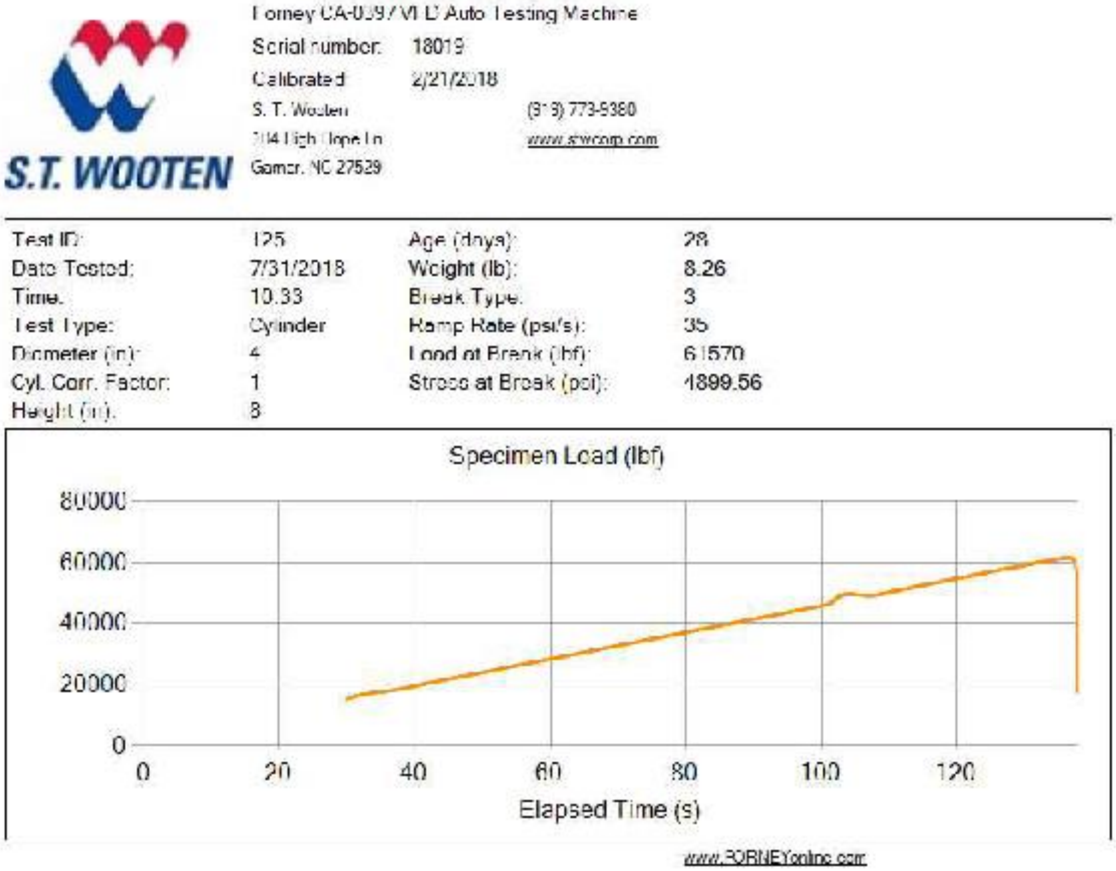
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	124	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:29	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	67600
Cyl. Corr. Factor:	1	Stress at Break (psi):	5379.4
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.34 30%RCA +70% CA – 28-day Compressive Strength, Division 1



Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S.T. WOOTEN
S. T. Wooten
214 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

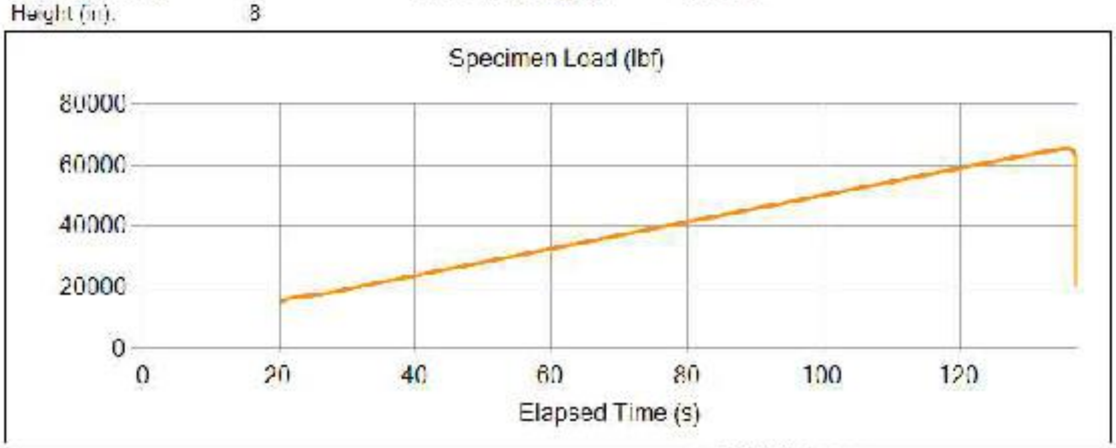
Test ID:	125	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10.33	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	61570
Cyl. Corr. Factor:	1	Stress at Break (psi):	4899.56
Height (in):	8		

Figure 12.9.35 30%RCA +70% CA – 28-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	126	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:38	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	65464
Cyl. Corr. Factor:	1	Stress at Break (psi):	5209.43
Height (in):	8		



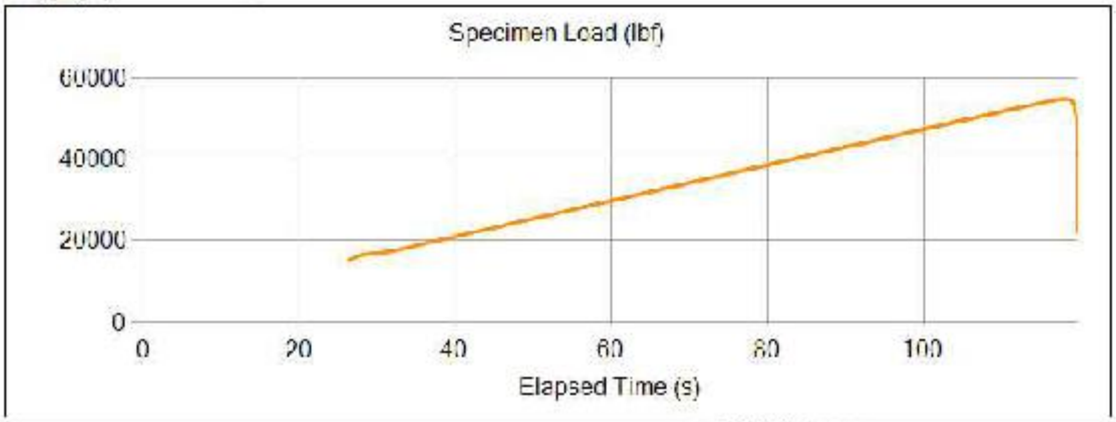
www.FORNEYonline.com

Figure 12.9.36 30%RCA +70% CA – 28-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	127	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:40	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	54973
Cyl. Corr. Factor:	1	Stress at Break (psi):	4374.65
Height (in):	8		



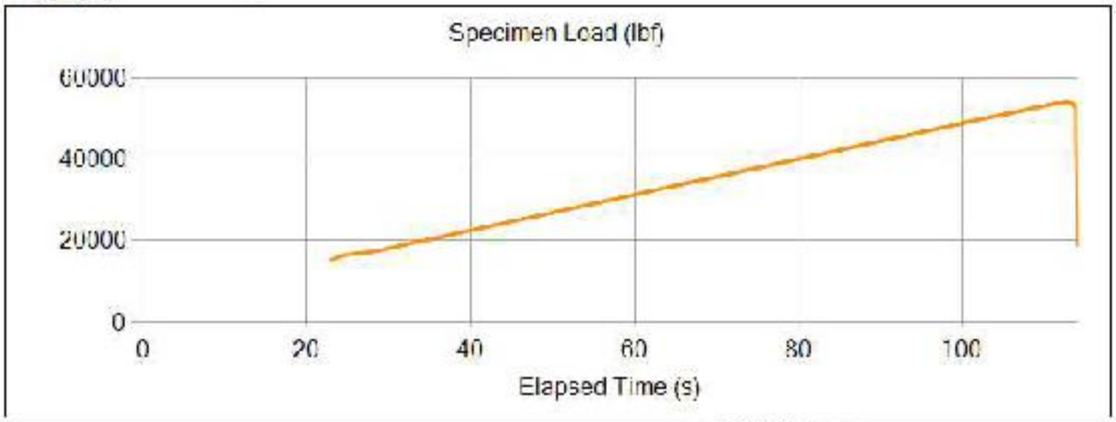
www.FORNEYonline.com

Figure 12.9.37 50%RCA +50% CA – 28-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	128	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:43	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	54168
Cyl. Corr. Factor:	1	Stress at Break (psi):	4310.57
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.38 50%RCA +50% CA – 28-day Compressive Strength, Division 2

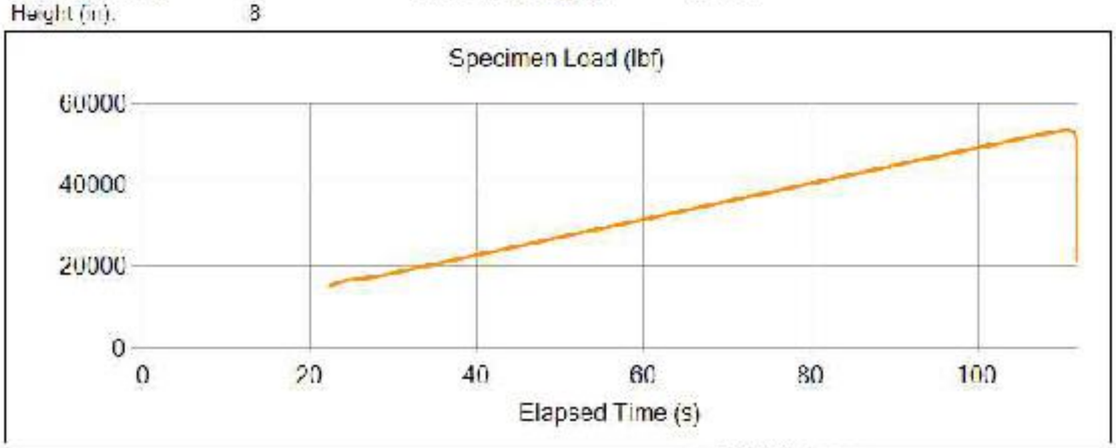
S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
304 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Test ID:	120	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:48	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	53622
Cyl. Corr. Factor:	1	Stress at Break (psi):	4267.07
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.39 50%RCA +50% CA – 28-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Test ID:	130	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:49	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	54184
Cyl. Corr. Factor:	1	Stress at Break (psi):	4311.8
Height (in):	8		

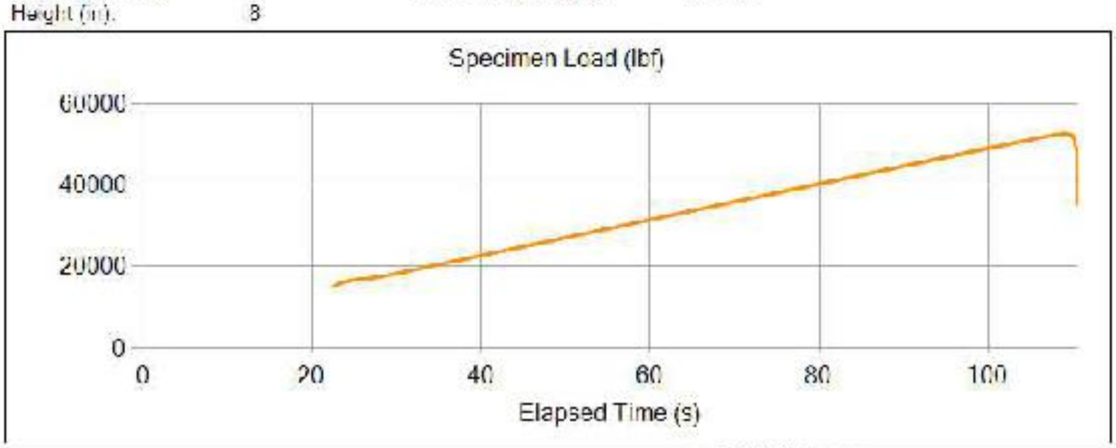
www.FORNEYonline.com

Figure 12.9.40 100%RCA – 28-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	131	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:55	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	52694
Cyl. Corr. Factor:	1	Stress at Break (psi):	4193.27
Height (in):	8		



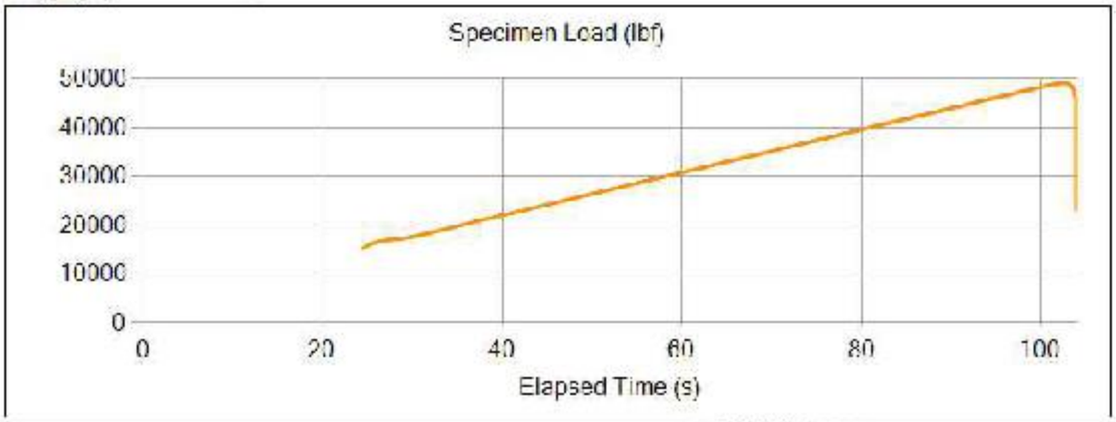
www.FORNEYonline.com

Figure 12.9.41 100%RCA – 28-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	132	Age (days):	28
Date Tested:	7/31/2018	Weight (lb):	8.26
Time:	10:58	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	49120
Cyl. Corr. Factor:	1	Stress at Break (psi):	3908.83
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.42 100%RCA – 28-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	104	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	10:51	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	77975
Cyl. Corr. Factor:	1	Stress at Break (psi):	6205.06
Height (in):	8		

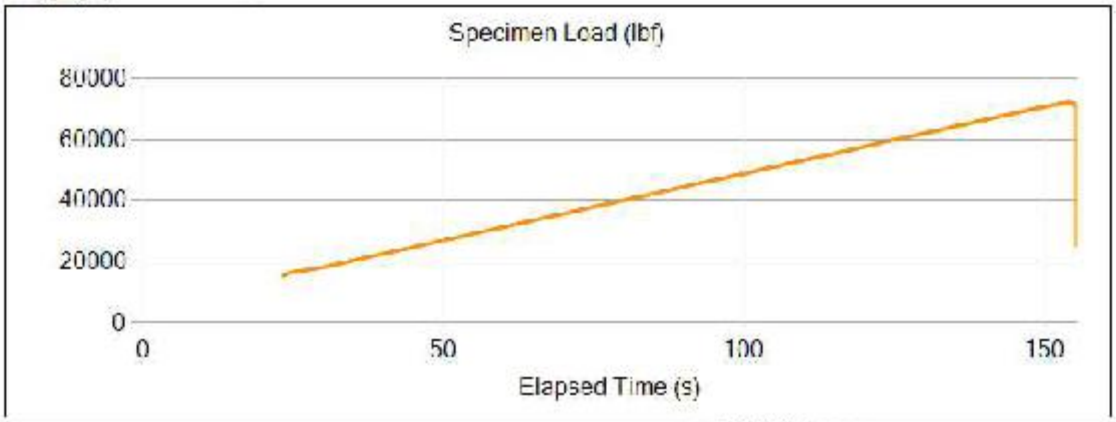
www.FORNEYonline.com

Figure 12.9.43 Control Concrete – 90-day Compressive Strength

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S.T. WOOTEN
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	105	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	11:48	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	72219
Cyl. Corr. Factor:	1	Stress at Break (psi):	5747.04
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.44 15% RCA + 85% CA – 90-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine

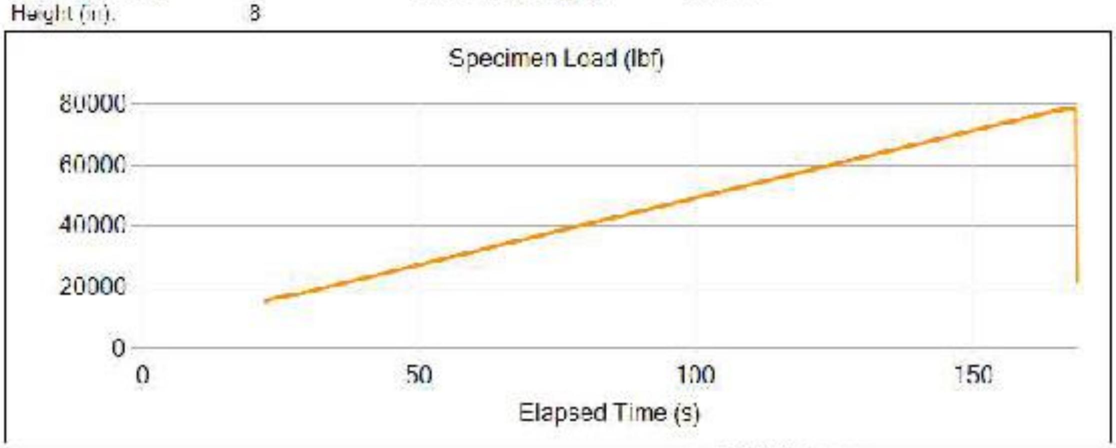
Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Test ID:	196	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	11:50	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	78662
Cyl. Corr. Factor:	1	Stress at Break (psi):	6259.73
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.45 30% RCA + 70% CA – 90-day Compressive Strength, Division 1

S.T. WOOTEN

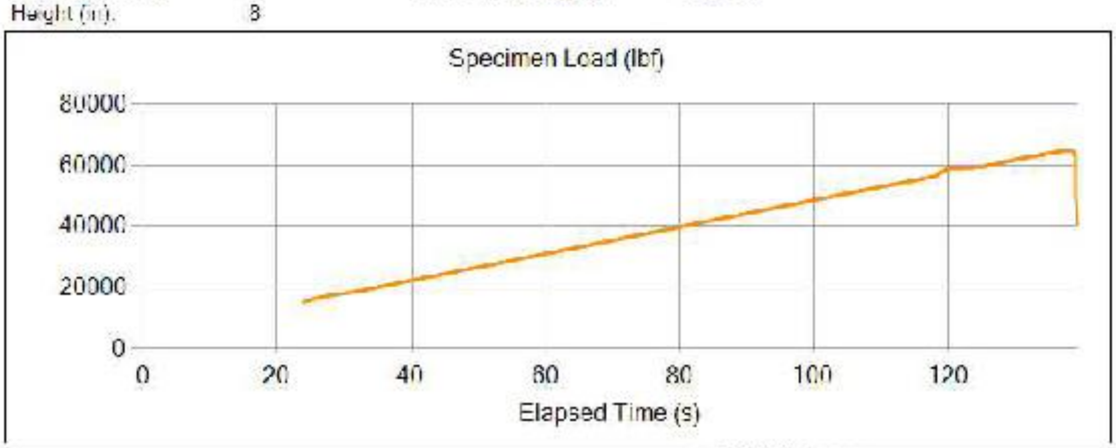
Forney CA-0397 VFD Auto Testing Machine

Serial number:	18019
Calibrated	2/21/2018

S. T. Wooten
104 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Test ID:	107	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	11:53	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	64841
Cyl. Corr. Factor:	1	Stress at Break (psi):	5159.92
Height (in):	8		



www.FORNEYonline.com

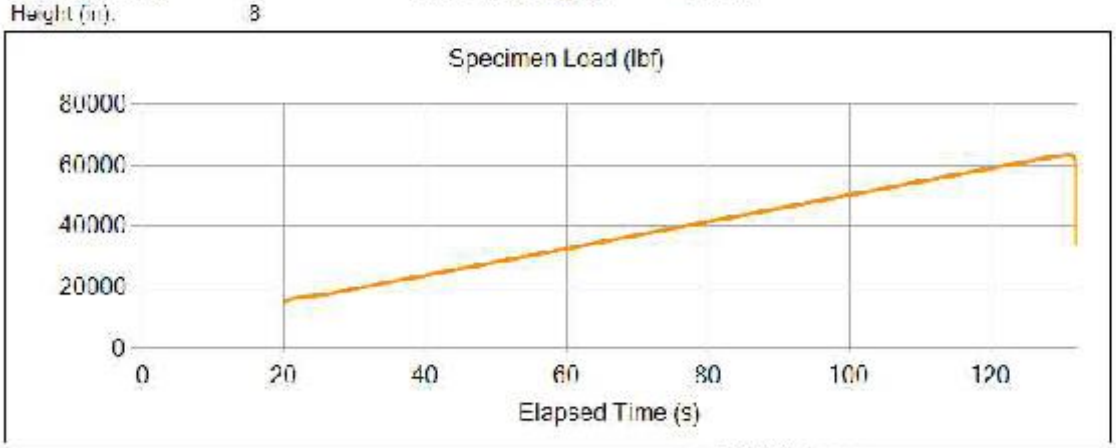
Figure 12.9.46 50% RCA + 50% CA – 90-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-8380
www.stwcorp.com

Test ID:	198	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	11:58	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	63450
Cyl. Corr. Factor:	1	Stress at Break (psi):	5049.21
Height (in):	8		



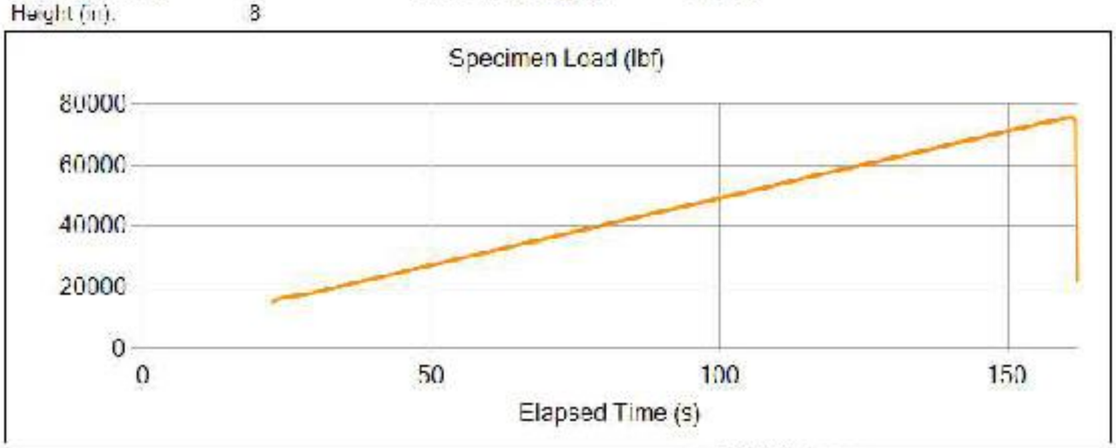
www.FORNEYonline.com

Figure 12.9.47 100% RCA – 90-day Compressive Strength, Division 1

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	100	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:00	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	75629
Cyl. Corr. Factor:	1	Stress at Break (psi):	6018.37
Height (in):	8		



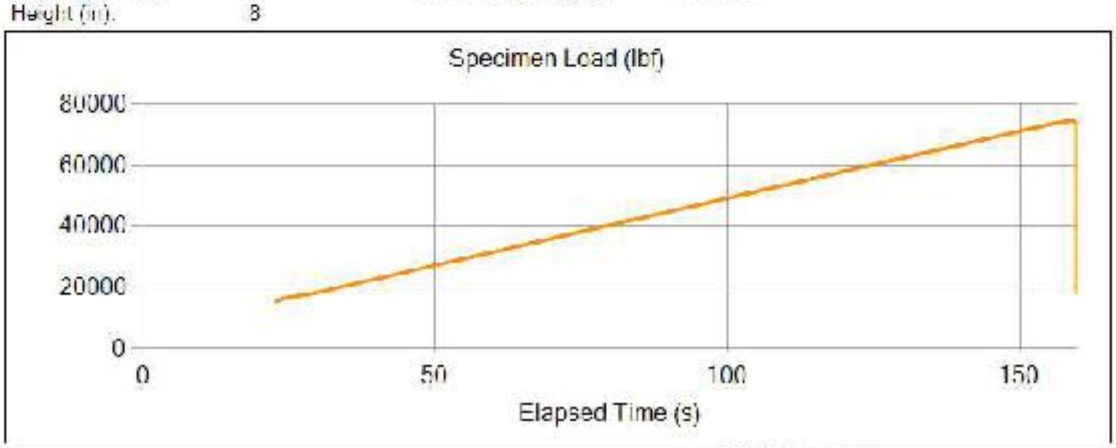
www.FORNEYonline.com

Figure 12.9.48 15% RCA + 85% CA – 90-day Compressive Strength, Division 2

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S.T. WOOTEN
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	200	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:03	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	74647
Cyl. Corr. Factor:	1	Stress at Break (psi):	5940.2
Height (in):	8		



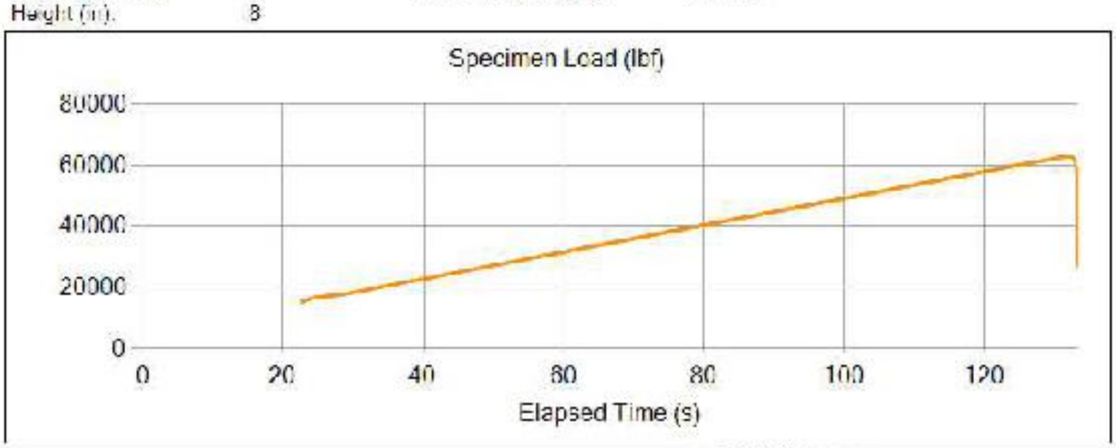
www.FORNEYonline.com

Figure 12.9.49 30% RCA + 70% CA – 90-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	201	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:07	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	62816
Cyl. Corr. Factor:	1	Stress at Break (psi):	4998.75
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.50 50% RCA + 50% CA – 90-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	202	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:10	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	63163
Cyl. Corr. Factor:	1	Stress at Break (psi):	5026.35
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.51 100% RCA – 90-day Compressive Strength, Division 2

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine

Serial number: 18019

Calibrated 2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529

(919) 773-5380
www.stwcorp.com

Test ID:	203	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:13	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	73494
Cyl. Corr. Factor:	1	Stress at Break (psi):	5848.46
Height (in):	8		

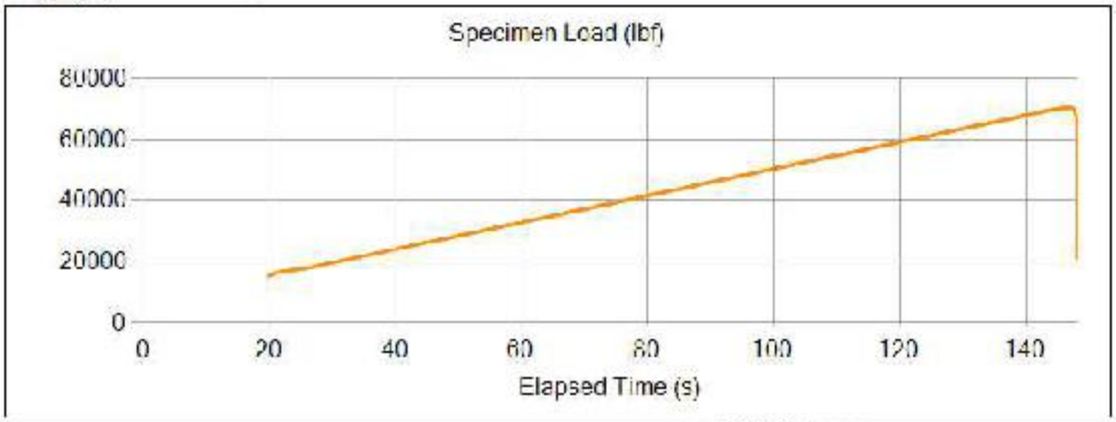
www.FORNEYonline.com

Figure 12.9.52 15% RCA + 85% CA – 90-day Compressive Strength, Division 3

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S.T. WOOTEN
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	204	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12.17	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	70467
Cyl. Corr. Factor:	1	Stress at Break (psi):	5607.55
Height (in):	8		



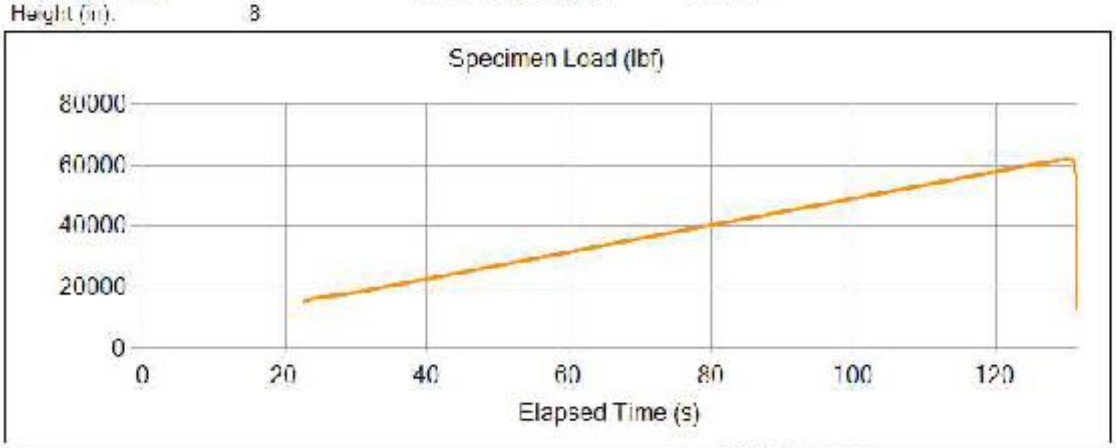
www.FORNEYonline.com

Figure 12.9.53 30% RCA + 70% CA – 90-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	205	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:20	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	61878
Cyl. Corr. Factor:	1	Stress at Break (psi):	4924.06
Height (in):	8		



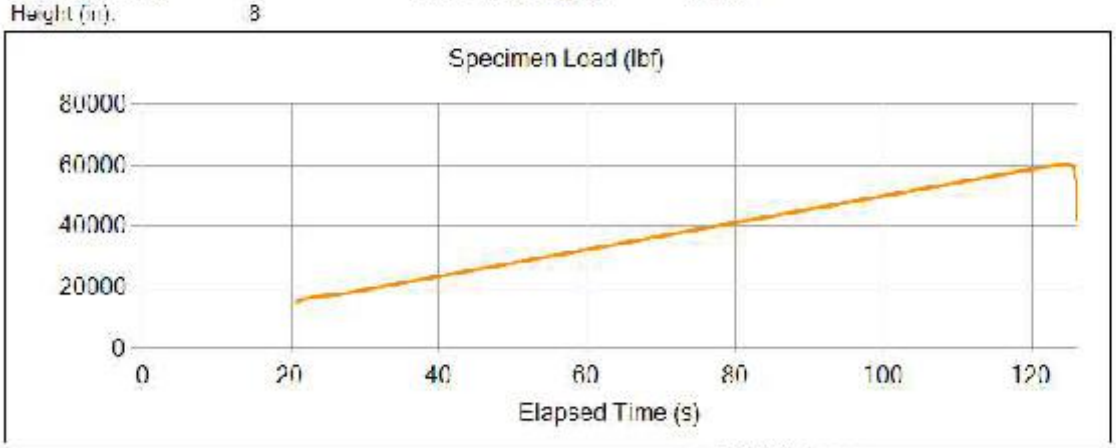
www.FORNEYonline.com

Figure 12.9.54 50% RCA + 50% CA – 90-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	206	Age (days):	90
Date Tested:	10/1/2018	Weight (lb):	8.46
Time:	12:23	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	60203
Cyl. Corr. Factor:	1	Stress at Break (psi):	4790.8
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.55 100% RCA – 90-day Compressive Strength, Division 3

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten
304 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

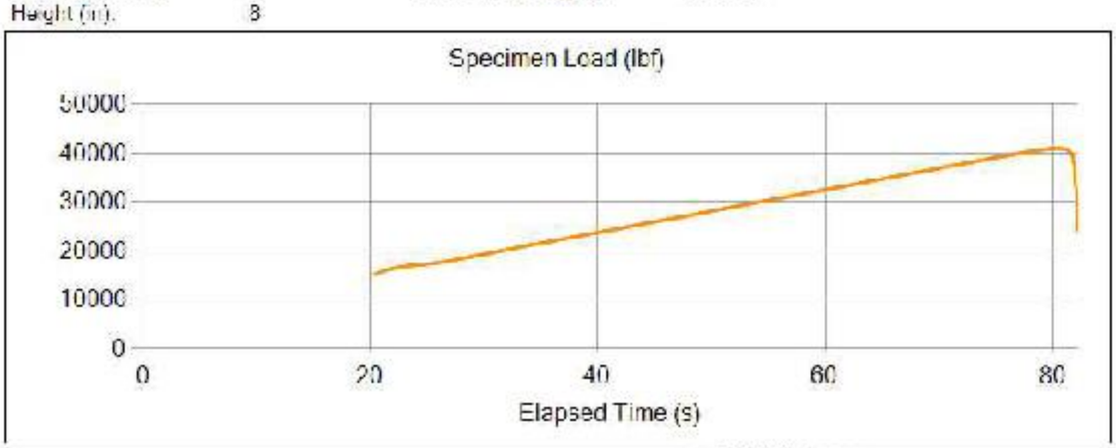
Test ID:	135	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11:00	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	40448
Cyl. Corr. Factor:	1	Stress at Break (psi):	3218.73
Height (in):	8		

www.FORNEYonline.com

Figure 12.9.56 50%EAF Slag + 50%RCA Concrete 7-day Strength

Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	136	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11:02	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	40992
Cyl. Corr. Factor:	1	Stress at Break (psi):	3262.05
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.57 50%EAF Slag + 50%RCA Concrete 7-day Strength

S.T. WOOTEN

Forney CA-0397/VLD Auto Testing Machine

Serial number: 18019

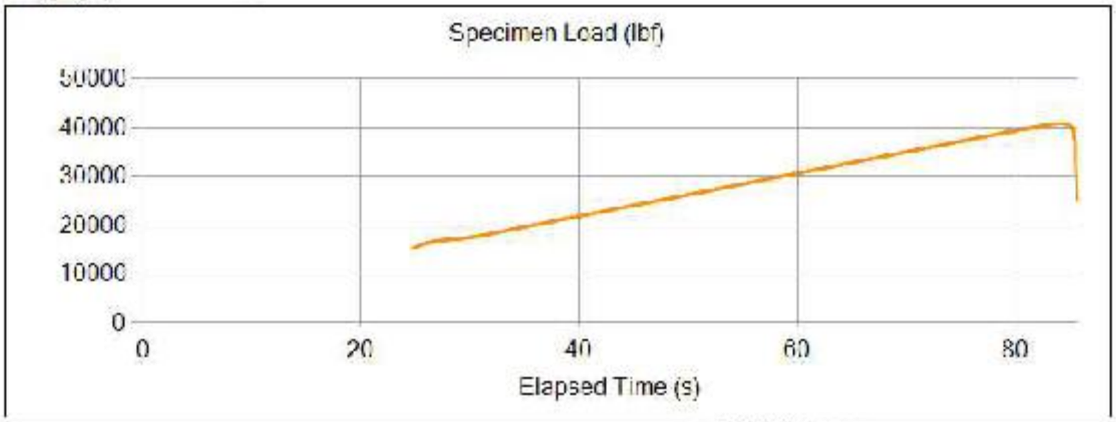
Calibrated: 2/21/2018

S. T. Wooten (919) 773-9380

204 High Hope Ln www.stwcorp.com

Garner, NC 27529

Test ID:	137	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11:09	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	40755
Cyl. Corr. Factor:	1	Stress at Break (psi):	3243.14
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.58 50%EAF Slag + 50%RCA Concrete 7-day Strength

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

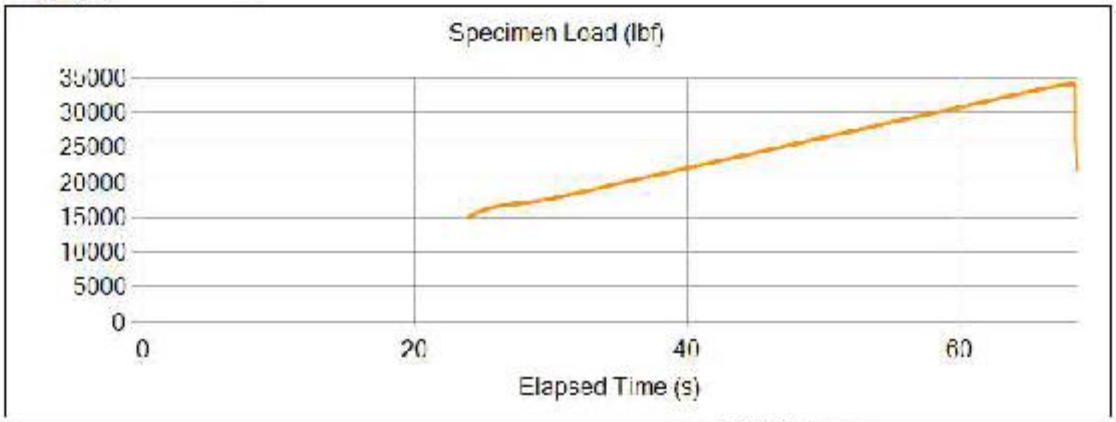
Calibrated: 2/21/2018

S.T. WOOTEN

S. T. Wooten
304 High Hope Ln
Garner, NC 27529

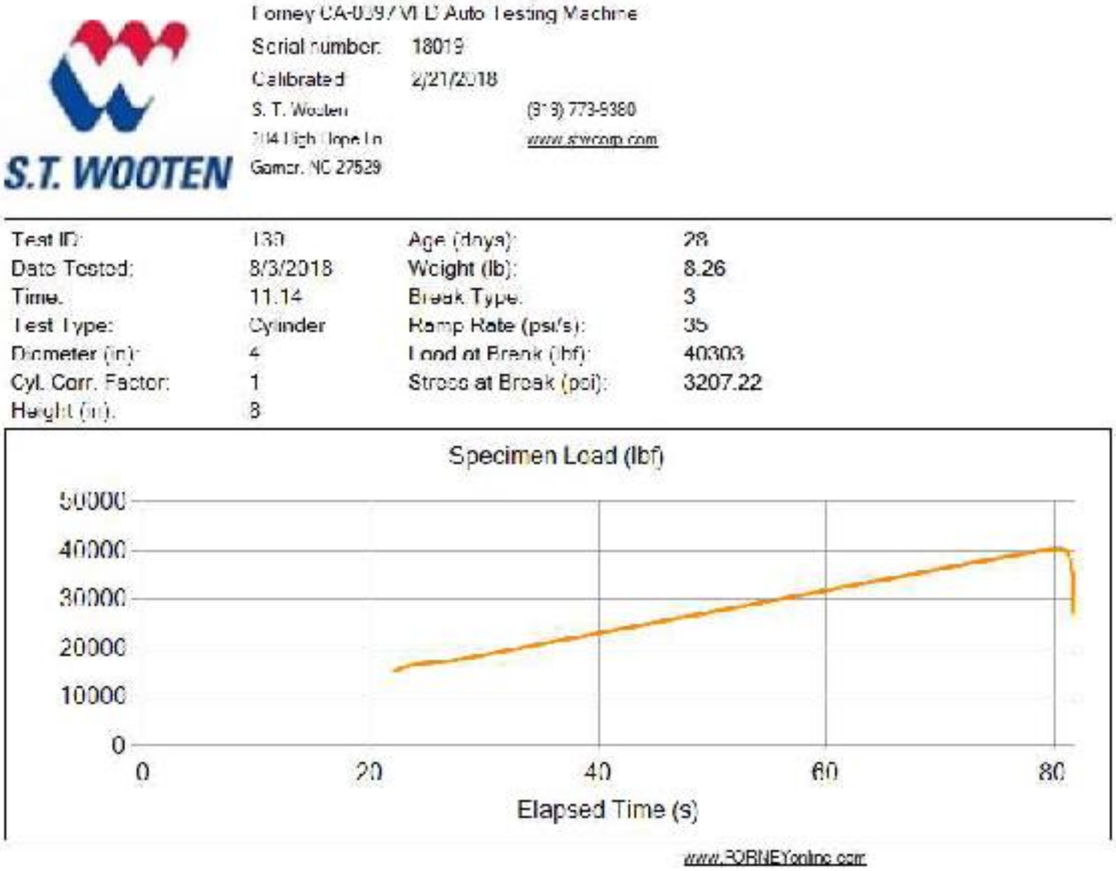
(919) 773-9380
www.stwcorp.com

Test ID:	138	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11.11	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	34242
Cyl. Corr. Factor:	1	Stress at Break (psi):	2721.92
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.59 20%EAF Slag + 80%RCA Concrete 7-day Strength

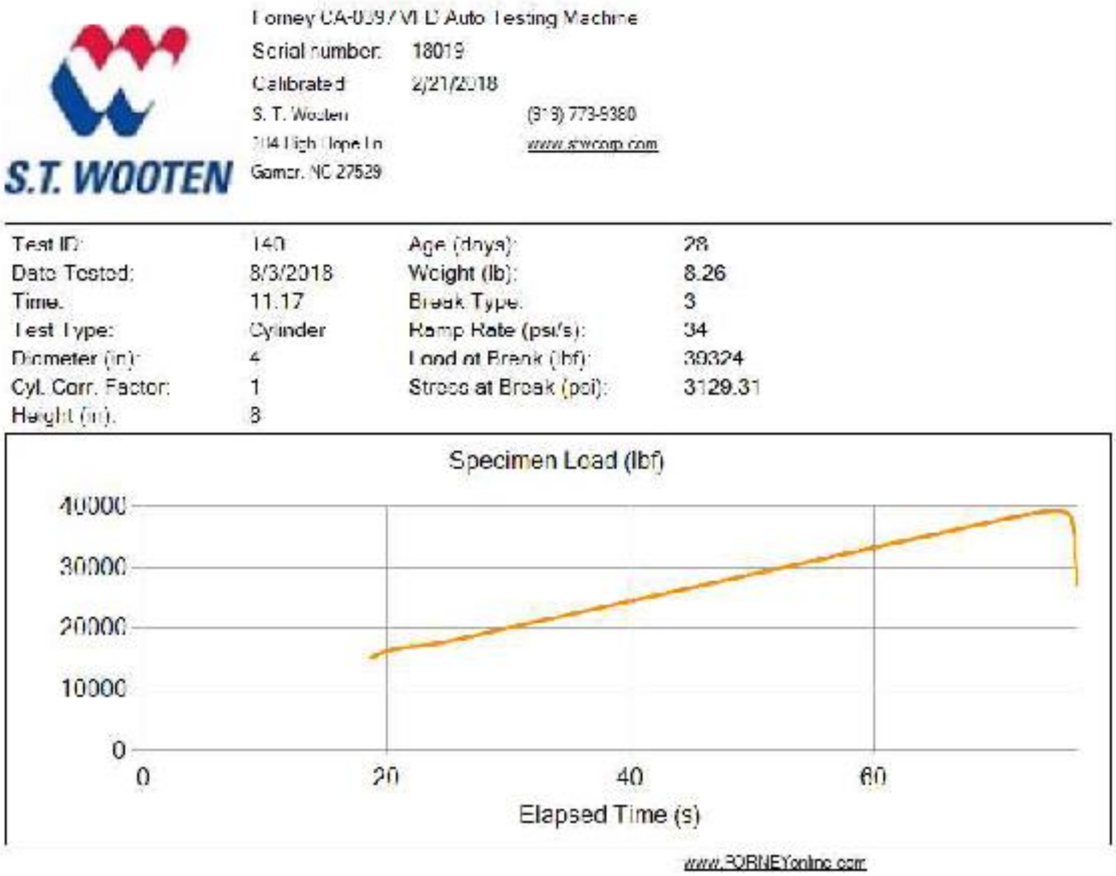


S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
3104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	130	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11.14	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	40303
Cyl. Corr. Factor:	1	Stress at Break (psi):	3207.22
Height (in):	8		

Figure 12.9.60 20%EAF Slag + 80%RCA Concrete 7-day Strength


Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
314 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

S.T. WOOTEN

Test ID:	140	Age (days):	28
Date Tested:	8/3/2018	Weight (lb):	8.26
Time:	11:17	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	34
Diameter (in):	4	Load at Break (lbf):	39324
Cyl. Corr. Factor:	1	Stress at Break (psi):	3129.31
Height (in):	8		

Figure 12.9.61 20%EAF Slag + 80%RCA Concrete 7-day Strength

Forney CA-0397 VFD Auto Testing Machine

Serial number: 18019

Calibrated: 2/21/2018

S. T. Wooten (919) 773-5380

204 High Hope Ln www.stwcorp.com

Garner, NC 27529

S.T. WOOTEN

Test ID:	158	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10:03	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	49725
Cyl. Corr. Factor:	1	Stress at Break (psi):	3957.02
Height (in):	8		

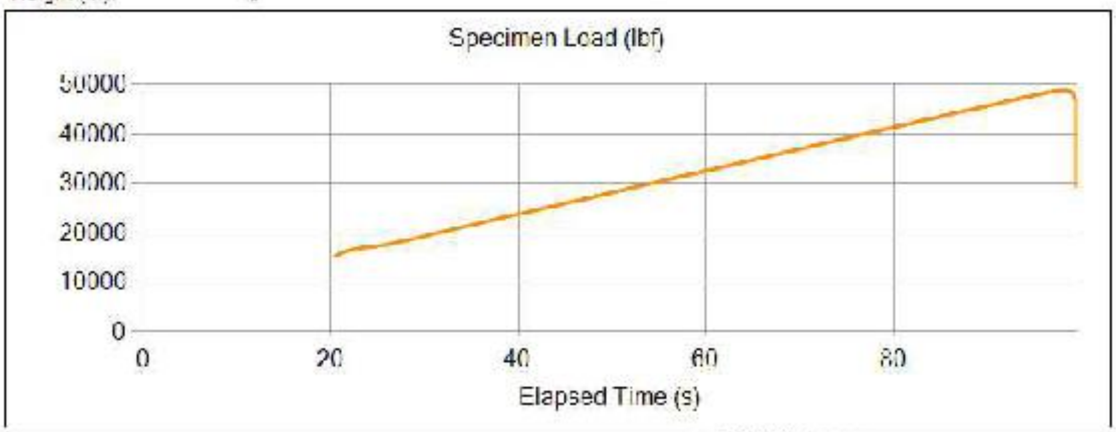
www.FORNEYonline.com

Figure 12.9.62 20%EAF Slag + 80%RCA Concrete 28-day Strength

S.T. WOOTEN

Forney CA-0397VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten (919) 773-9380
204 High Hope Ln www.stwcorp.com
Garner, NC 27529

Test ID:	150	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10:08	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	48845
Cyl. Corr. Factor:	1	Stress at Break (psi):	3886.98
Height (in):	8		



www.FORNEYonline.com

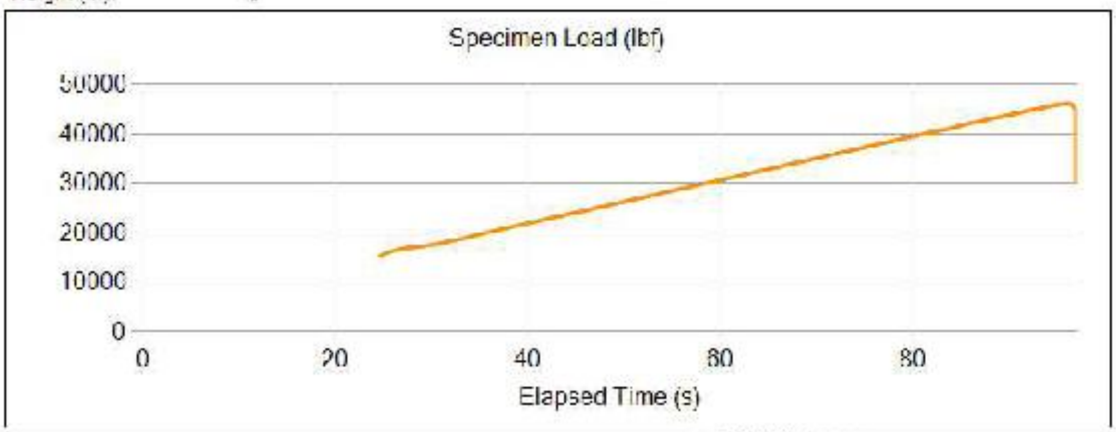
Figure 12.9.63 20%EAF Slag + 80%RCA Concrete 28-day Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S. T. Wooten
104 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	160	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10.11	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	46108
Cyl. Corr. Factor:	1	Stress at Break (psi):	3669.12
Height (in):	8		



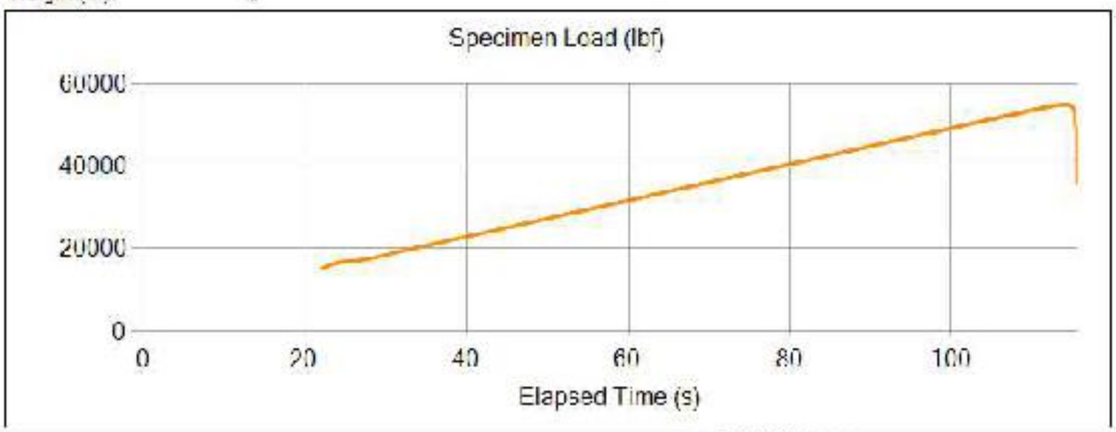
www.FORNEYonline.com

Figure 12.9.64 20%EAF Slag + 80%RCA Concrete 28-day Strength

S.T. WOOTEN

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
304 High Hope Ln
Garner, NC 27529
(919) 773-9360
www.stwcorp.com

Test ID:	161	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10:18	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	55156
Cyl. Corr. Factor:	1	Stress at Break (psi):	4389.14
Height (in):	8		



www.FORNEYonline.com

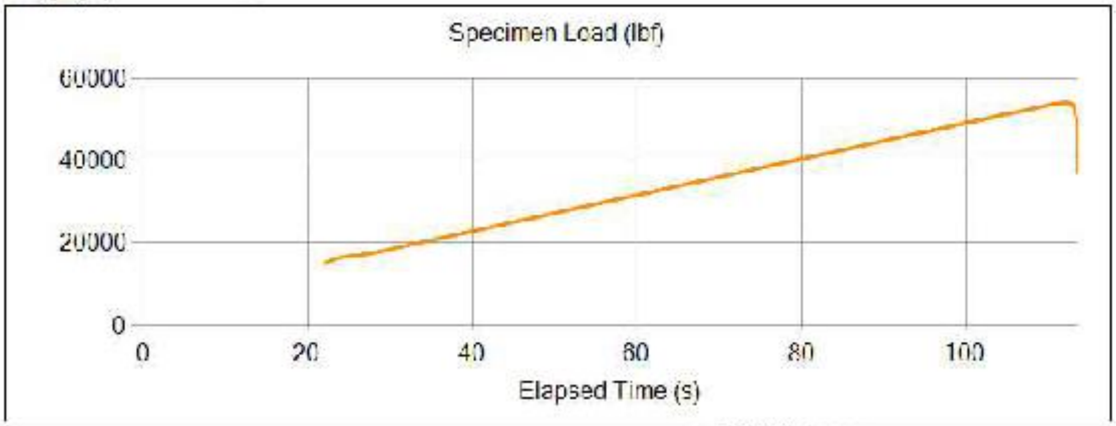
Figure 12.9.65 50%EAF Slag + 50%RCA Concrete 28-day Strength

Forney CA-0397/VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018

S.T. WOOTEN

S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	162	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10:22	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	54252
Cyl. Corr. Factor:	1	Stress at Break (psi):	4317.25
Height (in):	8		



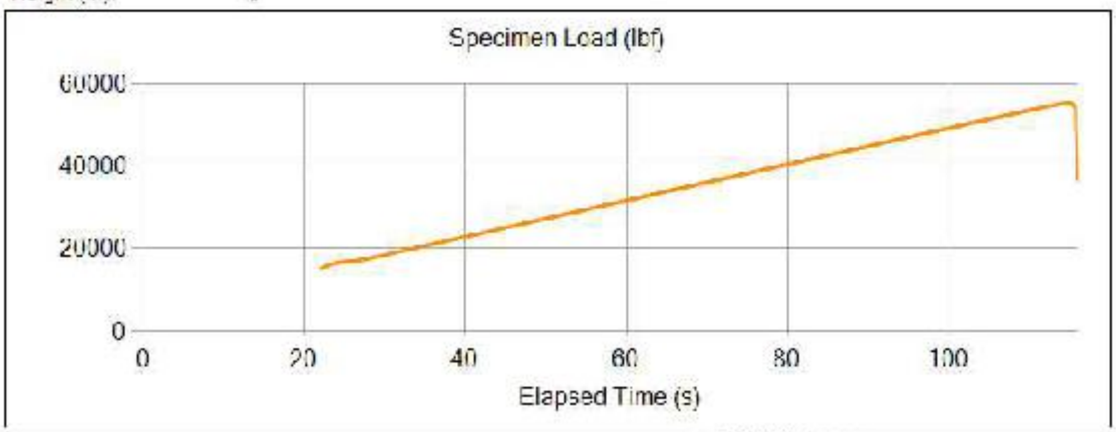
www.FORNEYonline.com

Figure 12.9.66 50%EAF Slag + 50%RCA Concrete 28-day Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated 2/21/2018
S. T. Wooten (919) 773-9380
204 High Hope Ln www.stwcorp.com
Garner, NC 27529

Test ID:	163	Age (days):	28
Date Tested:	8/21/2018	Weight (lb):	8.26
Time:	10:25	Break Type:	2
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	55440
Cyl. Corr. Factor:	1	Stress at Break (psi):	4411.79
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.67 50%EAF Slag + 50%RCA Concrete 28-day Strength

S.T. WOOTEN

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	247	Age (days):	90
Date Tested:	10/25/2018	Weight (lb):	16
Time:	11:41	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	62058
Cyl. Corr. Factor:	1	Stress at Break (psi):	4938.44
Height (in):	8		

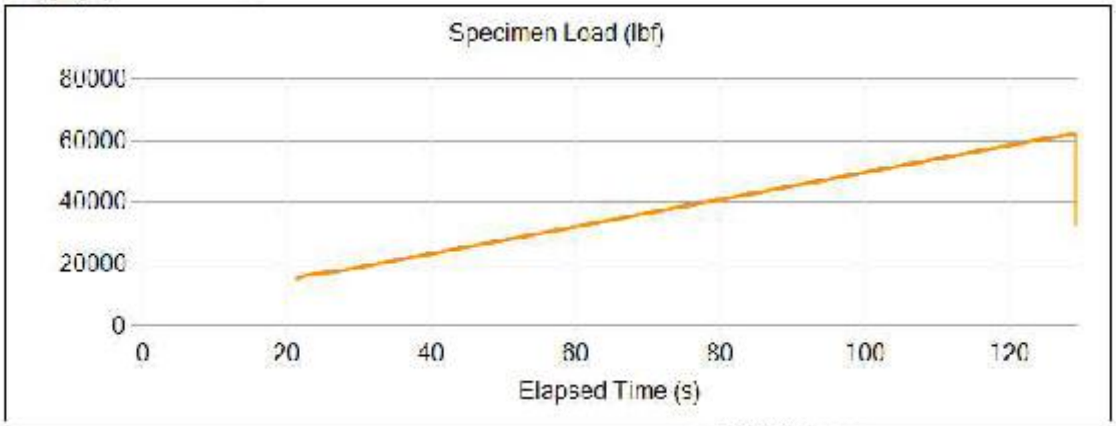
www.FORNEYonline.com

Figure 12.9.68 20%EAF Slag + 80%RCA Concrete 90-day Strength

Forney CA-0397 VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

S.T. WOOTEN

Test ID:	248	Age (days):	90
Date Tested:	10/25/2018	Weight (lb):	16
Time:	11:49	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	62080
Cyl. Corr. Factor:	1	Stress at Break (psi):	4940.15
Height (in):	8		



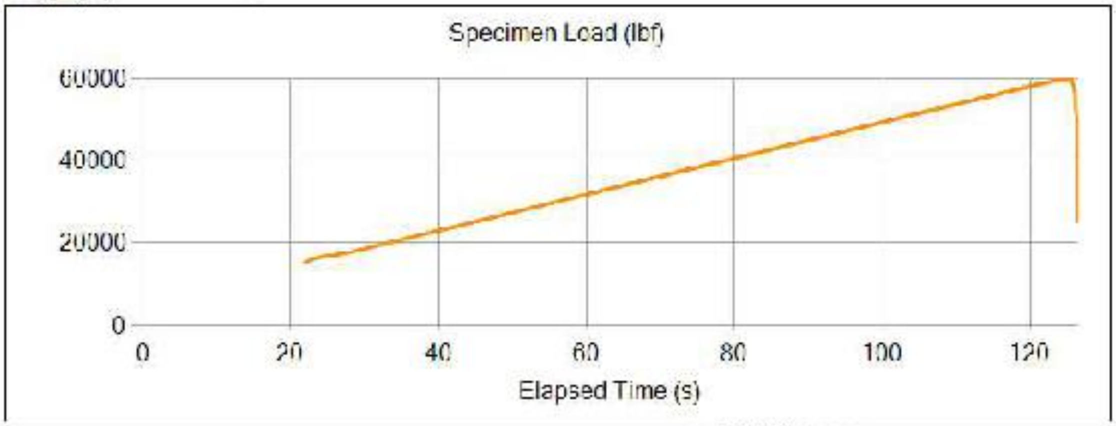
www.FORNEYonline.com

Figure 12.9.69 20%EAF Slag + 80%RCA Concrete 90-day Strength

S.T. WOOTEN

Forney CA-0397-VFD Auto Testing Machine
Serial number: 18019
Calibrated: 2/21/2018
S. T. Wooten
204 High Hope Ln
Garner, NC 27529
(919) 773-9380
www.stwcorp.com

Test ID:	240	Age (days):	90
Date Tested:	10/25/2018	Weight (lb):	16
Time:	11:52	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	35
Diameter (in):	4	Load at Break (lbf):	59932
Cyl. Corr. Factor:	1	Stress at Break (psi):	4769.24
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.70 50%EAF Slag + 50%RCA Concrete 90-day Strength

S.T. WOOTEN

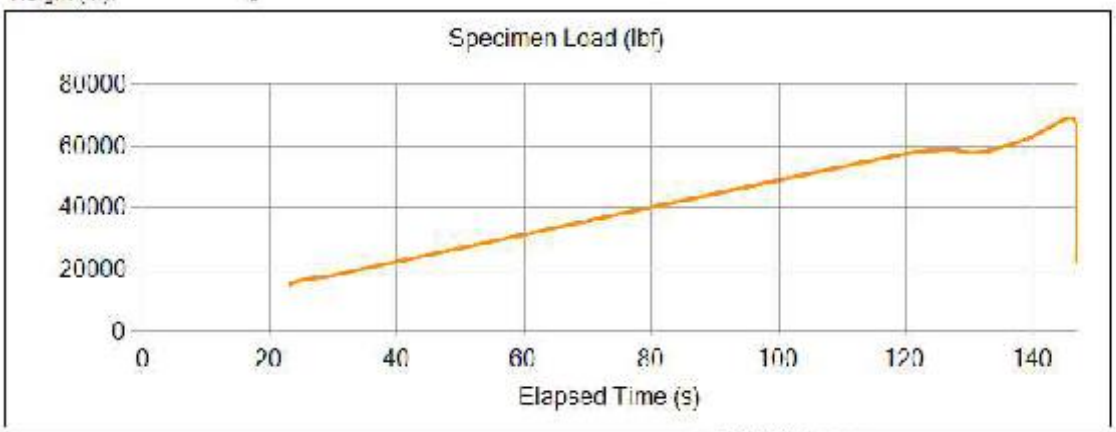
Forney CA-0397/VFD Auto Testing Machine

Serial number:	18019
Calibrated:	2/21/2018

S. T. Wooten
204 High Hope Ln
Garner, NC 27529

(919) 773-9380
www.stwcorp.com

Test ID:	250	Age (days):	90
Date Tested:	10/25/2018	Weight (lb):	16
Time:	11:58	Break Type:	3
Test Type:	Cylinder	Ramp Rate (psi/s):	33
Diameter (in):	4	Load at Break (lbf):	69170
Cyl. Corr. Factor:	1	Stress at Break (psi):	5504.4
Height (in):	8		



www.FORNEYonline.com

Figure 12.9.71 50%EAF Slag + 50%RCA Concrete 90-day Strength

12.10 Potential Alkali Reaction Test Results

Terracon

Potential Alkali Reactivity of Aggregate (Mortar Bar Method)
ASTM C1260

East Carolina University
NC-1

Aggregate	Crushed Concrete	**Cement**	Reference
		Date Cast	7.12.18

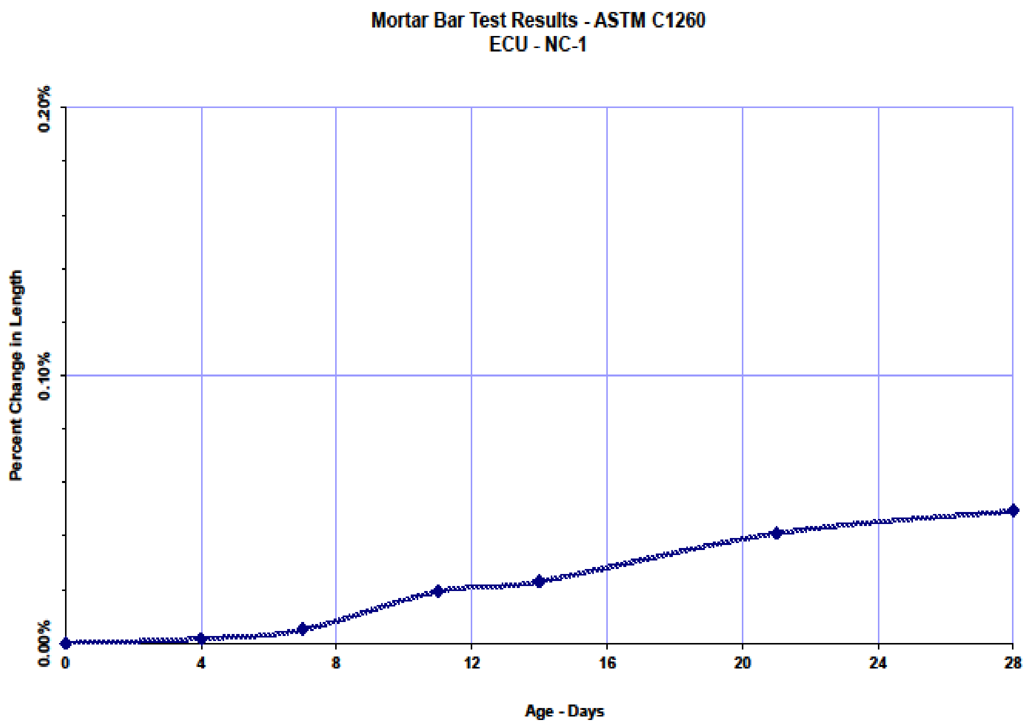
Average Length Change	
Zero Comparatory Reading	**0.00%**
4 day Reading	**0.00%**
7 day Reading	**0.01%**
11 day Reading	**0.02%**
14 day Reading	**0.02%**
21 day Reading	**0.04%**
28 day Reading	**0.05%**

Aggregate preparation was performed in accordance with ASTM C1260 Section 8.2.

Mixing Water: 206.8g of water; w/c ratio = 0.47

Terracon Consultants, Inc. 1450 Fifth Street West North Charleston, South Carolina 29405
P [843] 884 1234 F [843] 884 9234 terracon.com

Terracon



Mortar Bar Test Results - ASTM C1260
ECU - NC-1
Percent Change in Length
0.20%
0.10%
0.00%
0
4
8
12
16
20
24
28
Age - Days

Terracon

Potential Alkali Reactivity of Aggregate (Mortar Bar Method)
ASTM C1260

East Carolina University
NC-2

Aggregate Crushed Concrete

Cement Reference

Date Cast 7.15.18

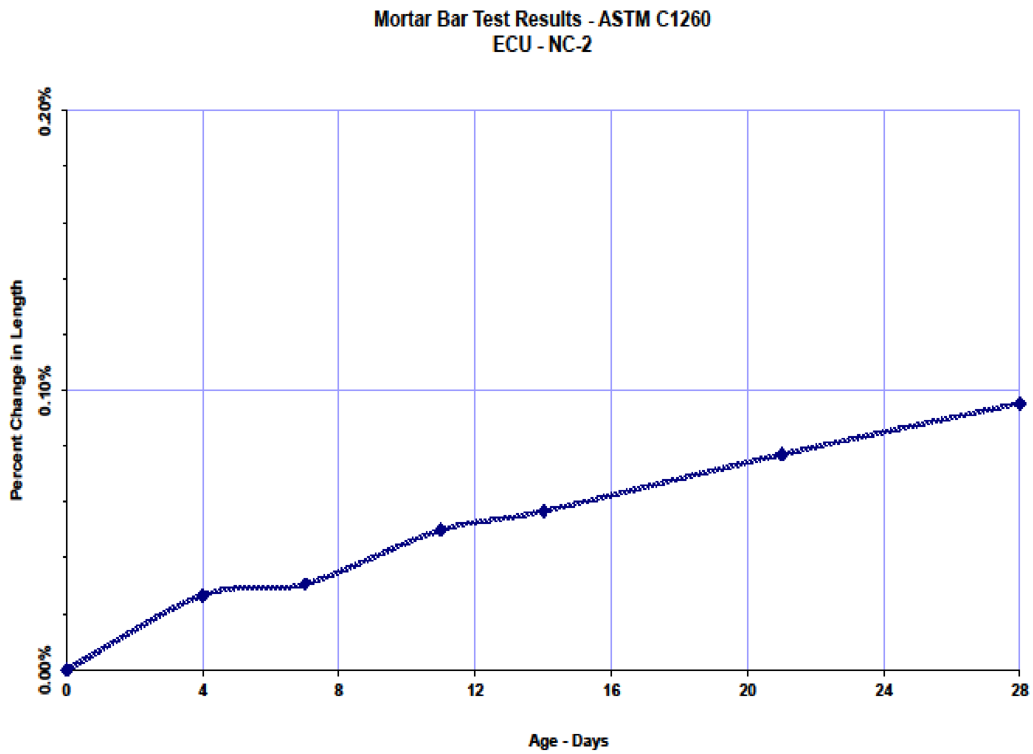
Average Length Change	
Zero Comparatory Reading	**0.00%**
4 day Reading	**0.03%**
7 day Reading	**0.03%**
11 day Reading	**0.05%**
14 day Reading	**0.06%**
21 day Reading	**0.08%**
28 day Reading	**0.10%**

Aggregate preparation was performed in accordance with ASTM C1260 Section 8.2.

Mixing Water: 206.8g of water; w/c ratio = 0.47

Terracon Consultants, Inc. 1450 Fifth Street West North Charleston, South Carolina 29405
P [843] 884 1234 F [843] 884 9234 terracon.com

Terracon


Mortar Bar Test Results - ASTM C1260
ECU - NC-2
Percent Change in Length
0.20%
0.10%
0.00%
0
4
8
12
16
20
24
28
Age - Days

Terracon

Potential Alkali Reactivity of Aggregate (Mortar Bar Method)
ASTM C1260

East Carolina University
NC-3

Aggregate	Crushed Concrete	**Cement**	Reference
		Date Cast	7.12.18

Average Length Change

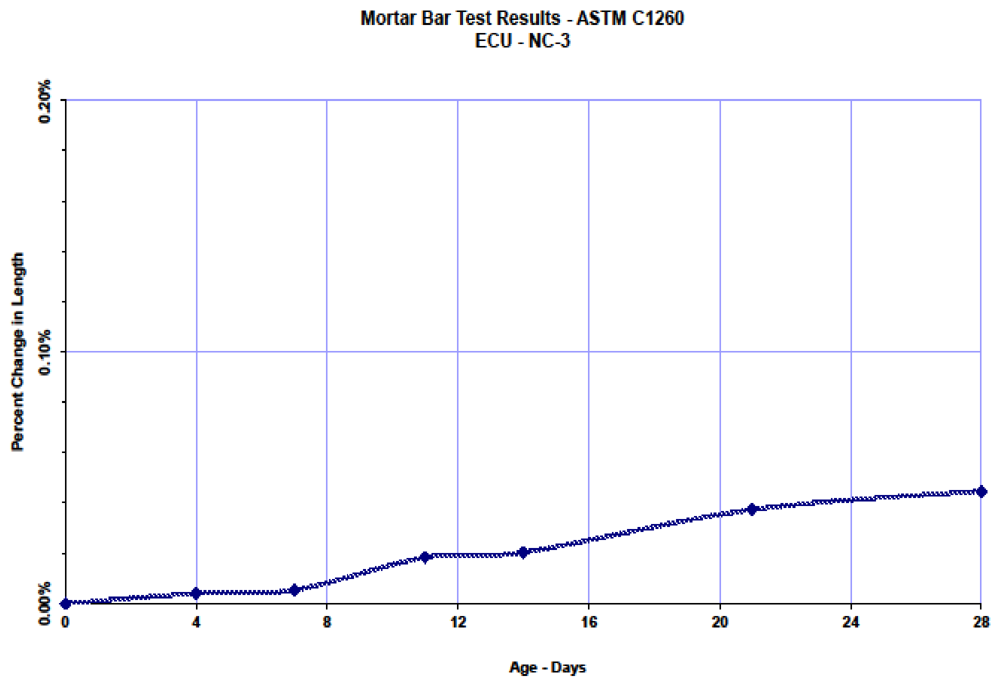
Zero Comparatory Reading	**0.00%**
4 day Reading	**0.00%**
7 day Reading	**0.01%**
11 day Reading	**0.02%**
14 day Reading	**0.02%**
21 day Reading	**0.04%**
28 day Reading	**0.04%**

Aggregate preparation was performed in accordance with ASTM C1260 Section 8.2.

Mixing Water: 206.8g of water; w/c ratio = 0.47

Terracon Consultants, Inc. 1450 Fifth Street West North Charleston, South Carolina 29405
P [843] 884 1234 F [843] 884 9234 terracon.com

Terracon



Mortar Bar Test Results - ASTM C1260
ECU - NC-3
Percent Change in Length
0.20%
0.10%
0.00%
0
4
8
12
16
20
24
28
Age - Days

12.11 Rapid Chloride Permeability Test Results

gcp applied technologies

Analytical & Technical Services
62 Whittemore Ave.
Cambridge, MA 02140-1692

CONFIDENTIAL

Rapid Chloride Permeability

ST Wooton Corp., Garner, NC

18-0410

9/13/2018

cc: Stephen Garrity
RFTS Folder

ecc: Jason Wimberly
Terry Harris
Dorota Kazmierczak
Ted Sibbick

CONFIDENTIAL

Rapid Chloride Permeability

ST Wooton Corp., Garner, NC

18-0410

9/13/2018

Background Information/Problem Details
ST Wooten has partnered with East Carolina University & the NCDOT to perform testing on concrete using different levels of recycled concrete as aggregate for use in DOT Class B Concrete. The NCDOT is requiring a Rapid Chloride Permeability (ASTM C-1202) test be performed on the different levels of recycled concrete content and if test results are favorable, the NCDOT may adopt a specification in which recycled concrete can be used in DOT Class B Concrete.

Mix Proportion
The concrete samples received reportedly had the following mix specifications:

Component	15%	30%	50%	100%
Cement: Giant – Harleyville Type I/II	436	436	436	436
Fly Ash: Ash Ventures - Belews Creek Type F	131	131	131	131
Total Cementious:	567	567	567	567
Coarse Aggregate: Martin Marietta – Garner #67	1488	1225	875	
Intermediate Aggregate: 15% Recycled Concrete	227			
Intermediate Aggregate: 30% Recycled Concrete		453		
Intermediate Aggregate: 50% Recycled Concrete			755	
Intermediate Aggregate: 100% Recycled Concrete				1510
Fine Aggregate: Hanson – Elliott 2S	1192	1192	1192	1192
Admixtures				
Mira 85	8 oz/cwt	8 oz/cwt	8 oz/cwt	8 oz/cwt
Darex II	2.1 oz/cwt	2.1 oz/cwt	2.1 oz/cwt	2.1 oz/cwt
Water	267	267	267	267
Designed w/cm	0.47	0.47	0.47	0.47
Designed air	6%	6%	6%	6%
Measured air	6%	5%	6%	6%
Designed strength	4,000 psi	4,000 psi	4,000 psi	4,000 psi

Components are given as pcy, unless otherwise stated.

Scope of this Project
Perform a RCP test on the four submitted cylinders. Each cylinder has different levels of recycled concrete: 15%, 30%, 50% & 100%.

Sample Description

Samples received had the following identifications:

Sample #	Identification	Sample Description	Tests performed
18-0410-1	D1 15%	4"x 8" concrete cylinder	Rapid Chloride Permeability
18-0410-2	D2 30%	4"x 8" concrete cylinder	
18-0410-3	D3 50%	4"x 8" concrete cylinder	
18-0410-4	D3 100%	4"x 8" concrete cylinder	

Results

ASTM C-1202 Rapid Chloride Permeability

Samples were tested according to ASTM C-1202. Results are given in the table below.

Rapid Chloride Permeability AASHTO T277 / ASTM C1202				
Sample ID	**Date Cast**	**Date Tested**	**Sample Age**	**Coulombs**
18-0410-1	7/3/18	8/28/18	56 days	3442
18-0410-2	7/3/18	8/28/18	56 days	5008
18-0410-3	7/3/18	8/28/18	56 days	2883
18-0410-4	7/3/18	8/28/18	56 days	5178

Rapid Chloride Permeability AASHTO T277 / ASTM C1202 Result Interpretation Table	
Charge Passed Coulombs	Chloride Permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Acknowledgements

ASTM C-1202 done by K. Totty

Reviewed By

Ted Sibbick – Principal Scientist

Stephen C. Garrity

Steve Garrity
Analytical & Technical Services
GCP Applied Technologies

12.12 Photographs taken During the Project

Figure 12.12.1 Bridge Construction Site in Division 1 to identify the Slabs to be Saw Cut

Figure 12.12.2 Bridge in Division 1 Where the Concrete Slab Was Saw Cut

Figure 12.12.3 Concrete Panel Removed – Division 2

Figure 12.12.4 Bridge Removal Construction Site in Division 2

Figure 12.12.5 Bridge Replacement Site in Division 3

Figure 12.12.6 Slab to be Transported to Crushing Plant in Wilson, NC (Division 3)

Figure 12.12.7 Terex Finlay 3-in-1 Crusher Used in the Process

Figure 12.12.8 A Close Look of the Crusher

Figure 12.12.9 Jaw Crusher of the Terex Finlay Machine

Figure 12.12.10 1.5" Screening Equipment

Figure 12.12.11 A Close Look of the Screening

Figure 12.12.12 Breaker, Screening, and Terex Finlay Machine

Figure 12.12.13 The Breaker for Initial Breakdown the Slabs and Remove Rebar

Figure 12.12.14 Concrete Panels Were Broken and Reba Was Removed

Figure 12.12.15 Reinforcing Steel is Removed

Figure 12.12.16 Crushed RCA

Figure 12.12.17 Crushed RCA

Figure 12.12.18 RCA Sampling (Division 1) at S.T. Wooten's Wilson Plant

Figure 12.12.19 RCA Sampling (Division 2) at S.T. Wooten's Wilson Plant

Figure 12.12.20 RCA Sampling (Division 3) at S.T. Wooten's Wilson Plant

Figure 12.12.21 Processed RCAs from Divisions 1, 2 and 3 Ready to Transport to Lab

Figure 12.12.22 RCA Samples Transported to S.T. Wooten's Garner Concrete Lab

Figure 12.12.23 Separate Fine Particles from Sampled RCA

Figure 12.12.24 Fine Particles Removed from RCA Samples

Figure 12.12.25 Large Quantity of Fine Particles are Removed from the RCA Sample

Figure 12.12.26 Coarse Aggregate for the Concreting

Figure 12.12.27 Impurities Removed from the RCA Samples

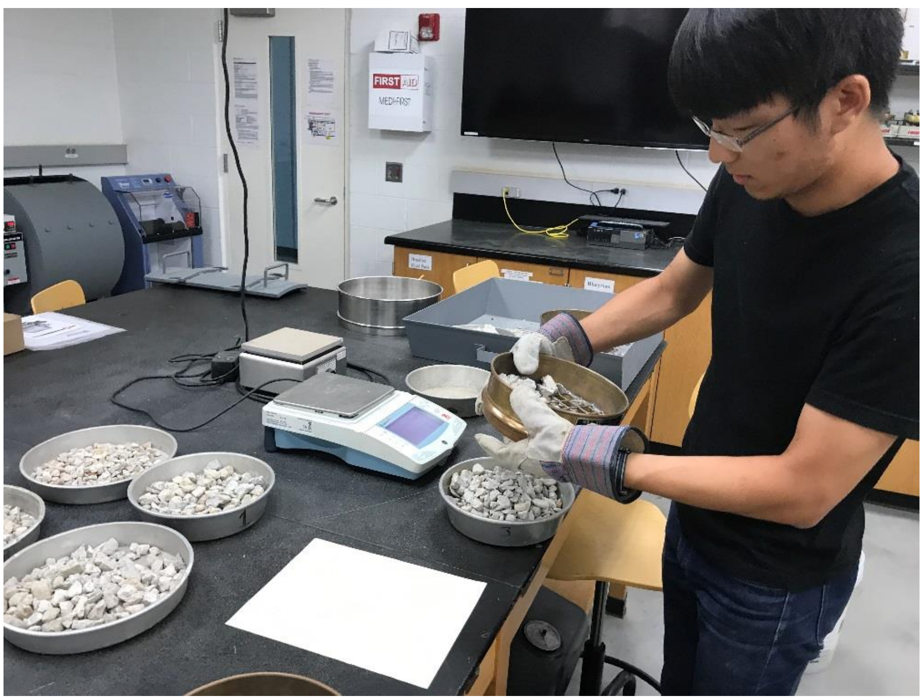


Figure 12.12.28 Preparing for LA Abrasion Test

Figure 12.12.29 RCA Bulk Specific Gravity Testing

Figure 12.12.30 RCA Bulk Specific Gravity Testing

Figure 12.12.31 Absorption Test Before Mixing

Figure 12.12.32 EAF Slag was Sampled and Transported to Lab

Figure 12.12.33 Sampling EAF Slag at Nucor Plant in Hertford County, NC

Figure 12.12.34 EAF Slag Underwent Pressure Cooker Test

Figure 12.12.35 EAF Slag is Volumetrically Stable After Testing

Figure 12.12.36 The Concreting Team Was Ready for Concrete Batching

Figure 12.12.37 Fly Ash Used in the Mixes

Figure 12.12.38 Portland Cement Used in the Mixes

Figure 12.12.39 Crushed Coarse Granite Aggregate (CA) Used in the Mixes

Figure 12.12.40 Natural Sand Used in the Mixes

Figure 12.12.41 4" Molds Prepared for Casting Cylinders

Figure 12.12.42 Materials and Equipment Were Ready

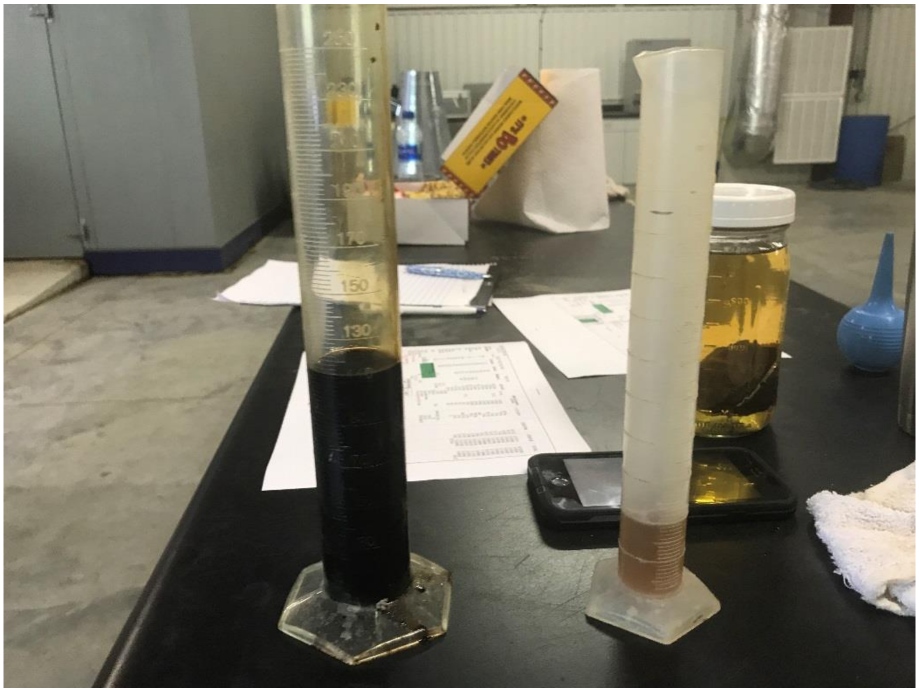


Figure 12.12.43 Air-Entrained Agent and Water Reducer Were Measured

Figure 12.12.44 Admixtures Added to the Mixer

Figure 12.12.45 Fresh RCA Concrete Discharged from Mixer

Figure 12.12.46 Cast Cylinders

Figure 12.12.47 Check the Workability

Figure 12.12.48 Slump Test for Fresh Concrete Containing RCA

Figure 12.12.49 Slump Test of Fresh RCA Concrete

Figure 12.12.50 Fresh Concrete Unit Weight and Air Content Test

Figure 12.12.51 First 24 Hours Before Demold and Move to Curing Room

Figure 12.12.52 Cylinders in Curing Room for 7-, 28-, 90-day Tests

Figure 12.12.53 Compressive Strength Test

Figure 12.12.54 Breaking Concrete Cylinders

Figure 12.12.55 Breaking 28-day Concrete Containing RCA and EAF Slag

Figure 12.12.56 Broken Cylinder Containing RCA and EAF Slag

Figure 12.12.57 Specimens Underwent Full Stress-Strain Testing

Figure 12.12.58 Repetitive Cyclic Testing to Obtain Full Stress-Strain