Use of Recycled Concrete Aggregate in Concrete Pavement Mixes

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16. Abstract
Natural virgin aggregates (NVAs) have become gradually exhausted across the state of Tennessee. There is a growing need for the Tennessee Department of Transportation (TDOT) to replace NVAs with more sustainable recycled concrete aggregates (RCAs). It is the intention of the project to quantitatively assess various RCAs available in Tennessee and to explore their suitability for TDOT new paving concrete mixes. This report documents the main findings of the project. A total of eight RCAs were collected representing different concrete origins of pavement, returned concrete, and mixed sources including buildings. Their basic properties were evaluated, including size and gradation, specific gravity, absorption, LA abrasion loss, chloride content, and pH value. These properties were observed to vary widely with RCA sources. This report also covers how RCAs affected the performance of concrete. It becomes evident that RCAs from good quality concrete origins such as pavements can be used in new paving concrete when adequately designed and proportioned. They demonstrated similar performance as NVAs. However, RCAs from unknow or mixed sources should be used with cautions as they may have inconsistent quality. Poor quality RCAs reflected by high absorption, high LA abrasion loss, and low specific gravity due to unsound adhered paste are not recommended for paving concrete because they will substantially reduce the strength and durability of concrete. RCAs with nondurable aggregate origins are also unsuitable for paving concrete applications.

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Executive Summary

The main tasks of this project were to evaluate recycled concrete aggregates (RCAs) from various sources in Tennessee and to determine how RCAs influence the performance of the Tennessee Department of Transportation (TDOT) paving concrete. Specifically, this project was focused on how to improve the performance of RCA concrete through mix design and optimization. The goal of this project was to provide information that aided TDOT professionals in developing methods and specifications for selecting adequate RCAs for future pavement constructions. In this report, information is available on the main sources of RCAs in the state of Tennessee, the main properties of theses RCAs, and how the use of these RCAs affects the performance of TDOT paving concrete. This report also reveals the main issues related to the use of RCAs in concrete as well as provides measures to improve the RCA concrete performance. Guidelines can be developed as to what RCAs are favored for paving concrete applications and what RCAs may present potential risks of reducing the performance of concrete. Guidelines can also be developed concerning what construction practices should be followed when RCAs are used.

Key Findings

Eight RCAs were collected in this project. Their basic properties were evaluated including size and gradation, absorption, specific gravity, Los Angeles (LA) abrasion loss, adhered paste and air content, and pH value. Then, these RCAs were used to replace Natural Virgin Aggregates (NVAs) in TDOT paving concrete, and the performance of RCA concretes was evaluated. After the successes and the problems were identified, various materials and methods were employed to improve the performance of RCA concretes. The main findings of this project are summarized as follows:

- RCAs collected in this study displayed wide variations in the basic properties, which in turn greatly affected the concrete performance such as workability, strength, modulus, shrinkage, and durability.
- Aggregate optimization helped to improve the workability of gap graded RCAs. Pre-mixing dry RCAs with 80% mixing water for 1 to 2 minutes made RCA's absorption equivalent to that of NVAs during mixing and placing, which controlled aggregate absorption-related problems such as rapid slump loss.
- RCAs reduced, or increased, or did not significantly affect the compressive strength of TDOT paving concrete depending on the quality of RCAs. RCAs normally reduced the flexural strength and the modulus of elasticity of TDOT paving concrete.
- RCAs significantly reduce or did not affect the freeze/thaw resistance of concrete depending on the aggregate origins and the quality of adhered paste of RCAs. Reducing RCA size and water to cementitious materials ratio as well as adding silica fume helped to increase the freeze/thaw resistance of concrete. RCAs reduced or did not significantly affect the scaling resistance of concrete depending on the aggregate origins, the quality of adhered paste, and more importantly the pH value of RCAs.
- RCAs increased the free shrinkage of concrete but delayed the restrained shrinkage cracking.

- RCAs affected the fresh air measurement. Pressure method measured the total air in both the new and the adhered pastes. Volumetric method determined the air content in the new paste.

Key Recommendations

The results of this study can aid TDOT engineers in developing specifications on the use of RCAs in TDOT new paving concrete. This new practice would save Tennessee's natural resources as well as landfill spaces. The continued recycling and unlimited reusing of concrete as aggregate in new concrete mixes would enable Tennessee transportation structures to be built and maintained more sustainably. Based on the findings of this research, the following recommendations can be made:

- RCAs from reliable concrete origins such as pavements with good residual strength and air entrainment are highly recommended to TDOT RCA paving concrete as they will behave like NVAs.
- RCAs from unknown sources particularly with a high percentage of non-concrete materials such as bricks, masonry unit, asphalt, and glass should be used with cautions as they may significantly reduce the strength, the modulus of elasticity, and the durability of concrete. Freshly crushed RCAs from uncarbonated concrete origins such as newly returned concrete should also be used with cautions because they will significantly accelerate the setting and increase the risk of surface scaling and the deicing salt attack.
- RCAs with nondurable aggregate origins are not recommended for TDOT paving applications as they will significantly reduce the durability of concrete. RCAs with porous unsound adhered paste (such as some returned concretes possibly owing to extra water added in the process of recycling) are also not recommended for TDOT paving concrete because of their negative effects on both the strength and the durability of concrete.
- Similar joint practice as that of NVA concrete can be used for coarse RCA concrete as coarse RCAs do not increase the risk of restrained shrinkage cracking.
- Dry RCAs without pre-soaking can be directly used for proportioning TDOT paving concrete when adequate mixing water addition procedures are followed. Pressure method can be used for measuring the fresh air content of RCA concrete as it will determine the total air content in the whole concrete paste, assuming that RCAs are not from light-weight concrete origins and do not contain excessive porous particles (e.g., bricks and masonry units).

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Chapter 1 Introduction

Concrete production continuously consumes natural virgin aggregate (NVA), which has gradually exhausted this natural resource especially near larger cities in the US. There are growing needs for replacing NVA with more sustainable materials. Recycled concrete aggregate (RCA) deserves serious considerations because it offers dual benefits of saving landfill spaces as well as creating a cheaper and more sustainable alternative. Although the use of RCA in non-structural applications such as fill, pavement base, foundation, and sidewalk has gained wide acceptance, its use in structural concrete such as pavement slabs has been exceptionally limited mostly due to concerns over RCA quality and wide variations in its sources. These major concerns are further aggravated by the lack of knowledge on its long-term performance as well as the absence of standards and specifications for its use. The uncertainty over RCA usage makes it possible for material engineers to overlook the opportunities of using RCA in new concrete mixes.

Currently, only two national standards, American Society for Testing and Materials (ASTM) C33[1] and American Association of State Highway and Transportation Officials (AASHTO) MP16[2], specify the use of RCA, however, the information is inexplicit, or the limit is too stringent. For examples, ASTM C33 permits the use of RCAs as aggregates in concrete, but there is no information on how to classify RCAs. Even in AASHTO MP16, which possibly represents the most detailed guidelines addressing the use of RCA in concrete today, the requirements for RCAs are simply the same as those for NVAs. Clearly, these requirements are too high and unnecessary for pavement applications because typical paving concrete (e.g., TDOT Class CP mix) only requires a 28-day compressive strength of 3000 psi. On the other hand, the use of this standard would restrict the wider application of RCAs in transportation structures. As a result, research is essential to investigate how different qualities of RCAs affect the performance of new concrete mixes with the goal of developing performance-based specifications for the best use of RCA in the transportation system.

The Tennessee Department of Transportation (TDOT) always advocates sustainable and cost-effective construction practices. The motivation for promoting RCAs in TDOT concrete pavement mixes is the same: negative impact of quarrying operations on Tennessee environment, increased cost for long hauling distances, limited space for landfill in Tennessee, conservation of natural resources, and reduced carbon footprint. Realizing so many benefits, Tennessee transportation communities are increasingly embracing the sustainable RCA usage. Similarly, very limited information is available in Tennessee regarding RCA qualification and classification as well as its applications. It is the intention of this project to develop methods and criteria for adequately qualifying RCA from different sources throughout Tennessee and to explore the suitability of various RCAs for TDOT concrete pavement mixes.

In this project, eight RCAs from various sources such as pavement, buildings, and returned concrete were requested from local concrete recycling facilities across the state of Tennessee. Their basic properties were evaluated. This included shape, texture, size, gradation, specific gravity, absorption, LA abrasion loss, adhered paste content, air content, chloride content, and pH value.

After the property evaluation, five RCAs (coarse portion) were used to equally replace coarse NVAs by volume in TDOT Class CP mix to see how they affected the performance of concrete including workability, unit weight, fresh air measurement, hardened air content, compressive strength development, flexural strength development, modulus of elasticity, free shrinkage, restrained shrinkage cracking, permeability, scaling resistance, and freeze and thaw durability. Particularly, one RCA was selected to investigate how different coarse RCA replacement levels (e.g., 25%, 35%, 45%, and 60%) affected the properties of TDOT paving concrete. In addition, one as-is RCA (coarse plus fine) was chosen to study how it affected the performance of concrete. Moreover, the gradation of RCA was optimized with either #7 or #4 crushed limestone based on the Tarantula Curve and the Coarseness Factor Chart to see how the optimized RCA gradation improved the concrete performance.

One issue related to RCAs was its excessive water absorption. Pre-saturating RCA before batching would avoid absorption-related problems such as rapid slump loss. However, this practice could be impractical for RCAs in some projects where RCAs were directly recycled and used on site. The use of as-is RCAs would require the mixing water adjustment to compensate for the high absorption. If all absorption water was added during mixing, the mixture might become very flowable, which would disturb the air entrainment and cause segregation. In this project, the absorption rate of RCA was investigated. Different water adjustment procedures (one-time, two-time, and multi-stage) were tested to see how they affected concrete performance.

Another concern related to RCAs was their freeze/thaw resistance when they had unsound adhered pastes particularly from non-air entrained concrete origins or had a nondurable aggregate origin. In this project, different measures were investigated to see how to increase the frost and scaling resistances of RCA concretes. These included reducing RCA size, moisture level, and replacement rate, as well as reducing the water to cementitious materials ratio (W/Cm) and adding silica fume.

Chapter 2 Literature Review

The use of RCAs has been a common practice for many years in Europe starting from the end of World War II mainly for nonstructural applications[3]. The earliest adoption of RCA in US roadway construction can be traced back to 1940s when the US Route 66 in Illinois was reconstructed using RCA from the old pavement[4]. The application of RCA in a structural layer of concrete pavement in US began in 1970s. Many concrete pavement sections were built using RCA as coarse aggregate between 1970s and 1990s, most of which showed fair to good performance[5]. For examples, RCA was used as a coarse aggregate in concrete slabs of nine highways and US routes in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming during 1980s[6]. Particularly, one section involved the use of RCA from a source with Alkali Silica Reactions (ASR); while in another section, the RCA was made from a deteriorated pavement with severe D-cracking. Based on the field evaluation (performed in 1994 and 2006 respectively), all sections with RCA generally showed equivalent performance as control sections using NVA. In addition, a 10" section of continuously reinforced concrete pavement on I-57 was constructed in Illinois from 1986 to 1987 using RCA as aggregate[7]. After 20 years of service, the overall performance of the pavement was comparable to that of similar pavements using NVA. Surprisingly, this practice was not continued[8]. In 2004, the Federal Highway Administration (FHWA) conducted a review on the use of RCA nationwide, no state Departments of Transportation (DOTs) were using RCA in their paving concrete[9]. The main obstacle came from a few failed projects. For examples, Michigan widely adopted RCA as a coarse aggregate in its paving concrete in 26 projects over 650 miles in 1980s. Some of these pavements demonstrated premature failures. Consequently, the Michigan DOT issued a moratorium in 1988 and a permanent one in 1991 on the use of RCA in new paving concrete although research results indicated that the premature deterioration also related to the bad design and construction practices. The RCA was then restricted to only nonstructural components such as curbs, gutters, sidewalks, barriers, and shoulders[10]. This example was implicitly followed by other states, which discouraged pavement engineers from considering RCA in new paving concrete. Fortunately, attitudes towards RCA in pavement community are currently changing due to recent interests in two-lift pavement[11] and composite pavement[12] as well as renewed interests in more sustainable pavement system[13]. Incorporating RCAs in new paving concrete production has now become increasingly common worldwide due to its social, environmental, and economical benefits[14,15].

It has been reported that the use of RCAs is primarily governed by the quality and the quantity of adhered paste in RCA particles. The porosity, air-entrainment, pre-existing cracking, and alkaline content in the adhered paste will not only affect the RCA properties such as absorption, specific gravity, and abrasion loss, but also impact the workability, strength, and durability of RCA concrete[16]. Sucic and Shehata[17] reported that RCA absorption greatly affected the workability of concrete and adequate mix practice should be followed to minimize the negative effects of absorption on the performance of concrete. Studies also showed that the specific gravity and the absorption of RCAs correlated well with their abrasion loss. Replacing NVAs with up to 40% RCAs in paving concrete had insignificant influence on the strength and durability of concrete pavement[18]. Interestingly, Marchi studied the effects of the adhered paste in RCA particles on the internal curing of high-performance concrete and observed that desorption of absorbed water in RCAs particles occurred, which helped to increase the strength of concrete[19]. Butler et.

al.[20,21] reviewed the current standards and specifications for using RCAs in new concrete mixes and proposed guidelines for selecting RCAs for structural concrete applications. Fathifazl et. al. proposed a new mix proportioning method that considered the adhered mortar as one portion of total mortar in new concrete, which helped to control the creep and shrinkage of RCA concrete[22].

In addition, numerous studies have been conducted to investigate how RCAs affected the concrete properties[23]. Most of these studies have shown that concrete with RCA showed similar or slightly lower performance as compared the concrete with NVA. For example, specimens cored from RCA concrete pavements exhibited higher, equal, or slightly less compressive and splitting tensile strength as compared with those from control sections with NVA[6]. Sadati and Khayat[24] reported the field performance of two concrete mixes with 30 and 40% RCAs. It was observed that RCAs reduced compressive strength and modulus of elasticity, but did not significantly influence the flexural strength, the splitting tensile strength, and the durability of concrete. Wen et al.[25] reported that replacing NVA with RCA up to 45% had no significant effects on the fresh and hardened properties of concrete. Pedro et al. investigated effects of different types of RCAs on the performance of structural concretes and concluded that RCA concrete displayed similar performance as compared with NVA concrete[26]. More interestingly, concrete specimens with RCA from good sources (e.g., gutter, curb, and sidewalk) displayed significantly higher compressive strength (12%) than those with NVA[27]. Kou et. al. studied how the source concrete affected the strength and durability of normal and high-performance concrete. It was found that concrete using RCAs from the high-grade concrete source with residual strength of 11,600psi to 14,500psi demonstrated higher strength and lower shrinkage and permeability as compared with those of NVAs. It was concluded that such RCAs were suitable for HPC applications[28]. Similarly, better, or equivalent compressive and flexural strengths as well as freeze/thaw resistance were noted for concretes with different levels of RCA replacement[29]. Additionally, Sadati and Khayat noticed that concrete made with RCA up to 100% from an air-entrained source could adequately resist freeze/thaw and deicing salt scaling[30]. Thomas et. al. studied the effects of RCAs on the strength and durability of concrete. It was found that replacing NVAs with RCAs by up to 25% did not significantly affect the strength of concrete. At low replacement levels, RCA concrete was applicable to a mild environment[31]. Smith and Tighe[32] studied the effects of RCAs on the coefficient of thermal expansion using cored concrete samples from a testing pavement section. It was observed that increasing the percentage of RCAs in concrete reduced the coefficient of thermal expansion, thus improving the pavement performance.

Conversely, research also showed that RCA could negatively affect concrete properties especially when low-quality RCA was used. For examples, the use of RCA in concrete increased water demand and reduced workability, which consequently increased the dosage of air-entraining and water-reducing admixtures[13]. The replacement of NVA with RCA also reduced compressive strength, modulus of elasticity[33], and abrasion resistance[14] as well as increased long-term shrinkage[34]. However, these properties can be improved by using admixtures and modifying mix proportioning[35]. Specifically, Dhir et.al. investigated the durability of concrete made with recycled aggregates of different sizes and types and concluded that RCAs normally had negative impacts on the freeze/thaw resistance of concrete[36]. Hwang et al. studied the durability of RCA concrete made with fly ash and slag. It was observed that RCAs reduced the strength and the freeze/thaw resistance as well as increased the chloride permeability and the risk of sulfate attack. However, using fly ash and slag helped to improve these properties[37]. Friedl et al.[38] observed that the use of chloride contaminated RCAs greatly increased the pitting corrosion of reinforcing steel, and the chloride transport inside concrete related to the porosity of RCAs.

Obviously, results in the literature were diverse and sometimes conflicting. This is not surprising because RCAs used in different studies might come from different sources and might have different properties. This also suggests that research is essential to qualify RCAs from different sources in Tennessee and to determine how they influence the properties of concrete so that suitable RCAs can be specified for TDOT concrete mixes.

Chapter 3 Methodology

3.1. RCA Property Evaluation

3.1.1 RCA Request, Site Visit, and Collection

This research project was primarily built on evaluating the RCAs that were available across the state of Tennessee and determining their suitability for future applications in TDOT paving concrete. Initially, the TDOT Project Lead Staff was contacted for information on the potential sources of RCAs in different regions of Tennessee. Requests were then sent out to the RCA suppliers. After receiving the responses from the suppliers, the research team visited the sites and collected the samples. In total, eight RCAs were collected, representing different regions (e.g., East, Middle, and West TN) and sources (e.g., pavement, returned concrete, and building). Five RCAs were collected in a relatively large quantity (approximately 3000 lbs.) for detailed investigations, while small to medium amounts of samples (approximately 400 to 1000 lbs.) were taken from three manufacturers mainly for the durability assessment. Table 3.1 lists the detailed information on the RCA name, quantity, and characteristics. More information regarding RCA site visits and source materials is summarized in the supplementary documents of this report (G), which can be provided upon requests.

Table 3.1 RCA Name, Quantity, and Characteristics

RCA Source	RCA Name	RCA Quantity	RCA Characteristics
Source 1	AF RCA	3000 lbs.	¾" sieved coarse RCA with mixed sources, including building, bricks, asphalt, returned concrete
Source 2	I-440 RCA	3000 lbs.	¾" un-sieved (coarse plus fine) RCA from I-440 concrete pavement
Source 3	SC RCA	3000 lbs.	1" sieved coarse RCA from mixed sources
Source 4	SCP RCA	3000 lbs.	1" un-sieved (coarse plus fine) RCA primarily from returned concrete. Manually sieved with No. 8 sieve. Only coarse portion was used for this research
Source 5	HC RCA	3000 lbs.	¾" sieved coarse RCA from mixed sources. Manually sieved with No. 8 sieve to remove dust and soil
Source 6	MM RCA	400 lbs.	1" sieved coarse RCA from mixed sources
Source 7	MJC RCA	400 lbs.	1" sieved coarse RCA primarily from demolished structures
Source 8	NRM RCA	1000 lbs.	¾" sieved coarse RCA primarily from returned concrete

3.1.2 RCA Physical Property Evaluation

Some RCAs collected in this study contained significant amounts of soils and dusts. These contaminants were greatly detrimental to concrete performance and not allowed in concrete. As a result, these fine particles were removed through pre-screening using No. 8 sieve before any property evaluation.

The type, shape, and texture of RCA particles were evaluated in this study based on visual examination using approximately 20 lbs. oven-dry representative samples. Special RCA particles (e.g., asphalt, bricks, and masonry unit) were separated and their weights were recorded.

The size and gradation of RCA were analyzed following the procedures described in ASTM C136[39]. For each RCA, a representative sample was taken and dried in oven at about 235°F for at least 24 hours. After cooling, approximately 30 lbs. of the sample were placed into a test device with an assortment of sieves and a mechanical shaker. After a sufficient period of agitation (typically 5 minutes in this study), the mass retained on each sieve was measured and recorded.

The specific gravity and the absorption of RCA (coarse portion retained on No. 8 sieve) were measured based on ASTM C127[40]. For each RCA, a representative sample (approximately 10 lbs.) was taken and pre-soaked in water for about 72 hours. It was then removed from the water and rolled in a wet but absorbent cloth to remove the surface moisture on RCA particles. After the saturated surface dry condition was achieved, the mass of the sample was measured. The sample was immediately transferred to a container (wire basket), submerged in water, slightly agitated, and weighed while immersed. After the mass in water was determined, the sample was dried in oven at 235°F for at least 24 hours. After cooling, its mass was again measured. The specific gravity and the absorption were calculated using the equations provided in ASTM C127.

3.1.3 RCA Abrasion Resistance Evaluation

The abrasion resistance of RCA was evaluated in this study following the procedures described in ASTM C131[41]. Most RCAs collected for this project had a nominal maximum aggregate size of 1", which was classified into B grading based on ASTM C131. Initially, a representative RCA sample was taken and washed to remove surface dust. After the free water was drained, the sample was dried in oven at 235°F for at least 24 hours, cooled to room temperature, and then sieved into different size fractions. Approximately, 2500 g samples were taken from ½"- ¾" fraction and 3/8" – ½" fraction respectively (Figure 3.1.1b), and then recombined, and subsequently placed into the LA testing machine (Figure 3.1.1a). The test was started after 11 steel spheres (approximately 4580 g) were introduced. After 500 revolutions, the sample was discharged and then separated into coarse and fine portions using No. 12 sieve (Figure 3.1.1c). The abrasion loss of each RCA can be calculated based on the equation provided in ASTM C131.

a. Los Angeles Testing Machine   b. 1" RCA sample (B grading) before testing   c. RCA sample after testing

Figure 3.1.1 Los Angeles Abrasion Resistance Test Setup

3.1.4 RCA Chloride and pH Evaluation

Before the evaluation, a powder RCA sample was prepared. Firstly, a representative RCA sample (approximately 300g) was taken and dried in oven at 235°F for 24 hours as shown in Figure 3.1.2a. It was then crushed into small pieces with a hammer and further ground into powder until all particles were less than 600µm (i.e., passing No.30 sieve) as shown in Figure 3.1.2b. The powder was immediately blended by transferring from one glazed paper to another for at least 10 times and stored in a sealed jar for the pH and chloride analyses.

Figure 3.1.2 Sample Preparation for RCA pH and Chloride Analysis

For the pH evaluation, 10 g of well-blended pulverized RCA sample was measured with an accuracy of 0.0001g and placed into 250ml beaker. After 50mL distilled water was added, the beaker was covered with a watch glass, placed on a hot plate, and boiled for 5 minutes. After 24 hours cooling, the sample solution in the beaker was filtrated through suction using filter paper and the filtrate was transferred to a beaker. The pH value of the filtrate was immediately measured using a pH electrode as shown in Figure 3.1.3.

The water-soluble chloride analysis was conducted following the procedure described in the ASTM C1218[42]. The filtrate preparation was exactly same as that for pH evaluation. After filtration, 3mL of diluted nitric acid and 3mL of hydrogen peroxide were added to the filtrate. The beaker with the filtrate in it was then placed on a hot plate and boiled for 3 to 5 seconds. After the filtrate cooled to the room temperature, 2mL standard 0.05N NaCl solution was added and thoroughly mixed with the filtrate. Titration was conducted on the filtrate using the standard 0.05N silver nitrate solution following the procedure described in the ASTM C114[43]. The water-soluble chloride content was calculated based on the equation in ASTM C114.

The acid-soluble chloride analysis was performed in this study based on the procedure described in ASTM C1152[44]. The main steps for preparing the filtrate and conducting titration were similar as those described in the water-soluble chloride analysis. The main difference was that 12mL diluted nitric acid was added to dissolve the RCA sample in the acid-soluble chloride analysis during the filtrate preparation. The acid soluble chloride content was also calculated based on the equation in ASTM C114.

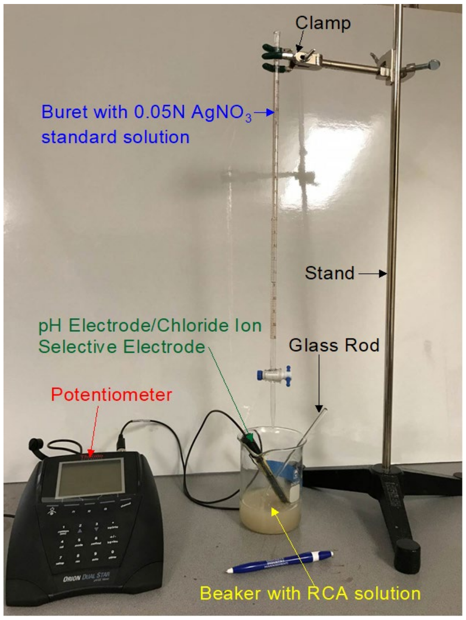
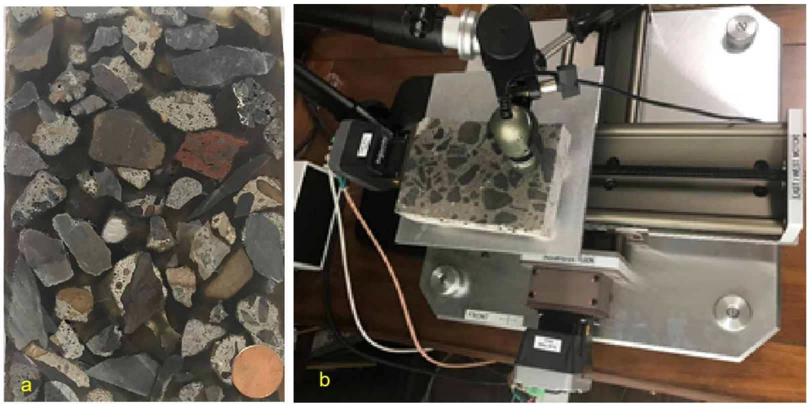


Figure 3.1.3 Test Setup for RCA pH Measurement and Chloride Content Analysis

3.1.5 Adhered Paste and Air Void Evaluation of RCA Particles

Most RCA particles contained adhered paste and air voids, which reduced the density and increased the absorption of RCAs. These air voids might affect the fresh air measurement and the freeze/thaw durability of concrete. As a result, the adhered paste and air voids were important properties for RCAs. In this study, they were evaluated through microscopic evaluation following the modified point count method described in ASTM C457[45]. Preparation of the section started with selecting a representative oven-dried RCA sample and densely packing it in a 4x8" cylindrical mold. A transparent epoxy was then slowly poured into the mold until it was full. During this process, a steel rod was used to slightly tap the side of mold to facilitate the escape of entrapped air voids. The specimen was then cured at room temperature. After the epoxy was hardened, the specimen was demolded, and sawn into a 2" slice along the middle section perpendicular to the layer in which RCA was placed. The surface of the slice was lapped with successively finer abrasives (No. 220, 320, 600, and 800). Figure 3.1.4a shows an example of the polished surface of an epoxy bonded RCA sample. The paste and air voids in RCA particles were determined using a computerized microscopic device (Figure 3.1.4b). The modified point count method described in ASTM C457 was followed with a magnification of 170x and an interval of 0.05" between stops and lines. It should be noted that the hardened epoxy was excluded during the counting process. The air content and the paste content were calculated based on the equations provided in ASTM C457.

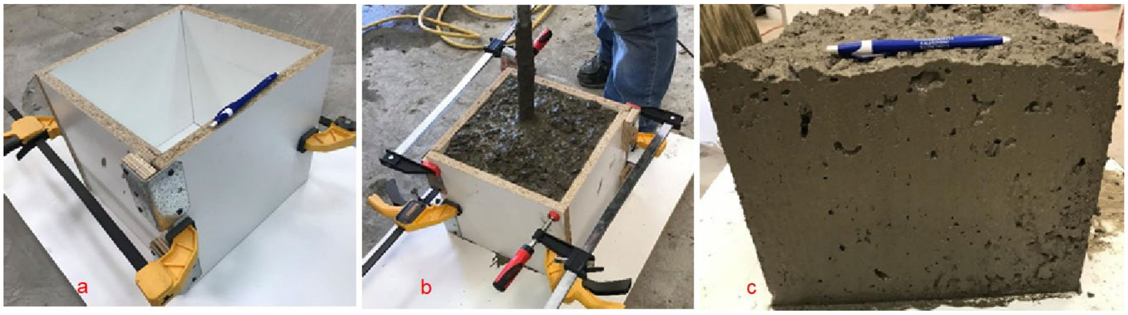


(a) Epoxy-Bonded RCA Specimen (b) Point Count Device
Figure 3.1.4 Microscopic Examination of RCA

3.2 RCA Concrete Property Evaluation

3.2.1 Workability

The workability of fresh RCA concrete was firstly evaluated by the slump test following the procedures in ASTM C143[46]. However, the slump test measured the falling of concrete under its own weight, which was not very effective in assessing the workability of a paving concrete because a slipform paving concrete typically had a low slump (½" to 2"), which enabled the concrete to hold its edges after vibration was completed and side forms were removed. As a result, the box test was employed to evaluate the ease of consolidation and the ability of concrete to hold its edges. After mixing, approximately 9.5" fresh concrete was placed in a 12"x12"x12" wood form (Figure 3.2.1a), and internally vibrated downward for approximately 4 seconds and then upward for 2 seconds using a portable Klutch electric vibrator with a diameter of 1 ¼" and a vibration frequency of 12,000 VPM (Figure 3.2.1b). After the removal of side forms, the concrete specimen was inspected for side voids and the edge slump (Figure 3.2.1c). If the sides had excessive voids, the mixture did not consolidate well under vibration. If an excessive edge slump occurred, the concrete was not suitable for the slipform paving.



(a) 1 ft^3 form (b) internal vibration (c) concrete specimen after vibration and form removal
Figure 3.2.1 Box Test Procedure Illustration

3.2.2 Fresh Air Content and Unit Weight

The air content of freshly mixed concrete was measured using the pressure method (ASTM C231[47]) and the volumetric method (ASTM C173[48]). The unit weight of concrete was determined using the measuring bowl of pressure air meter following the procedures in ASTM C138[49]. In addition, a sequential pressure method was employed to evaluate the air content as well as the

Sequential Air Meter (SAM) number based on AASHTO TP 118[50]. The placement, consolidation, and striking-off of concrete sample in the measuring bowl was same as those described in ASTM C231 for the type B meter. After cover was clamped, water was added through one petcock until it emerged from the other petcock. After the petcocks were closed, two sequences of pressure were manually pumped into the air chamber. In each sequence, three pressures (14.5, 30, and 45psi) were applied starting from 14.5psi and ending with 45psi. After each pressure was applied and stabilized, the air valve between the air chamber and the bowl was opened and held for approximately 10 seconds. The equilibrium pressure was then recoded. After the first run was finished, the pressure in the air chamber and the measuring bowl was released, and the second run was continued. The SAM number was calculated by comparing the difference between the equilibrium pressure of both runs.

3.2.3 Time of Setting

The fresh RCA concrete mixture was wet-sieved using #4 sieve (4.75 mm), placed into a 12x6" cylindrical plastic container, and externally vibrated for approximately 15 seconds. The sample was then stored in a room with a constant temperature of 72°F and 50% relative humidity. The penetration resistance was measured periodically using a penetrometer (Figure 3.2.2) following ASTM C403[51] until the penetration resistance reached more than 4000 psi.

Figure 3.2.2 Test Setup for Time of Setting of RCA Concrete

3.2.4 Strength Development

The compressive strength of RCA concrete was evaluated at 1, 7, and 28 days based on the procedures in ASTM C39[52]. Three specimens were tested at each age and the average value was used to represent the compressive strength of concrete at that age. After mixing, the fresh RCA concrete was placed into 4x8" cylindrical plastic molds and externally vibrated for approximately 20 seconds. The specimens were subsequently finished, capped, stored on the lab floor at approximately 72°F for approximately 24 hours. After the initial curing, the specimens were demolded and cured in lime-saturated water at approximately 72°F until the time of testing. The compressive strength testing was performed using SATEC SYSTEMS Model 5500 supplied by INSTRON. A load control mode was used at a loading rate of 35 psi/s.

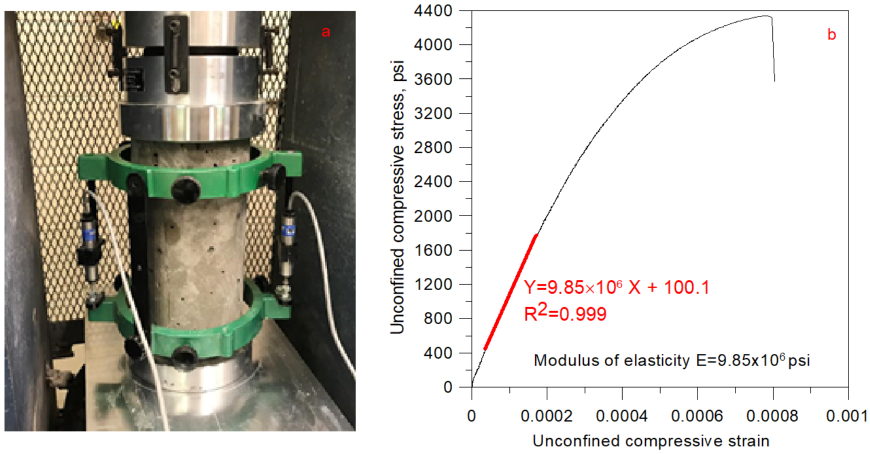
The flexural strength of RCA concrete was also tested at 1, 7, and 28 days following the procedures in ASTM C78[53]. One or two specimens were tested at a specific age, and the average value was used as the flexural strength of concrete. The freshly mixed RCA concrete was placed into 6x6x21” plastic molds, consolidated by the external vibration, finished with a trowel, and covered with plastic sheeting. After 24 hours initial curing at the room temperature (72°F), the beam specimen was removed from the mold and submerged into the lime-saturated water until testing. The flexural test was conducted based on the third point loading method (Figure 3.2.3). The machine described in the compressive strength test above was also employed for the flexural test with a loading rate of 1800 lb./min.

(a) Third Point Loading (b) Example of Failure Section

Figure 3.2.3 Flexural Test Setup

3.2.5 Modulus of Elasticity

The modulus of elasticity (static) of RCA concrete was evaluated at 1, 7, and 28 days following the procedure similar to the one described in ASTM C469[54]. The fresh concrete was placed into 6x12” cylindrical plastic molds with two equal layers and each layer was rodded for 25 times. The specimen was then consolidated by the external vibration for approximately 20 seconds. After consolidation, the specimens were finished, covered with plastic sheets, and initially stored in air at 72°F for approximately 24 hours. After demolding, the specimens were cured in lime-saturated water until the time of testing. Before testing, the specimens were capped, and one Linear Variable Differential Transducer (LVDT) was attached on each side of the specimen. Two supporting yokes were used to hold the LVDTs and rigidly attached to the specimens. The top yoke was located 2 inches below the top of the specimen, while the bottom yoke was placed 2 inches above the bottom of the specimen. The distance between the yokes was approximately 8 inches. The two LVDTs were interfaced with a displacement scanning and recording system which was controlled by the computer software. The test setup is illustrated in Figure 3.2.4a. After the specimen was positioned, the load was applied at a constant rate of 35 psi/s and continuously recorded at a constant time interval. Meanwhile, the displacement was scanned and recorded at the same time interval. The stress and strain curve was developed based on the recorded data (Figure 3.2.4b). The slope of the curve between 10% and 40% stress levels was calculated and used as the modulus of elasticity of the specimen. For the 1-day calculation, higher stress levels (typically between 40% and 70%) were used because the stress and the strain were not well related at low stress levels. Three specimens were tested at each age and the average value was used to represent the modulus of elasticity of concrete at that age.

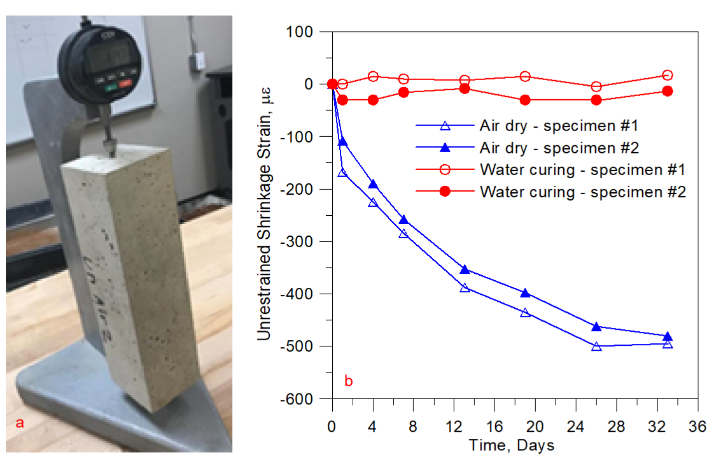


(a) Test Specimen and Setup **(b) Example of Test Result**

Figure 3.2.4 Modulus of Elasticity Test

3.2.6 Free Shrinkage and Restrained Shrinkage Cracking

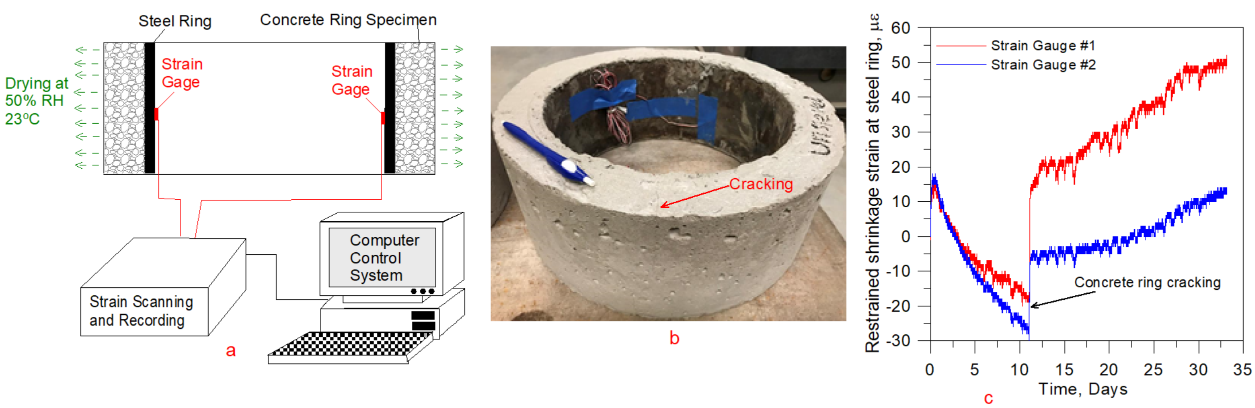
The free shrinkage of RCA concrete mixes was evaluated following the procedures in ASTM C157[55]. The prisms (3x3x11-¼ in.) with a gage length of 10 in. were prepared using the molds described in ASTM C490[56]. The freshly mixed RCA concrete was placed into four molds, externally vibrated for approximately 20 seconds, and finished with a steel trowel. The four specimens were then covered with plastic sheets and initially cured in air at 72°F for 24 hours. The specimens were removed from the molds and measured with a comparator as shown in Figure 3.2.5. After the initial comparator reading was taken, two specimens were stored in air in an environmental chamber with constant relative humidity (RH) of 50% and temperature of 72°F. Two specimens were cured in the lime-saturated water at the temperature of 72°F. For each specimen, the comparator reading was taken approximately weekly for a period of at least 28 days. In addition, the fresh concrete was wet-sieved to remove big aggregate particles using a ½" sieve and the free shrinkage of sieved concrete was measured following the same procedures as those used for un-sieved concrete.



(a) Comparator **(b) An Example of Test Result**

Figure 3.2.5 Free Shrinkage Test Setup

The restrained shrinkage ring test was performed in this study following ASTM C1581[57]. It was used to evaluate the risk of shrinkage cracking of concrete that was exposed to a restrained drying environment using the strain that developed in the steel ring. After mixing, the RCA concrete was wet-sieved with a ½" sieve to remove the large aggregate particles due to the aggregate size limit in this test. The sieved concrete was then placed into the space between the outer ring (a 1/8" steel ring) and inner ½" steel ring. During the placement, the concrete was consolidated using external vibration and finished with a steel trowel to achieve a smooth surface. The specimen was then covered with a plastic sheet to prevent moisture loss and maintained in air at 72°F. The outer ring was removed at an age of 24 hours and the concrete and the inner steel rings were placed in a constant dry environment with a temperature of 72°F and RH of 50%. The two strain gages that were horizontally attached to the steel ring at the mid-height were then interfaced with the data acquisition system (a strain scanning and recording system and a computer control system). The test set up is shown in Figures 3.2.6a and b. The strain was scanned and registered every 10 minutes for a period of approximately 5 weeks. An example of test result is shown in Figure 3.2.6c.



(a) System Setup **(b) Test Specimen** **(c) An Example of Test Result**

Figure 3.2.6 Restrained Shrinkage Ring Test

3.2.7 Rapid Chloride Permeability

The rapid chloride permeability test was conducted using "PROOVE it" system manufactured by GERMANN INSTRUMENTS following ASTM C1202[58]. The test setup is shown in Figure 3.2.7a. After mixing, the fresh RCA concrete was cast into three 4x8" cylindrical plastic molds and consolidated by the external vibration for about 20 seconds. After finishing, the top of molds was sealed with plastic caps. The molds together with the specimens were then transferred to the initial curing area with a constant temperature of 72°F. After 24 hours initial curing, the specimens were demolded and then cured in the lime-saturated water at 72°F for 28 days. The specimens were taken out of the curing tank and a 2" slice (Figure 3.2.7b) was cut from the middle portion of each cylinder using the water-cooled diamond saw. The slices were air dry for 1 hour and then vacuum saturated with water. After side surface coating, each slice was mounted into a two-part specimen cell. One side of the cell was filled with 3.0% NaCl solution and the other side of the cell was filled with 0.3 N NaOH solution. The cell was then connected to the test apparatus and 60 Volts was applied. The charges in coulombs that passed through the slice were measured for a period of 6 hours. The total charges passed were used as an indication of concrete permeability. A total of 3 slices for each mix were tested. The average value was used to represent the permeability of that mix.

(a) Test Setup **(b) Test Specimens**

Figure 3.2.7 Rapid Chloride Permeability Test

3.2.8 Rapid Freeze and Thaw Durability

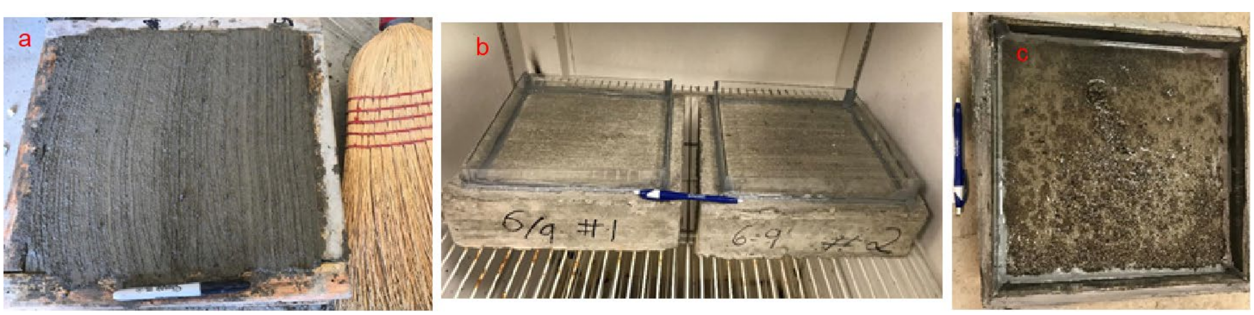
The rapid freeze and thaw test was conducted following the procedures described in ASTM C666[59]. After mixing, the fresh RCA concrete was placed into three metal molds (3x4x16"), which were externally vibrated on a vibration table for approximately 20 seconds and finished using a trowel. After finishing, the specimens were covered with plastic sheets and stored wet at room temperature of 72°F. After 24 hours initial curing, the specimens were de-molded and cured in the lime-saturated water at 72°F for 14 days. After curing, the specimens were taken out of the curing tank and their surface moisture was removed with a wet towel. The initial mass and the initial transverse resonant frequency (i.e., 0 freeze/thaw cycles) of each specimen were measured and recorded. All specimens were placed into specimen holders. Water was added to each specimen holder until each specimen was fully surrounded by 1/8" of water. The test was then started after all specimens together with their holders were positioned into the freeze and thaw chamber (Figure 3.2.8a). The mass and the transverse resonant frequency of each specimen were measured regularly (at approximately 35 cycles) until the specimen broke or underwent 300 cycles. Before each measurement, all specimens were fully thawed and the free water on their surface was removed with wet cloth. A Resonance Tester (supplied by Olson Instruments) and the Forced Resonance Method in ASTM C215[60] were used in this study to measure the transverse resonant frequency (Figure 3.2.8b). The mass loss, relative dynamic modulus, and durability factor were calculated and used to indicate the durability of RCA concrete mixes.

(a) Freeze/Thaw Chamber **(b) Resonant Frequency Measurement**

Figure 3.2.8 Freeze and Thaw Test Setup

3.2.9 Scaling Resistance

The scaling resistance of RCA concrete surface was examined following ASTM C672[61]. The freshly mixed RCA concrete was casted into a 12x12x3.5" wood mold, externally vibrated for 20 seconds, and finished with a trowel. The fresh surface was textured with a medium-stiff broom (Figure 3.2.9a) and then covered with plastic sheet. After initial curing at 72°F in air for 24 hours, the specimen was demolded and cured in lime-saturated water for 14 days. After moist curing, the specimen was stored in air with approximately 72°F and 50% RH for 14 days, during which a dike with a ponding area of 10x10" and a height of 1" was built on the surface of specimen. After air curing, $CaCl_2$ solution (made by adding 4g $CaCl_2$ to 100 ml of distilled water) was added into the dike until the solution covered the whole surface with a depth of approximately ¼". The specimen was then placed in a chamber that could provide a freezing environment with a temperature of -18°C for approximately 16 hours as well as a thawing environment with a temperature of 23°C for approximately 8 hours (Figure 3.2.9b). After approximately 5 to 7 cycles (1 cycle per day), the surface was flushed off and the mass scaled was collected and oven dried. After 50 cycles, the surface of the specimen was visually examined and rated following the criteria in ASTM C672. An example of scaled surface of a concrete specimen is shown in Figure 3.2.9c. The mass scaled was also used as an indication of scaling resistance of RCA concrete in this study.



(a) Broom-Textured Specimen **(b) Freeze/Thaw Chamber** **(c) Specimen after 50 Cycles**

Figure 3.2.9 Scaling Resistance Test

3.2.10 Hardened Air Void Analysis

The hardened air content and the air void spacing factor of RCA concrete was determined using the modified point count method following the procedures in ASTM C457. The apparatus used for the point count method here was same as the one described above in section 3.1.5. The 4x8" cylindrical concrete specimen was prepared using the same procedures as described above in the compressive strength test section. After curing for at least 28 days, the concrete cylinder was first sawed along the middle section perpendicular to the finished surface. This would achieve a 4”x8” surface that included the top, middle, and bottom of concrete in the cylinder. The section was further cut to achieve a flat base. After cutting, the 4”x8” surface was polished using a lapping wheel and the silicon carbide abrasives in the order of No. 220, 320, 600, and 800. After polishing, the section was placed on the stage of point count device and examined under an optical microscope with a magnification of 170x. In the point count process, the interval between stops was 0.05” and between lines was 0.1”. For each section, approximately 2500 stops were examined and counted and the intersected air voids by the line of traverse were also recorded. The air content (%) and the air spacing factor (in.) were calculated based on the equations given in ASTM C457.

Chapter 4 Results and Discussion

4.1 Properties of RCAs

In general, conventional crushed limestone had an angular shape and relatively smooth texture; however, all RCAs collected in this study showed more rounded shape and rougher grainy surface texture. This was primarily because most RCA particles were fully or partially surrounded by the residual mortar, which smoothed out the angularity of original aggregate particles. The shape and texture of different RCAs collected in this study can also be viewed in the supplementary documents of this report (G). Some RCAs contained non-concrete particles such as bricks, asphalt, and masonry unit. For each RCA, these external particles were classified and evaluated, and the results are also provided in the supplementary documents of this report (G).

The gradation of RCAs is shown in Figure 4.1.1. All RCAs demonstrated good gradation based on the criteria provided in ASTM C33. Some RCAs only slightly exceeded the grading limits. Two RCAs (AF and SC RCAs) were relatively coarse. They almost met the grading requirements of #56. The SC RCA gradation was close to the upper limit of #56 and it was the coarsest RCA in this study. Four RCAs (I-440, SCP, HC, and NRM RCAs) were comparatively fine. They satisfied the grading requirements of #57. The gradation of I-440 and SCP RCAs was near the lower limit of #57 and they were the finest RCAs in this study.

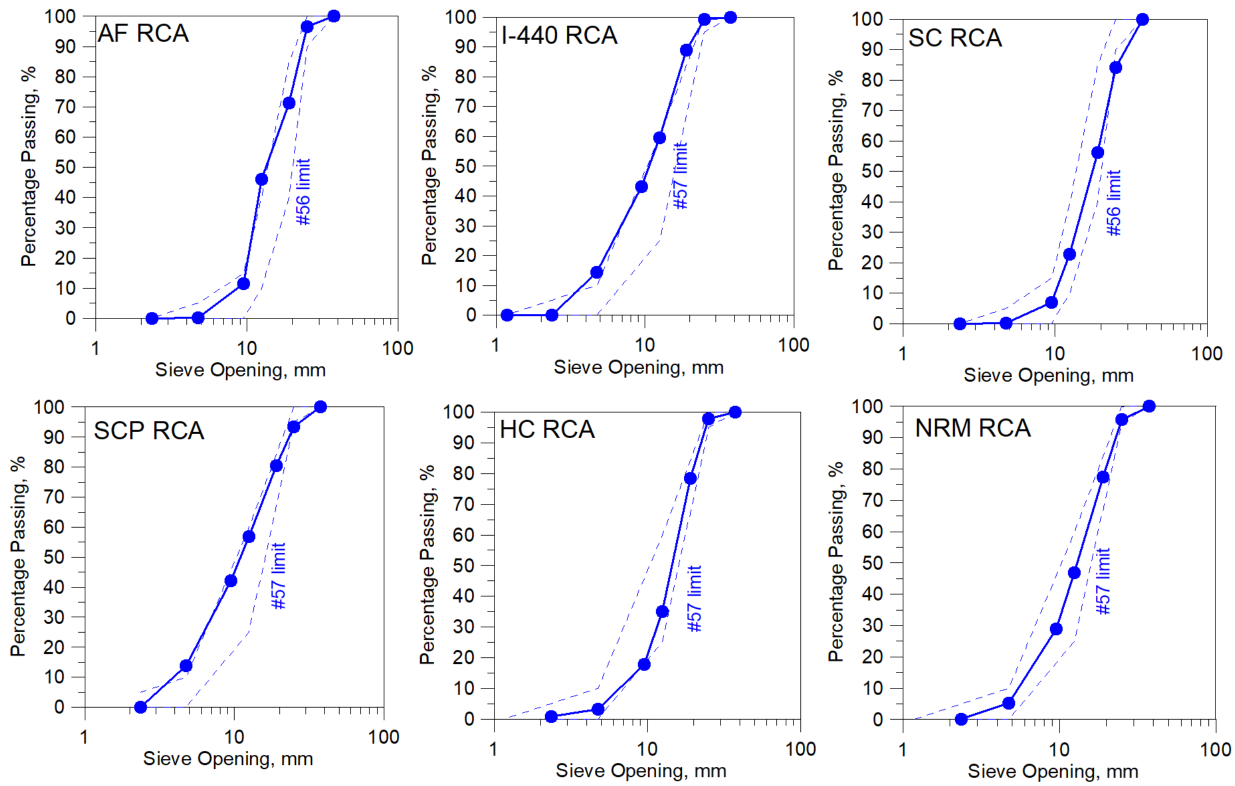


Figure 4.1.1 Gradation of RCAs used in this study

Additionally, the gradation of natural virgin aggregates (NVAs) used in this study is provided in Figure 4.1.2. In general, all NVAs displayed good to acceptable gradations based on the grading requirements in ASTM C33, however, some NVAs (e.g., #7 and sand) slightly deviated from the grading limits.

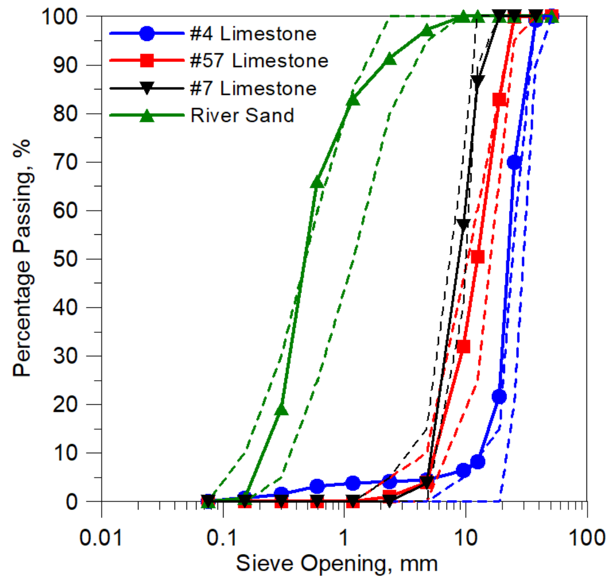


Figure 4.1.2 Gradation of NVAs used in this study

Other properties of RCAs tested in this study are summarized in Table 4.1. In general, RCAs had a specific gravity of 2.28 to 2.43, absorption of 5.52% to 11.9%, LA abrasion loss of 31.7% to 38.2%, adhered paste content of 14.1% to 26.5% by volume, and air content of 0.88% to 2.2%. As a comparison, the #57 crushed limestone showed a specific gravity of 2.66, absorption of 1.04%, and LA abrasion loss of 25.1%. Averagely, RCAs demonstrated approximately 11% decrease in specific gravity, 613% increase in absorption, and 40% reduction in LA abrasion loss as compared with #57 limestone. The primary reason was that most RCA particles contained adhered pastes. These pastes contained pores, thus making RCA particles lighter, more absorptive, and less resistant to abrasion. Any RCAs with a higher paste volume and more porous paste would have lower specific gravity, higher absorption, and lower abrasion resistance. For some RCAs, the chloride contents (water-soluble and acid-soluble) and the pH value were also analyzed and summarized in Table 4.1. As compared with #57 limestone, RCAs typically had a higher chloride content and a higher pH value.

Table 4.1 Basic Properties of RCAs

RCA Source	Specific Gravity (SSD)	Absorption, %	LA Abrasion Loss, %	Paste Content, %vol.	Air Content, %	Chloride Content, %wt.		pH
						Water-soluble	Acid-soluble	
AF	2.38	5.59	34	14.1	0.88	0.019	0.033	10.33
I-440	2.4	5.52	31.7	20.2	1.6	0.024	0.033	12.23
SC	2.35	7.53	36.9	21.6	1.7	0.025	0.03	11.0
MJC	2.35	6.71	38.2	NT	NT	NT	NT	NT
MM	2.39	7.62	33.2	NT	NT	NT	NT	NT
SCP	2.28	11.9	38.4	26.5	1.75	0.021	0.040	11.65
HC	2.43	7.04	35.2	24.2	2.2	0.01	0.042	11.74
NRM	2.37	7.46	34.5	NT	NT	0.022	0.043	12.77
#57 Limestone (control)	2.66	1.04	25.1	NA	NA	0.01	0.01	8.95

Note: NA – Not applicable, NT – Not tested due to lack of RCA samples

Specifically, I-440 RCA (as-is) was sieved into different sizes and the specific gravity and the absorption of different sizes of RCA particles were measured and shown in Figure 4.1.3. Clearly, smaller particles had higher absorption, but lower specific gravity. Again, it was the paste that reduced the specific gravity and increased the absorption. Small RCA particles commonly contained more paste and some very fine RCA particles could fully be paste.

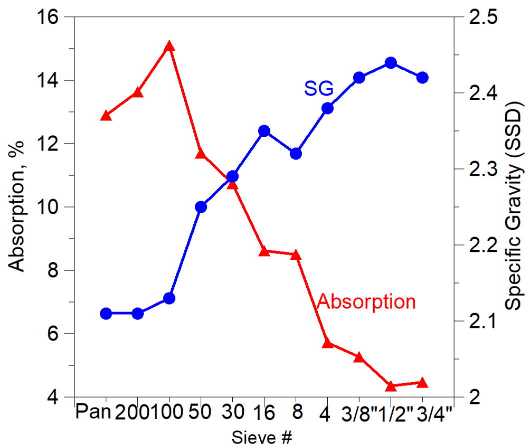


Figure 4.1.3 Effects of Particle Size on Specific Gravity and Absorption of I-440 RCA

The absorption, specific gravity, and LA abrasion loss of RCAs were found to correlate very well as illustrated in Figure 4.1.4. RCAs with higher absorption appeared to have lower specific gravity and higher LA abrasion loss, and the relationships were nearly linear. An increase in absorption by 1% would increase the LA abrasion loss by 1.3% and reduce the specific gravity by 0.032%.

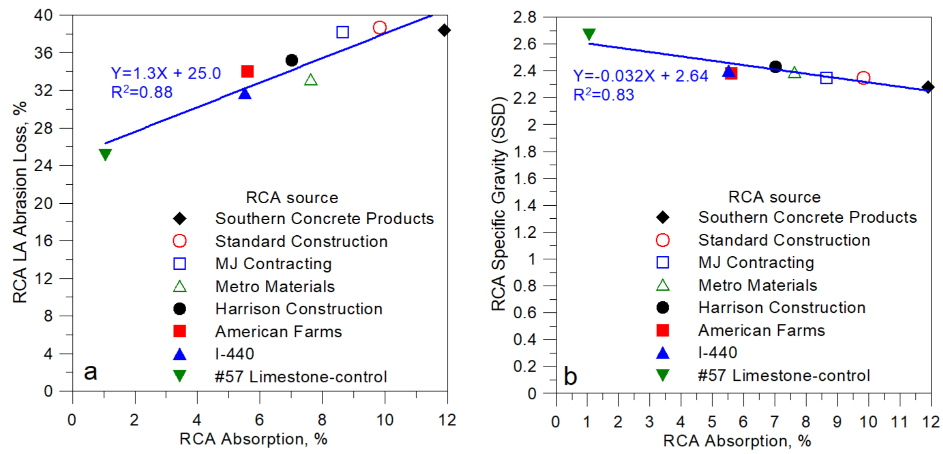


Figure 4.1.4 Relationships between Absorption, Specific Gravity, and LA Abrasion Loss of RCAs

4.2 RCA Concrete Mix Proportioning and Optimization

The main goal of this project was to develop new paving concrete mixes using different RCAs. The research work started with evaluating the TDOT Class CP concrete mix with NVAs. Its fresh and hardened properties were measured and used as the baseline properties. Then, the NVAs in the mix were equally replaced with different types of pre-soaked RCAs by volume. The properties of RCA concrete mixes were determined. Then, #7 or #4 crushed limestone was introduced to optimize the gradation of different RCAs based on the Coarseness Factor Chart and the Tarantula Curve. It was found that using 15 to 25% of either #7 or #4 crushed limestone to blend with RCAs significantly improved the combined aggregate gradation in the mix, which in most cases resulted in a better performance of concrete. The following sections described in detail the mix proportion and optimization for each RCA.

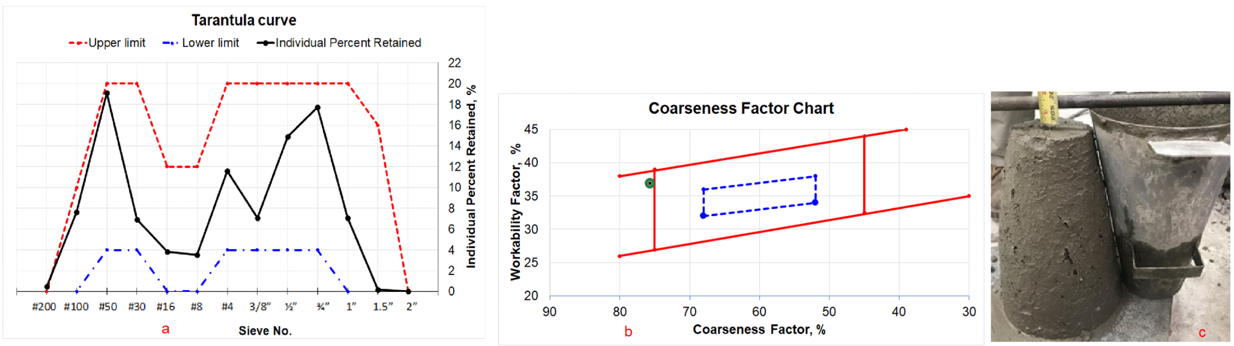
The type I/II cement was provided by CEMEX and its chemical composition is given in the supplementary documents of this report (A). The class F fly ash was supplied by the Cumberland Fossil plant, SEFA Group and its chemical composition is also summarized in the supplementary document of this report (A). The chemical admixtures used in this study were provided by the BASF corporation including the Air-Entraining Admixture (Master Air AE 200), the Middle-Range Water-Reducing Admixture (MasterPolyheed 997), and the High-Range Water-Reducing Admixture (MasterGlenium 7920).

4.2.1 TDOT Class CP Mix

60% Crushed Limestone + 40% Sand

TDOT specified that a paving concrete (i.e., Class CP mix) should have a minimum 28-days compressive strength of 3000 psi, minimum cementitious material content of 526 lbs./yd^3 (when the coarse aggregate is crushed stone), maximum W/Cm of 0.45, entrained air content of 5%, and a slump of 0-2 inches (slipform paving).[62] In this study, a typical proportion was selected, which consisted of type I cement (395 lbs./yd^3), class F fly ash (131 lbs./yd^3), #57 crushed limestone (1130 lbs./yd^3, SSD), #4 crushed limestone (765 lbs./yd^3, SSD), natural river sand (1240 lbs./yd^3, SSD), water (237 lbs./yd^3), and air-entraining admixture (1.0 to 1.6 fl. oz/cwt). The combined aggregates were 36% #57, 24% #4, and 40% sand. It should be noted that the specific gravity of both crushed limestone and river sand in this study was almost same and thus the aggregate percentage by weight was approximately equal to that by volume.

The combined aggregate gradation and the workability of TDOT Class CP mix were evaluated. The results are shown in Figure 4.2.1. Obviously, the combined gradation was within the upper and the lower limits of the Tarantula Curve (Figure 4.2.1a), indicating that the aggregates were well-graded based on this criterion. However, the aggregate seemed relatively coarse, gap-graded, and susceptible to segregation based on the Coarseness Factor Chart (Figure 4.2.1b). The workability of the mix was evaluated based on the slump test (Figure 4.2.1c) and the box test. The measured slump was typically 1.5” on average, which was acceptable for slipform paving. The overall surface void content after the box test was less than 10%, indicating that the mix responded well to vibration and was easy to consolidate in the slipform paving. Also, there was no significant edge slump after the form removal, implying that the fresh mix was able to hold its edge. As a result, TDOT Class CP mix had a good workability despite that it was rated as coarse and gap-graded in the Coarseness Factor Chart.

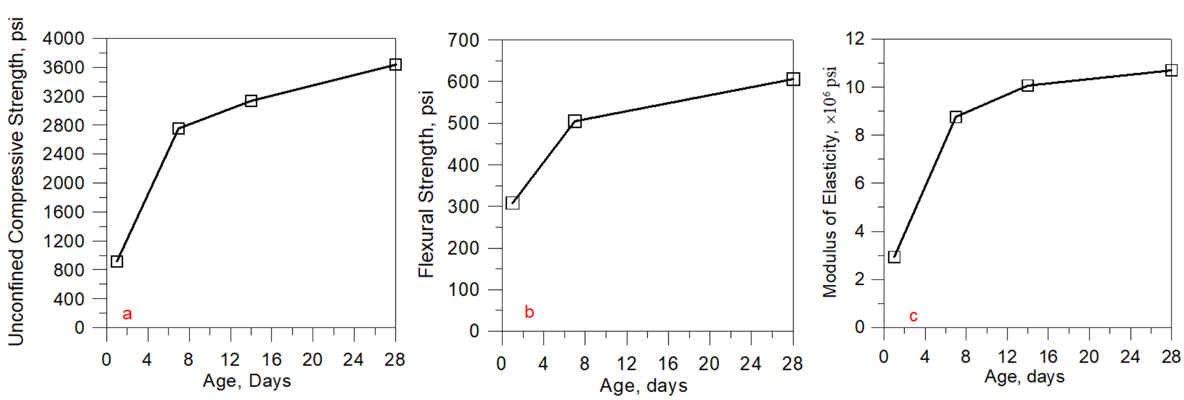


(a) Tarantula Curve **(b) Coarseness Factor Chart** **(c) Slump**

Figure 4.2.1 Aggregate Gradation and Workability of TDOT Class CP Mix

Compressive Strength, Flexural Strength, and Modulus of Elasticity of TDOT Class CP Concrete Mix

The basic mechanical properties (compressive strength, flexural strength, and modulus of elasticity) of TDOT Class CP mix at different ages were evaluated and the results are illustrated in Figure 4.2.2. For examples, the average compressive strength at 28 days was 3639 psi (Figure 4.2.2a), which was well above the value (3000psi) specified for the paving concrete in Tennessee. The average flexural strength at 28 days was 606 psi (Figure 4.2.2b), and the average modulus of elasticity at 28 days was $10.7x10^6$ psi (Figure 4.2.2c). All these properties were used as baselines for comparing the performance of RCAs when they were used to replace the NVAs in the mix.



(a) Compressive Strength **(b) Flexural Strength** **(c) Modulus of Elasticity**

Figure 4.2.2 Mechanical Properties of TDOT Class CP Mix

4.2.2 AF RCA Concrete Mix

<u>60% AF RCA + 40% Sand</u>

AF RCA was used to equally replace the coarse aggregates by volume (i.e., 60%) in TDOT Class CP mix. Figure 4.2.3 presents the results of the aggregate gradation and the workability of the mix. From the Tarantula curve (Figure 4.2.3a), the combined gradation at 3/8" slightly exceeded the upper limit of the curve, meaning that the combined aggregates were slightly gap graded. From the Coarseness Factor Chart (Figure 4.2.3c), the mix was located in Zone I, but far away from Zone II, indicating that the combined aggregates were very coarse, and gap graded. Interestingly, the workability of the mix was observed to be acceptable based on the slump test (Figure 4.2.3b) and the box test (Figure 4.2.3d) with a relatively high slump of 2.75" and an overall surface void of less than 10%. However, the main limitation of this mix was its low compressive strength (2800psi at 28 days), which did not meet the TDOT requirements for paving concrete. Also, a slight edge slump occurred in the box test after the vibration was complete and the form was removed.

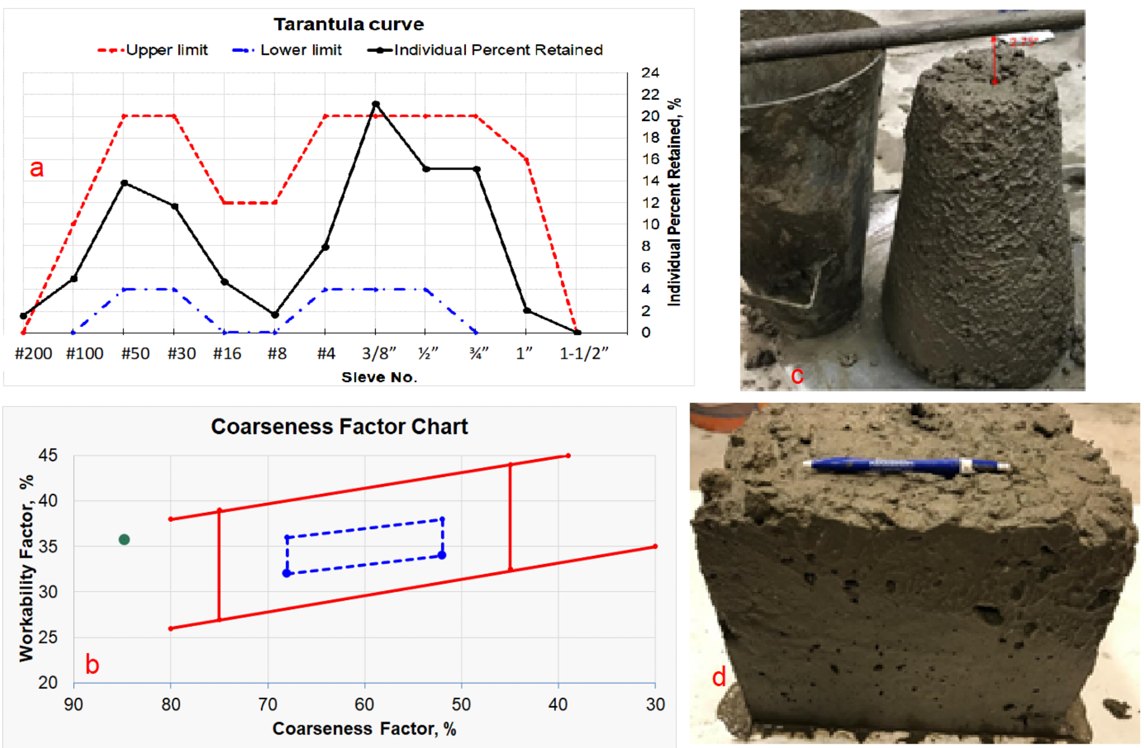


Figure 4.2.3 Aggregate Gradation and Workability of 60% AF RCA Concrete Mix (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

<u>40% AF RCA +20% #7 + 40% Sand</u>

The proportion of above mix (60% AF RCA) was adjusted by introducing an intermediate aggregate (i.e., #7 crushed limestone) to reduce the particles retained on 3/8" as well as the coarseness of mix. A combination of 40% AF RCA, 20% #7 crushed limestone, and 40% river sand by volume was observed to exhibit better gradation. Figure 4.2.4 shows the results of the combined gradation of aggregates and the workability of the mix. Obviously, adding 20% #7 crushed limestone into the mix slightly improved the aggregate gradation based on the Tarantula Curve with all particle sizes locating between the upper and the lower limits (Figure 4.2.4a). This also greatly reduced the coarseness of the mix by moving from Zone I to Zone II in the Coarseness Factor Chart (Figure 4.2.4b). Surprisingly, this improvement in aggregate gradation seemed to reduce the workability of the mix because the measured slump decreased to approximately 3/4" (Figure 4.2.4c) and the overall surface void was noted to slightly increase (Figure 4.2.4d). However, better aggregate gradation appeared to control the edge slump.

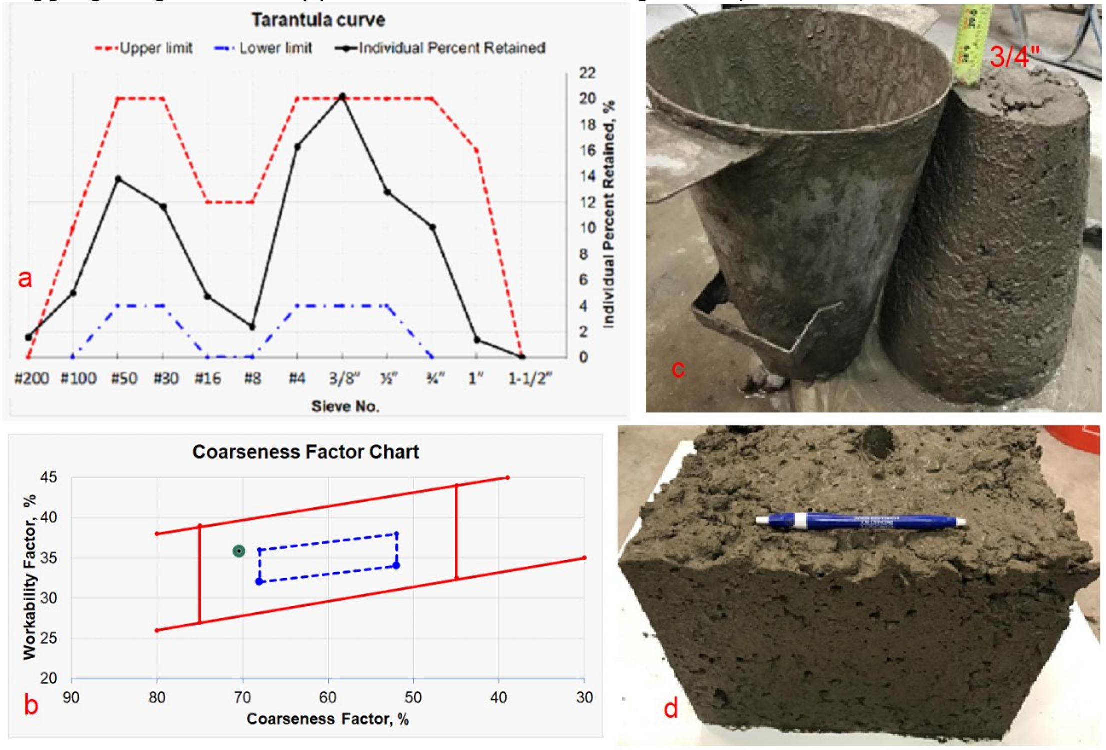


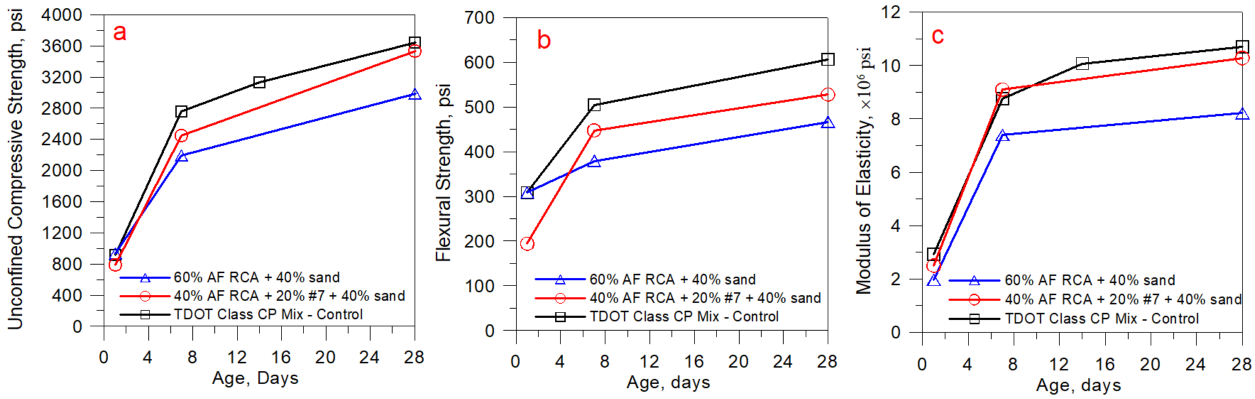
Figure 4.2.4 Aggregate Gradation and Workability of Concrete Mix with AF RCA and #7 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

Compressive Strength, Flexural Strength, and Modulus of Elasticity of AF RCA Concrete Mixes

The compressive strength, the flexural strength, and the modulus of elasticity of AF RCA concrete mixes at different ages are shown in Figure 4.2.5. The use of AF RCA to fully replace the coarse NVAs in TDOT Class CP mix (60% AF RCA) noticeably reduced the compressive strength (Figure 4.2.5a), the flexural strength (Figure 4.2.5b), and the modulus of elasticity (Figure 4.2.5c) at late ages (e.g., 7 and 28 days). However, the early-age strength and the modulus (e.g., 1 day) did not change significantly. The compressive strength at 28 days was below 3000psi, which did not meet the TDOT requirement.

Adding 20% #7 crushed limestone to optimize the gradation of AF RCA improved the compressive strength, the flexural strength, and the modulus of elasticity, but in most cases, these properties were still lower than those of TDOT Class CP mix (control). The 28-days compressive strength was above 3000psi, which satisfied the requirement for paving concrete in Tennessee. Again, the early age strength and modulus did not vary significantly.

AF RCA noticeably reduced the strength and the modulus at the late age but had less effects at the early age. One plausible explanation was that at the early age, the paste was weak, and the strength and the modulus of concrete were controlled by the paste and thus aggregates had little effects. At late ages, the paste gained its strength and was able to transfer loads to the aggregate particles. Both paste and aggregate played important roles in the strength and the modulus of concrete. The weak particles in AF RCA such as bricks would weaken the concrete.



(a) Compressive Strength **(b) Flexural Strength** **(c) Modulus of Elasticity**

Figure 4.2.5 Mechanical Properties of Concrete Mixes Using AF RCA

4.2.3 I-440 RCA Concrete Mix

100% As-Is I-440 RCA (Coarse plus Fine)

The I-440 RCA (as-is) consisted of both coarse and fine particles. Firstly, all aggregates including sand in TDOT Class CP mix were replaced with I-440 RCA (as-is) by volume. The concrete mix was extremely unworkable and incohesive with a measured slump of nearly zero. The mix proportion was then adjusted by increasing W/Cm to 0.5 and adding 3.5 fl oz/cwt of MRWR and 7.5 fl oz/cwt of HRWR. The combined gradation of aggregates and the workability of the adjusted concrete mix were evaluated, and the results are illustrated in Figure 4.2.6. The aggregates were gap graded based on the Tarantula Curve with excessive particles retained on ½", No.4, and #200 sieves respectively (Figure 4.2.6a). The mix was in Zone 5 based on the Coarseness Factor Chart (Figure 4.2.6b) indicating that it was rocky, lean, and non-plastic. At high W/Cm and high dosages of water-reducing admixtures, the measured slump was approximately 1" (Figure 4.2.6c). The overall surface void was more than 50% (Figure 4.2.6d), meaning that the mix had very poor workability and was very difficult to consolidate. Moreover, the breakage and collapse of fresh concrete specimen occurred following the removal of side forms in the box test, indicating that the mix lacked cohesiveness. This poor performance was attributed to the gap graded aggregates, particularly the angular fine aggregates that demanded extra pastes for workability. Without increasing the paste, the mix became rocky, lean, and non-plastic. Undoubtedly, directly using as-is I-440 RCA to fully replace the aggregates in TDOT Class CP mix was not recommended.

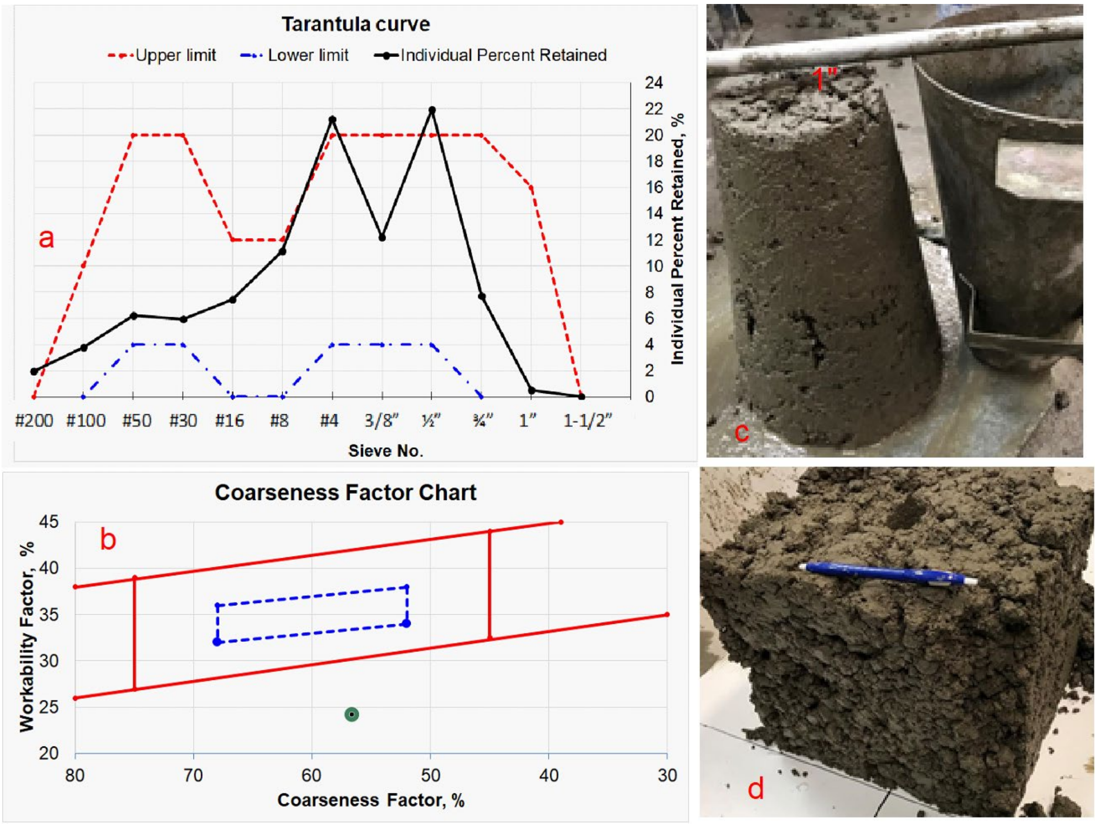


Figure 4.2.6 Aggregate Gradation and Workability of Concrete Mix with 100% as-is I-440 RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

80% I-440 RCA (As-Is) + 20% Sand

The aggregate gradation was adjusted by reducing I-440 RCA (as-is) from 100% to 80% by volume and adding 20% by volume of river sand. Other materials and proportions were kept same. Figure 4.2.7 presents the combined aggregate gradation and the workability measurements. The combined aggregate gradation was significantly improved based on the Tarantula Curve (Figure 4.2.7a). Only particles retained on #200 sieve looked slightly excessive. Also, the combined aggregates were deemed well-graded based on the Coarseness Factor Chart (Figure 4.2.7b) because the mix was positioned in Zone II. The measured slump was 2" (Figure 4.2.7c), which was acceptable for the slipform paving. However, the mix responded very weakly to vibration during the box test with the overall surface void content of more than 50% (Figure 4.2.7d). It appeared that the mix still lacked cohesiveness and plasticity. This suggested that good aggregate gradation did not always assure good workability. Other factors such as aggregate size, shape, and angularity also played important roles. Again, using as-is I-440 RCA in new paving concrete should be done with caution.

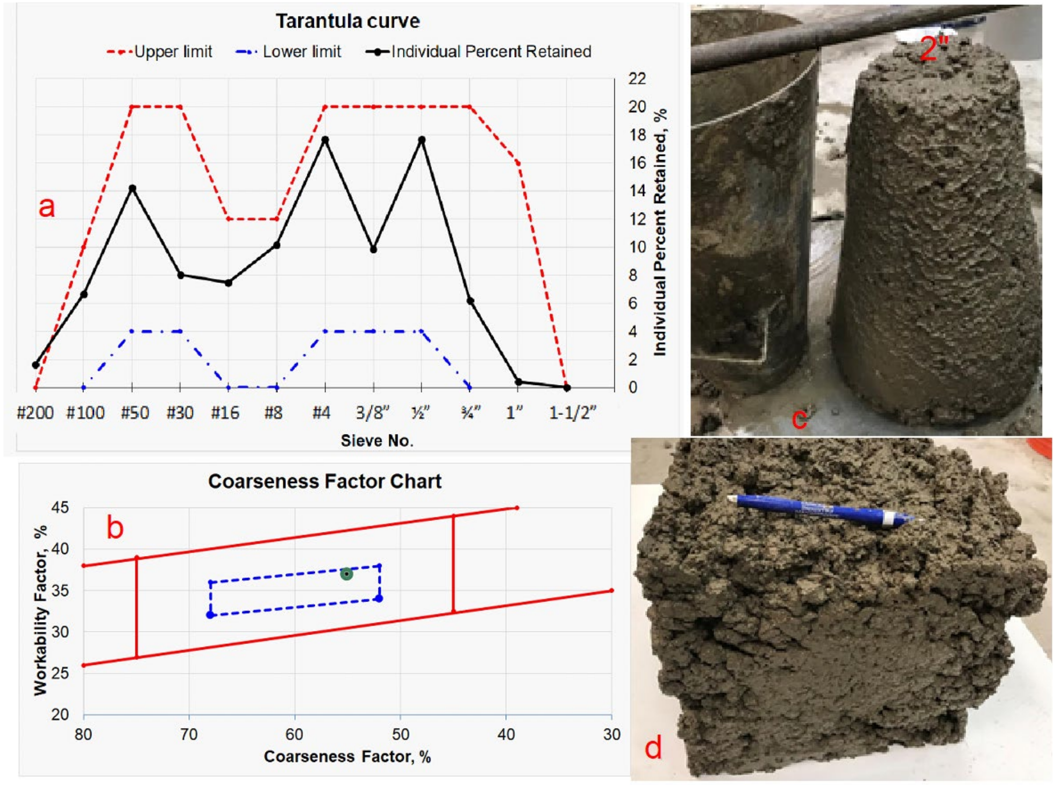


Figure 4.2.7 Aggregate Gradation and Workability of Concrete Mix with 80% I-440 RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

100% Optimized I-440 RCA (Coarse plus Fine)

One interesting study in this project was to sieve the I-440 RCA into different sizes and then choose a specific percentage from each size and recombine them into a desirable gradation. Figure 4.2.8 shows the results of a concrete mix using such recombined aggregates. The aggregate was well-graded based on the Tarantula Curve with all sizes between the upper and the lower limits (Figure 4.2.8a). From the Coarseness Factor Chart (Figure 4.2.8b), the mix located at the Zone II, which also meant well-graded aggregate. Interestingly, the mix became more workable although all coarse and fine aggregates were RCAs. The measured slump was approximately 1" (Figure 4.2.8c) and the overall surface void was between 10 and 30% (Figure 4.2.8d). It should be noted that the mix used similar proportions with a reduced W/Cm (0.45). As a result, the increase in workability was primarily due to the improvement in the aggregate gradation. One implication of this result was that as-is RCA (coarse plus fine) could be potentially used to 100% replace all NVAs in TDOT paving concrete when an ideal RCA gradation could be achieved during crushing.

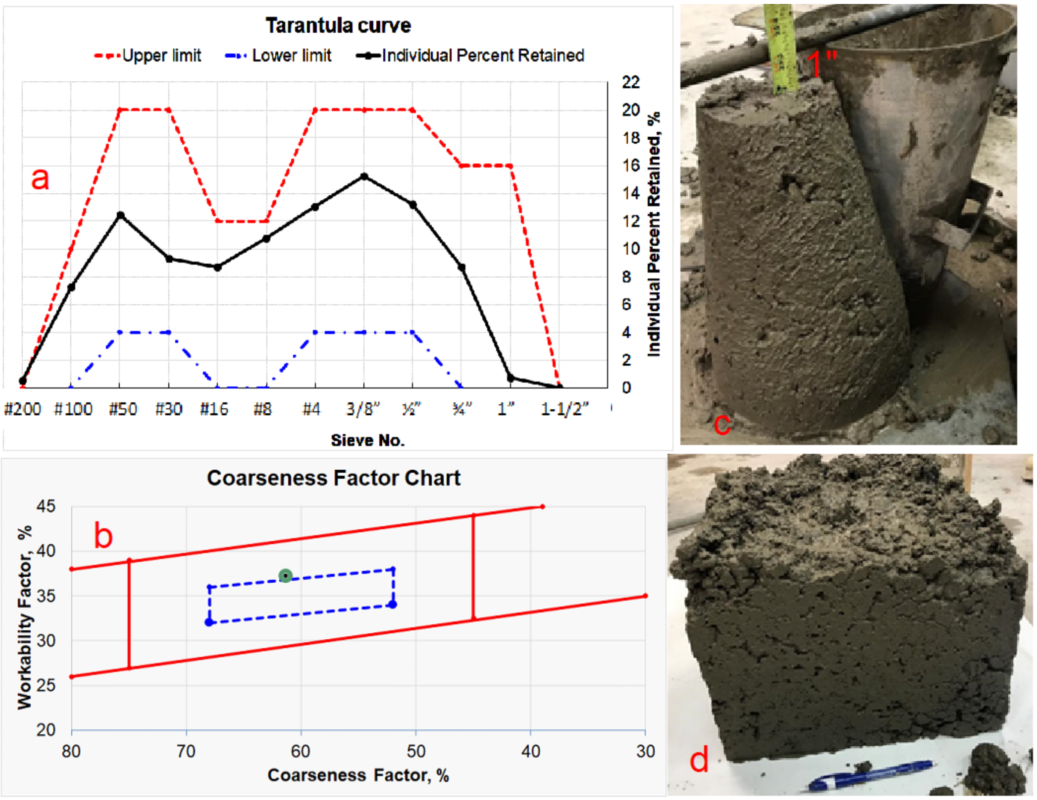


Figure 4.2.8 Aggregate Gradation and Workability of Concrete Mix with 100% Optimized I-440 RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

60% I-440 RCA (Coarse) + 40% Sand

The use of the coarse portion (retained on #8 sieve) of I-440 RCA to fully replace by volume the coarse NVAs in TDOT Class CP mix was investigated and the results are shown in Figure 4.2.9. Again, other materials and proportions kept same. The combined aggregate gradation was acceptable based on the Tarantula Curve (Figure 4.2.9a) because it was within the upper and the lower limits. However, the coarse sand particles (No. 8 to No. 30) looked relatively low. From the Coarseness Factor Chart (Figure 4.2.9b), the combined aggregate appeared at the Zone II suggesting well-gradation. Surprisingly, the concrete looked rocky and non-plastic, and responded poorly to both rodding in the slump test and the vibration during the box test. The measured slump was approximately ½" (Figure 4.2.9c) and the overall surface void was above 50% (Figure 4.2.9d). This again suggested that well gradation, particularly based on the Coarseness Factor Chart, did not always assure good workability. This might be associated with the lack of coarse sand particles (No.30 to No. 8) that were believed to affect the cohesion to the mix[63]. Another reason for this lean mix was that I-440 RCA was relatively small with the Nominal Maximum Size of Aggregate (NMSA) of ¾". In general, smaller aggregates had higher specific surface and demanded more pastes for workability. Without an increase in the paste content, the mix would become lean, and lack cohesiveness.

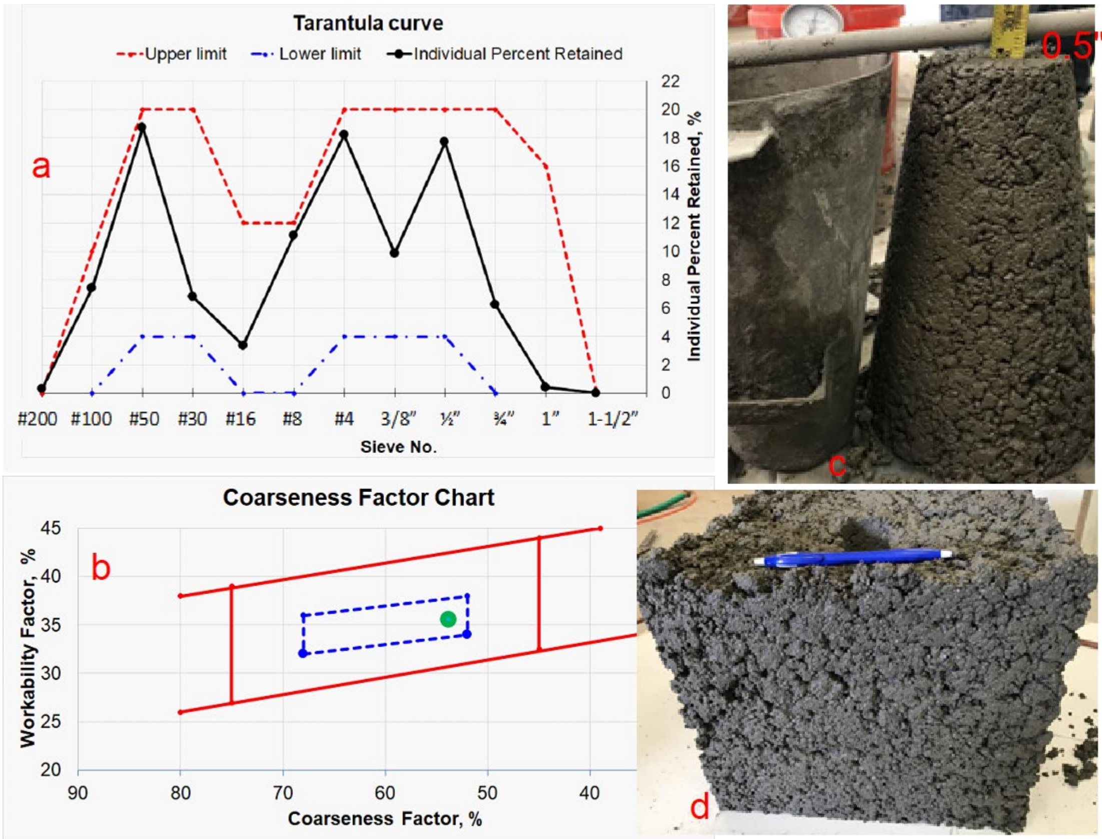


Figure 4.2.9 Aggregate Gradation and Workability of Concrete Mix with 60% Coarse I-440 RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

45% I-440 RCA (Coarse) + 20% #4 + 35% Sand

Since I-440 RCA (coarse) was comparatively small, a relatively larger aggregate (#4) was used to optimize its gradation. A combination of 45%vol I-440 RCA (coarse), 20%vol #4, and 35%vol river sand provided a good gradation as shown in Figure 4.2.10. The combined aggregates were well-graded based on both the Tarantula Curve (Figure 4.2.10a) and the Coarseness Factor Chart (Figure 4.2.10b). The coarseness factor was substantially increased due to the introduction of a larger coarse aggregate (#4), thus reducing the paste demand. An improved performance of concrete was achieved with a measured slump of approximately 1" (Figure 4.2.10c) and an overall surface void content of less than 10% (Figure 4.2.10d). No edge slump was observed. All these results suggested that this mix was suitable for the slipform paving.

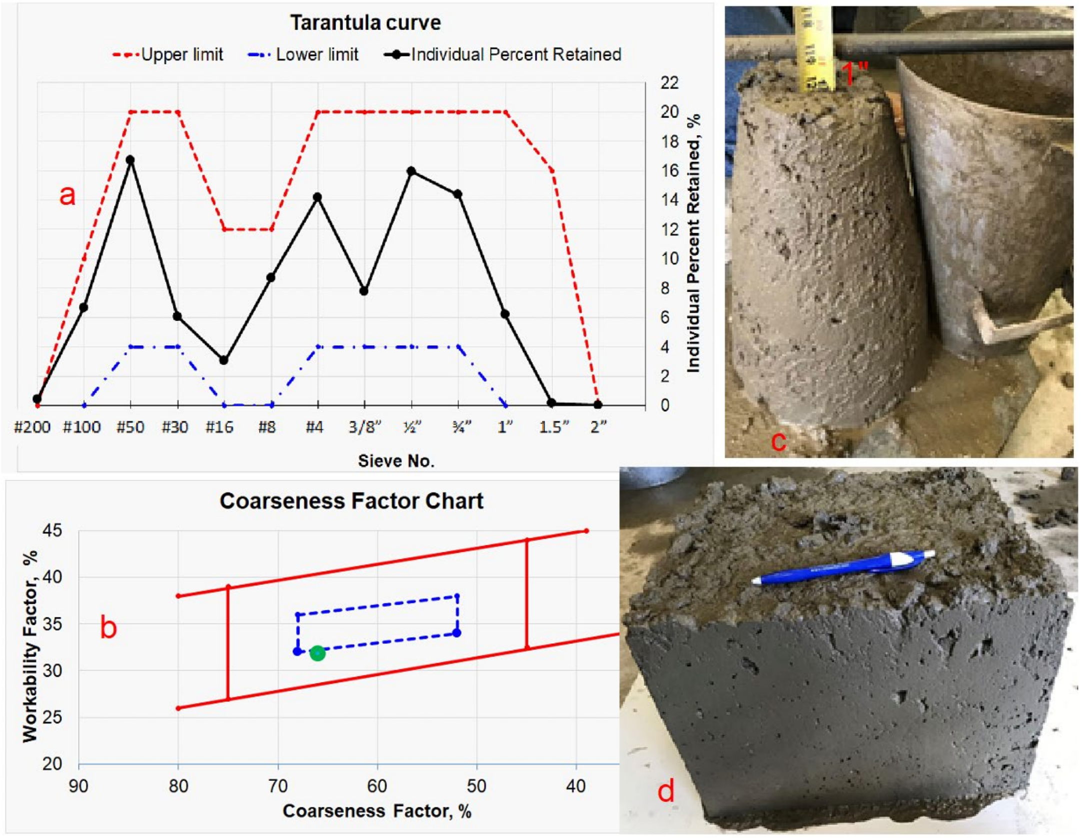
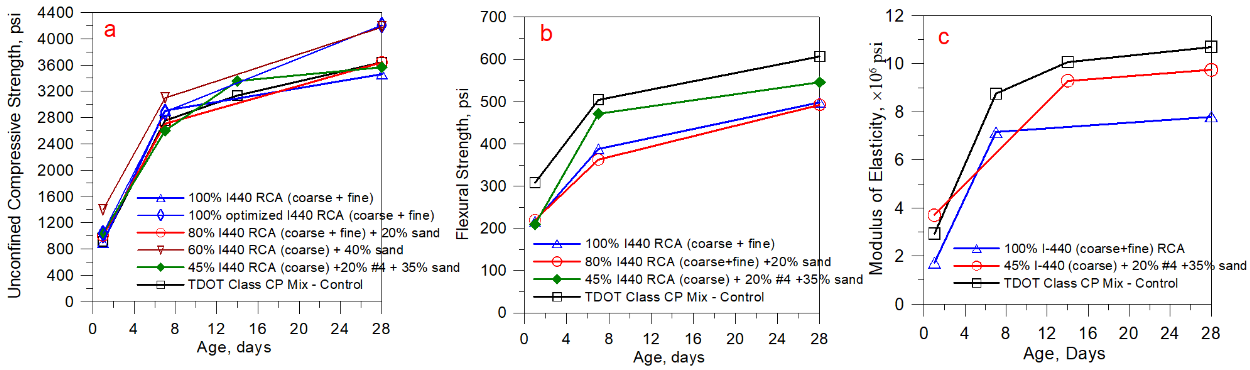


Figure 4.2.10 Aggregate Gradation and Workability of Concrete with 45% Coarse I-440 RCA and 20% #4 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

Compressive Strength, Flexural Strength, and Modulus of Elasticity of I-440 RCA Concrete Mixes

In general, using I-440 RCA to replace NVAs fully or partially did not significantly affect the compressive strength of concrete at all ages as shown in Figure 4.2.11a. This was because the I-440 RCA was made from a concrete pavement that had an average compressive strength of approximately 5300psi based on the cored samples before crushing. The uniform and strong concrete source led to a high-quality RCA, which was anticipated to have less effects on the compressive strength. Oppositely, using coarse I-440 RCA (60%vol of the total) slightly increased the compressive strength. One reason was that the I-440 RCA was relatively small with a NMSA of ¾", which aided in increasing the compressive strength of concrete although it reduced the workability. Interestingly, optimized I-440 RCA (coarse and fine) also demonstrated a higher compressive strength. This again suggested that both coarse and fine portions of RCAs could be potentially used in new paving concrete when RCAs had good quality and gradation.

The flexural strength (Figure 4.2.11b) and the modulus of elasticity (Figure 4.2.11c) of concrete using I-440 RCAs were reduced particularly at late ages (i.e., 7 and 28 days). Increasing levels of RCA replacement resulted in a decrease in the flexural strength and the modulus of elasticity. One reason was that RCAs typically contained some cracks mostly at the old interface (ITZ), which was also observed during the microscopic examination. These pre-existing cracks might have little effects on the compressive strength (compression tended to close the cracks) but might significantly affect the flexural strength (tension opened the cracks). These cracks might also weaken the concrete's ability to transfer loads, thereby reducing the modulus of elasticity.



(a) Compressive Strength **(b) Flexural Strength** **(c) Modulus of Elasticity**

Figure 4.2.11 Mechanical Properties of Concrete Mixes Using I-440 RCA

4.2.4 SC RCA Mix

60% SC RCA + 40% Sand

The results of using SC RCA to replace all coarse aggregates by volume (60%) in TDOT Class CP mix are given in Figure 4.2.12. The combined gradation of aggregates was almost acceptable based on the Tarantula Curve (Figure 4.2.12a) with particles retained on ½" and #200 sieves slightly exceeding the upper limits. It also appeared coarse, and gap graded based on the Coarseness Factor Chart (Figure 4.2.12b). This coarse and gap gradation negatively affected the workability of concrete. The mix had a measured slump of 1.5" (Figure 4.2.12c), which was acceptable for paving concrete, but it had a surface void content of 10 – 30% (Figure 4.2.12d) indicating its poor response to vibration. The mix also displayed an edge slump, meaning that it was not suitable for slipform paving.

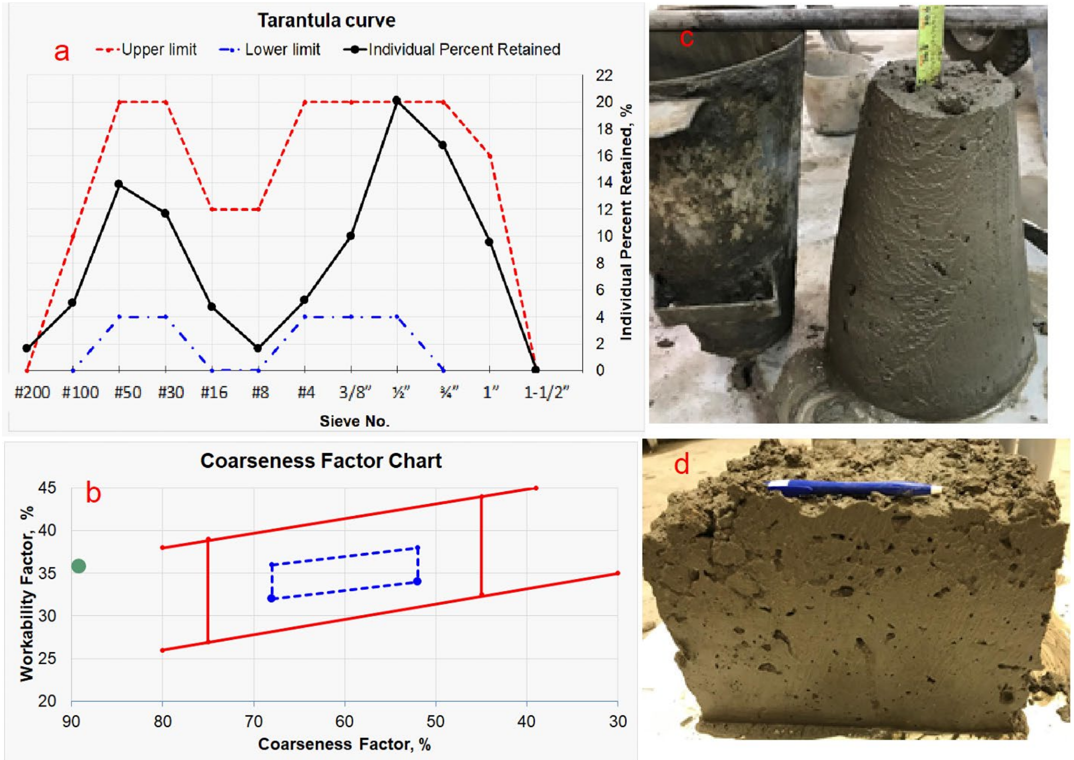


Figure 4.2.12 Aggregate Gradation and Workability of Concrete Mix with 60% SC RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

35% SC RCA + 25% #7 + 40% Sand

To improve the gradation of SC RCA, an intermediate aggregate (#7) was introduced to reduce the particles retained on ½" sieve as well as the coarseness of the mix. In this study, it was found that a combination of 35% SC RCA, 25% #7, and 40% sand demonstrated a better gradation. The results are illustrated in Figure 4.2.13. From the Tarantula Curve (Figure 4.2.13a), the individual percent retained on each sieve (except #200) was within the limits indicating good gradation. From the Coarseness Factor Chart (Figure 4.2.13b), the mix was in the optimum zone (Zone II) indicating again well gradation. The measured slump was 1"at a reduced W/Cm (0.05 reduction as compared with the 60% SC RCA mix above) (Figure 4.2.13c). More importantly, the mix had a better response to vibration with the surface void content of less than 10% (Figure 4.2.13d). The improved workability was attributed to the improved aggregate gradation that led to less voids between aggregate particles, thus minimizing the paste demand and increasing the workability. In addition, no edge slump occurred. Again, this was due to the improved aggregate gradation that increased the particle-to-particle contact, which helped to hold the edge. Another plausible reason was that #7 crushed limestone was relatively more angular that SC RCA. Introducing #7 aggregate into concrete increased the particle-to particle friction, which helped to control the edge slump. These results indicated that gap graded RCA could be used in new paving concrete when its gradation was improved through aggregate optimization.

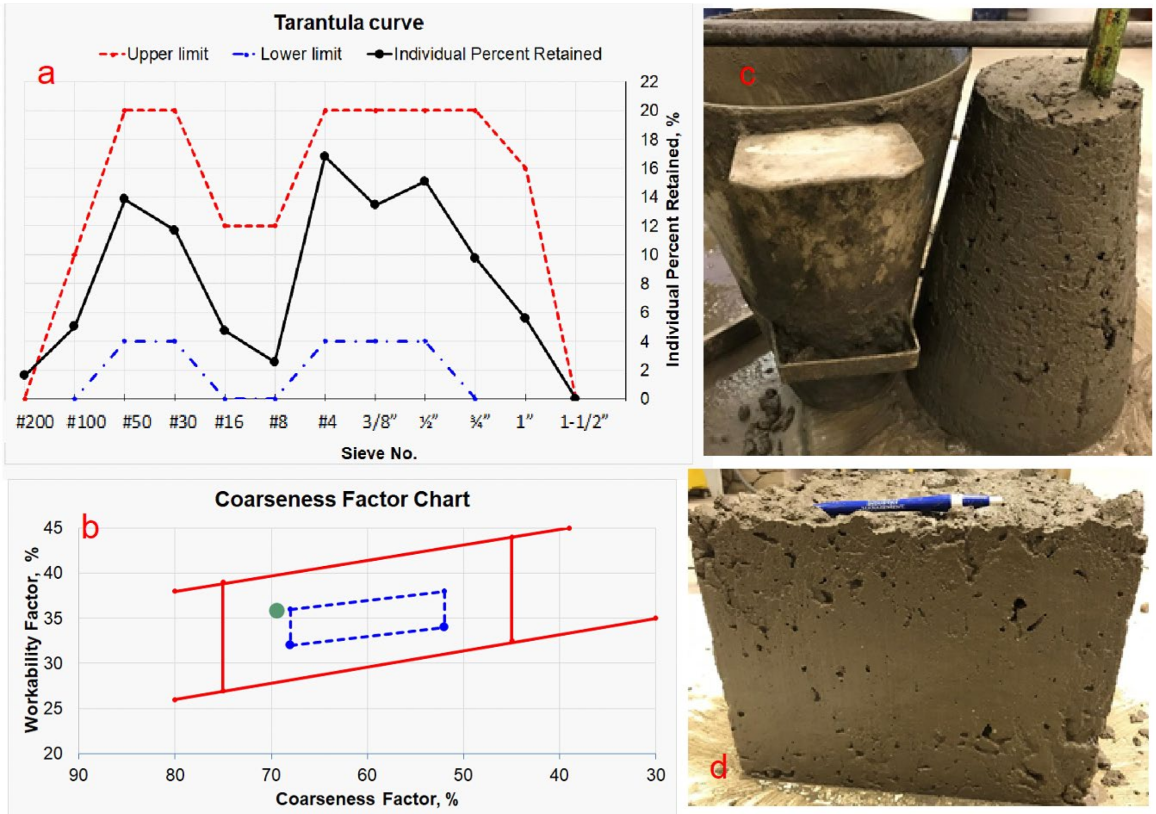


Figure 4.2.13 Aggregate Gradation and Workability of Concrete Mix with 35% SC RCA + 25% #7 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

45% SC RCA + 15% #7 + 40% Sand

In this project, different levels of SC RCA replacements were investigated to see how they affected the concrete properties. Figure 4.2.14 shows the results of the concrete mix that contained 45%vol SC RCA, 15%vol #7, and 40%vol sand. As compared with the optimized mix above, a lower percentage of intermediate #7 aggregate (15%) was incorporated. The combined aggregate was well-graded according to the Tarantula Curve (Figure 4.2.14a). The mix looked slightly coarse, and gap graded based on the Coarseness Factor Chart (Figure 4.2.14b). Its workability was not as good as that of the optimized mix. The measured slump was ¾" (Figure 4.2.14c), a slight edge slump occurred (Figure 4.2.14d), and a higher surface void content was observed. However, as compared with the mix that did not incorporate any #7 aggregate, it clearly demonstrated a better performance with a reduced edge slump and better cohesion.

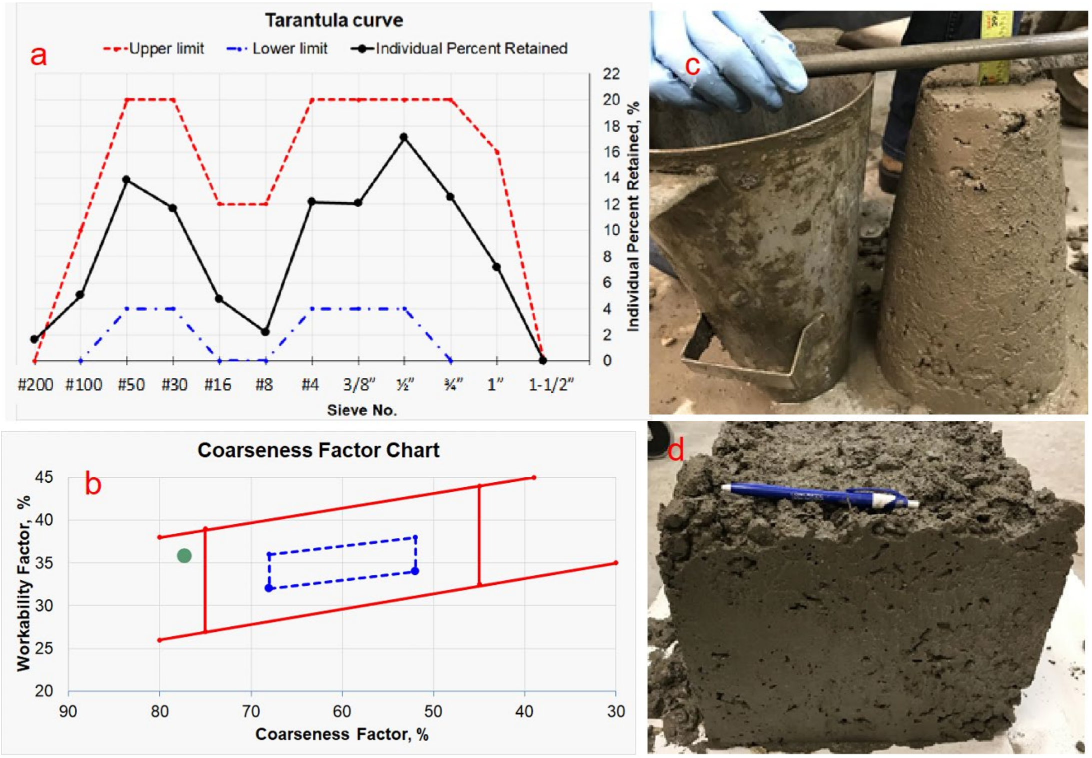


Figure 4.2.14 Aggregate Gradation and Workability of Concrete Mix with 45% SC RCA + 15% #7 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

25% SC RCA + 35% #7 + 40% Sand

Additionally, a lower level of SC RCA replacement (25%vol SC RCA, 35%vol #7, and 40%vol sand) was investigated and the results are provided in Figure 4.2.15. A combination of a high percentage of #7 and a low percentage of SC RCA increased the intermediate particles in the mix, causing gap gradation with excessive particles retained on #4 sieve (Figure 4.2.15a). Undoubtedly, this combination also reduced the coarseness of the mix (Figure 4.2.15b). With an increase in fine particles as well as gap-gradation of aggregates, the concrete mix would demand more paste/mortar. Without increasing the paste/mortar content, the mix would become rocky/lean, and a reduced workability can be anticipated. As compared with the optimized mix, the measured slump was reduced from 1" to ½" (Figure 4.2.15c) and the surface void content was increased from less than 10% to 10-30% (Figure 4.2.15d). Interestingly, no edge slump was seen after the form removal. This was again because #7 crushed stone were more angular than SC RCA, which aided in controlling the edge slump.

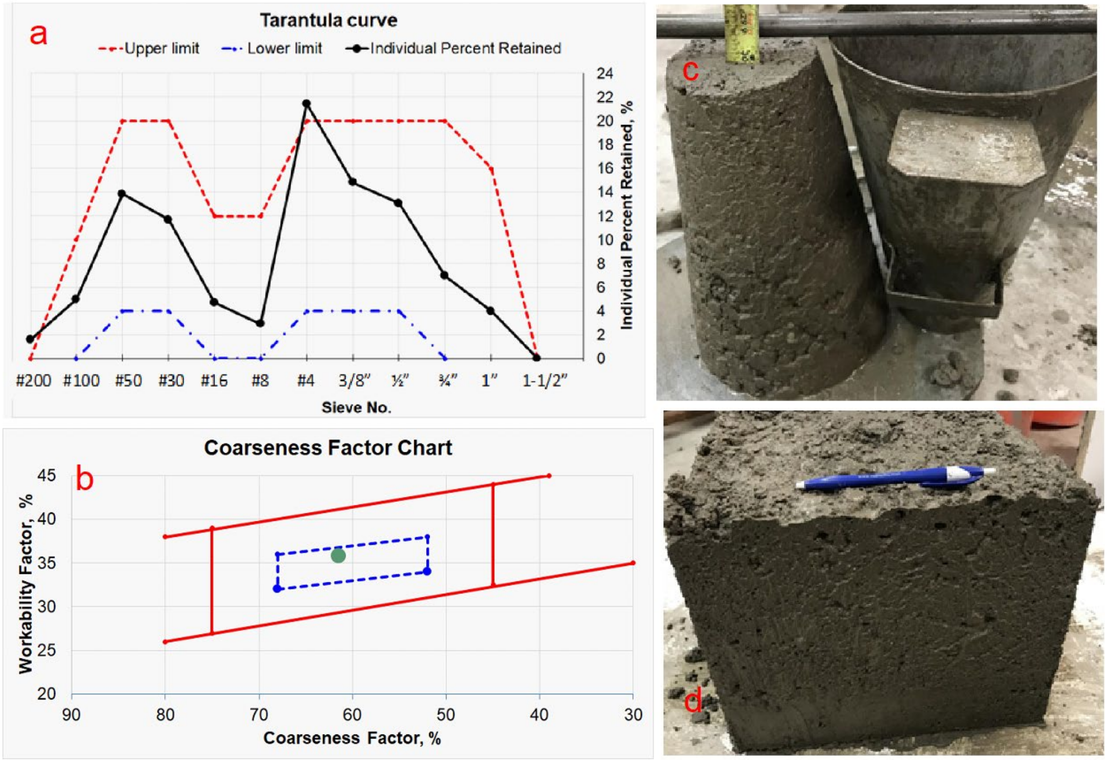


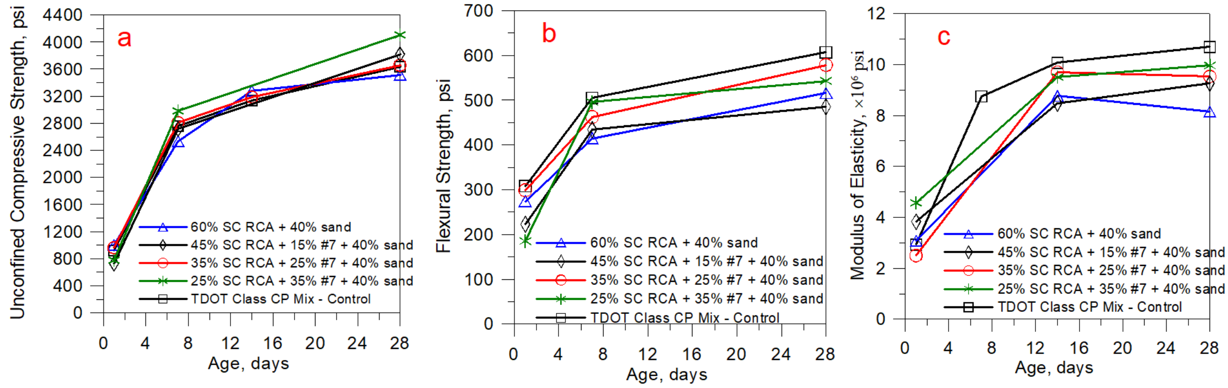
Figure 4.2.15 Aggregate Gradation and Workability of Concrete Mix with 25% SC RCA + 35% #7 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

It could be concluded that using SC RCA to fully replace the coarse NVAs in TDOT Class CP mix would reduce workability and cause edge slump. Using #7 crushed limestone to optimize the gradation of SC RCA facilitated the consolidation and controlled the edge slump.

Compressive Strength, Flexural Strength, and Modulus of Elasticity of SC RCA Concrete Mixes

The compressive strength development of concrete mixes incorporated different levels of SC RCA is shown in Figure 4.2.16a. Clearly, the replacement level of SC RCA in concrete did not significantly affect its compressive strength development. All SC RCA concrete mixes met the TDOT compressive strength requirement. One possible reason was that SC RCA mainly came from old structural concretes such as buildings, which was relatively consistent with a small percentage of weak particles (e.g., bricks and asphalt). Accordingly, it had small impacts on the compressive strength of concrete.

Conversely, using 60%vol SC RCA to replace the coarse aggregates in TDOT Class CP mix significantly reduced the flexural strength (Figure 4.2.16b) and the modulus of elasticity (Figure 4.2.16c) especially at late ages. Again, the main reason was that there were pre-existing cracks, which reduced the flexural strength of concrete. These cracks might also lower the concrete's ability to transfer loads, thus reducing the modulus of elasticity of concrete.



(a) Compressive Strength **(b) Flexural Strength** **(c) Modulus of Elasticity**

Figure 4.2.16 Mechanical Properties of Concrete Mixes Using SC RCA

4.2.5 SCP RCA Mix

60% SCP RCA + 40% Sand

Fully replacing the coarse aggregates by volume in TDOT Class CP mix with the coarse SCP RCA was studied in this project. Figure 4.2.17 illustrates its effects on the combined aggregate gradation and the workability of concrete. The combined aggregate was within the limits of the Tarantula Curve, suggesting well gradation (Figure 4.2.17a), however, it was relatively finer and contained a high percentage of particles retained on #4 and #50 sieves. From the Coarseness Factor Chart (Figure 4.2.17b), the mix was in the center of zone II, indicating that well-graded aggregate was achieved. Surprisingly, the mix exhibited low workability with a measured slump of ¾" (Figure 4.2.17c) and a surface void content of 10 to 30% (Figure 4.2.17d). This was again because SCP RCA (NMSA=3/4") was finer than the coarse aggregates in TDOT Class CP mix (NMSA=1.5"). Using a smaller SCP RCA to replace the larger NVAs would cause lower workability when the paste/mortar content was not increased.

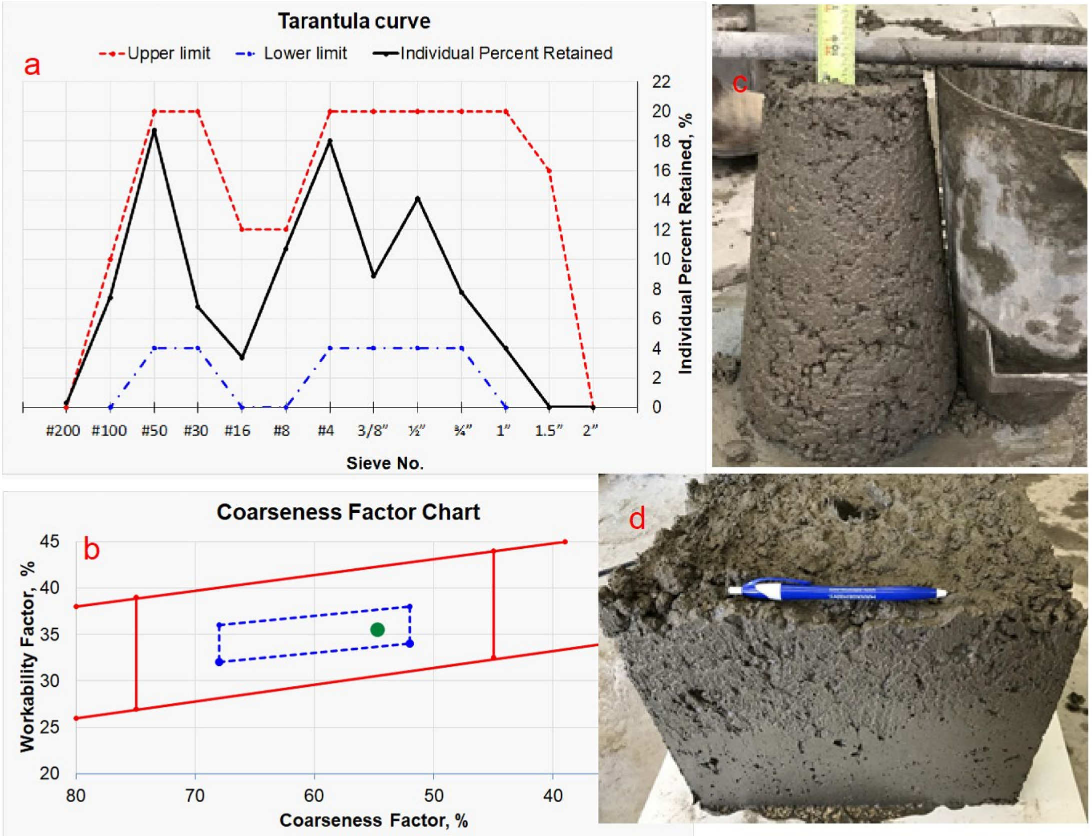


Figure 4.2.17 Aggregate Gradation and Workability of Concrete Mix with 60% SCP RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

45% SCP RCA + 20% #4 + 35% Sand

To increase the workability of SCP RCA mix, the #4 crushed limestone was incorporated to increase the coarseness of the mix. A combination of 45%vol SCP RCA, 20%vol #4 crushed limestone, and 35% river sand was observed to display a better performance (Figure 4.2.18). The combined aggregate gradation was within the limits of the Tarantula Curve (Figure 4.2.18a). The mix remained in zone II of the Coarseness Factor Chart (Figure 4.2.18b), but its coarseness was markedly increased. Expectedly, the workability of the mix was considerably improved with a measured slump of 1.25" (Figure 4.2.18c) and a surface void content of less than 10% (Figure 4.2.18d). No significant edge slump took place. All suggested that a workable SCP RCA concrete mix was achieved through aggregate optimization.

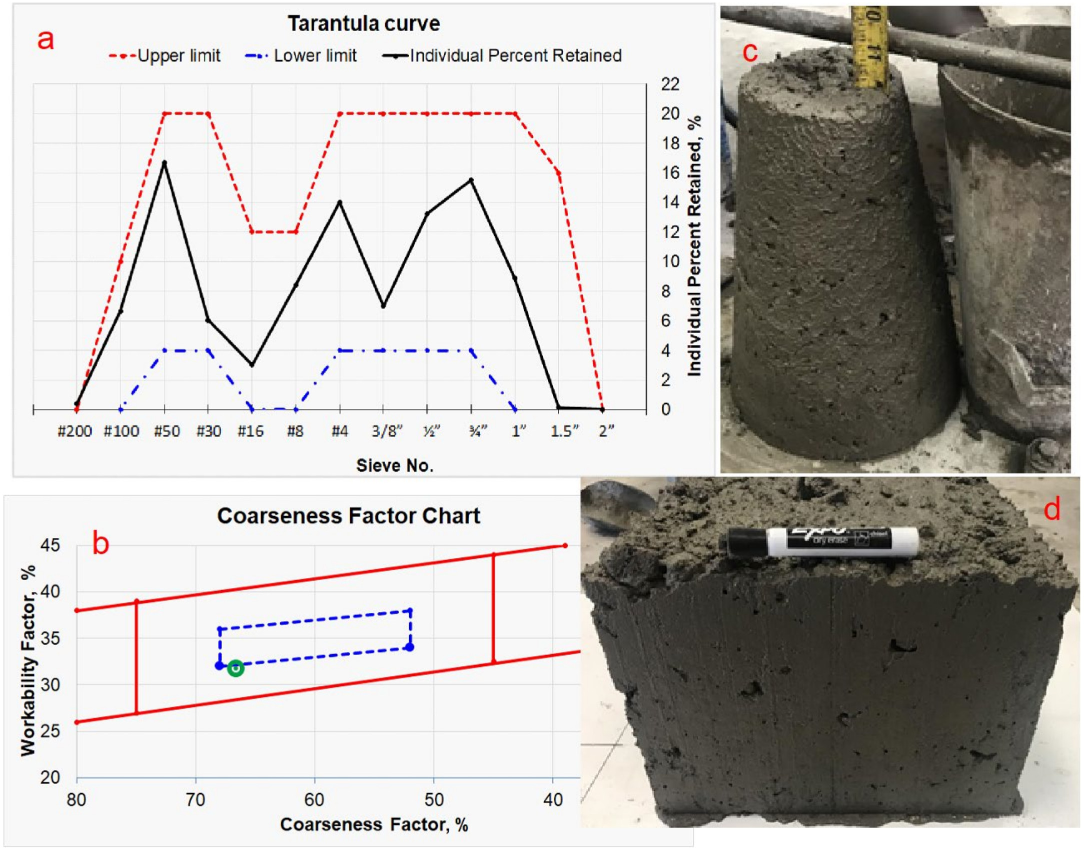
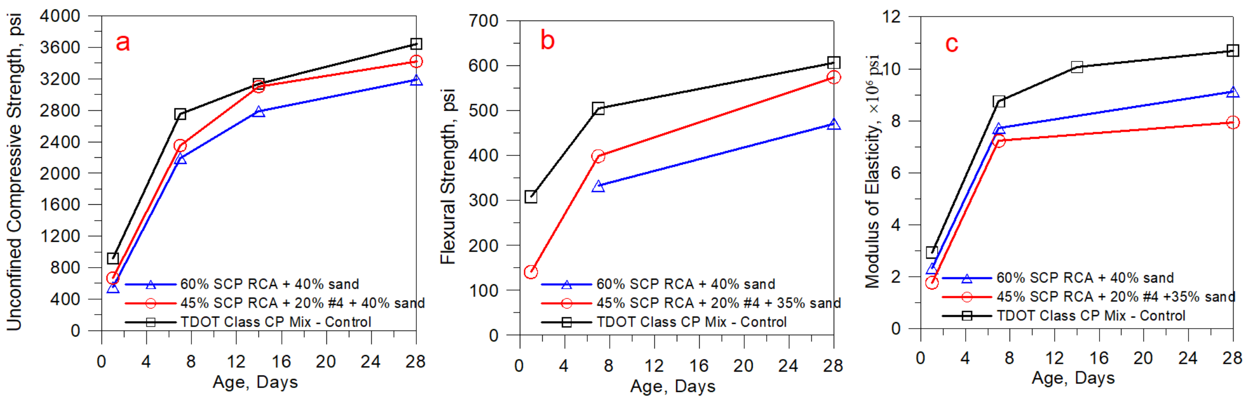


Figure 4.2.18 Aggregate Gradation and Workability of Concrete Mix with 45% SCP RCA + 20% #4 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

Compressive Strength, Flexural Strength, and Modulus of Elasticity of SCP RCA Concrete Mixes

SCP RCA reduced the compressive strength (Figure 4.2.19a), the flexural strength (Figure 4.2.19b), and the modulus of elasticity (Figure 4.2.19c) of concrete particularly at a late age. The primary reason was that SCP RCA contained weak adhered paste as well as soft asphalt particles that weakened the concrete. As described in previous sections, SCP RCA primarily came from the returned concrete. Additional water might be added during the recycling, leading to unsound paste. This also agreed with the results from other tests such as excessively high absorption (11.9%) and LA abrasion loss (38.4%), which could be associated with porous adhered pastes due to high W/Cm. In addition, the reduction in the flexural strength and the modulus of elasticity of concrete was more pronounced as compared with that of the compressive strength. This was again due to the pre-existing cracks that had more negative impacts on flexural strength and the modulus of concrete. It should be mentioned that the compressive strength of SCP RCA concrete at 28 days was still above 3000psi, which satisfied the TDOT specification for paving concrete.



(a) Compressive Strength **(b) Flexural Strength** **(c) Modulus of Elasticity**

Figure 4.2.19 Mechanical Properties of Concrete Mixes Using SCP RCA

4.2.6 HC RCA Mix

60% HC RCA + 40% sand

Using HC RCA to replace the coarse NVAs (60% vol.) in TDOT Class CP mix was studied and its effects on the combined aggregate gradation and the workability of concrete are displayed in Figure 4.2.20. From the Tarantula Curve (Figure 4.2.20a), the combined aggregate was gap graded with excessive particles retained on ½" sieve. From the Coarseness Factor Chart (Figure 4.2.20b), the mix was in Zone 1, which meant that aggregates were gap-graded with excessive coarseness. However, the mix demonstrated excellent workability with a slump of 1" (Figure 4.2.20c) and a surface void content of less than 10% (Figure 4.2.20d). This suggested that some gap-graded RCAs could be successfully used to achieve a workable paving concrete.

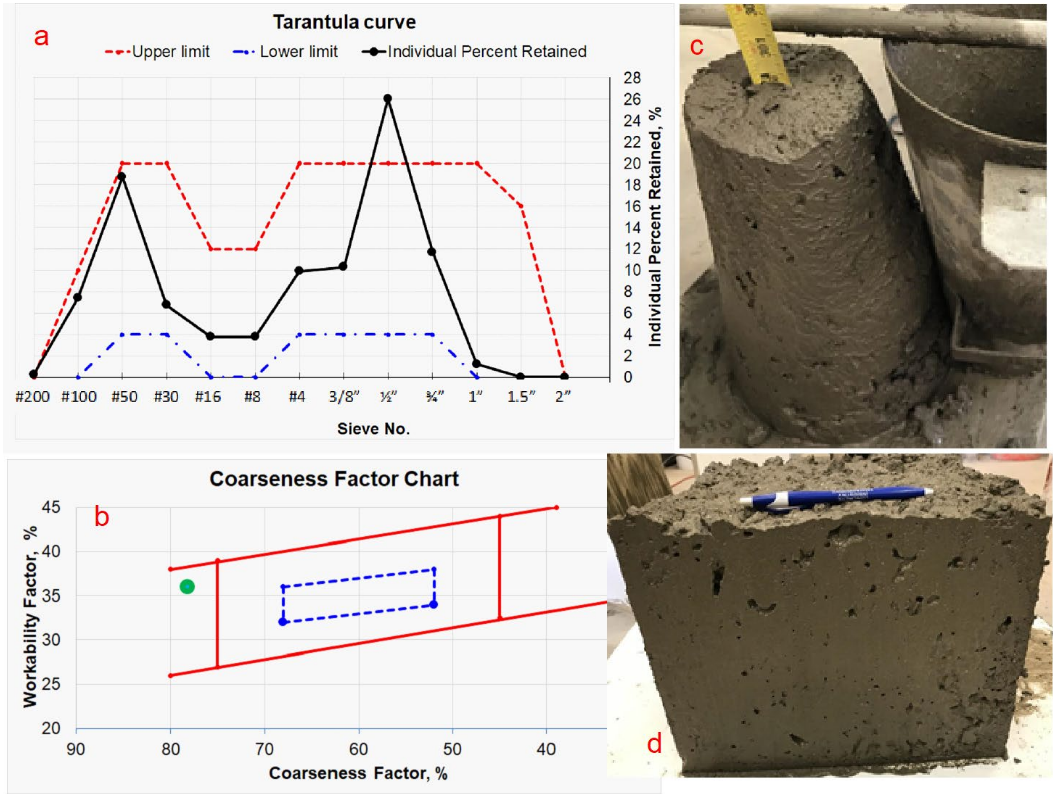


Figure 4.2.20 Aggregate Gradation and Workability of Concrete Mix with 60% HC RCA (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

40% HC RCA + 20% #7

Similarly, an intermediate crushed limestone (#7) was introduced to optimize the gradation of HC RCA and to reduce the coarseness of the mix. In this study, using 20%vol of #7 was found to achieve a better gradation by effectively reducing the particles retained on ½" sieve. The detailed results are shown in Figure 4.2.21. The individual percent retained was within the limits (Figure 4.2.21a), and the mix was in the center box of Zone II (Figure 4.2.21b). All indicated that well-graded aggregate was achieved. However, this optimized aggregate led to less workable concrete. The mix looked slightly rocky and less plastic. Although the measured slump of fresh concrete was same (1") (Figure 4.2.21c), but the surface void content increased to 10-30% (Figure 4.2.21d). This again implied that well-graded aggregate did not always secure good workability. One of the reasons for this reduced workability could be that adding #7 to partially replace a coarser aggregate would demand more paste/mortar for workability.

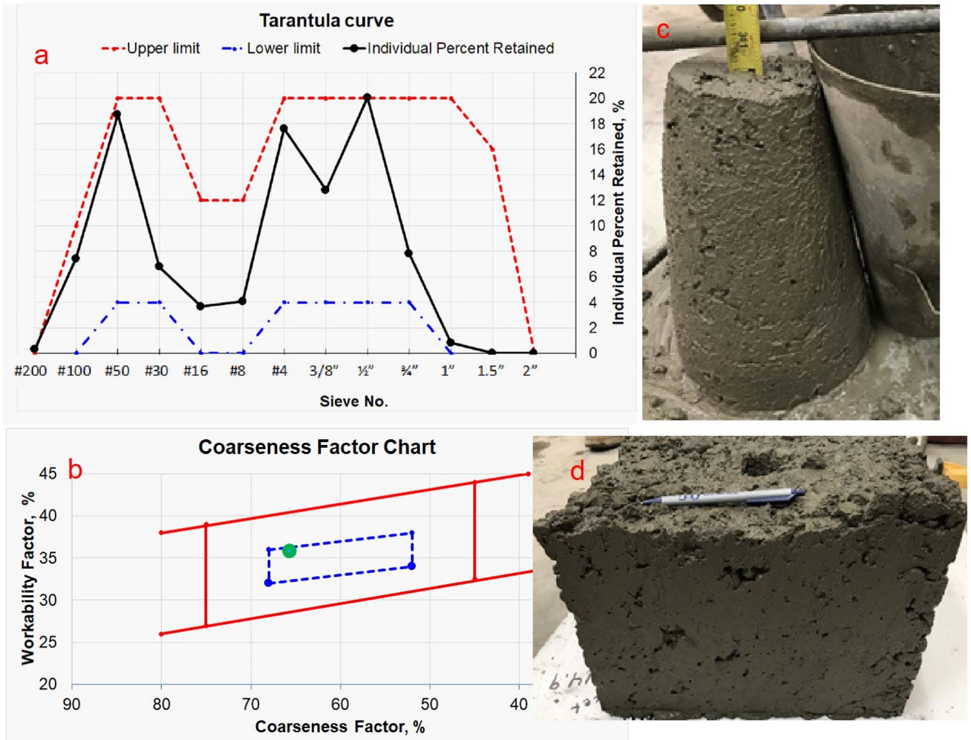
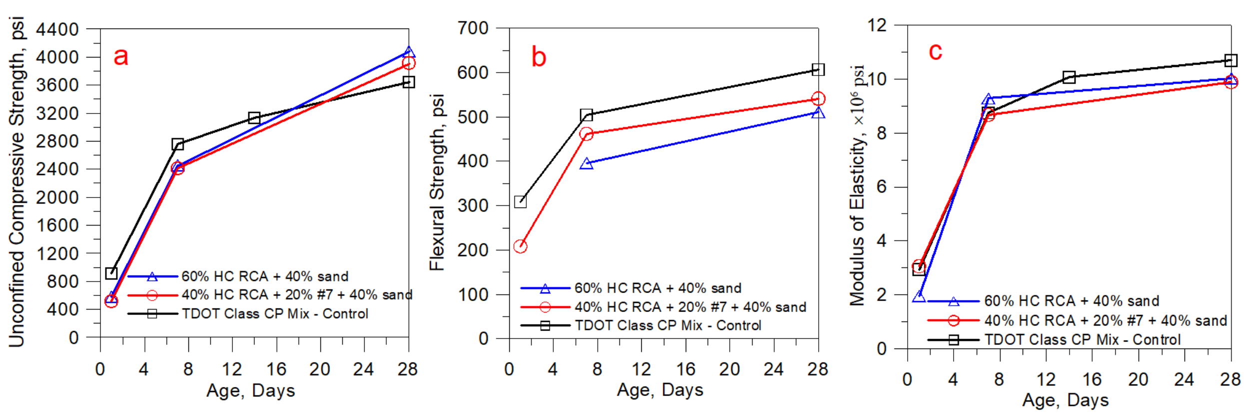


Figure 4.2.21 Aggregate Gradation and Workability of Concrete Mix with 40% HC RCA + 20% #7 (a) Tarantula Curve, (b) Coarseness Factor Chart, (c) Slump Test, and (d) Box Test

<u>*Compressive Strength, Flexural Strength, and Modulus of Elasticity of HC RCA Concrete Mixes*</u>

Coarse HC RCA had insignificant impacts on the compressive strength of TDOT paving concrete as shown in Figure 4.2.22a. Again, the reason was that HC RCA was mainly crushed from the demolished structural concrete, which was relatively strong. However, HC RCA clearly reduced the flexural strength (Figure 4.2.22b) and the modulus of elasticity (Figure 4.2.22a) of concrete. Again, this could be associated with the pre-existing cracking. It could be noted that the 28-day compressive strength of concrete using HC RCA was well above 3000psi, which met the TDOT specification for paving concrete.



(a) Compressive Strength (b) Flexural Strength (c) Modulus of Elasticity

Figure 4.2.22 Mechanical Properties of Concrete Mixes Using HC RCA

It could be concluded that all RCAs collected in this study could be successfully used to replace NVAs fully or partially in TDOT Class CP mix with adequate workability and acceptable 28-day compressive strength. In most cases, optimized RCA gradation based on the Tarantula Curve and the Coarseness Factor Chart aided in improving the workability of fresh concrete, however, it sometimes led to less workable concrete.

4.3 Fresh Property Evaluation of RCA Concrete Mixes

4.3.1 Effects of RCA on Unit Weight of Concrete

In general, using RCAs to replace NVAs in TDOT Class CP mix slightly reduced the unit weight of fresh concrete as shown in Figure 4.3.1. This was because RCAs were typically lighter than NVAs due to the adhered paste. The average specific gravity of RCAs in this study was 2.37, which was approximately 10% lower than that of the crushed limestone (2.66). The decrease in the unit weight related to the type, the replacement rate, and the moisture level of RCAs. The SCP RCA that had the lowest specific gravity (2.28) exhibited the highest drop in the unit weight. With an increase in the RCA replacement rate in concrete or a decrease in the moisture content of RCA, the unit weight of concrete also decreased. It should be noted that all concrete mixes in Figure 4.3.1 had similar materials and proportions except aggregates. The change in unit weight of concrete was primarily due to the variation of RCAs.

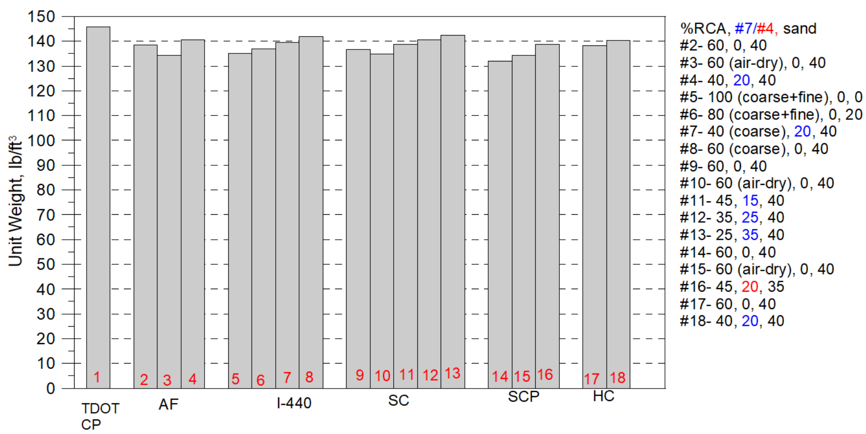


Figure 4.3.1 Effects of RCA Type, Replacement Rate, and Moisture Level on Unit Weight of Concrete

4.3.2 Effects of RCA on Fresh Air Measurement

The fresh air content of concrete mixes was measured using both the pressure method and the volumetric method. The results are shown in Figure 4.3.2. For the control mix (TDOT Class CP) with NVAs, the fresh air content measured by both methods was nearly equal, indicating that the NVAs had little effects on the fresh air measurement and both methods were equally applicable. However, in RCA concrete mixes, the fresh air measured by the pressure method was higher than that by the volumetric method. This was reasonable because typical RCA particles consisted of adhered paste that contained air voids. These air voids were likely to respond to the applied pressure through the interconnected pore system and thus could be included in the pressure method measurement. However, the rolling and shaking motion in the volumetric method was unable to break the solid RCA particles, and thus the air voids within the RCA particles could not be measured by the volumetric method. This also agreed with the microscopic observation in this study. The average air content in RCA particles was approximately 1.63% (Table 4.1). Its contribution to the fresh air content by the pressure method would be approximately 1% if the fresh concrete averagely consisted of 60%vol of RCA. The average fresh air content of all RCA mixes was approximately 5.9% by the pressure method, and approximately 4.4% by the volumetric method. The difference of fresh air content between the two methods was 1.5%, which was reasonably close to 1%. It should be noted that the air content in RCA particles was based on a limited number of specimens and some RCAs had inconsistent quality, all of which could affect the accuracy of air content evaluation in RCA particles. The practical implication was that both the pressure and the volumetric methods were applicable to the RCA concrete mixes. The pressure method would measure all air in the new fresh paste as well as some or potentially all air in the adhered hardened paste provided that the original aggregates in RCAs were dense. In contrast, the volumetric method only measured the air in the new fresh paste exclusive of any air in the adhered hardened paste. It should be noted that all RCAs for the fresh air measurement were pre-soaked for at least 48 hours before mixing and thus the effects of RCA absorption on the fresh air evaluation would be negligible, however, the pre-soaking might partially saturate some air voids in the adhered paste, which might affect the measurement by the pressure method.

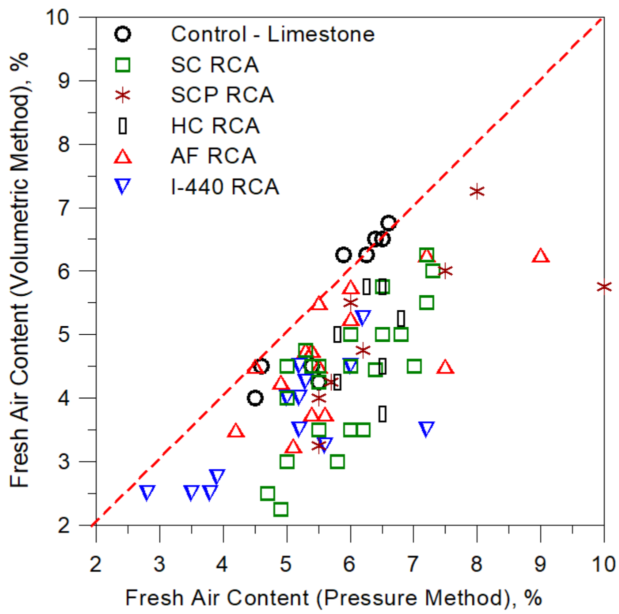


Figure 4.3.2 Effects of RCA on Fresh Air Measurement

4.3.3 Effects of RCA Absorption on Slump Loss and Strength of Concrete

All RCAs collected in this study exhibited high water absorption. Pre-soaking RCA before mixing was performed in this study to avoid absorption-related problems such as rapid slump and air losses. However, this practice might be impractical in some field projects where RCA was directly recycled and used on site. The use of as-is RCA would require mixing water adjustment to compensate for high absorption. If all absorption water was added after the cementitious materials during mixing, the mixture became very flowable, which disturbed the air entrainment and caused segregation. In this study, different water addition procedures (one-time, two-time, and multi-stage water addition) were investigated using oven-dry and air-dry SC RCAs, and the results are summarized in the following sections.

In the one-time water addition procedure, all water was introduced at one time during the initial mixing after the RCA and the cementitious materials were added into the mixer. Immediately after the mixing, the slump was measured and recorded. Then, the slump was measured at a certain time interval for approximately 3.5 hours. After each slump test, the concrete was returned to the mixer. Right prior to the next measurement, the concrete was re-mixed for approximately 45 seconds. The slump change with time due to the RCA absorption is shown in Figure 4.3.3a. Due to excessive free water in the mix, the concrete displayed high initial slump (5.5" for air-dry RCA and 7" for oven-dry RCA). Aggregate-paste separation occurred in the oven-dry RCA concrete for more than 30 minutes. The slump measurements were also shown in the supplementary documents of this report (A).

A multi-stage water addition procedure was also performed. In this procedure, 80% of mixing water was added during the initial mixing after the aggregates and the cementitious materials were added into the mixer. This would achieve an initial slump of approximately ½" to 2" depending on the moisture levels of RCA. The remaining 20% of mixing water was added to the mix at different times to maintain this slump as illustrated in Figure 4.3.3b. Since the concrete retained almost a constant low slump during testing, no segregation occurred. The Air-Entraining Admixture (AEA) was added at the end of testing to easily target the desirable air content. If the AEA was added earlier, excessive air gain or loss could occur due to the free water variation in concrete and the continued mixing operation. The slump measurements were also shown in the supplementary documents of this report (A).

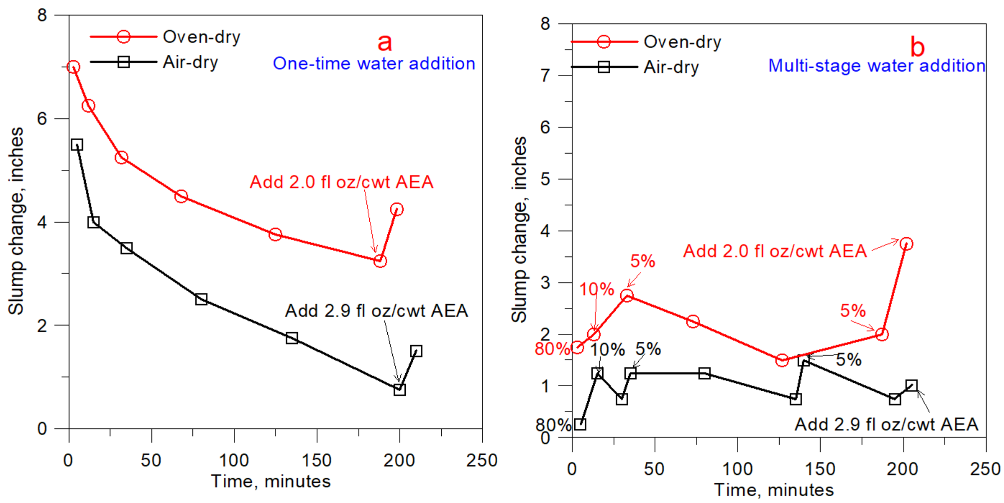


Figure 4.3.3 Effects of SC RCA Absorption on Slump Change of Fresh Concrete

In addition, a two-time water addition procedure was investigated in this study, in which 80% of the mixing water was first added with the RCA and pre-mixed for approximately 2 minutes. This allowed the RCA particles to rapidly absorb some water, which slowed down the water absorption later from the fresh concrete. Then, the cementitious materials were introduced together with the remaining 20% of mixing water and AEA. Immediately after mixing, the slump of concrete was measured with a value of 1.25". The slump was measured again after 10 minutes, and no significant change was observed. No segregation occurred during mixing and testing. This suggested that after the 2-minutes pre-soaking, the water absorption of RCA from the fresh concrete was very slow, which was close to that of NVA. This was not surprising because oven-dry SC RCA could reach its 50% saturation level in just 1 minute, and 70% saturation level in 10 to 15 minutes (Figure 4.3.4). Obviously, this procedure was simple and easy to perform, and thus highly recommended for future TDOT applications.

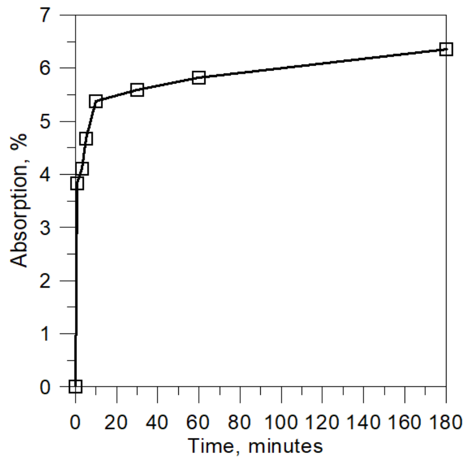
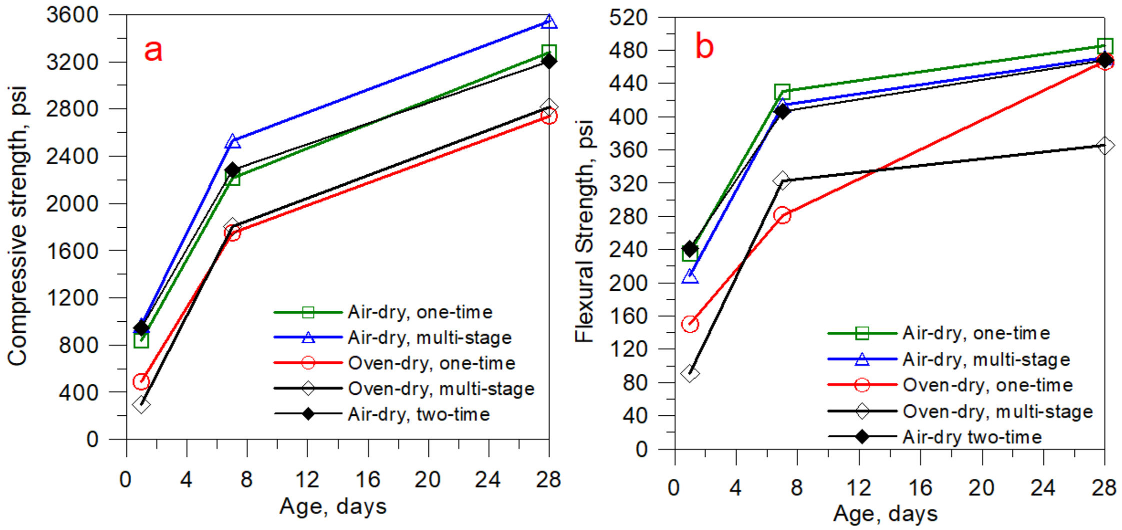


Figure 4.3.4 Absorption of Oven-Dry SC RCA with Time

The compressive strength of concrete using the dry SC RCA varied significantly with the moisture state of RCA and the mixing water addition sequence as shown in Figure 4.3.5. It should be noted that all mixes used the same materials and proportions. The only differences were the moisture state of RCA and the sequence of water addition. Oven-dry SC RCA demonstrated the lowest compressive strength development particularly using one-time water addition (Figure 4.3.5a). This was because for oven-dry SC RCA, a large amount of additional water was added to compensate for the high absorption of oven-dry RCA, however, absorption was gradual especially at a later age. Consequently, some absorption water would remain in the hardened concrete, thus weakening the concrete. Another reason could be that high temperature oven-dry might induce damage in RCA particles due to excessive expansion, contraction (upon cooling), or shrinkage (moisture loss) within the particles, leading to a weak concrete. In contrast, air-dry RCA required less additional water to adjust its absorption. There would be less water remained in hardened concrete, and thus less reduction in the compressive strength. Similarly, the flexural strength development of RCA concrete was also affected (Figure 4.3.5b). Oven-dry RCA exhibited lower flexural strength. This again could be attributed to the excessive absorption water that remained in concrete and weakened the concrete.



(a) Compressive Strength **(b) Flexural Strength**

Figure 4.3.5 Effects of SC RCA Moisture Conditions and Water Addition Sequence on Strength Development of Concrete

4.3.4 Effects of RCA on Setting of Concrete

The use of RCAs in TDOT Class CP mix affected the setting of concrete particularly the final setting. Figure 4.3.6 illustrates the change of penetration resistance with time for different concrete mixes that used different types and percentages of RCAs. The initial setting time was specified as the time at which the penetration resistance reached 500 psi; while the time when the penetration resistance approached 4000 psi was defined as the final setting time. As compared with the control mix, the initial setting time decreased by a maximum of approximately 100 minutes, and the final setting time was reduced by approximately 90 minutes. This was because RCAs contained residual alkali, which accelerated the setting of concrete. For examples, I-440 RCA that had a higher pH value of 12.23 exhibited faster setting, while slower setting was observed in concrete with the AF RCA that had a lower pH value of 10.33. The practical implication was that freshly crushed RCA should be used with cautions as it could accelerate the setting of concrete.

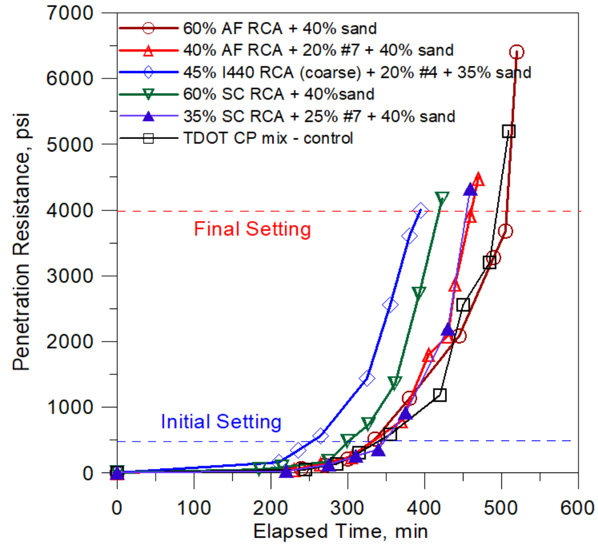


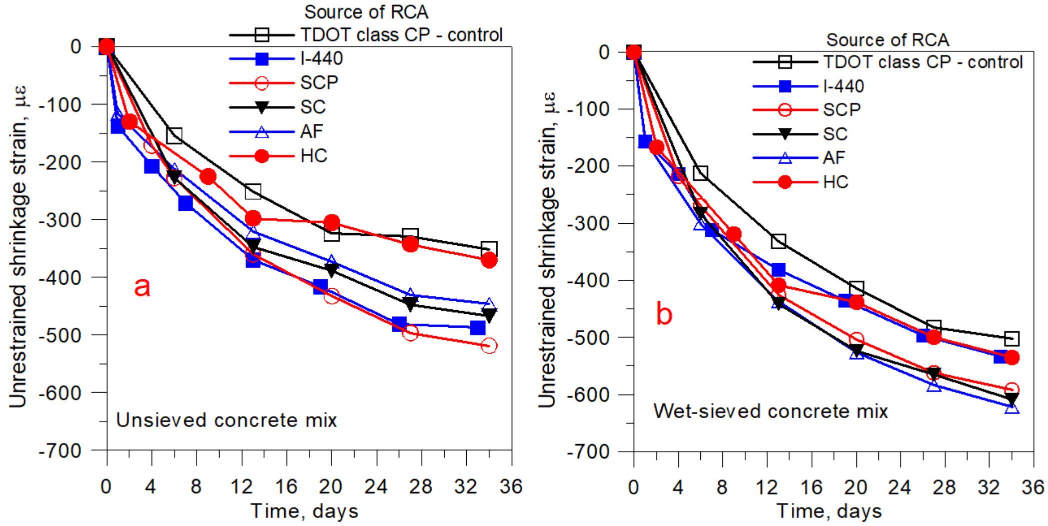
Figure 4.3.6 Effects of RCAs on Setting of Concrete

4.4 Dry Shrinkage and Cracking Evaluation of RCA Concrete Mixes

Concrete would shrink when it was exposed to a dry environment due to moisture loss. Typically, paving concrete slab was restrained by the substrate, causing tensile stress to develop in concrete pavements. The magnitude of stress could be estimated as the product of the restrained shrinkage strain and the modulus of elasticity of concrete. On the other hand, some of this stress could be relaxed as concrete creeped under sustained loading. However, when the residual stress after relaxation exceeded the tensile strength of concrete, shrinkage cracking would take place. Accordingly, factors that influence the shrinkage cracking would include restrained shrinkage strain, modulus of elasticity, creep, and tensile strength of concrete. To reduce the risk of shrinkage cracking, it was always desirable for a paving concrete to have low shrinkage, low modulus of elasticity, high tensile strength, and high creep.

4.4.1 Effect of RCA on Free Shrinkage of Concrete

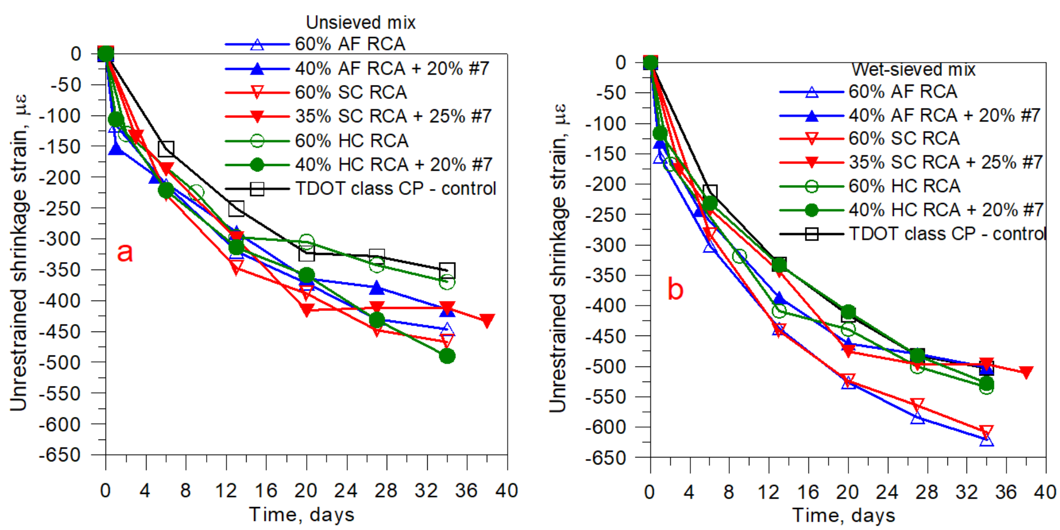
Figure 4.4.1 presents the free (unrestrained) shrinkage development as a function of time for concrete mixes with different types of RCAs. Again, all mixes had the same materials and proportions except the types of coarse aggregate (60% of total aggregate by volume). Also, the shrinkage measurement was conducted on both un-sieved and wet-sieved concretes. The reason of measuring wet-sieved concrete shrinkage was to agree with the restrained shrinkage ring test, in which the maximum aggregate size was ½”. It was evident that all RCAs increased the free shrinkage strain of concrete mixes. This was because the dry shrinkage primarily took place in the paste of concrete and the total paste content of RCA concrete (adhered plus new) was higher than that of NVA concrete. For un-sieved concrete mixes (Figure 4.4.1a), the free shrinkage strain at 28 days increased by 5% (HC RCA) to 51% (SCP RCA). The high free shrinkage of SCP RCA concrete could be attributed to the high porous paste adhered in SCP RCA particles. It should be noted that the maximum 28-day shrinkage of all RCA concretes in Figure 4.4.1a was approximately 500 micro-strain (με) (0.05%), which was still below the limit (0.06%) specified by TDOT for paving concrete. For wet-sieved concrete mixes (Figure 4.4.1b), an increase of 4% (HC RCA) to 23% (AF RCA) in the free shrinkage strain was observed. In addition, the wet-sieved concrete had higher shrinkage than the un-sieved concrete because there was more paste in the wet-sieved concrete.



(a) Un-sieved Concrete Mix **(b) Wet-sieved Concrete Mix**

Figure 4.4.1 Effect of RCA Source on Free Shrinkage of Concrete

Reducing RCA replacement rate from 60% to 40% or 35% in TDOT paving concrete was seen to slightly reduce the free shrinkage of concrete (Figure 4.4.2). This was owing to the reduction in the adhered paste content as RCA was reduced. For un-sieved concrete mixes (Figure 4.4.2a), the shrinkage was reduced by approximately 4 to 10%. However, concrete with HC RCA showed the opposite trend, in which reducing HC RCA from 60% to 40% increased the shrinkage of concrete. This was unreasonable possibly owing to the inconsistent quality of HC RCA as it contained relatively high amounts of external particles such as masonry unit, brick, and asphalt. For wet-sieved concrete mixes (Figure 4.4.2b), the free shrinkage strain was reduced by 0.1% to 17%. Again, the wet-sieved concrete mixes exhibited higher free shrinkage than the un-sieved concrete mixes.



(a) Un-sieved Concrete Mix **(b) Wet-sieved Concrete Mix**

Figure 4.4.2 Effect of RCA Replacement Rate on Free Shrinkage of Concrete

Figure 4.4.3 presents the results of how different I-440 RCA replacement rates affected the free shrinkage of TDOT paving concrete. Using as-is I-440 RCA that consisted of both coarse and fine particles to replace all NVA aggregates (100% by volume) in TDOT paving concrete dramatically increased the shrinkage with the 28-day free shrinkage strain of 805 με (0.0805%) for the un-sieved concrete and 1040 με (0.104%) for the wet-sieved concrete respectively. As compared with the control mix, the free shrinkage strain increased by 144% for the un-sieved mix and 117% for the sieved mix. This drastic increase in the free shrinkage was mainly attributed to the fine RCA that contained a large percentage of reclaimed paste. Concrete with 80% I-440 RCA (as-is) and 20% river sand had a 28-day free shrinkage strain of 675 με (0.0675%) for un-sieved concrete and 840 με (0.0840%) for sieved concrete. Obviously, reducing I-440 RCA (as-is) from 100% to 80% significantly reduced the free shrinkage of concrete. Similarly, further reducing I-440 RCA from 80% (as-is) to 60% (coarse only) considerably lowered the free shrinkage of concrete. Clearly, this substantial decrease in shrinkage was owing to the reduction in reclaimed paste in the new concrete mix.

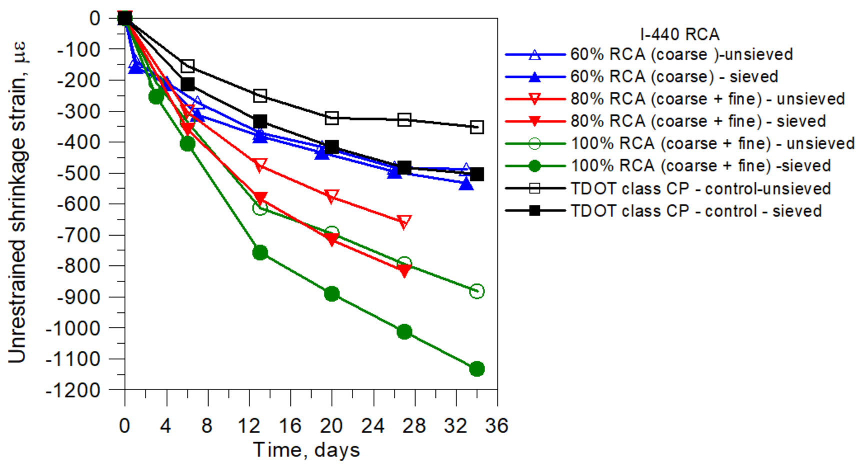


Figure 4.4.3 Effect of I-440 RCA Replacement Rate on Free Shrinkage of Concrete

4.4.2 Effect of RCA on Restrained Shrinkage Cracking

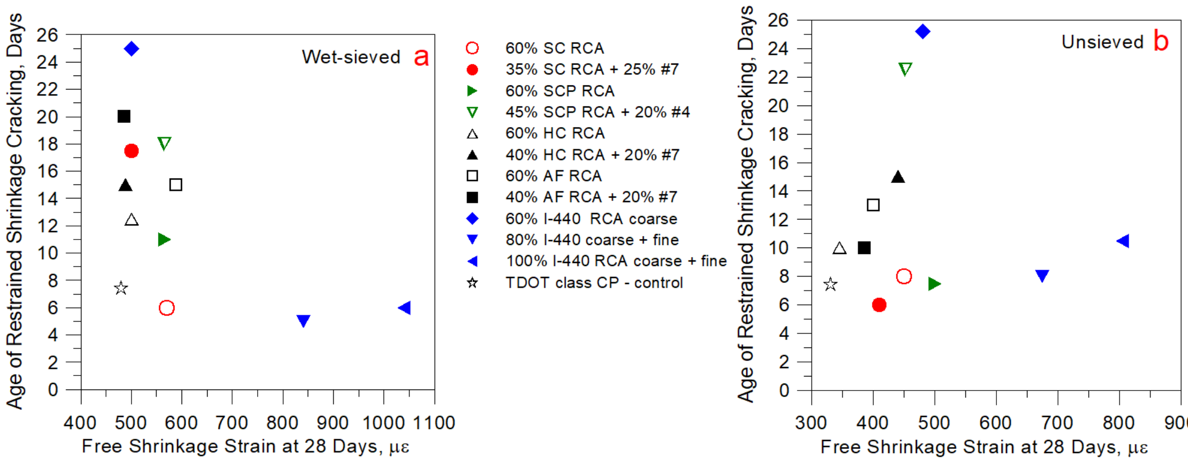
The restrained shrinkage ring test was conducted on both wet-sieved and un-sieved concrete mixes. The wet-sieving was performed to remove aggregate particles that were greater than ½" because the thickness of concrete ring was only 1 ½". However, the focus of this study was on investigating how RCA affected shrinkage cracking. Including all aggregate sizes into the test specimens was important for accurate evaluation. As a result, the un-sieved concrete was also tested. Table 4.2 summarizes the age and the size of restrained shrinkage cracking for TDOT paving concrete using different types and replacement levels of RCAs. In general, using coarse RCAs to replace the coarse NVAs in TDOT paving concrete delayed the restrained shrinkage cracking. The TDOT Class CP mix with NVAs cracked at approximately 7.5 days for both wet-sieved and un-sieved concretes. When RCAs were used, the cracking occurred at a wide range of time from 6 to 25.2 days for un-sieved concrete and from 5 to 25 days for wet-sieved concrete. This wide variation was owing to the mixed effects of RCAs. The use of RCAs typically increased the dry shrinkage and possibly the creep of concrete (30 – 60% greater[64]). It also reduced the tensile strength (reflected by the reduction in the flexural strength) and the modulus of elasticity of concrete. An increase in dry shrinkage or a reduction in tensile strength increased the risk of cracking, however, an increase in creep or a decrease in modulus of elasticity reduced the risk of cracking. Different RCAs tended to have different effects on these properties and thus a wide variation in the age of cracking could be anticipated.

In this study, the size of restrained shrinkage cracking was classified into three groups: large, medium to small, very small to not visible. A wide-open crack (width>0.5mm) going through the whole depth of concrete ring at approximately 28 days was called a large crack, while any cracks with an average width of less than 0.1 mm at 28 days were categorized as very small cracks. Typically, they did not propagate to the full depth of concrete ring. Medium to small cracks were characterized as a wide variety of cracks with the crack width between 0.1 mm and 0.5 mm at approximately 28 days, in which a medium crack looked wider and continuously run through the full depth of concrete ring, while a small crack showed discontinuity and jump patterns. A review of test results in Table 4.2 revealed that using coarse RCAs did not significantly increase the size of cracking. In some cases, a reduced crack size was observed. This was again owing to the mixed effects of RCAs on the shrinkage cracking. However, when the fine RCA was used (e.g., 80% or 100% as-is I-440 RCA), the crack size was substantially increased. The primary reason was that using fine RCA excessively increased the free shrinkage of concrete (by up to 144% in this study), which dominated the crack development.

Table 4.2 Age and Size of Restrained Shrinkage Cracking of RCA Concrete

Mix ID	Age of Cracking, Days		Size of Cracking	
	Un-sieved	Wet-sieved	Un-sieved	Wet-sieved
60% AF RCA	13	15	Small	Medium
40% AF RCA + 20% #7	10	20	Medium	Very small
60% SC RCA	8	6	Small	Medium
35% SC RCA + 25% #7	6	17.5	Not visible	Very small
60% HC RCA	10	12.5	Not visible	Medium
40% HC RCA + 20% #7	15	15	Not visible	Small
60% SCP RCA	7.5	11	Small	Medium
45% SCP RCA + 20% #4	22.5	18	Not visible	Medium
100% I-440 RCA coarse + fine	10.5	6	Medium	Large
80% I-440 RCA coarse + fine	8	5	Medium	Large
60% I-440 RCA coarse	25.2	25	Very small	Small
TDOT Class CP mix (control)	7.5	7.5	Not visible	Medium

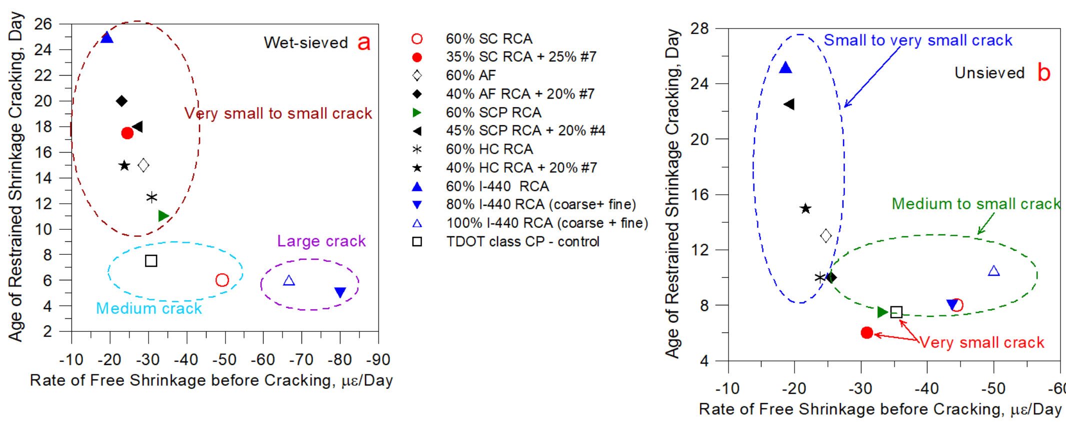
Figure 4.4.4 illustrates the relationship between the 28-day free shrinkage and the age of restrained shrinkage cracking. Unfortunately, no clear trends were observed. Concrete with coarse RCAs typically shrunk 450 to 580με for wet-sieved mix and 300 to 510με for un-sieved mix. Shrinkage cracking typically occurred at 6 to 26 days for both wet-sieved and un-sieved mixes. Concrete with higher shrinkage did not necessarily result in earlier cracking. However, using a high percentage of fine RCA in concrete such as 36% in the 100% as-is I-440 RCA mix led to excessive shrinkage and early shrinkage cracking.



(a) Wet-sieved Concrete Mix (b) Un-sieved Concrete Mix

Figure 4.4.4 Relationship between Free Shrinkage Strain at 28 days and Age of Restrained Shrinkage Cracking for Different RCA Concrete Mixes

Figure 4.4.5 presents the effects of free shrinkage rate on the age of shrinkage crack. For wet-sieved concrete mixes, a clear trend was seen (Figure 4.4.5a), in which faster shrinkage typically resulted in earlier cracking and a larger crack size. One plausible explanation was that a faster shrinkage would lead to higher earlier shrinkage stress because the modulus of elasticity of concrete also developed faster at early ages, however, concrete might not have enough time to fully creep and relax this stress, thus leading to higher residual stress that cracked the concrete. For un-sieved concrete mixes, similar trends were observed. However, there were some exceptions. For example, some concrete mixes (such as TDOT Class CP mix or the mix with 35% SC RCA + 25% #7) had relatively faster shrinkage, but very small cracks were noted during the testing.



(a) Wet-sieved Concrete Mix (b) Un-sieved Concrete Mix

Figure 4.4.5 Relationship between Rate of Free Shrinkage before Cracking and Age of Restrained Shrinkage Cracking for Different Concrete Mixes

The detailed shrinkage test results of all RCA concrete mixes are provided in the supplementary documents of this report (B), including the development of free shrinkage strain with time, the development of restrained shrinkage strain at the steel ring with time, and the restrained shrinkage cracking illustration in the concrete ring after 28 days.

4.5 Freeze and Thaw Durability of RCA Concrete Mixes

This section assessed the effects of using RCAs in TDOT Class CP mix on the freeze/thaw durability of concrete. Concrete specimens with different RCA sources, sizes, moisture levels, and replacement rates as well as different mixture proportions (e.g., W/Cm and silica fume addition) were examined for the freeze/thaw resistance based on variations in the relative dynamic modulus and the weight during cyclic freezing and thawing. The results are summarized below.

4.5.1 Effect of RCA Source on Freeze and Thaw Durability

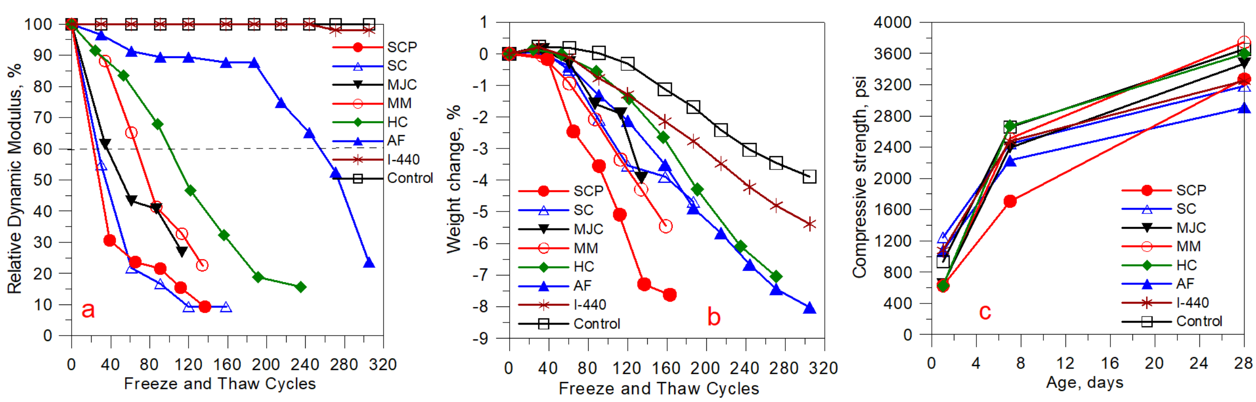
Different RCAs were found to exhibit very different freeze/thaw resistance as shown in Figure 4.5.1. All concrete mixes in Figure 4.5.1 used similar materials and proportions except the aggregates. Clearly, concrete specimens with NVAs and I-440 RCA showed the highest freeze/thaw resistance with a relative dynamic modulus of 100% and 98% respectively after exposed to 300 freeze/thaw cycles (Figure 4.5.1a). This meant that there were essentially no deteriorations in concrete specimens after 300 cycles. The excellent freeze/thaw resistance of I-440 RCA was again attributed to its consistent high quality as it solely originated from an air-entrained concrete pavement with a residual compressive strength of more than 5000psi. In contrast, concrete specimens using RCAs other than I-440 all failed since their relatively dynamic modulus dropped below 60% in less than 300 cycles.

Concrete specimens with SCP and SC RCAs displayed extremely poor freezing and thawing resistance, in which the relative dynamic modulus decreased to 60% in less than 30 to 40 cycles. Similarly, poor performance was observed for concrete specimens with the MJC and MM RCAs and their relative dynamic modulus reduced to 60% in 40 to 100 cycles. Based on the visual examination during the test, the poor freeze/thaw durability was primarily caused by nondurable aggregate origins of RCA particles (from Region 4, West Tennessee). Surface popout or spalling was observed in less than 30 to 40 cycles, and most of them were associated with the coarse aggregate in RCA particles. A review of failure sections of concrete specimens also revealed that the deterioration of these aggregates was the major mechanism that led to the ultimate failure of concrete. The surface deteriorations and/or the failure sections of all concrete specimens after the test stopped were illustrated in the supplementary documents of this report (C). Another mechanism contributing to the deterioration of concrete during freezing/thawing was related to RCA particles with unsound porous adhered paste reflected by the excessive water absorption and high LA abrasion loss of RCAs. From microscopic observations (shown in the supplementary documents of this report), these particles typically contained some pre-existing cracks mostly at the old ITZ possibly due to crushing as well as some paste damage possibly induced during specimen preparation. These particles were especially troublesome if not from air-entrained concrete origins. Based on the visual examination, some deteriorations were associated with the adhered paste of RCA particles (pictures were provided in the supplementary documents of this report C).

Concrete specimens using AF RCA demonstrated relatively better freeze/thaw resistance and almost passed the freeze and thaw test, and their relative dynamic modulus reduced to 60% in approximately 250 cycles. This was because AF RCA had relatively better quality reflected as lower absorption (5.59%) and lower LA abrasion loss (34%). However, AF RCA contained some non-concrete particles such as bricks and asphalt. These external porous particles when critically saturated, were likely to accelerate the freeze and thaw deterioration as they often appeared in the failure section of specimens.

Figure 4.5.1b illustrates the weight change of concrete specimens subjected to freeze/thaw cycles. Initially, slight weight gain was observed in all specimens due to water absorption. After approximately 30 to 60 cycles, weight loss occurred owing to surface scaling, popout, or spalling. Concrete specimens made with crushed limestone (control) and I-440 RCA showed lower weight loss, while the highest weight loss appeared in concrete specimens with SCP RCA. A comparison of weight change with the variation of the relative dynamic modulus revealed that both showed similar trends, in which concrete specimens with a higher weight loss typically had a faster drop in the relative dynamic modulus. This suggested that the weight loss could be a reasonable indication of freeze/thaw deterioration for RCA concretes.

Conventionally, the compressive strength was used as an indication of overall concrete quality. Concrete with low compressive strength typically had poor overall performance including freeze and thaw durability. Figure 4.5.1c shows the compressive strength development of concrete mixes with different sources of RCAs. Mostly, these concrete mixes displayed similar compressive strength development because they had similar W/Cm and cementitious material contents. However, concrete mixes with SCP and SC RCAs demonstrated relatively lower compressive strength possibly caused by the presence of weak and soft RCA particles. Interestingly, concrete with AF RCA had relatively lower compressive strength, but higher freeze/thaw durability. This discrepancy may be caused by the weak particles such as bricks and masonry units, which lowered the compressive strength of concrete, however, they might have less effects on the freeze and thaw durability when not critically saturated.



(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

Figure 4.5.1 Effects of RCA Source on Freeze/Thaw Durability of Concrete

4.5.2 Measures to Improve Freeze/Thaw Durability

Most RCAs in the study demonstrated poor freeze/thaw resistance when they were directly used in TDOT paving concrete. One task of this project was to investigate how to improve the durability of RCA concrete mixes through adjusting materials and proportions of concrete. This included reducing RCA size, varying RCA moisture level or replacement rate, lowering W/Cm, and adding silica fume and using high cement content.

SC RCA

Figure 4.5.2 illustrates effects of W/Cm, RCA size, moisture level, and replacement rate on freeze/thaw resistance of SC RCA concrete. Generally, some improvements in freeze/thaw resistance were achieved when various measures were used, however, all concrete specimens were unable to pass the freeze/thaw test with the relative dynamic modulus dropped to 60% in less than 190 cycles (Figure 4.5.2a).

Reducing W/Cm from 0.45 to 0.42 seemed to slightly improve the freeze/thaw durability of concrete. This was reasonable because the poor freeze/thaw resistance of concrete using SC RCA was caused by nondurable aggregate origins or porous adhered paste. Improving the quality of new paste by reducing W/Cm was likely to slow down the water transport in concrete, but unable to reduce the pressure buildup inside the RCA particles during freezing. High pressure accumulation first cracked the RCA particles, then cracking propagated to the new paste and eventually broke the specimen.

Surprisingly, using air-dry (approximately 35% saturation level) SC RCA together with low W/Cm (0.38) did not increase but reduced the freeze/thaw resistance of concrete. Concrete specimens completely broke in less than 80 cycles. One possible reason was that the high absorption water adjusted during mixing to compensate the dry RCA was partially remained in the paste, which not only weakened the concrete (indicated in Figure 4.5.2c as the lowest compressive strength development of the mix), but also facilitated the water ingression (reflected in Figure 4.5.2b as the rapid weight gain of the specimen). When the RCA particles reached the critical degree of saturation, damage would develop upon freezing. This indicated that using air-dry RCA together with one-time water addition during mixing should be cautious as this might cause poor freeze/thaw resistance.

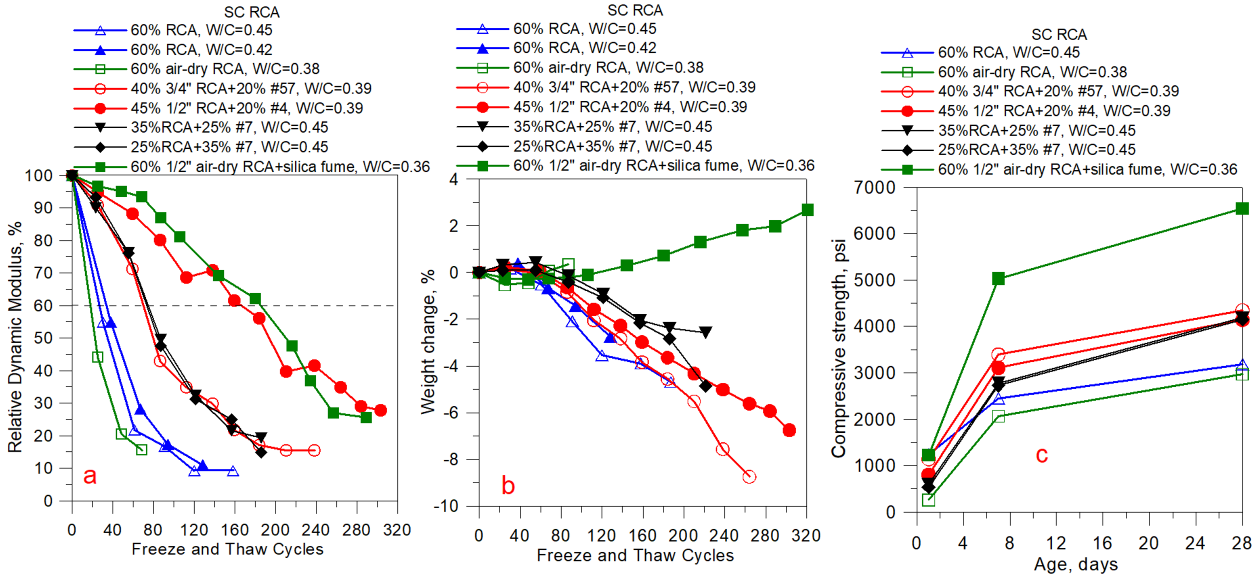
Reducing the size of SC RCA particles from 1" (NMSA) to ¾" combined with low W/Cm (0.39) greatly enhanced the freeze/thaw durability of concrete. Further reducing the size to ½" led to further substantial improvements in the freeze/thaw durability of concrete. This was not surprising because there would be less pressure buildup in smaller RCA particles as the pressure could be relatively easily released to the nearby entrained air voids in the new paste. It should be noted that in these mixes, 20% #57 or #4 crushed limestone was used to optimize the aggregate gradation and to improve the workability. They might also help to increase the freeze/thaw durability of concrete.

Reducing SC RCA replacement rates from 60% RCA (i.e., replace 100%vol coarse NVAs in TDOT paving concrete) to 35% RCA (replace 58.3%vol coarse NVAs) or 25% RCA (replace 41.7%vol coarse NVAs) noticeably improved the freeze/thaw durability of concrete. This was easy to understand because reducing the RCA replacement rate diluted the unsound aggregate particles in concrete, thus slowing down the damage development.

Specifically, a concrete mix using a combination of small (½") and air-dry SC RCA (60%vol), 40% river sand, low W/Cm (0.36), high cement content (600 lb/yd^3), and silica fume addition (60 lb/yd^3) was investigated. Among all SC RCA concretes, this mix exhibited the highest freeze/thaw durability. Undoubtedly, all measures used in this mix either reduced the water availability to RCA particles or limited the pressure generation during freezing. However, this concrete still did not pass the freeze/thaw test, in which the relative dynamic modulus reduced to 60% in approximately 190 cycles. It should be noted that although the use of air-dry RCA resulted in more free water remained in the new paste, which could lead to more porous paste, however, the use of silica fume as well as a very low W/Cm (0.36) offset this negative effect.

Figure 4.5.2b illustrates the weight change of concrete specimens using SC RCA during freezing and thawing. Concrete specimens with pre-soaked RCA experienced slight weight gain during the first 30 to 60 cycles, and then gradual weight loss until the end of testing. As explained above, the weight gain was attributed to the water absorption and the weight loss later was mainly caused by the surface scaling or popouts. However, concrete specimens with air-dry RCA demonstrated a slow weight reduction during the initial 60 to 100 cycles, and a steady weight gain after that until the end of testing. Again, the later weight gain was due to the water absorption particularly by the air-dry RCA particles. However, it was unclear why the weight loss occurred at the beginning of the test because surface scaling or popout did not take place at the beginning. This phenomenon was also noted in all other concrete specimens using different types of air-dry RCAs. It was hypothesized that in concrete with partially saturated (i.e., air-dry) RCA particles, freezing might cause overall shrinkage of concrete, which forced water out of the specimen at the initial stage of test. This was possible because in partially saturated adhered paste, small pores were more saturated and big pores were less saturated due to the difference in the surface tension. However, upon freezing, ice formed first in a big pore due to its lower surface tension. As freezing continued, more and more water would be attracted to the freezing site, causing water loss in the surrounding small pores. This led to the shrinkage of RCA particles and subsequently overall shrinkage of concrete, which could squeeze some water out of the specimen, causing weight loss. During thawing, water might be absorbed into concrete specimens including RCA particles. As the RCA particles became more saturated, less shrinkage would occur during freezing and thus less forced water escape. It was interesting to note that the concrete specimen with silica fume had a denser paste and thus slower water transport. The weight loss/gain became more gradual and took longer time. Again, the rate of weight loss/gain could be an indication of freeze/thaw deterioration. For concrete specimens with pre-soaked SC RCA, a faster drop in the relative dynamic modulus typically corresponded to a more rapid weight loss. For concrete specimens with air-dry SC RCA, a faster decrease in the relative dynamic modulus typically related to a quicker weight gain.

Figure 4.5.2c showes the compressive strength development of concrete mixes using different sizes, moisture levels, and replacement rates of SC RCA. Concrete with as-is SC RCA (air-dry and 1” size) and relatively low W/Cm (0.38) exhibited lowest compressive strength (approximately 2900psi at 28 days). This was again because water from moisture adjustment of dry RCA was left in the paste. Concrete using ½” air-dry SC RCA together with low W/Cm (0.36) and silica fume displayed highest compressive strength (approximately 6500psi at 28 days). This was because small aggregate, low W/Cm, and silica fume all helped to improve the strength of concrete although the use of air-dry RCA might have negative impacts on the compressive strength. Reducing SC RCA size to ¾” or ½” or reducing SC RCA replacement rates appeared to slightly increase the compressive strength of concrete.



(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

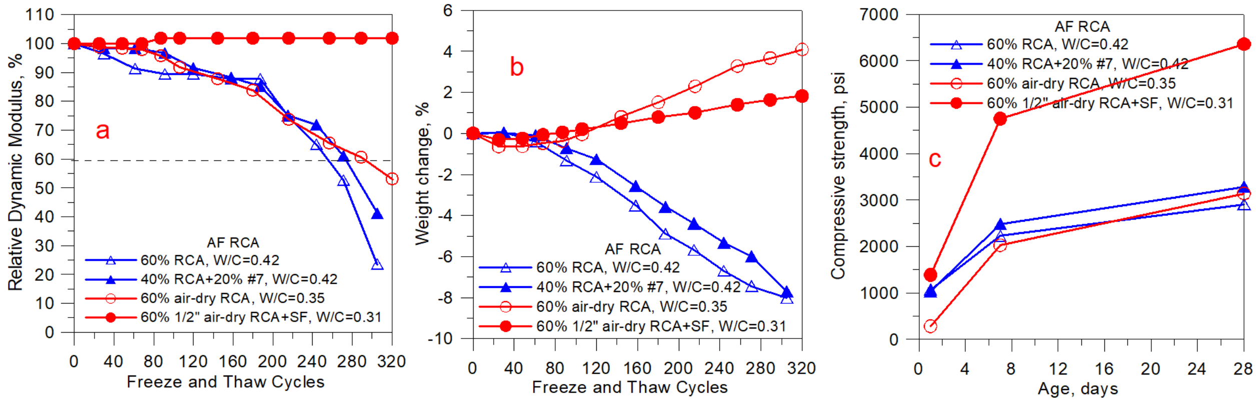
Figure 4.5.2 Effect of Material and Proportion on Freeze/Thaw Durability and Compressive Strength of SC RCA Concrete

AF RCA

In general, concrete with AF RCA demonstrated relatively high freeze/thaw resistance as compared with other RCAs in this study as shown in Figure 4.5.3. Using 60% AF RCA reduced the freeze/thaw resistance of TDOT paving concrete (Figure 4.5.3a). Reducing the AF RCA replacement rate from 60% (of total aggregates) to 40% or using air-dry AF RCA and low W/Cm (0.35) seemed to slightly improve the freeze/thaw resistance of concrete. The relative dynamic modulus of concrete decreased to 60% in approximately 280 cycles. A combination of reduced AF RCA size (½") and moisture level (air-dry) as well as the use of high cement content (600 lb/yd^3), silica fume addition (60 lb/yd^3), and low W/Cm (0.31) dramatically enhanced the freeze and thaw resistance of concrete. The relative dynamic modulus was observed to increase slightly with a value of 102% after 320 cycles. This implied that there was no deterioration developed during freezing and thawing, but instead, the concrete became more densified. Obviously, this performance was equivalent to or better than that of TDOT Class CP mix (NVA control), indicating that AF RCA could be frost resistant when adequately designed and proportioned.

Figure 4.5.3b shows the weight change of concrete specimens with AF RCA. For pre-soaked AF RCA, slight weight gain occurred during initial 30 to 60 cycles, and then gradual weight loss took place until the end of testing. Conversely, for air-dry AF RCA, slight weight loss was observed during initial 60 to 100 cycles, and a steady weight gain was seen until the end of testing. These trends were same as those observed in SC RCA concrete specimens and the reasons remained same.

The compressive strength development of AF concrete mixes was provided in Figure 4.5.3c. Concrete mixes having better freeze/thaw resistance showed higher compressive strength. Particularly, concrete specimens with ½" air-dry AF RCA, low W/Cm (0.31), and silica fume displayed the highest compressive strength (approximately 6500psi at 28 days). Similar trends were observed in SC RCA concrete specimens and the reasons were again same.

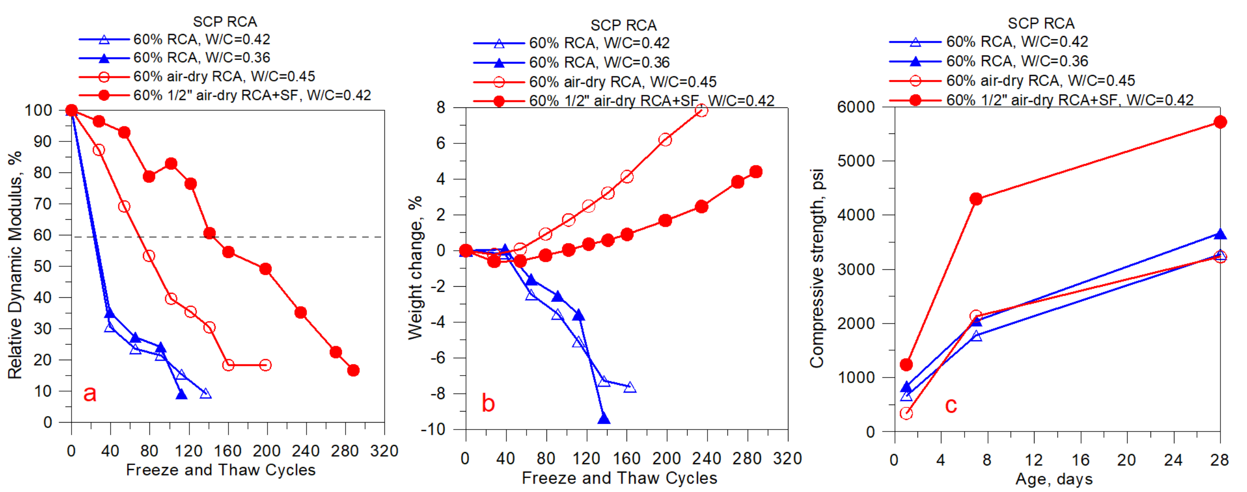


(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

Figure 4.5.3 Effect of Material and Proportion on Freeze/Thaw Durability and Compressive Strength of AF RCA Concrete

SCP RCA

Concrete using SCP RCA demonstrated very poor freeze/thaw resistance as shown in Figure 4.5.4. Similar performance was observed in concrete with SC RCA. Adjusting materials and proportion could help to improve freeze/thaw resistance of concrete, however, all mixes designed in this study failed to pass the freeze/thaw test. For example, using small SCP RCA size (½") and adding silica fume increased the compressive strength (Figure 4.5.4c) and reduced the permeability of concrete (slow water absorption or weight gain in Figure 4.5.4b), however, this concrete still showed fast deterioration with the relative dynamic modulus dropped to 60% in approximately 150 cycles. The reason was simple; the deterioration originated from RCA particles (nondurable aggregate origins and porous adhered old paste), not the new paste.

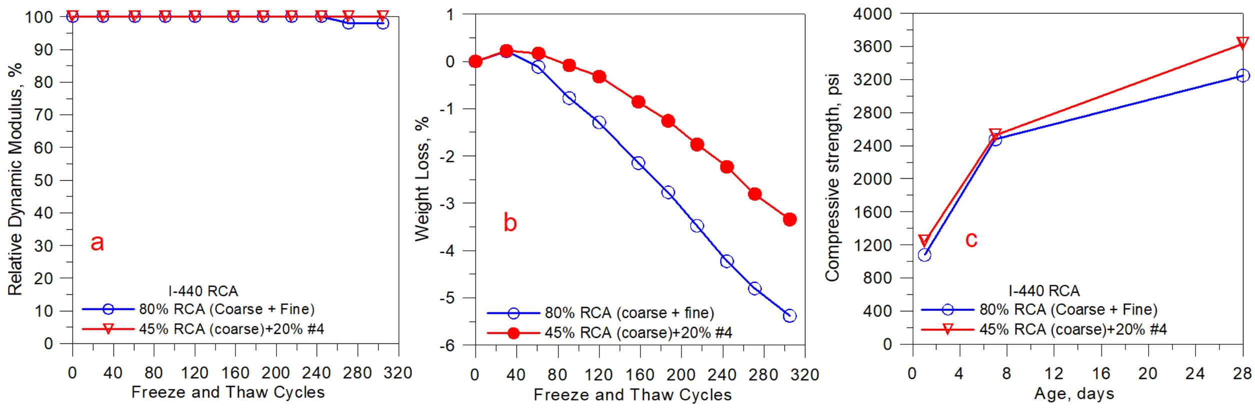


(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

Figure 4.5.4 Effect of Material and Proportion on Freeze/Thaw Durability and Compressive Strength of SCP RCA Concrete

I-440 RCA

Concrete with I-440 RCA demonstrated excellent freeze/thaw durability as shown in Figure 4.5.5. It was true that using 80% as-is I-440 RCA (coarse + fine) and 20% sand to fully replace all aggregates in TDOT Class CP mix resulted in less workable concrete, however, this did not significantly affect the freeze/thaw durability of concrete. Using 45% coarse I-440 RCA optimized with 20% #4 to fully replace coarse NVAs in TDOT Class CP mix would lead to a workable (Figure 4.2.10), strong (Figure 4.5.5c), and durable (Figures 4.5.5a and b) concrete. This suggested that optimized I-440 RCA could be used in TDOT new paving concrete.

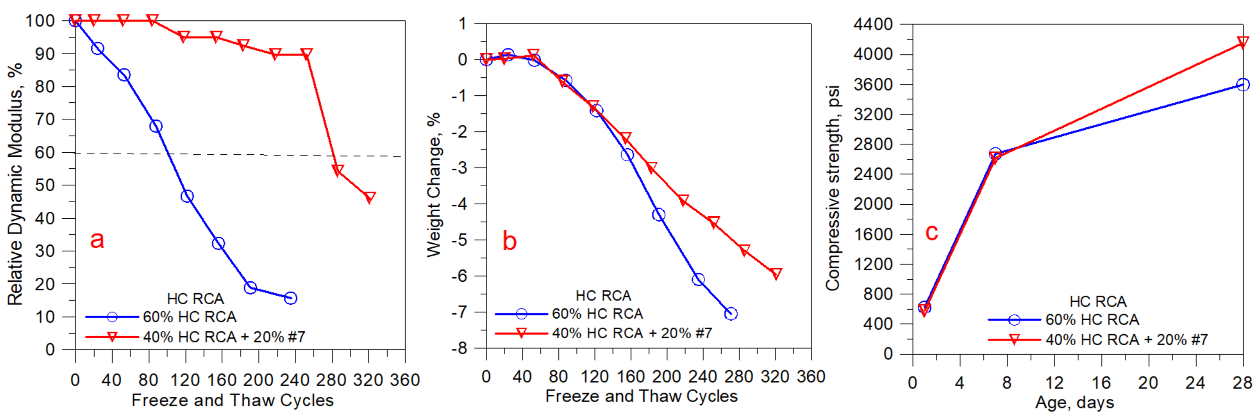


(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

Figure 4.5.5 Effect of Material and Proportion on Freeze/Thaw Durability and Compressive Strength of I-440 RCA Concrete

HC RCA

Using HC RCA to fully replace coarse NVAs (60%vol) in TDOT Class CP mix reduced the freeze and thaw resistance of concrete (Figure 4.5.6). Reducing the HC RCA replacement level from 60% to 40% together with adding 20% #7 significantly slowed down the freeze/thaw deterioration of concrete (Figure 4.5.6a). It also slightly slowed down the weight loss due to surface scaling or popout (Figure 4.5.6b) and improved the compressive strength of concrete (Figure 4.5.6c). Concrete with HC RCA performed better during freezing/thawing than concretes with SC RCA and SCP RCA, but poorer than concrete with AF RCA. The main reason was that HC RCA had a higher quality than SC/SCP RCAs, but a lower quality than AF RCA. HC RCA had a durable aggregate origin, which was better than SC/SCP RCAs. However, it had a higher number of soft non-concrete particles (the supplementary documents of this report G), which was worse than AF RCA. This was also supported by the fact that the absorption and the LA abrasion loss of HC RCA was lower than those of SC/SCP RCAs, but higher than those of AF RCA.



(a) Relative Dynamic Modulus **(b) Weight Change** **(c) Compressive Strength Development**

Figure 4.5.6 Effect of Material and Proportion on Freeze/Thaw Durability and Compressive Strength of HC RCA Concrete

In this study, the durability factor of different concrete mixes using different RCAs was calculated using the equation in ASTM C666. The results are shown in Figure 4.5.7. In the freeze and thaw test, each specimen was exposed to 300 cycles, or its relative dynamic modulus decreased to 60% of its initial modulus, whichever occurred first. Concrete with I-440 RCA had the highest durability with a durability factor of 100, which was equal to that of the control mix (TDOT Class CP) using NVAs. Concrete with AF RCAs had medium durability with a durability factor from 50 to 100. When properly designed and proportioned, AF RCA concrete could be durable. Concrete with other RCAs exhibited poor durability and they had a durability factor of 5 to 20.

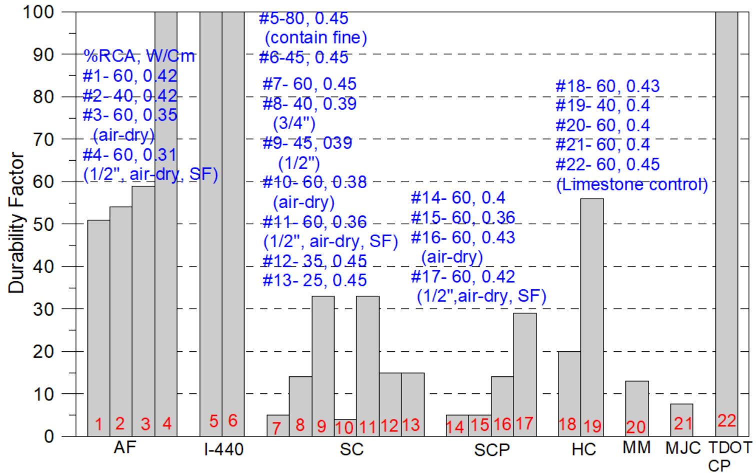


Figure 4.5.7 Comparison on Durability Factor of Concrete Mixes with Different RCAs

4.5.3 RCA Properties vs. Freeze/Thaw Durability

Good relationships were observed in this study between the basic properties (absorption, LA abrasion loss, and specific gravity) of RCA and the freeze/thaw durability of RCA concrete as shown in Figure 4.5.8. An increase in the absorption or the LA abrasion loss, or a decrease in the specific gravity of RCA, the freeze/thaw durability of RCA concrete would decrease. High absorption, high LA abrasion loss, and low specific gravity were associated with the adhered paste that was porous, soft, and light, which in turn led to the poor freeze/thaw resistance of concrete. Based on the results from this study, it could be reasonably concluded that an RCA with absorption of more than 6%, LA abrasion loss of more than 34%, and specific gravity of less than 2.38 was unlikely to resist cyclic freezing and thawing.

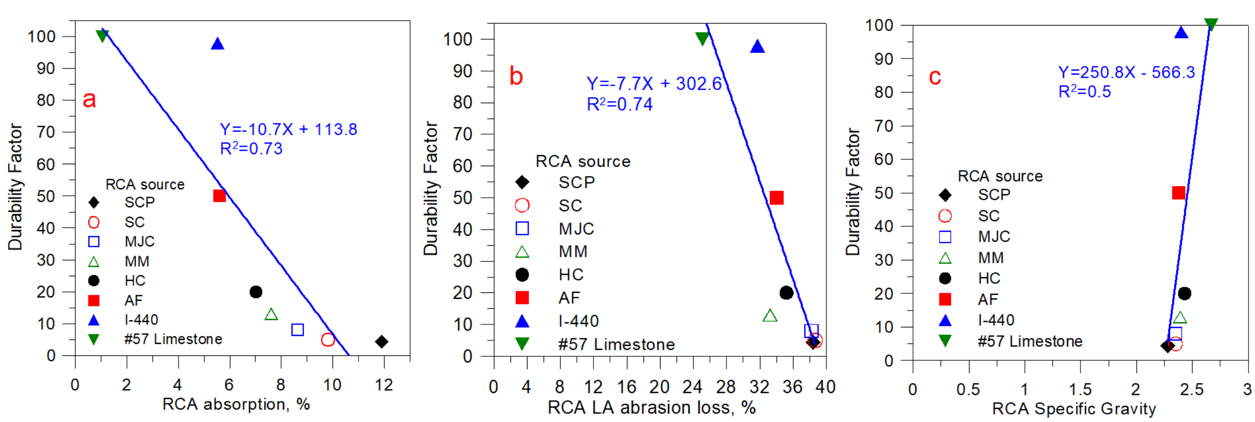


Figure 4.5.8 Relationships between RCA Properties and Freeze/Thaw Durability of Concrete

4.6 Deicing Salt Scaling Resistance of RCA Concrete Mixes

In general, the use of RCAs to replace the NVAs in TDOT Class CP mix reduced the scaling resistance of concrete. Figure 4.6.1 illustrates the cumulative mass loss (oven-dried) with the freeze/thaw cycles for concrete mixes using different RCAs. The surface scaling deterioration of each concrete specimen after 50 freeze/thaw cycles was also shown in the supplementary documents of this report (D). In this study, the total ponding area of each specimen was approximately 100 in^2. The condition of surface was visually rated based on the criteria (0 to 5) described in ASTM C672. It appeared that a cumulative mass loss of less than 10g after 50 cycles was equivalent to the scaling rates of 1 to 2; 10 to 30g to the scaling rate of 3; 30 to 70 g to the scaling rate of 4; and more than 70g to the scaling rate of 5 respectively.

Different types of RCAs substantially influenced the scaling resistance of concrete as shown in Figure 4.6.1a. All mixes in Figure 4.6.1a used similar materials and proportions as the TDOT paving concrete except the coarse aggregate. In some RCA mixes (such as with AF and SCP RCAs), the W/Cm was slightly reduced (e.g., 0.42) to achieve a desirable slump of 1" to 2". Concrete mixes with AF RCA exhibited excellent scaling resistance with a slight mass loss of less than 10g and a scaling rate of 2 after 50 cycles, which was similar to that of control mix. Concrete specimens with SC RCA showed moderate scaling with a scaling rate of 3 and the cumulative mass loss of approximately 20g after 50 freeze/thaw cycles. Concrete specimens using MM, MJC, I-440, and HC RCAs demonstrated severe scaling with a scaling rate of 4 and the cumulative mass loss between 45g and 55g after 50 cycles. Concrete specimens with SCP RCA displayed very severe scaling with a scaling rate of 5 and the cumulative mass loss of 102g after 50 cycles. It was interesting to note that SC RCA concrete, which performed very poorly during the rapid freeze and thaw test (ASTM C666) with a Durability Factor of approximately 5%, showed moderate scaling resistance. Oppositely, I-440 RCA concrete, which had excellent freeze /thaw durability with a Durability Factor of 100%, exhibited poor scaling resistance. One explanation was that in the rapid freeze/thaw test, the primary damage mechanism was the dilative pressure generated by the ice formation or osmosis; however, in the scaling test, besides this expansive pressure, deicing salt attack could take place, in which the deicing salt (calcium chloride) reacted with the calcium hydroxide in paste to form calcium oxychloride ($3CaO.CaCl_2.15H_2O$)[65]. At low temperature such as 40°F, calcium oxychloride crystallized, causing additional expansive pressure that accelerated the deterioration. Since the adhered paste of RCA particles when not carbonated contained extra calcium hydroxide, this would increase the calcium hydroxide availability and promote the deicer attack. This attack was further maximized when the temperature dropped near freezing because calcium hydroxide became more soluble at a lower temperature. As a result, freshly crushed I-440 RCA, which contained a high calcium hydroxide content reflected by its relatively high pH value (Table 4.1), was anticipated to have more deicer attack and thus more scaling. Conversely, SC RCA possibly from carbonated concrete origins reflected by its low pH value (Table 4.1) had a lower calcium hydroxide content and thus a lower risk of deicer attack. Meanwhile, a slow freezing rate during the scaling test reduced the hydraulic pressure and alleviated the deterioration caused by nondurable aggregate origins. Consequently, only moderate scaling occurred in SC RCA concrete specimens. The mechanism of deicer attack also explained why concrete with SCP RCA displayed very severe scaling. This was because SCP RCA was freshly crushed from newly returned concrete, thus having high calcium hydroxide content. It also had nondurable aggregates. A combination of freeze/thaw deterioration and deicer attack contributed to stressing the concrete surface, leading to very severe scaling.

Figure 4.6.1b illustrates the scaled mass loss of concrete mixes using SC RCA with different sizes, moisture levels, and replacement rates. Based on the visual examination, the surface deterioration of concrete specimens was primarily in the form of popout or spalling due to unsound aggregate origins, which was also illustrated in the supplementary documents of this report (D4). Reducing SC RCA size combined with a decrease in W/Cm was anticipated to improve the scaling resistance of concrete; however, a mixed effect was observed. For example, reducing SC RCA size from 1" to ¾" and W/Cm from 0.45 to 0.39 was observed to slightly reduce the surface scaling of concrete; while a substantially increased surface scaling was noted when SC RCA was further reduced to ½" (W/Cm=0.39). The exact reason was unclear, but it was noted that more sites of popout occurred on the surface of concrete specimens when SC RCA was reduced to ½". Using air-dry (35% saturation) SC RCA together with a reduced W/Cm (0.38) greatly increased the surface scaling of concrete. This might be again due to the high absorption water remained in the new paste that increased the permeability of concrete. Reducing the SC RCA replacement levels (from 60% to 35%, and then 25% of total aggregate by volume) in concrete mix did not noticeably affect the scaling resistance of concrete. One possible reason was that SC RCA had low calcium hydroxide content. Changing its replacement rate did not significantly change the calcium hydroxide content in concrete. Consequently, there would be less effects on the deicer attack. More interestingly, a combination of reduced SC RCA size (½") and moisture level (air-dry) as well as the silica fume addition (60 lb./yd^3), high cement content (600 lb./yd^3), and a reduced W/Cm (0.36) did not significantly improve the scaling resistance of concrete. One possible reason was that this mix contained a high cement content and did not use 25% class F fly ash. Consequently, there would be higher calcium hydroxide in the mix, which offset the positive effects of reduced permeability on the scaling resistance.

Figure 4.6.1c shows the mass loss of concrete specimens using SCP RCA. Reducing W/Cm from 0.42 to 0.36 dramatically reduced the surface scaling due to reduced permeability of concrete. Using air-dry SCP RCA (70% saturation) reduced the surface scaling as compared with the pre-soaked SCP RCA. This result was opposite to what was observed in SC RCA, in which air-dry SC RCA increased surface scaling. One reason was that air-dry SCP RCA had high saturation level (70%). There was less absorption water adjustment during mixing, and thus less water remained in the mix. A combination of reduced SCP RCA size (½") and moisture level (air-dry) as well as the silica fume addition (60 lb./yd^3), and high cement content (600 lb./yd^3) slightly reduced the surface scaling of concrete.

Figure 4.6.1d shows the mass loss of concrete specimens using AF RCA. All concrete specimens showed relatively low surface scaling due to the lower calcium hydroxide content and relatively durable aggregate origins in AF RCA particles. Use air-dry AF RCA (33% saturation) slightly increased the surface scaling. This was again due to the negative effect of high absorption water remained in the mix.

Figure 4.6.1e shows the mass loss of concrete specimens using I-440 RCA. I-440 RCA particles had a high calcium hydroxide content, but a durable aggregate origin. As a result, concrete with higher percentage of I-440 RCA was anticipated to have higher deicer attack, and thus more surface scaling. This was exactly observed in this study. Concrete with 80% I-440 RCA showed very severe scaling, while concretes with 60% and 45% coarse I-440 RCA exhibited severe and moderate surface scaling respectively.

Figure 4.6.1f shows the mass loss of concrete specimens using HC RCA. Reducing the HC RCA percentage in concrete appeared to reduce the surface scaling.

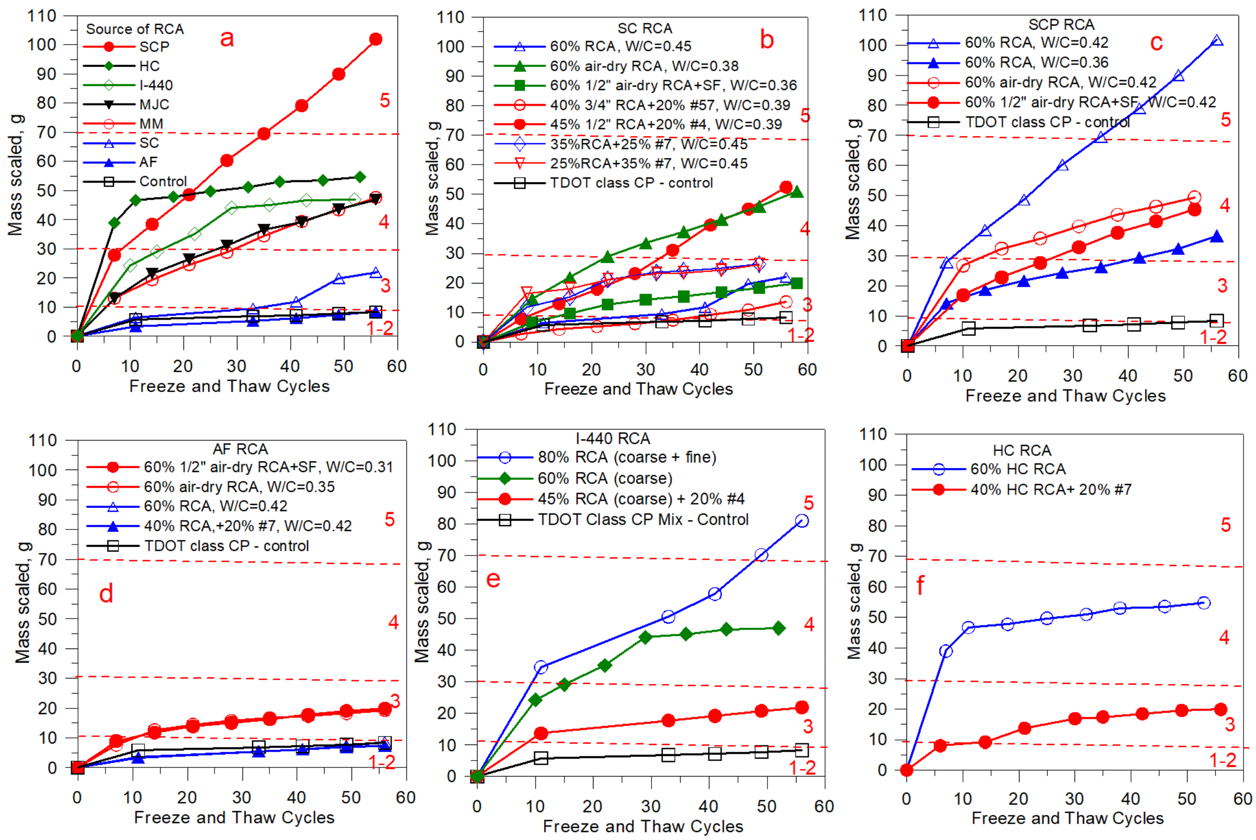


Figure 4.6.1 Effect of RCA Source and Mix Proportioning on Scaling Resistance of Concrete

4.7 Rapid Chloride Permeability of RCA Concrete Mixes

Figure 4.7.1 presents the rapid chloride permeability of concrete mixes using different RCA types, replacement rates, and moisture levels as well as the silica fume addition and different W/Cm. Most concrete mixes including the TDOT Class CP mix (control) exhibited high chloride ion penetrability based on the criteria provided in ASTM C1202 with the cumulative charge passed over a period of 6 hours greater than 4000 coulombs. This was reasonable because the TDOT Class CP mix had a W/Cm of 0.45 with an expected 28-day compressive strength of 3000psi. In general, the use of RCA to replace NVAs in TDOT Class CP mix increased the rapid chloride permeability of concrete. This was primarily attributed to the adhered paste in RCA particles, which could be more porous and contained pre-existing cracks. The attached paste also contained additional alkali and potentially ionic contaminants, which increased the conductivity of pore solution and facilitated the ion transport. In addition, some RCA materials included very porous non-concrete particles such as bricks and masonry units. They also increased the electric conductance of concrete and assisted in the chloride transport.

Using AF RCA significantly increased the permeability of TDOT paving concrete. The reason remained the same: porous adhered paste and porous external brick particles. Reducing AF RCA percentage from 60% to 40% slightly reduced the permeability of concrete due to reduced porous paste and external particles. Using air-dry (33% saturation) AF RCA combined with a low W/Cm (0.35) did not noticeably affect the permeability of concrete. This could be because the positive effect of lowering W/Cm was offset by the negative impacts of high absorption water remained in the mix. Concrete with a combination of small AF RCA size (½"), lower AF RCA moisture level (air-dry), lower W/Cm (0.31), silica fume addition (60 lb./yd^3), and high cement content (600 lb./yd^3) showed a moderate level of chloride ion penetrability, indicating the permeability of concrete was drastically reduced. The primary contribution might include the silica fume addition, which helped to densify the paste, and low W/Cm (0.31), which compensated for the negative impact of air-dry RCA.

Concrete with 45% coarse I-440 RCA demonstrated high chloride permeability due to the porosity and the possible cracks in the adhered paste. Surprisingly, concrete with 80% as-is (coarse + fine) I-440 RCA showed low chloride ion penetrability. The exact reason was unclear. One possible reason was that extra consolidation/vibration effort was used in preparing the cylindrical specimens because the mix was very stiff and unworkable due to the use of fine I-440 RCA, which could lead to a dense concrete.

Using SC RCA significantly increased the permeability of TDOT paving concrete. Reducing the SC RCA size and replacement rate, as well as W/Cm reduced the permeability of concrete. Air-dry SC RCA (35% saturation) increased the permeability of concrete. The use of silica fume reduced the permeability of concrete. All these trends were same as those described in AF RCA and the reasons remained same.

The use of SCP RCA in TDOT paving concrete showed the highest permeability. This was again attributed to its highly porous adhered paste and some pre-existing cracks. Likewise, reducing W/Cm or adding silica fume helped to reduce the permeability of concrete. Using air-dry (70% saturation) SCP RCA increased the permeability of concrete. Comparably, with the same proportioning, the use of HC, MM, and MJC RCAs in TDOT paving concrete also increased the permeability of concrete because all these RCAs contained porous adhered paste.

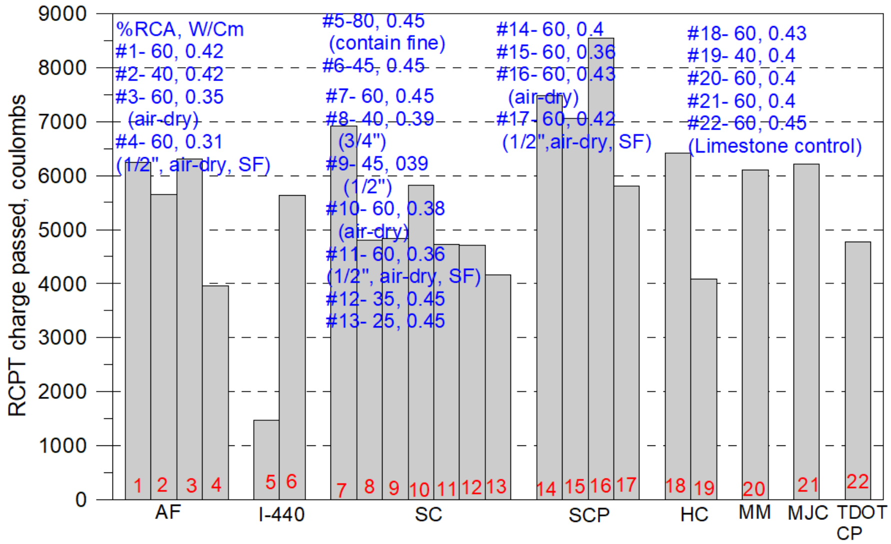


Figure 4.7.1 Effects of RCA Type, Moisture Level, and Replacement Rate on Rapid Chloride Permeability of Concrete

The rapid chloride permeability of RCA concrete was found to correlate very well with the absorption of RCA materials (Figure 4.7.2a). Using RCA with high absorption in TDOT paving concrete would lead to high chloride permeability. This was because high absorption meant highly porous adhered paste in RCA particles, and thus high permeability of new concrete. The rapid chloride permeability of RCA concrete also correlated well with its freeze/thaw durability (Figure 4.7.2b). An RCA concrete with high chloride permeability would have low freeze/thaw durability. This was obvious because more permeable concrete facilitated the saturation of concrete.

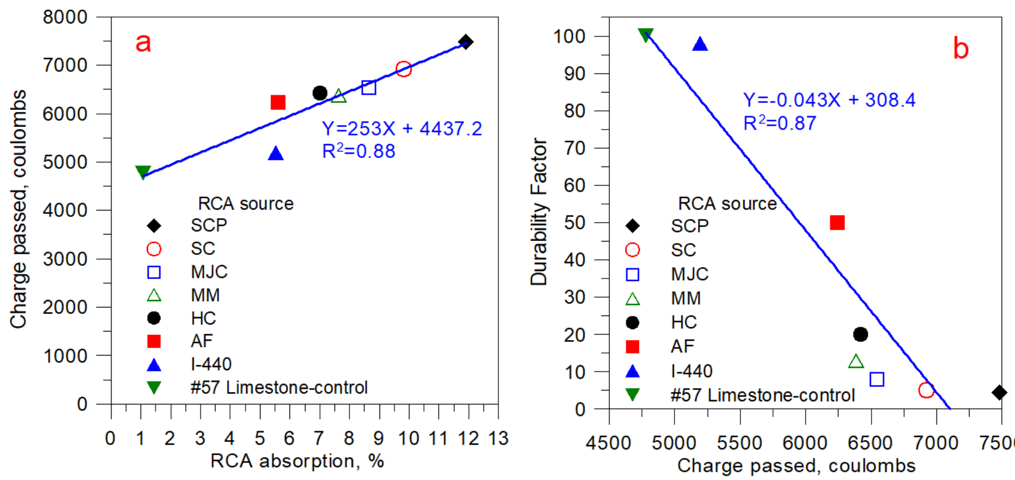


Figure 4.7.2 Relationships among RCA Absorption, Chloride Permeability, and Durability Factor of Concrete

4.8 Microscopic Examination and Hardened Air Analysis

4.8.1 Microscopic Examination of RCA Particles

AF RCA contained some pre-existing cracks particularly near the old ITZ as well as some paste damage possibly induced during crushing or specimen preparation. This reflected that some adhered pastes were soft and unsound. Most AF RCA particles did not contain entrained air voids in their adhered paste/mortar, while some AF RCA particles were from the air-entrained concrete origins. Also, some air voids were partially filled with secondary products. There were some asphalt particles that appeared to be very porous. Representative images captured during the microscopic examination are presented in the supplementary documents of this report (F2).

For I-440 RCA, the adhered paste/mortar in the RCA particles was mostly air entrained and again some air voids were partially filled with white deposits. There were some pre-existing cracks largely located at the old ITZ and possibly caused by crushing. Typical images captured during the microscopic examination are shown in the supplementary documents of this report (F3).

Most SC RCA particles were from entrained air concrete origins and some of entrained air voids were also filled with secondary reaction products. There were paste damage and pre-existing cracks particularly near the old ITZ, indicating soft unsound paste. Some coarse aggregate particles in SC RCA appeared to be porous and non-durable. Characteristic images captured during the microscopic examination are provided in the supplementary documents of this report (F4).

For SCP RCA, some particles had entrained air voids in their adhered paste, while some were from non-air-entrained concrete origins. There were cracks or damages in the particles, which mostly occurred in paste and along the old ITZ, implying that some pastes were weak and unsound. Some original coarse aggregates in the RCA particles were porous and possibly nondurable. Typical images taken during the microscopic examination are given in the supplementary documents of this report (F5).

For HC RCA, entrained air voids were observed in the adhered paste of most particles and some voids were filled with secondary products. Some RCA particles contained cracks that mostly occurred in the adhered paste along the old ITZ. Representative views captured during the microscopic examination are presented in the supplementary documents of this report (F6).

4.8.2 Hardened Air Void Analysis of RCA Concrete Mixes

The hardened air void system of RCA concrete mixes was analyzed using the modified point-count method described in ASTM C457. The polished concrete samples are presented in the supplementary documents of this report (E). The results are also summarized in the supplementary documents of this report (A). The hardened air content varied from 3.7% to 7.6% with an average value of 5.5% and the air spacing factor ranged from 0.008” to 0.021” with an average value of 0.012”. This indicated that the entrained air voids in this study were relatively big. Figure 4.8.1 presents the correlations between the fresh air content and the hardened air content as well as between the SAM number and the air spacing factor.

For most RCA concrete mixes, the fresh air content measured by the pressure method was higher than the hardened air content (Figure 4.8.1a). The average fresh air by the pressure method was 6.4%, which was 0.9% higher than the average hardened air. For TDOT Class CP mix, the deviation was expectedly small (0.4%). However, for some RCA mixes, the variation was unexpectedly high (up to 3.5%). This unusual discrepancy was probably caused by the air void instability due to the lack of free water in the mix and/or the admixture interactions. It was noted that all mixes that exhibited big difference (2.0 – 3.5%) had low W/Cm and used middle and high-range water-reducing admixtures and/or silica fume (the supplementary documents of this report A). In this study, water-reducing admixtures were observed to promote the air entrainment during mixing, however, rapid air loss was followed after mixing during the measurements possibly due to the free water availability and/or the admixture incompatibility in the mix. Another factor that affected the air entrainment in this study was the moisture level of RCA. The use of air-dry RCA increased the free water availability during mixing, thus facilitating the air entrainment, however, the gradual water absorption of RCA after mixing would reduce the free water in the mix, which could destabilize the air voids.

Oppositely, the fresh air content measured by the volumetric method was lower than the hardened air content for most RCA mixes (Figure 4.8.1b). The average fresh air by the volumetric method was 4.8%, which was 0.7% lower than the average hardened air content. One reason was that the hardened air content included the air bubbles in the adhered paste of RCA particles, while these air voids were not measured by the volumetric method.

In this study, the SAM number did not correlate very well with the air spacing factor (Figure 4.8.1c). One possible reason was that the air voids in the adhered paste of RCA particles were included in the hardened air analysis (e.g., the air spacing factor calculation), but they were inside the adhered paste, which limited its contact with the pore water during the SAM air measurement, and thus might not effectively affect the SAM number.

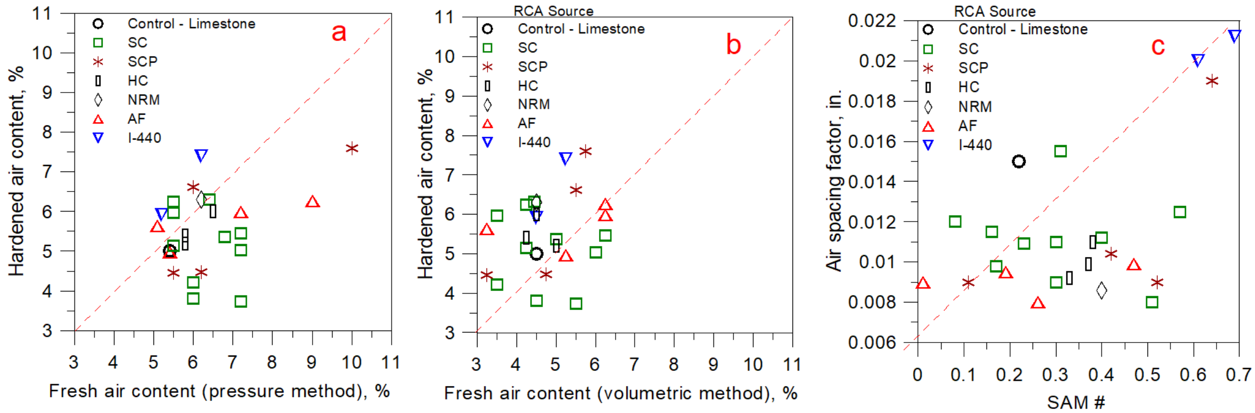


Figure 4.8.1 Relationships between Fresh Air Content and Hardened Air Content and between SAM Number and Air Spacing Factor for RCA Concrete Mixes

Chapter 5 Conclusion

The main goal of this project was to evaluate RCAs from various sources throughout the state of Tennessee and to determine how the use of RCAs in TDOT paving concrete affected the performance of concrete. A summary of main test results in this study is presented in Table 5.1.

Table 5.1 Main Test Results Summary of This Study

Properties	Crushed limestone (control)	AF RCA	I-440	SC RCA	SCP RCA	HC RCA
RCA property						
Specific gravity (SSD)	2.66	2.38	2.4	2.35	2.28	2.43
Absorption, %	1.04	5.59	5.52	7.53	11.9	7.04
LA abrasion loss, %	25.1	34	31.7	36.9	38.4	35.2
pH value	8.95	10.33	12.23	11.0	11.65	11.74
Non-crushed-concrete particles, %	NA	2.1	0.0	0.5	1.3	4.4
NMSA, in.	1 ½	¾	¾	1	1	¾
Concrete source	NA	S, R, U	P	S, U	R, U	S, U
Unsound paste	NA	Low	None	Medium	High	Medium
Freeze/thaw resistance	Excellent	Fair	Excellent	Poor	Poor	Fair
RCA Concrete property and performance						
Workability*	Good	Fair	Low	Fair	Low	Good
Air entrainment	Constant	Variable and more difficult to control				
28-day compressive strength*, psi	3693	2986	4182	3518	3193	4086
28-day flexural strength*, psi	606	467	520	516	471	511
28-day modulus of elasticity*, x10^6 psi	10.7	8.2	9.0	8.2	9.1	10.0
28-day free shrinkage*, %	0.033	0.040	0.048	0.045	0.05	0.035
Age of restrained shrinkage cracking*, day	7.5	13 -15	25	6 - 8	7.5 - 11	10 – 12.5
Rapid chloride permeability*, coulombs	4780	6241	5633	6922	7479	6419
Durability factor*	100	51	100	5	5	20
Deicing salt scaling*	Slight	Slight	Moderate /Severe	Moderate	Severe	Moderate /severe

Note: * Concrete mixes that used the coarse RCA to fully replace by volume the coarse NVA in TDOT Class CP mix were summarized. NA-Not applicable, S-Structural concrete, R-Returned concrete, P-Pavement, U-Unknown

In general, all RCAs collected in this study exhibited a wide variety of physical, chemical, and mechanical properties. All coarse RCAs had a nominal maximum size of ¾" to 1" and demonstrated relatively well gradation that met the grading requirements of either #56 or #57 described in ASTM C33. They exhibited lower specific gravity, higher absorption, higher LA abrasion loss, and higher pH value as compared with NVAs such as crushed limestone. The adhered paste of RCA particles varied from 14.1% to 26.5% vol, which also included 0.88% to 2.2% air voids.

Using coarse RCAs in TDOT paving concrete mostly resulted in a reduced workability and an increased edge slump. Optimizing the RCA gradation by incorporating either an intermediate (#7) or a larger (#4) crushed limestone assisted in improving the workability, reducing the surface voids, and controlling the edge slump during the box test. Using as-is RCAs (coarse plus fine) in TDOT paving concrete should be cautious as they dramatically reduced the workability of concrete. However, optimized RCA (coarse plus fine) gradation showed acceptable performance. In addition, the use of RCAs in TDOT paving concrete reduced the unit weight of concrete.

RCAs accelerated the setting of concrete. A concrete mix using RCA with a higher pH value (i.e., less carbonated) typically exhibited quicker setting.

RCAs affected the fresh air measurement of concrete mix. The pressure air method measured the total air content in the mix, which included the fresh air in the new paste as well as the hardened air in the adhered paste; while in the volumetric method, only fresh air was determined. For the protection of RCA concrete from cyclic freezing and thawing, the pressure air was obviously more meaningful assuming that the RCAs were not from structural light weight concrete origins and did not contain high percentage of porous particles (e.g., bricks and masonry unit).

RCAs typically reduced the compressive strength of concrete particularly at late ages (i.e., 7 and 28 days). However, a good quality RCA from a strong and constant concrete source such as I-440 increased the compressive strength of concrete. Most RCA concrete mixes tested in this study had a 28-day compressive strength of more than 3000psi, which satisfied the TDOT's requirement for paving concrete.

It became evident that RCAs constantly reduced the flexural strength and the modulus of elasticity of concrete particularly at late ages. The magnitude of reduction depended on the quality and the replacement rates of RCA. Poor quality RCAs with a high number of external soft particles such as bricks, asphalt, and masonry unit or porous unsound adhered paste would significantly reduce the flexural strength and the modulus of elasticity. A higher RCA replacement rate in the mix would lead to more reductions.

RCAs (coarse) increased the free dry shrinkage of concrete by up to 51% at 28 days. RCAs with more adhered porous paste would lead to more free shrinkage of concrete. Concrete with higher RCA replacement rates would expect higher free shrinkage. The use of as-is RCA (coarse plus fine) drastically increased the free shrinkage of concrete by up to 144% at 28 days.

RCAs (coarse) typically delayed the age of restrained shrinkage cracking in TDOT paving concrete and did not increase the width of cracking at 28 days. This indicated that although RCAs increased the free shrinkage of concrete, they did not increase the risk of shrinkage cracking. Therefore, similar joint practice can be used when coarse RCAs are used in TDOT pavement construction. However, using as-is RCA (coarse plus fine) resulted in earlier and wider cracking in concrete. Consequently, earlier sawing and shorter joint spacing were recommended.

RCAs increased the rapid chloride permeability of concrete. Reducing W/Cm and adding silica fume helped to reduce the permeability

Most RCAs in this study reduced the freeze/thaw resistance of concrete. Some RCAs showed very poor freeze/thaw resistance. Main reasons included nondurable aggregate origins, porous and unsound adhered paste particularly without air entrainment, and a high number of external particles (e.g., bricks, masonry unit, and glass). Reducing RCA size and/or W/Cm helped to increase the freeze/thaw resistance of RCA concrete. A combination of small RCA (½"), low W/Cm (0.36), high cement content (600 lb./yd^3), and silica fume addition (60 lb./yd^3) noticeably improve the freeze/thaw resistance of concrete. High quality RCAs from strong and air-entrained concrete origins such as I-440 displayed excellent freeze/thaw durability.

Similarly, most RCAs in this study reduced the scaling resistance of concrete. Main surface deteriorations included paste scaling and popouts. RCAs with a high pH value typically caused high surface paste scaling, while RCAs with nondurable aggregate origins and/or porous unsound adhered paste typically induced surface popouts. RCAs from freshly crushed uncarbonated concrete should be used with cautions as they would significantly increase the surface scaling and the deicing salt attack. Even in a two-lift pavement practice, the high calcium hydroxide in the bottom lift would increase the risk of joint deterioration.

Air-dry RCAs without pre-saturation could be directly used in new paving concrete when correct water addition procedures were followed. Pre-mixing dry RCAs with 80% mixing water for 1 to 2 minutes followed by the addition of other ingredient materials including cement exhibited the best performance, and thus was recommended.

Based on the experimental results in this study, a detailed classification guideline was proposed for determining whether a particular RCA was suitable for TDOT paving concrete applications. Table 5.2 presents three RCA classes (A, B, and C) and their specific requirements. High-grade Class A RCA manufactured from strong, constant, and air-entrained concrete origins would be essentially equivalent to NVAs and thus can always be used in TDOT paving concrete. Medium-grade Class B RCAs may be used in TDOT paving concrete, but cautionary assessments should be conducted as they may reduce the strength, the modulus, and/or the durability of concrete. Low-grade Class C RCAs indicated by high absorption (>7%), high LA abrasion loss (>35%), and low specific gravity (<2.35) were not recommended for TDOT paving concrete applications as they contained a high percentage of unsound adhered paste and/or non-crushed-concrete particles, which could substantially reduce the strength, the modulus, and the durability of concrete. Low-grade Class C RCAs due to non-durable aggregate origins were also not suitable for TDOT paving concrete because they could cause D-cracking and popouts in new concrete pavements.

Table 5.2 Proposed Coarse RCA Classification for TDOT Paving Concrete

RCA property requirements	Class A (high grade)	Class B (medium grade)	Class C (low grade)
NMSA, gradation	¾” – 1”, well-graded	¾” – 1”, well-graded	¾” – 1 ½”, well-graded
Specific gravity	≥2.4	2.35 – 2.4	≤2.35
Absorption, %	≤5.6	5.6 – 7.0	≥7.0
LA abrasion loss, %	≤32	32 - 35	≥35
Deleterious materials (soil/clay, wood, coal, etc.)	None	None	None
Non-crushed-concrete particles (asphalt, brick, masonry unit, glass, etc.), %	<1	<2.5	>2.5
Source concrete	* Consistent * High residual strength (>3000psi) * Air-entrained * Durable aggregate origin * Preferably low pH	* Durable aggregate origin * Could be mixed sources, but constant quality * Preferably low pH	* May contain unsound adhered paste * May contain non-durable aggregate origins
RCA examples in this study	I-440	AF RCA	SC RCA, SCP RCA

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