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Effect of Low and Moderate Recycled Concrete Aggregate Replacement Levels on Concrete Properties

Rita Lederle, Principal Investigator
Department of Civil Engineering
University of St. Thomas

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16. Abstract (Limit: 250 words)

This research investigated the effects of incorporating recycled concrete aggregate (RCA) at low replacement levels on the properties of concrete. Four different RCA sources were used, each with different aggregate properties. For each source, replacement levels of 5, 10, and 15% were tested and compared to a control group, which had no RCA. Of the four RCA sources investigated, three had similar levels of absorption capacity and percent fines, while one source had higher levels of both properties. RCA replaced virgin aggregate of a similar gradation and replacement was on the basis of volume.

Fresh and hardened concrete properties were tested, including air content, super air meter (SAM) number, slump, workability via the box test, compressive strength, flexural strength, elastic modulus, Poisson's ratio, coefficient of thermal expansion, surface resistivity, freeze-thaw durability, and unrestrained shrinkage. Digital image correlation was used to visualize strain fields during compression testing. A statistical analysis was conducted to determine if any observed differences in hardened properties between the test mixes and the control group were statistically significant. This research found that using up to 15% of an RCA with reasonable values of absorption capacity and percent fines would not negatively impact most concrete properties. It also provided an outline for future research to develop a specification to define what constitutes reasonable values of RCA properties for future use.

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Prepared by:

Rita Lederle, PhD, PE
Evan Selin
Lucas Gross
Mohamud Abdimuhsin
Department of Civil Engineering
University of St. Thomas

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Executive Summary

Recycled concrete aggregate (RCA) is an alternative coarse aggregate made of crushed concrete either from construction and demolition waste or unused concrete returned to ready-mix plants. Using RCA at high replacement levels is known to negatively impact the properties of the new concrete and test sections of concrete made with RCA, and several states experienced poor performance over the last few decades. As a result, many states have specifications that either make RCA difficult to use or impose an outright ban on RCA in new concrete, though it is very commonly used as the base layer in both asphalt and concrete pavements. The popularity of RCA base brings an additional challenge to using RCA in new concrete because there is often not enough RCA available to replace all the virgin aggregate in new concrete. However, anticipated aggregate shortages in many population centers and the need to increase concrete sustainability are prompting transportation agencies to reinvestigate the potential to incorporate RCA into new concrete pavements. Using RCA to replace even a portion of virgin aggregate in concrete has the potential to help address aggregate shortages while simultaneously reducing mining of virgin aggregate and landfilling of waste concrete.

The goal of this research was to determine if low levels of RCA would have negative impacts on new concrete pavements or if they could be used with little effect. Low replacement levels would help with aggregate shortages and improve the sustainability of the new pavement while being more palatable for agencies that have had negative experiences with high RCA replacement levels. Additionally, low RCA replacement levels may be the only option in markets where much of the available RCA is used for base material. This would also be similar to policy for recycled asphalt pavement (RAP), where many states currently allow 10-15% RAP in new asphalt pavement. This research focused on the effects of RCA on concrete properties when low replacement levels (5-15%) of RCA were used. The literature review showed that levels of 20-30% could cause negative effects in some concrete mixes but there was little information available on levels below 20%.

This work investigated four different RCA sources, each with different properties. For each RCA source, replacement levels of 5, 10, and 15% were investigated and compared to a control made solely of virgin limestone aggregate. Hardened concrete properties tested were:

- Compressive strength at 3, 7, 14, 21, 28, and 56 days
- Flexural strength at 3, 7, 14, 21, 28, and 56 days
- Elastic modulus
- Poisson’s ratio
- Coefficient of thermal expansion
- Surface resistivity at 3, 7, 14, 21, 28, and 56 days
- Freeze-thaw durability
- Unrestrained shrinkage

For three of the four RCA sources tested, the presence of RCA was only found to have a statistically significant effect on compressive strength and the value of surface resistivity, although the associated

category of chloride ion penetration risk was unaffected. For the fourth RCA source, compressive strength, surface resistivity, elastic modulus, and coefficient of thermal expansion were found to be statistically, significantly different from the control at one or more replacement levels. However, this RCA source also had values of absorption capacity and percent fines that would likely preclude it from use in many cases. Therefore, this research concluded that RCA with reasonable aggregate properties would likely have negligible impacts on concrete properties other than compressive strength. Standard relationships between compressive strength and flexural strength were found to be fairly accurate when RCA was incorporated but the standard relationship between compressive strength and elastic modulus was found to overpredict by an average of 25%.

Fresh properties tested included workability by both the slump and box tests, air content, and super air meter (SAM) number. The inclusion of RCA was found to have an impact on all tests, but statistical significance could not be determined due to lack of replicates. Air content and SAM number both showed good agreement with freeze-thaw durability, but this research project was not large enough to determine if these tests would be predictive because no samples failed the freeze-thaw durability test. Even low levels of RCA were found to change the slump and air content enough that constructability or acceptance could be issues. This could have been due to the short amount of time between mixing and testing, which was not reflective of actual construction practices where transit time could allow more water to be absorbed by the RCA, and future work in this area is needed.

Before RCA can be incorporated into pavements at low levels, a specification would be needed to define reasonable levels of certain RCA properties. While this research project was not intended to find those limits, it can provide a roadmap for future research. The linear regression analysis identified specific gravity, absorption capacity, percent fines, and Micro-Deval loss as properties that could be useful for defining specification limits. Gradation as quantified via fineness modulus was generally not found to have a large impact on changes in concrete properties, suggesting that replacing virgin aggregate with RCA of the same gradation type, as was done here, was acceptable. Future research will be needed to further define an RCA specification.

Chapter 1: Introduction

Aggregate consumption in the United States in 2021 was estimated at 1.0 billion tons of sand and gravel, 46% of which was used in concrete production, and an additional 1.5 billion tons of crushed stone, the majority of which was used for road construction [1]. As demand for aggregate only increases, there are concerns about the future availability of aggregates. Many major metropolitan areas in the United States are currently experiencing or are soon predicted to have shortages of viable aggregates for concrete production [2]. Meanwhile, 405.2 million tons of concrete construction and demolition waste was generated in 2018 (the most recent year with data available), mostly due to road and bridge construction [3]. Of that waste, 301 million tons was turned into aggregate and 71 million tons was landfilled [3], and an increasing percentage is being recycled every year [1].

As the demand for aggregate increases, recycling concrete waste as aggregate for new construction has been recognized as a sustainable solution. The use of recycled concrete aggregates (RCA) as replacements for virgin aggregates in construction applications is an excellent approach for recycling materials from construction and demolition waste because it decreases the need to quarry and haul virgin aggregates while decreasing disposal space and costs associated with landfilling old concrete [4].

However, RCA cannot simply replace virgin aggregate in concrete without consideration for how the concrete's properties and performance will be affected [4,5]. Recycled concrete aggregates are composed of the original natural aggregates used for preparing the parent concrete and the cement mortar of the original mix adhered to its surface. The properties of concrete containing RCA depend on both the original aggregate characteristics as well as the mortar content and properties of the RCA parent concrete [6].

While recycled concrete fines have also been investigated, they are generally considered too detrimental to the new concrete to be used [7–10] and will not be considered in this research.

1.1 Background

The use of coarse recycled concrete aggregate (RCA) in pavements has been documented as early as the 1940s and was attempted by many states in the 1970s to 1990s. Initial results were mixed, but some major performance issues left many states hesitant to allow or specify the use of RCA in concrete [11,12]. A 1994 survey sponsored by the Federal Highway Administration (FHWA) showed 11 states had tried using RCA as an aggregate in pavements at least once in the preceding decades [12]. However, some of these tests resulted in failures and subsequent bans on the use of RCA in paving concrete, resulting in a dearth of RCA projects [11]. A 2004 FHWA study still showed only 11 states as current users of RCA in paving concrete, though not all were states that participated in the initial round of RCA use [13]. An analysis of several national studies on RCA use by various states showed that 22 states had tried at least a test section of RCA between 1976 and 2012 [12], though several had disallowed the use of RCA following a trial [11]. A more recent survey in 2018 of 14 departments of transportation and one tollway authority found only six of the 15 entities surveyed currently use RCA in concrete [14].

Barriers to using RCA in concrete pavements include [14–16]:

- Concerns over the quality and performance of concrete made with RCA, potentially due to previous experience with poorly performing projects
- Concerns over the quality, availability, and consistency of the parent concrete
- Concerns over the potential for material-related distresses of the parent concrete (such as alkali silica reaction and D-cracking) to reappear in the new concrete
- A lack of technical guidance on how to design and proportion mixes using RCA
- A failure to account for differences in material properties of concrete made with RCA vs. virgin aggregate in pavement design
- Specifications that eliminate RCA from consideration as an aggregate either by holding it to the same standard as virgin aggregate or by banning RCA outright
- A lack of uniformity in specifications for pavement construction with RCA or a complete lack of specifications
- Increased bid prices from contractors when RCA is specified due to performance concerns and perceived increased risk
- Little financial incentive to encourage the use of RCA relative to its perceived risk
- A lack of technology transfer between researchers and practicing engineers and contractors

1.2 Study Motivation

When used as a replacement for coarse aggregate in concrete, RCA has been known to affect many of the properties of concern for pavement design and construction. The degree of severity of these effects depends on the characteristics of the RCA, the mix design, and the amount of RCA used [6]. Many of the studies on RCA used only 100% replacement of virgin aggregate and RCA or consider various percentages, but often skew toward high replacement levels (50 – 100%). The replacement levels used by a variety of studies on various aspects of using RCA are summarized in Figure 1.1. From this figure, it can be seen that many studies examined only complete replacement, or only the 50% and 100% replacement levels, with far fewer studies focused on lower replacement levels.

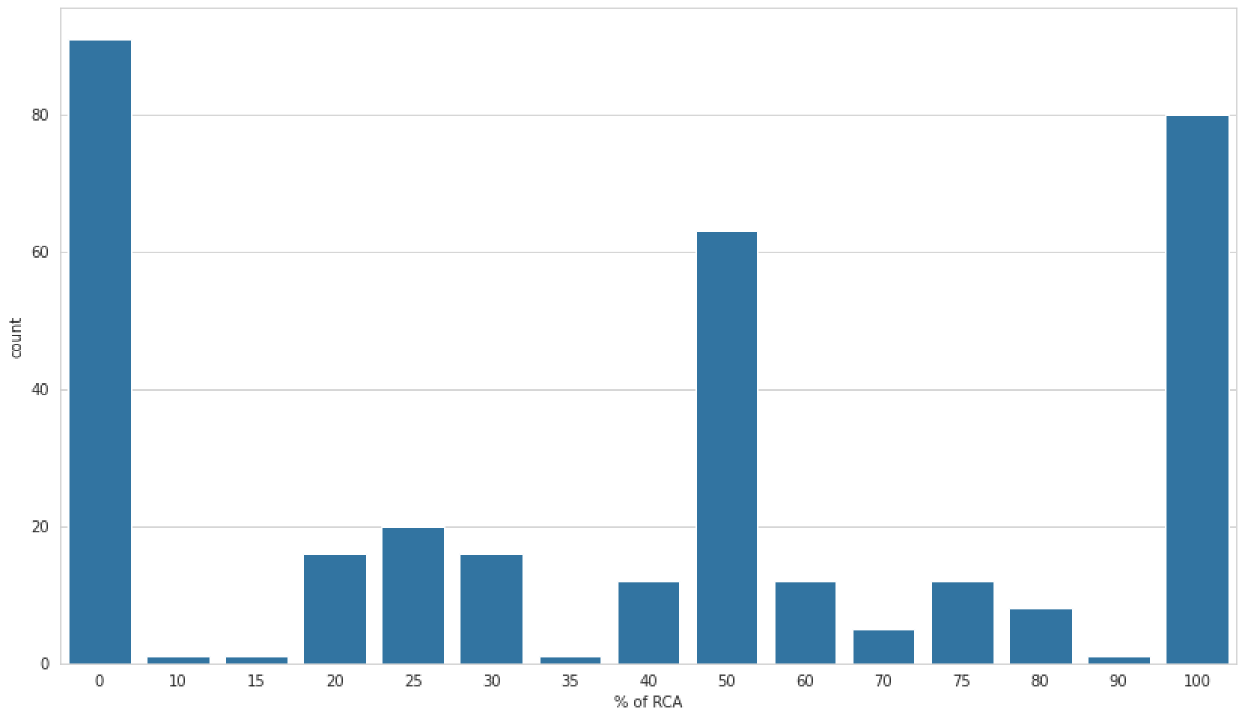

Figure 1.1: RCA percentage investigated in a variety of recent studies [17–99]

While an understanding of how complete replacement of coarse aggregate with RCA is important as well as academically interesting, it is not always consistent with the information state departments of transportation (DOTs) and other agencies need. Many DOTs lack access to sufficient quantities of material to use RCA at high replacement levels [100] because RCA is already used as a base material. An existing concrete pavement generally does not produce enough RCA to be used as both the base and aggregate in a new pavement [12]. There is therefore a need to investigate the effect of RCA use at lower replacement levels, which are less documented in the literature.

Theoretically, it is possible to replace a small amount of the coarse aggregate in concrete with RCA and experience no noticeable effect on concrete properties. For each concrete property, there will be a limit on RCA replacement level below which the presence of RCA can be neglected from an engineering standpoint. Depending on which source is consulted, that limit is generally considered to be between 10 and 30% [10], with 20% as a commonly stated value [101], though some have found replacement levels up to 45% to be acceptable if the parent concrete was of high quality [86]. Many countries currently allow up to 20% RCA in their concrete [102], though practices in the United States vary by agency [14]. For comparison, most DOTs in the United States allow 10-15% recycled asphalt pavement in new asphalt pavement because that level is considered to have a negligible impact [103]. The European Standard for Ready Mix Concrete (EN 206) sets limits on the replacement of coarse aggregate with RCA based on the characteristics of the parent concrete as well as the exposure level and required strength of the new concrete; allowable RCA levels range from 0 to 50% [104].

This study is focused on the effects of RCA replacement levels of 5, 10, and 15% on concrete properties of interest for concrete pavements. Four different RCA sources were tested at each replacement level and results were compared with a control group of concrete made entirely with virgin aggregate. One goal of this project was to ensure that results were representative of industry practices. Working with the technical advisory panel and local producers, project decisions were made based on how this research would be implemented in the future.

1.3 Report Organization

A literature review is presented in Chapter 2, which explores the effects of RCA replacement level on various concrete properties. The results of this review were used to help guide the project. Chapter 3 explains the materials selection process and testing methods. Results and discussion of testing are presented in Chapter 4. Chapter 5 provides conclusions and recommendations for both future research and future implementation of this work, as well as an exploration of the potential benefits of the project.

Chapter 2: Literature Review

This literature review covers the current state of knowledge of recycled concrete aggregate (RCA) as coarse aggregate in concrete. It presents a review of available literature on the mechanical and durability properties of concrete made coarse RCA. Though this study is focused on low to moderate replacement levels of RCA, the literature available on the effects of using RCA centers on moderate to high replacement levels. Where possible, this literature review will concentrate on low and moderate replacement levels, but will include information on all replacement levels for completeness.

2.1 Properties and Characteristics of Recycled Concrete Aggregates

Some of the properties of RCA differ from those of virgin aggregates, resulting in differences in many of the plastic and hardened properties of concrete. The properties of the RCA itself depend on the parent concrete from which the RCA was derived, the demolition technique, and any treatment of the RCA [105]. Because there are so many different variables that can affect the RCA properties, RCA has much more variability than virgin aggregate, but this variability can be reduced with proper processing techniques [10]. Processing can also improve the properties of the RCA, for example washing the aggregate increases the performance measured by many metrics [101]. RCA from quality concrete generally meets most ASTM criteria for use as aggregate [7]. One way to ensure quality RCA is to limit sources of RCA for concrete production to concrete from pavements and other elements that were constructed to meet strict state specifications [106].

2.1.1 Mortar Content

The distinguishing feature of RCA compared to virgin aggregate is the presence of adhered mortar in RCA (paste from the parent concrete). This adhered mortar is highly porous when compared to virgin aggregate, and the subsequently high porosity of RCA results in different physical properties than those of typical aggregates. A higher mortar content is associated with lower density and increased water absorption [107], as well as a higher LA abrasion loss [105]. A high mortar content will also result in decreased RCA and concrete stiffness because mortar is less stiff than aggregate [10], which may cause more cracking in concrete pavements made with RCA [85].

There is currently no standard test for measuring the amount of adhered mortar present in RCA, though several techniques are discussed in the literature. Mortar content has been found to be between 25 and 70%, depending on both the RCA itself and the measurement technique used [107]. While this is a wide range, other researchers have suggested 30-35% represents a common value [108]. Because the mortar differs substantially in properties compared to rock, the amount of adhered mortar plays a large role in determining the properties of the RCA. The amount of adhered mortar increases as RCA particle size decreases [109]. The strength of the parent concrete may also play a role in how the adhered mortar breaks apart during the crushing process, which could affect the quantity of adhered mortar.

Some of the adhered mortar can be removed using certain processing techniques [102]. For example, crushing the RCA to a smaller size has been found to remove more mortar and results in better aggregate and concrete properties [107]. When concrete is made with RCA and virgin aggregates having similar levels of absorption capacity and specific gravity, similar mechanical properties can be achieved [38].

The presence of adhered mortar also means there is an interfacial transition zone (ITZ) between the original aggregate and the mortar in addition to the ITZ between the new paste and the RCA particle that will affect concrete properties and behavior. Both ITZs need a high-quality bond between aggregate and paste to have sufficient strength in the concrete [10]. When only partial replacement of RCA is used, a third ITZ forms between the new paste and the virgin aggregate; this ITZ may have different properties than the other two [110]. The presence of multiple, different ITZs has an impact on the properties of the concrete.

It is generally considered desirable to reduce the amount of adhered mortar, with the theory that this will cause the RCA to behave more like virgin aggregate. Pavements constructed of RCA with most of the adhered mortar removed have better performance that those made of RCA with a higher mortar content [111]. However, over-processing of the RCA to reduce the mortar content can damage the original aggregate and may be expensive [15]. It has also been suggested that the total mortar content (adhered mortar and new mortar combined) has an influence on cracking [111]. Because of the large impact RCA can have on performance, any specifications for RCA should pay particular attention to aggregate properties affecting performance and durability, such as gradation, specific gravity, and absorption [112].

2.1.2 Size and Gradation

As with any aggregate, processing techniques can be used to achieve a desired gradation. It has been found that washing and proper gradation of RCA leads to less strength loss [101]. RCA can also break down during handling, causing gradation changes [105]. Crushing the same parent concrete with different crusher types results in different gradations [113]. The crushing process used to produce RCA can also result in RCA having a smaller particle size than virgin aggregate crushed with the same process. This can result in earlier loss of load transfer across cracks via aggregate interlock in pavements because smaller cracks are required to separate the aggregate particles [114]. Requiring a sufficiently large top size can avoid this reduced load transfer at cracks and joints [112]. Concerns have been raised that the abrasion of the adhered mortar during the sieving process to measure gradation could alter the gradation of the aggregate itself, resulting in a higher number of smaller particles being measured by the test than are actually present in the sample [115].

2.1.3 Strength and Stiffness

The strength and stiffness of RCA itself (not the concrete it produces) are generally accepted to be lower than that of virgin aggregate [116] and more variable [106]. This is mainly attributed to the presence of the adhered mortar, which has less strength and stiffness than aggregate and reduces the overall strength and stiffness of the RCA. Strength and stiffness are not commonly tested properties for aggregate due to the difficulty of testing and variability among individual aggregate particles [117], so the lack of data on RCA strength and stiffness is not surprising. The strength and stiffness of the RCA will depend on the strength and stiffness of both the paste and aggregate used in the parent concrete [116].

2.1.4 Porosity and Absorption Capacity

Many of the differences in aggregate properties between RCA and virgin aggregate can be directly attributed to the increased porosity and associated absorption capacity of RCA that results from the adhered mortar. Absorption capacity is generally less than 12% for RCA (compared to less than 3% for virgin aggregate) [10], with common absorption capacity values for RCA around 4-7% [105,118]; however, values as high as 20% have been reported [10]. It has been suggested that limiting absorption to less than 5% is desirable. This requires limiting mortar content to 26-39% mortar, depending on which test method is used to measure mortar content [107].

One study found that using traditional methods to measure absorption capacity in RCA underestimates the absorption significantly because the time period for water to absorb into the adhered mortar is insufficient. However, there is also concern that soaking the RCA in water could hydrate any remaining unhydrated cement particles present in the RCA, leading to a denser mortar than is present in the stockpile aggregate and subsequent underestimation of the absorption capacity [119]. The subjectivity associated with determining the saturated surface dry state in standard absorption capacity tests (such as ASTM C127 [120]) is also a concern [121]. Some proposed solutions have included a three month soaking time frame [115] or use of a helium [119] or vacuum pycnometer [115] to measure absorption capacity. These suggestions may be found impractical due to the lengthy time requirement and specialized equipment needed.

The porosity and absorption capacity of the RCA is a function of the properties of the parent concrete. Different mix designs for the parent concrete will result in different levels of porosity and pore sizes. Parent concretes with high strength due to either a lower water/cement (w/c) ratio or the use of supplementary cementitious materials like silica fume have been found to result in denser adhered mortar with lower porosity, and therefore produce lower porosity and absorption capacity RCA [108]. Also, the crushing process use to produce RCA can result in cracks in the RCA, which increase its porosity [122].

The higher absorption capacity of RCA results in higher amounts of mix water or admixtures being required to maintain workability [10]. Higher absorption also leads to faster slump loss, even when admixtures are used for workability [101]. Pre-saturating aggregates has been suggested as means of mitigating these issue [9,10,101], and this is currently standard practice in several states that use RCA [12] even though some producers find this impractical. One study comparing concrete made with pre-saturated RCA to concrete made with RCA that was added in the stockpile state found that pre-saturation had little effect, as long as moisture corrections were properly accounted for in mix design [123]. This may be because RCA can absorb water quickly, though there is no consensus on the rate of the absorption. Times to reach a certain percentage of the maximum absorption capacity range include

70% in 10 minutes [124], 85% in 30 minutes [125], and 90% in either 5 minutes [88,123] or 24 hours [125]. Another study found that using RCA in a saturated surface dry condition could actually reduce mechanical properties compared to air-dry RCA with proper moisture corrections made during mix design [126]. It has also been suggested that using fly ash as a supplementary cementitious material may counteract some of the decreased workability associated with using RCA [86]. Other methods used with traditional concrete to increase workability without increasing water demand, for example using superplasticizer [127], can also be used with concrete made with RCA.

There are a few advantages to the higher absorption capacity associated with RCA. Neville has suggested it could be used for internal curing [8] and this has been found to increase durability in concrete made with RCA [128] and decrease shrinkage in concrete made with crushed returned concrete [129], which is similar to RCA. The higher absorption capacity of RCA also results in decreased bleeding of the concrete, provided extra water is not added to increase workability [30]. The extra mortar on the RCA has been found to absorb the film of water that normally forms around aggregate particles and causes a localized high water/cement ratio and weaker ITZ. If the correct amount of water is absorbed, this effect can be mitigated, resulting in a denser ITZ; however, if too much water is absorbed, the hydration products end up more spaced out and cause a more open or looser ITZ [108]. One study found that the rough texture associated with the coarse RCA, as a result of their high porosity, provided a higher content of hydration products in the pores of the aggregate, which in turn lead to densification of the ITZ, and thus an improvement of the final performance of the final concrete [57,58].

A two-stage mixing process has been used to combat extra absorption, which has been done in multiple ways by different researchers. Li et al. [130] coated the RCA with a cement paste slurry before adding the fine aggregate, with the theory that the slurry would fill any voids in the RCA with paste. The ITZ of concrete made with this two-stage mixing process had less porosity, more C-S-H, and fewer CH crystals compared to concrete made with standard mixing practices. This was attributed to a thinner layer of water forming around the RCA particle than would normally be expected, because the remaining water was contained in the slurry that filled the cracks and voids in the RCA. The researchers also observed a dense zone of calcium carbonate that formed between the old and new ITZs, which they believed was due to the surface carbonation of the RCA. The resulting concrete had higher strength and durability.

Similarly, Tam et al. [131] used a two-stage mixing process with a different mixing procedure but the same goal of filling the voids and microcracks in the original mortar adhered to the RCA. The RCA and fine aggregate were mixed with half the mix water, then the cement was added, then the remaining mix water. This method seems to combine aspects of pre-wetting the RCA and coating the particles with the cement slurry. Improvements in the quality of both the old and new ITZ were found, resulting in improved concrete properties.

2.1.5 Density

In general, the density of RCA is lower than that of virgin aggregate [6], with a difference on the order of 5% [96]. This difference is due to the presence of the adhered mortar on the RCA particles, which is more porous. Typical values of specific gravity for RCA are between 2.0 and 2.5 [112]. Because of differences in density between RCA and virgin aggregate, any substitutions must be made on the basis of volume, not weight [10].

The density of the concrete decreases as RCA content increases due to the lower specific gravity of the RCA [10,132]. This is shown in Figure 2.1, which shows the density of concrete when various amounts of virgin coarse aggregate are replaced with RCA. All values plotted are taken from the literature and represent a range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results.

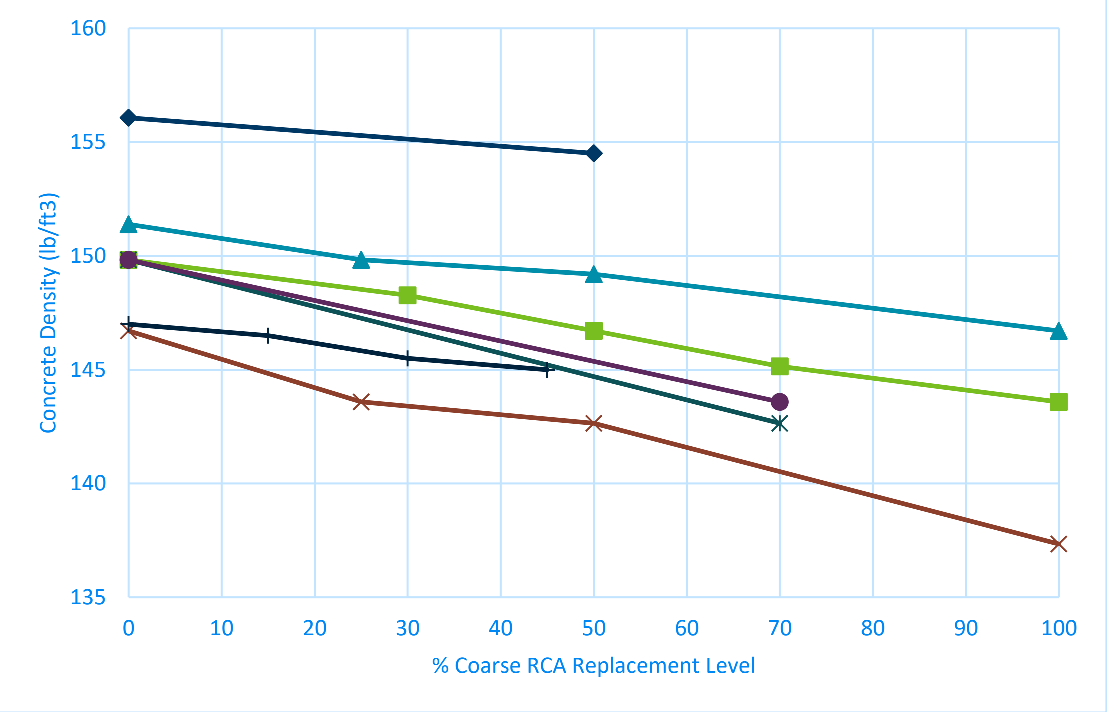

Figure 2.1: Effect of RCA replacement level on concrete density [25,27,69,73,85–87]

2.1.6 Aggregate Durability

Aggregate durability can be measured by a number of metrics, such as sulfate soundness, alkali-silica reactivity (ASR) resistance, and degradation factor [86]. The most common metric cited in the literature for measuring aggregate durability of RCA is the Los Angeles (LA) Abrasion Loss test [133], though some agencies use the Micro-Deval test [134] instead [116,135]; aggregate porosity is also a good indicator of durability [6]. ASR testing is also recommended if ASR was a concern in the parent concrete [86], see Section 2.4.5 .

As discussed in Section 2.1.3 , most RCA is significantly more porous than virgin aggregate due to the presence of adhered mortar. Though most RCA is found to have a higher LA abrasion loss coefficient than virgin aggregates [6,105,114], the LA abrasion coefficient of RCA is generally still less than the 40% considered acceptable by many agencies [105]. The reduced LA abrasion coefficient is likely due to the presence of adhered mortar, which is weaker than aggregate and may separate from the original aggregate during testing [40]. One study suggests that RCA composed of less than 44% adhered mortar is required to achieve an acceptable LA abrasion coefficient of less than 40% [107]; as discussed in Section 2.1.1 , most RCA meets this mortar content limit [108].

While many state agencies require virgin aggregates to pass a sulfate soundness test as part of durability testing, RCA often fails this test [114] because the sulfate reacts with the adhered mortar, resulting in excessive mass loss [136]. Some European standards recommend using a magnesium soundness test rather than a sulfate soundness test to resolve this issue [15], while some state DOTs simply waive the sulfate soundness test requirement all together [114]. Specific gravity and absorption criteria have also been found to be poor predictors of RCA durability [136].

2.1.7 Shape and Surface Texture

Aggregate shape can influence both the workability and strength of concrete. RCA can have an angular [114] or rounded shape [137], depending on how it is processed. Angular shapes create a harsher mix [114], while rounded shapes result in increased workability [137], though this increase in workability is often overpowered by the decrease in workability due to the higher absorption capacity of RCA (see Section 2.1.3). This results in an overall loss in workability unless adjustments are made to the mix or mixing procedures. If the crushing process results in an angular shape, this may contribute to concrete strength [112], though other factors decreasing strength may negate this benefit (see Section 2.1.7). The crushing process generally results in few flat and elongated particles [101].

RCA generally has a large number of fractured faces due to the crushing process, but this is partially dependent on the aggregate used in parent concrete [105]. Particles typically have a rougher surface texture [6,114] and a porous appearance due to the presence of adhered mortar [105].

2.2 Fresh Properties

The main fresh properties of concern when specifying concrete or ensuring quality control are air content, workability, and temperature. While concrete temperature is very important, it should not be affected by the use of RCA and is not often measured or reported in the literature. However, the unique characteristics of RCA, in particular its increased porosity and absorption capacity, can have an effect on air content and workability.

2.2.1 Air Content

Appropriate air content is needed to ensure freeze-thaw durability of concrete. Air content is typically measured in the field by the pressure method [138]. A study that compared the volumetric and pressure methods for measuring air content found that both test methods yielded similar results, indicating that the more commonly used pressure method can be used on concrete made with RCA [113]. However, the numeric value of air content provided by the pressure method cannot distinguish between entrained and entrapped air, nor can it estimate the spacing factor of air void system [9]. Concern has also been expressed that the standard air content test measures total air content, not just the air content of the new paste [111], though others claim that the hardened air content does not correlate well with fresh air content for concrete made with RCA, because only air content of the new paste is being measured [57]. The gravimetric air content method could prove less accurate when used with RCA because of the higher variability of RCA, and therefore increased difficulty of accurately characterizing the specific gravity of the aggregate needed for computations [109].

The super air meter (SAM) [139] is a test aimed at providing additional information on the air void system in the concrete that uses a modified standard air test apparatus with sequential pressurization to higher pressure levels. The resulting SAM number can characterize the quality of the air void system without the need for a hardened air content test. This is a relatively new test and proper training is required because most people are unfamiliar with it. In a trial use of the SAM during construction, it was found that 46% of tests were likely performed incorrectly after the contractor received training on the SAM but was otherwise unfamiliar with it [140].

There is little information in the literature on the use of the SAM test on RCA concrete, likely because the SAM test is not yet in widespread use. The AASTHO performance specification for concrete calls for either an air content of 5-8%, or an air content of at least 4% and a SAM number less than or equal to 0.20 [141]. Further research will be required to determine if the SAM number of concrete made with RCA has similar concerns related to the effect of adhered mortar as the traditional air content test does.

2.2.2 Workability

The workability of concrete is a measure of its ability to be placed, and is important to ensure constructability. RCA has been found to decrease slump due to the higher absorption capacity, angularity, and rougher surface texture of RCA [52,111]. Slump decreases as the RCA replacement level increases [86]. Additional water reducer may be required to achieve the same level of slump for concrete made with RCA, as seen in concrete made with virgin aggregate while maintaining w/c ratio and workability. Alternately, 5-15% additional water can be added to maintain the slump [85], but this will have the standard negative effects on strength and durability typically associated with higher w/c. It has also been suggested that fly ash can be used to improve workability of concrete with RCA rather than increasing w/c ratio [52].

Workability of concrete has traditionally been measured with the slump test [142]. There is no indication in the literature or theoretical reason why the slump test would produce different results for RCA concrete. Aggregate characteristics that change the slump (such as aggregate gradation, shape, and surface texture) may be different for RCA than virgin aggregates and would likely therefore have the expected effects on slump as using virgin aggregates with the same characteristics.

Though the slump test is common throughout industry, there are concerns that this test does not always provide meaningful information [143]. Concrete pavements in particular need more information than the slump test can provide, including how well the concrete will hold an edge and how it will respond to vibration [144]. The box test [145] can be used to determine both of these characteristics and is part of the suite of tests used for performance engineered mix design [141].

The box test has been used on mixes containing RCA to evaluate the test method, but results were not provided in the literature [12]. As with the slump test, there are no theoretical reasons why this test would not work equally well on RCA as on virgin aggregates. Similarly, the same aggregate characteristics that could change the results of the box test (such as aggregate gradation, shape, and surface texture) for concrete made with virgin aggregates [146] would be expected to have the same effects for concrete made with RCA.

2.3 Mechanical Properties

Because RCA parent concrete properties have such a large effect on new concrete properties, RCA concrete will have more variation than concrete made with virgin aggregates [7]. Higher strength and higher quality concrete tends to have larger reductions in mechanical properties when RCA is used than lower strength/quality concrete do [147]. Additionally, traditional relationships between strength properties, for example the correlation between compressive and tensile strength, may not hold for concrete made with RCA [148]. The high absorption capacity of the paste also makes determining the water demand of the RCA difficult, which introduces additional variability to strength properties dependent on w/c ratio [114]. Standard ASTM/AASHTO test procedures for mechanical properties such as compressive, flexural, and split tensile strength can still be used for concrete made with RCA [112].

2.3.1 Compressive Strength

Concrete compressive strength is the most common metric used to characterize concrete, even if it is not the most important parameter for the design of a specific element. Compressive strength is easy to measure and is therefore often correlated with other properties needed in design, such as stiffness. RCA replacement level and the mortar content of the RCA are two of the main factors influencing the compressive strength of concrete made with RCA.

Compressive strengths of concrete containing RCA are typically lower than those of concrete made with virgin aggregates, though the amount of RCA has an influence on the compressive strength of concrete [6,7,9,116]. The strength properties of the parent concrete from which the RCA was derived will also influence the compressive strength of the new concrete [8], but it is possible to compensate for low strength RCA to produce a new concrete with strength higher than that of the parent concrete [149,150].

Figure 2.2 shows the effect of RCA replacement level on compressive strength for 68 different mixes. The ordinate on this graph is the compressive strength ratio, which is the compressive strength of a given RCA replacement level divided by the control compressive strength where no RCA was used. All values plotted are taken from the literature and represent a wide range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results. From this figure, it can be seen that most mixes follow the expected trend of decreasing compressive strength with increasing RCA replacement level. The magnitude of this decrease varies greatly. There are also several instances where compressive strength increased with RCA use, and a few studies where there was both an increase and a decrease in compressive strength, depending on the RCA replacement level.

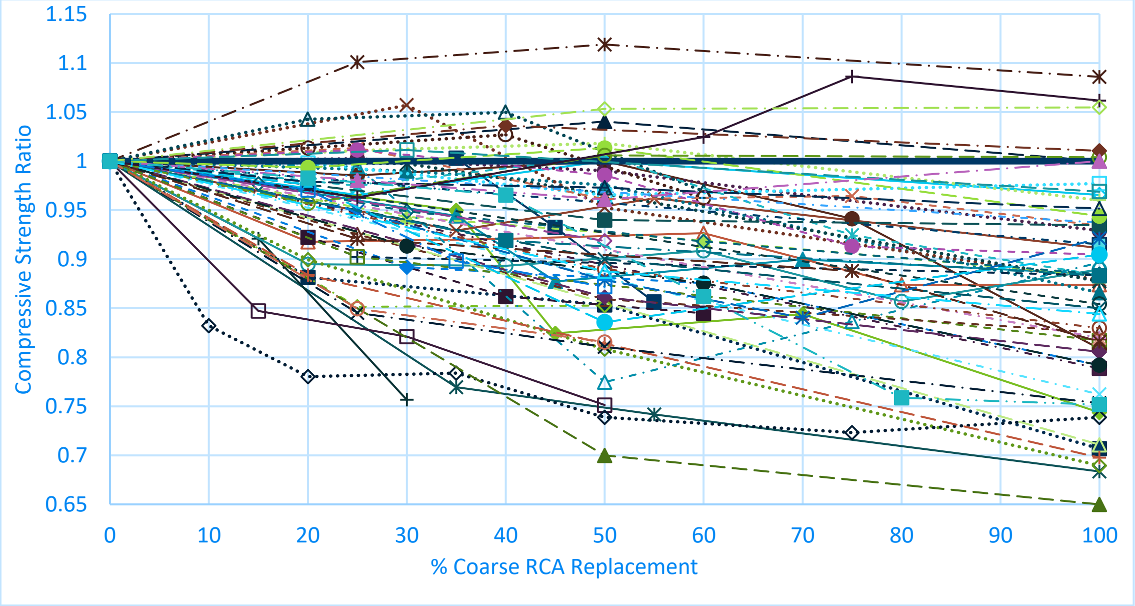

Figure 2.2: Effect of RCA replacement level on compressive strength [17–84]

This figure also shows that most studies considering a moderate to low replacement level used 20 or 25% replacement as their lowest replacement level. At these low levels, most studies found reductions in compressive strength on the order of 10 to 20%. For studies that found an increase in compressive strength with RCA use, low replacement levels were associated with strength increases on the order of 5 to 10%.

Many of the studies shown in Figure 2.2 focus on compressive strength at the traditional 28-day mark or earlier. In looking at longer term strength, the lower strengths observed in RCA concrete at 28 days were mostly recovered by the age of 120 days, which can be attributed to hydration of the adhered mortar on the RCA and a potential internal curing effect from the increased absorption of the RCA [96]. However, it has also been found that not all mixes achieve the same long term strength gains [108].

There are several theories as to why compressive strength is typically lower, though in general, the type of RCA and the replacement level are considered to have the largest impact on strength [10]. Possible reasons for lower compressive strength in concrete made with RCA include:

- The strength of recycled aggregate is typically lower than that of natural aggregate [151].
- Concrete made with RCA has a lower amount of natural aggregate in the concrete compared to a concrete made with the same volume of virgin aggregate because the RCA is composed of both aggregate and adhered mortar, and the adhered mortar therefore occupies some of the volume traditionally occupied by the aggregate phase [114].

- RCA typically has higher porosity, and lower LA abrasion resistance, which are generally associated with lower quality aggregate where lower performance would be expected [10].

- There is a lower bond force between recycled aggregates and new cement paste compared to that between virgin aggregate and new cement paste [151], though if the RCA has a rough texture, it is possible to achieve a bond that does not decrease strength [152].

- Concrete made with RCA generally has a higher air content, which is associated with lower compressive strength [114].

- RCA introduces a second ITZ (as discussed in Section 2.1) and the ITZ is generally the weak link in concrete [10]. However, it has been suggested that the RCA will only decrease the strength of the concrete if the new ITZ between the RCA and the new paste is stronger than the ITZ between the original aggregate and the adhered mortar in the RCA [153].

- The accumulation of cement paste on the surface of the RCA aggregates produces a locally low w/c ratio and effectively introduces another interfacial transition zone [40].

- The large variability in RCA also has an effect on compressive strength, with concrete made with RCA found to have double the coefficient of variation as concrete made with virgin aggregate [10].

- Concrete made with RCA, particularly at replacement levels in excess of 50%, produces a less cohesive mix, which could make it harder to properly cast samples [126].

As seen in Figure 2.2, there are several instances where concrete made with RCA had higher compressive strength than that made with virgin aggregate. There are several reasons why the concrete made with RCA could have resulted in higher strength:

- If the researchers are not doing moisture corrections and the RCA absorbs a significant portion the mix water, this would create an effectively different and lower w/c ratio than the control concrete to which they are comparing [10,27].

- RCA concrete can gain strength faster than concrete made with virgin aggregate [40], which could result in RCA concrete appearing to have a higher strength than the control concrete in the short term. This could also be due to effectively different w/c ratios (see above), which would be expected to result in faster strength gain.

- Some mixes actually experience improvements in the ITZ when RCA is used [88].

- Concrete produced with RCA from high performance parent concrete could have paste that is weaker than the adhered mortar on the RCA, so the RCA would no longer be the weak point in the system [108].

- The unhydrated cement in the RCA could hydrate in the new concrete, effectively increasing the overall cement content and therefore the strength [88,109].

There is also a body of research focused on ways to improve either RCA or the concrete made from RCA so that it behaves more like concrete made with virgin aggregates. That work is outside the scope of this literature review. However, it is interesting to note that if RCA replacement is used at levels high enough to decrease the properties of the concrete, such as the strength, it may result in higher cement content to offset this decrease in properties. This decreases the environmental benefits associated with using RCA because of the high environmental impact of cement. It also could increase overall costs [10].

2.3.2 Stress-Strain Behavior

The stress-strain relationship of concrete provides significant insight into the behavior of concrete but is not often investigated because of the difficulties in measuring it. Because of the effects of RCA, traditional models for predicting stress-strain behavior may need to be adjusted to account for the presence of RCA [124].

In one experiment [154], five w/c ratios and replacement rates of RCA from 0 to 60% were tested to determine the uniaxial stress-strain behavior. They found that the shape of the stress-strain curve for concrete made with RCA was very similar to that of concrete made with virgin aggregates, though the RCA concretes all had a lower peak stress. Additionally, the peak stress in the RCA concrete often occurred at a slightly higher strain level than in the control concrete. Other researchers have found similar results of a lower peak stress but higher associated strain level and a very comparable curve shape that is shifted slightly to the right [25,96,124]. Changes in the stress-strain behavior were more pronounced when higher replacement levels of RCA were used [124]; as recycled content increased, peak stress decreased but the shift to the right also became less pronounced [154]. The differences in stress-strain behavior between concrete made with virgin versus recycled aggregate were attributed to the presence of microcracks in the original mortar adhered to the RCA [154] and the reduced stiffness of RCA compared to virgin aggregate [124].

While some researchers observed higher strains for lower RCA replacement levels with the peak strain shifting back towards a similar value of strain as the control concrete for more moderate replacement levels [154], others have found that the strain at peak stress increases with RCA content for all replacement levels [25,96]. No similar pattern was observed for the ultimate strain (defined as the strain at 85% of the peak stress), though higher RCA replacement levels were associated with an overall decrease in ductility [25].

2.3.3 Modulus of Elasticity

The elastic modulus is a measure of stiffness of the concrete and is an important parameter in determining both how load is distributed in the pavement and how much a deflection a pavement will experience during loading. A lower modulus results in lower tensile stresses, which can improve fatigue resistance, but higher deflections, making pumping and faulting more likely to be a concern [114]. Replacing virgin aggregate with RCA generally results in a decrease in stiffness on the order of 20-45% [10,106,114], though larger reductions can be seen.

Figure 2.3 shows the effect of RCA replacement level on elastic modulus for 30 mixes. The ordinate on this graph is the elastic modulus ratio, which is the elastic modulus of a given RCA replacement level divided by the control elastic modulus when no RCA was used. All values plotted are taken from the literature and represent a range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results. From this figure, it can be seen that most mixes follow the expected trend of decreasing elastic moduli with increasing replacement level, though a few mixes experienced modest gains in stiffness or had no appreciable change.

Looking at the low to moderate replacement levels in Figure 2.3 (20-30%), it can be seen that most decreases in elastic modulus were on the order of 5 to 15%, though some tests found much more significant reductions in stiffness.

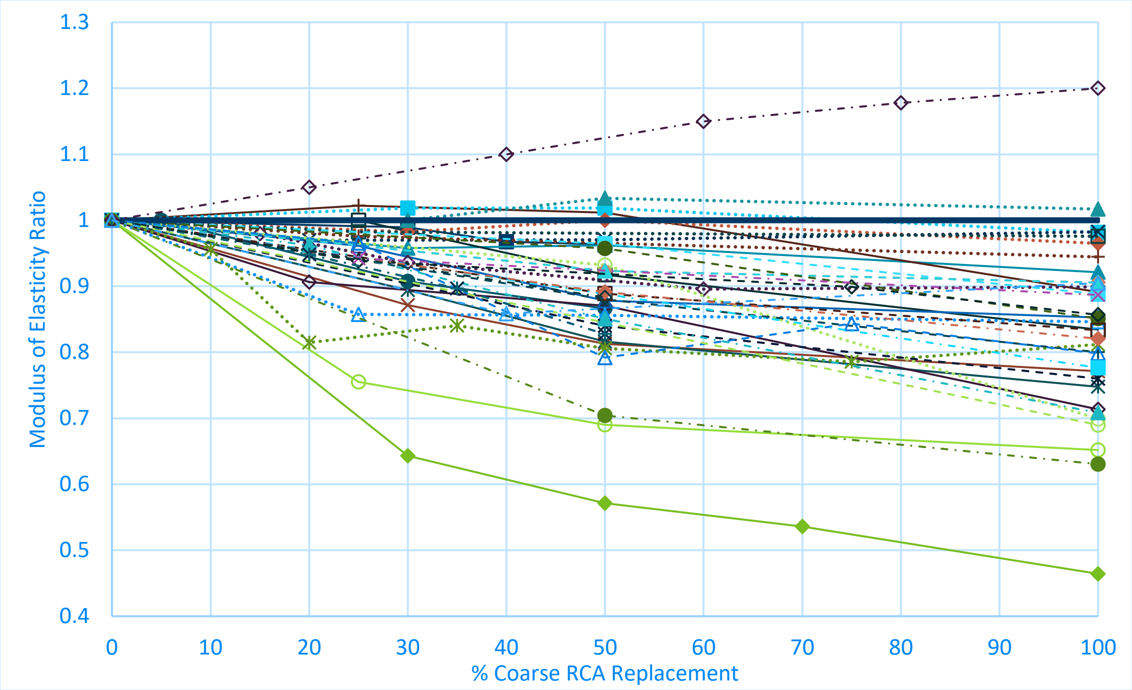

Figure 2.3: Effect of RCA replacement level on elastic modulus [18,24–30,33,34,38–40,47,50,56,58,63,73,74,82–84,93,96–99]

Lower elastic moduli for concrete containing RCA has been attributed to the lower elastic modulus of the RCA itself [114], which is due in part to the higher porosity of RCA [77] and the weaker ITZ [40]. A higher fraction of adhered mortar can exacerbate the reduction in concrete modulus [10]. In instances where the elastic modulus remained relatively constant despite the use of RCA, it is possible this could be due to how the RCA replacement was made. If coarse aggregate is replaced with RCA on the basis of weight, not volume, there will actually be more coarse aggregate present relative to paste in the mix containing RCA relative to the control mix [77]. Even though RCA is generally less stiff than virgin aggregates, both are typically much stiffer than paste and the elastic modulus of the concrete depends on volumetric proportions of the paste and aggregate as well as their individual stiffnesses [8]. Therefore, the larger volume of RCA could be partially compensating for its lower stiffness level, resulting in a negligible change in the overall concrete stiffness [77].

Traditional relationships between concrete strength and elastic modulus may not hold for concrete made with RCA. One study [155] looked at several relationships from the literature for predicting elastic modulus from compressive strength and found that modification was required to improve these relationships for concrete made from RCA. It should be noted that this study focused mainly on relationships from European literature that are based only on compressive strength of the concrete. The relationship typically used in the United States from ACI 318 [156] also includes a term for unit weight of the concrete, which is known to be lower for concrete made from RCA (see Section 2.1.5)

2.3.4 Poisson’s Ratio

Poisson’s ratio is a measure of the lateral strain relative to axial strain experienced during loading. In concrete pavement design, Poisson’s ratio is used to compute the radius of relative stiffness and is a parameter for both cracking and faulting computations, but is often an assumed value because it does not cause much variation in predicted results [157]. One study found that Poisson’s ratio increases slightly with increasing recycled content [96] while others found that mixtures containing RCA had slightly higher [113] or lower [27] values of Poisson’s ratio than concrete with only virgin aggregate, but no specific correlation with RCA content.

2.3.5 Split Tensile Strength

Split tensile strength of concrete is an indirect measure of the tensile strength of concrete and is used to determine when concrete will crack. This value is an input in some mechanistic-empirical pavement design models [157]. Replacing virgin aggregate with RCA typically reduces tensile strength by less than 10% [7,116], though reductions up to 20% [7] or higher can be seen.

Figure 2.4 shows the effect of RCA replacement level on split tensile strength for 26 mixes. The ordinate on this graph is the tensile strength ratio, which is the split tensile strength of a given RCA replacement level divided by the control tensile strength when no RCA was used. All values plotted are taken from the literature and represent a range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results. From this figure, it can be seen that many studies show the split tensile strength of concrete is found to decrease with the increase in RCA replacement level. These decreases can be greater than the typically assumed 10% value, but many are within that range. Reductions in split tensile strength are generally less drastic than those in compressive strength for similar RCA replacement levels. There are also several studies that show an increase in split tensile strength when RCA is used.

Of the studies that considered low and moderate levels of RCA replacement, most found moderate reduction in strength (<10%) though some also found increases in strength of this magnitude. The majority of the studies represented in Figure 2.4 are for tests at the standard 28-day mark. However, it has been found that the effect of RCA on split tensile strength is most noticeable at early ages (up to 28 days) and that by 90 days, RCA effect is negligible [10].

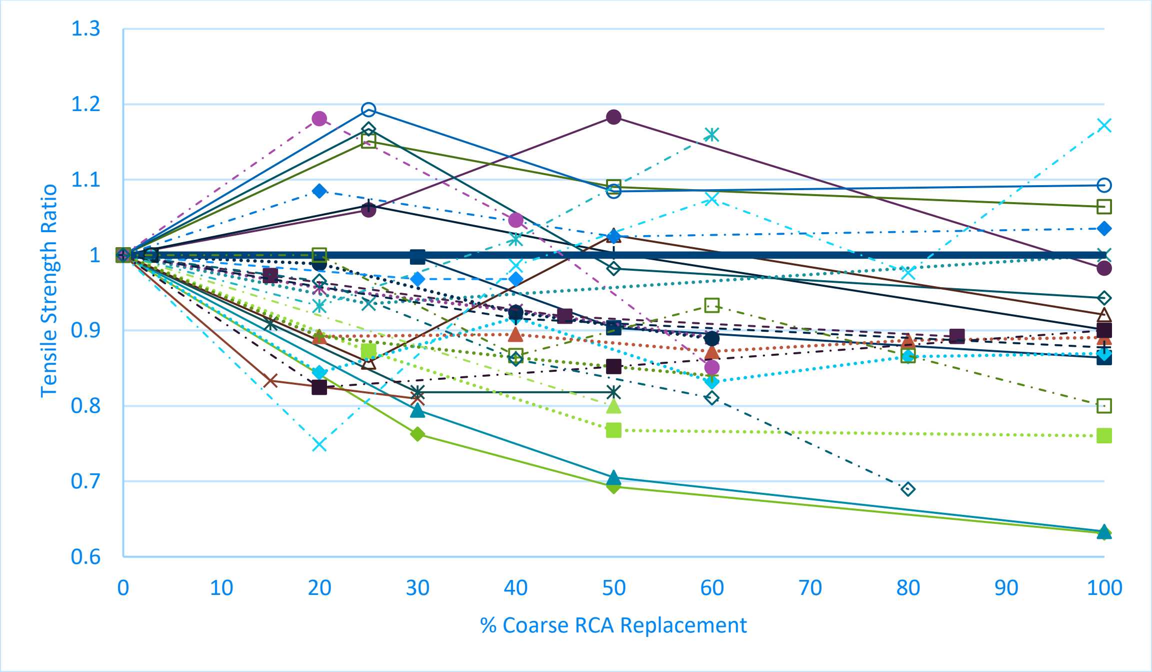

Figure 2.4: Effect of RCA replacement level on tensile strength [17,18,24,26,27,29,30,33,34,36,38,39,61,63,74,82,92,93,97]

While the reduction in tensile strength may stem from many of the same factors that result in reduced compressive strength, it has been observed that both the aggregate itself as well as the adhered mortar fracture during tensile testing of concrete made with RCA [40]. In comparison, concrete made with virgin aggregates tends to fracture along the ITZ and not through the aggregates, suggesting that the aggregate itself may somehow be compromised, perhaps in part due to the crushing process.

2.3.6 Flexural Strength

Concrete pavements carry load in flexure, so the flexural strength (also called the modulus of rupture) is a major parameter used in pavement design. The presence of RCA is not generally considered to decrease flexural strength significantly [7], though large decreases can be found in the literature. Typically, flexural strength of concrete made with RCA is expected to be less than 10% lower than that of conventional concrete [7,112].

Figure 2.5 shows the effect of RCA replacement level on flexural strength for 28 mixes. The ordinate on this graph is the flexural strength ratio, which is the flexural strength of a given RCA replacement level divided by the control flexural strength when no RCA was used. All values plotted are taken from the literature and represent a range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results. From this figure, it can be seen that concrete made with RCA generally experiences a decrease in flexural strength on the order of 10-15%, though some researchers found greater decreases in flexural strength and some found modest increases. For mixes that experience a larger decrease in flexural strength, larger RCA replacement levels result in a larger decrease in flexural strength; mixes with a lower decrease in flexural strength seem to be less affected by RCA replacement level. Of the studies that considered low and moderate levels of RCA replacement, flexural strength decreases were still in the order of 2-5%, though some saw greater reductions.

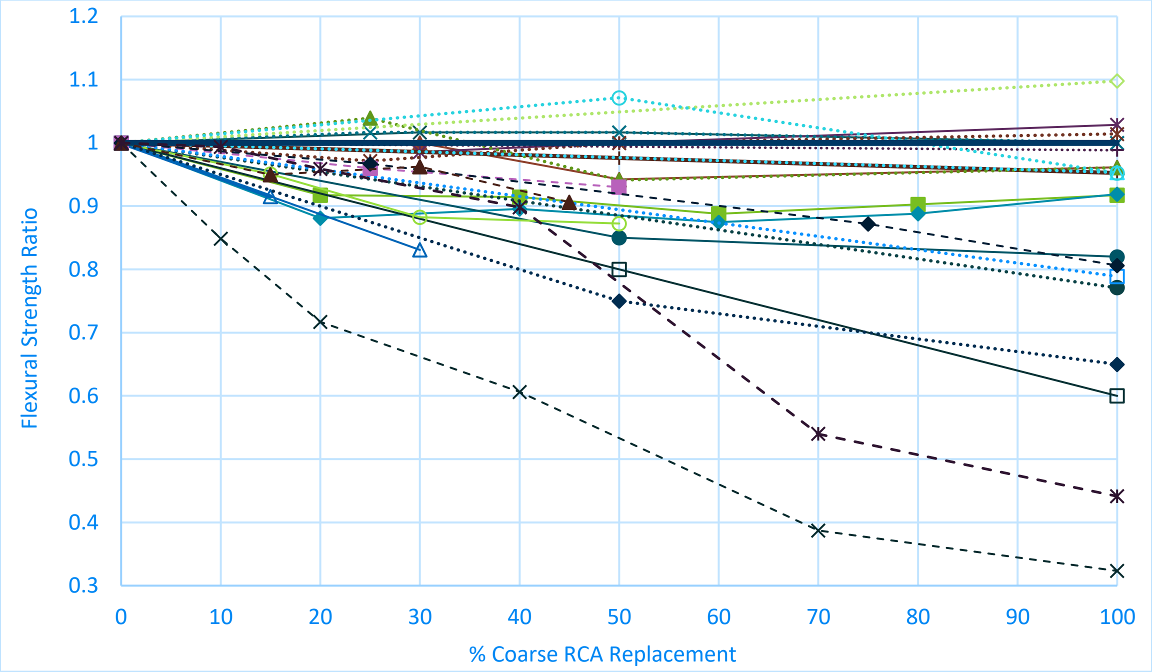

Figure 2.5: Effect of RCA replacement level on flexural strength [18,23,26,29,41,47,54,59,63,76–80,82,92–95]

In addition to the factors discussed in Section 2.3.1 for reduction in compressive strength, there are several theories on why concrete made with RCA had lower flexural strength specifically than concrete made with virgin aggregate. The lower tensile strength of the RCA concrete (as discussed in Section 2.3.5) may contribute because flexure includes both tension and compression [71,158]. Additionally, flexural strength depends on paste-aggregate bond strength and concrete made with RCA has two sets of those bonds (between the RCA aggregate and the new paste, and within the RCA aggregate between the adhered mortar and the original aggregate); these bonds each have different properties [114]. In concrete made with only partial RCA replacement, there would an additional set of bonds between virgin aggregate and the new paste, with a still different set of properties. One study also noted that the reduced flexural strength was most notable at early ages (up to 28 days), but that differences in flexural strength between concrete made with RCA and concrete made with virgin aggregate were negligible by 90 days [10].

2.3.7 Coefficient of Thermal Expansion

The Coefficient of Thermal Expansion (CTE) is a material property that quantifies the relationship between change in length and temperature variation. The aggregate CTE plays a large role in determining the overall concrete CTE because aggregates make up such a large portion of the concrete volume [8]. Higher CTE can lead to more curling [103] and lower load transfer efficiency [111], which can both cause more mid-slab cracking in jointed plain concrete pavements [114]. CTE is a parameter in mechanistic empirical pavement design and an understanding of how the CTE of concrete changes when RCA is important, particularly for accurately predicting fatigue cracking [121].

It has generally been found that using RCA decreases the CTE of concrete [57,86,159,160]. Higher levels of RCA replacement can be associated with lower CTE values [159], though there is no definitive trend because of the large variability in parent concrete of the RCA [160] and it has been found that RCA use can result in a higher concrete CTE [82,111,161]. At low replacement levels (<30%), the presence of RCA has been found to decrease CTE slightly, but values remained within the normal range for standard concrete [86].

The overall contribution of RCA to CTE likely depends in part on the adhered mortar content, with a lower mortar content causing a lower CTE [111]. While the lower CTE stemming from RCA use should be associated with better pavement performance [103,111,114] and mechanistic-empirical pavement modeling predicts it will, this was not found to play out in field studies [159].

2.4 Durability Properties

The durability of concrete is its ability to resist degradation from the environment and chemical attack. It is greatly dependent on porosity and permeability of the mix. When RCA is used, the durability of both the parent concrete and the new paste contribute to the overall concrete durability. In general, more durable parent concrete will produce more durable new concrete.

2.4.1 Porosity and Permeability

Permeability is the ease or difficulty with which water flows through concrete. While porosity and permeability are inter-related, they differ in that permeability is dependent on the level of interconnectedness and tortuosity of the pore structure while porosity is simply a measure of the volume of the pores. Because so many durability distresses are related to the ability of water to enter and move within the concrete, permeability is one of the main drivers of concrete durability. Broadly speaking, concrete made with RCA can be considered to have two to five times more permeability that concrete made with virgin aggregates [7].

When discussing permeability, it is important to understand what exactly permeability tests are measuring. While concrete permeability is often characterized by rapid chloride permeability testing [162] and more recently by its electrical resistivity [163], these tests do not actually measure permeability [164]. Resistance to chloride ingress is just one of several durability factors that depend on concrete permeability. Several researchers measured the actual permeability of concrete via water immersion and capillarity [88,165] and others have devised additional, less common methods [122]. ASTM C642 [166] can also be used to characterize the bulk absorption of the concrete, which could provide additional insights into its permeability [164].

Water immersion tests on mixes made with RCA were found to absorb more water after curing than those made with virgin aggregates, though the increase depended on both the RCA source and replacement level [88,165]. One study [165] found that RCA replacement levels of 25% or less produced concrete with water absorption levels similar to those of virgin concrete, though another study found this depended partially on curing condition [88]. Capillary water absorption has been found to decrease for mixes with 10% RCA regardless of the RCA source, but then increased significantly (up to 45%) with higher RCA replacement levels [165]. Others have found a more proportional relationship between RCA content and capillary water absorption [88].

The increased permeability of concrete made with RCA is mainly due to the increased porosity of the RCA stemming from the presence of adhered mortar [7,8]. Additional factors affecting permeability include the particle size of the RCA, with larger particle sizes resulting in more permeable concrete [167] and the presence of cracks and fissures in the RCA due to the crushing process, which could create additional pathways for fluid movement [122]. The use of SCMs like fly ash can improve permeability of concrete made with RCA because the additional hydration products from the pozzolanic reaction can help to fill in pores [167].

2.4.2 Chloride Ingress and Resistivity

Chloride ingress refers to the depth to which chloride ions can penetrate concrete. The presence of chloride ions can exacerbate corrosion of reinforced concrete elements such as dowel and tie bars. While chloride ingress in new concrete is generally directional from exposed surfaces inward, when concrete is made with RCA whose parent concrete contains chlorides, those chlorides are then introduced throughout the new concrete. The chloride content of the original concrete can accelerate corrosion of new steel [8,114] and there is concern that high levels of chlorides could interfere with set time and/or change the behavior of chemical admixtures in the new concrete [113]. Using RCA increases the potential for chloride penetration because of increased concrete porosity due to the adhered mortar on the RCA [153].

Use of RCA in new concrete has been found to increase the chloride diffusion coefficient of concrete [88,165,167], with increasing RCA content resulting in decreased resistance to chloride penetration [88]. One study found that an RCA content of 30% did not significantly change rapid chloride permeability test values, but higher RCA contents still resulted in worse performance [113]. In general, the effect of using RCA for full or partial replacement was quite variable, depending on the RCA source [165]. RCA decreased the chloride resistance of the concrete regardless of RCA quality or source, but the magnitude of the increase did depend on the RCA characteristics [167].

Resistivity is being recognized as an alternative test to the more traditional rapid chloride permeability test for providing insight into the diffusivity of concrete. The resistivity test runs more quickly and correlates well with the rapid chloride permeability test. This correlation holds for concrete made with RCA and plain cement, but breaks down when fly ash is also used [113]. Lower values of resistivity indicate the concrete is more porous. It has been found that resistivity decreased as the RCA replacement level increased [113,152]. Depending on the type of RCA used, some concretes made with

RCA can still meet the criteria for very low [12], low or moderate [113,152] chloride permeability based on resistivity values, but high RCA replacement levels can also result in resistivity values associated with high risk of chloride permeability [113,152]. Electrical resistivity increased with age for all RCA replacement levels [57].

The higher porosity of RCA that results in more permeable concrete is responsible for the decreased resistance to chloride penetration observed in concrete made with RCA compared with concrete made of virgin aggregates [88]. The increase in the diffusion coefficient could also stem from the higher w/c ratio used to compensate for the higher water demand of the more permeable RCA [165]. Higher permeability can also lead to lower electrical resistivity, as can cracks in the adhered mortar, ionic contamination, and the lower quality ITZ associated with RCA [57].

As with conventional concrete, better curing results in a denser microstructure and more resistance to chloride ingress. Concrete made with RCA was found to more sensitive to curing regime than concrete made with standard aggregates [88]. Resistance to chloride penetration can be improved by decreasing w/c ratio, using SCMs, and curing the concrete for a longer time [167]. RCA from higher quality parent concrete is associated with better performance on resistivity testing, regardless of replacement level [152]. A two-stage mixing method similar to those discussed in Section 2.1.3 can also be used to mitigate the decreased chloride penetration resistance associated with using RCA [153].

2.4.3 Freeze-Thaw Resistance

Freeze-thaw resistance is an important factor for pavement durability in cold climates and is a function of the air void structure of the concrete. While air entrainer is often used to create an air void system to resist the effects of freeze-thaw cycles, some aggregates are also susceptible to freeze-thaw damage. This damage manifests itself as D-cracking and is not mitigated by air entraining [168]. When exploring how RCA affects freeze-thaw resistance, it is important to consider both the paste and aggregate fractions of the RCA.

Proper air void structure is critical for ensuring freeze-thaw durability of the paste. When RCA is used in concrete, the air void system of both the adhered mortar on the RCA and the new paste impact overall resistance to freeze-thaw damage [8,101]. The air content of concrete made with RCA is more variable and tends to be higher because of the increased porosity of the adhered mortar fraction [114].

There is no consensus on the effect of RCA on freeze-thaw resistance. ACI claims there is no difference in freeze-thaw durability for concrete made with RCA versus virgin aggregate [7]. Others claim that freeze-thaw resistance can actually improve the with the use of RCA if the parent concrete was air entrained [114] and/or from high strength concrete [167]. Conversely, RCA has also been found to reduce freeze-thaw durability, with a variety of theories as to why, including:

- The higher porosity of RCA due to the adhered mortar allows more water movement in the concrete [96,167].

- Concrete made with RCA has a higher paste content because it has paste fractions from both the new paste and the adhered mortar of the RCA, and paste is the source of freeze-thaw damage [101].
- A mismatch between the air void systems of the adhered mortar and the new paste [121].
- The porous adhered mortar fraction of the RCA could hold more water in the concrete [167,169].
- It has been suggested that the RCA itself may be less strong and more prone to freeze-thaw damage [122], but the crushing process used to produce RCA does not appear to introduce cracks in the aggregate that contribute to additional deterioration during freeze-thaw cycles [170].

Concrete made with RCA from non-air entrained parent concrete was detrimental to freeze-thaw durability even when the new concrete achieved required air entrainment levels as a whole. Even mixes where only 12.5% of the RCA used was from non-air entrained parent concrete, freeze-thaw durability was negatively impacted [170]. Higher target air contents are sometimes recommended to ensure freeze-thaw resistance [114], but this does not address issues of RCA from non-air entrained parent concrete.

D-cracking potential is reduced when susceptible aggregates in the parent concrete are used in RCA because the RCA production process renders the original aggregates smaller [114] and smaller particle sizes are generally associated with reduced D-cracking [168]. The smaller particle sizes can reduce aggregate interlock, but this is often mitigated by now standard paving practices of shorter panel lengths and use of dowel bars [116]. There is also a school of thought that the damage to the aggregate in the parent concrete has already occurred and will continue only at a reduced level, if at all. Other strategies that reduce D-cracking in conventional concrete, such as reduced w/c and the use of fly ash can also be used in RCA concrete [114]. There have been pavements constructed with RCA whose parent concrete suffered from D-cracking and the new pavements did not experience D-cracking [116].

2.4.4 Abrasion Resistance

The abrasion resistance of concrete itself is a resistance to wear or breakdown from mechanical loading. This is different from aggregate abrasion resistance, which is commonly used in aggregate specifications and is discussed in Section 2.1.6 . Abrasion resistance of the concrete made with RCA has received less attention in the literature than the abrasion resistance of recycled aggregates themselves. RCA generally produces concrete that has lower abrasion resistance than concrete made with virgin aggregates. This lower abrasion resistance can lead to loss of load transfer from aggregate interlock [114].

Previous studies have found that the abrasion resistance of concrete can be on the order of 12% [137] to 22% [171] when RCA is used in place of virgin aggregate, but others have reported insignificant changes in abrasion resistance when RCA is used [172]. When RCA does decrease abrasion resistance, higher RCA replacement levels result in a larger decrease [171].

Using more porous aggregates, lower strength concrete, and higher w/c ratios leads to concrete with less abrasion resistance [9]. Not only is RCA typically more porous than virgin aggregates, it also produces a lower strength concrete and the extra absorption sometimes results in the use of higher w/c ratios to maintain workability. Therefore, it is not surprising that use of RCA generally results in lower strength concrete and lower abrasion resistance. Additionally, the ITZ that forms around RCA can be weakened due to the high absorption content of the RCA, which could make it easier for aggregates to separate from the paste [171]. Decreased abrasion resistance has been also been attributed to having more variability in the RCA, leading to more fines and surface laitance [101]. Reducing the w/c ratio of concrete made with RCA can help reduce the decrease in abrasion resistance from the RCA [57].

2.4.5 Alkali-Silica Reactivity

Reactions between the alkalis in cement and siliceous compounds in certain aggregates can produce an expansive gel, which forms both inside and around the aggregate. The resulting expansion can cause significant cracking and damage, as well as reduced strength and stiffness [6]. A common concern when using RCA is that if the parent concrete experienced ASR, the new concrete made with RCA will also be susceptible [16]. Processing of RCA exposes new sites for the ASR reaction to occur in the new concrete [114,136]. Increasing the RCA replacement level increases the amount of ASR in the new concrete [173].

The crushing procedure can have a considerable effect on ASR levels [174] because it determines how much adhered mortar is present on the RCA, and how much of the parent concrete’s original ASR susceptible aggregate is exposed [16]. Typical ASR mitigation strategies, such as using low-alkali cement, binary blends with fly ash, ternary blends with fly ash and metakaolin, slag, aggregate blending, reduced permeability through low w/c, and admixtures such as lithium nitrate are effective for ASR-susceptible RCA [114,116,125].

There are concerns that traditional methods for testing an aggregate’s susceptibility to ASR may not provide accurate results because of the increased absorption capacity of RCA [175] and the mixing method used in testing [174]. It has also been suggested that the precision and bias statements from the ASTM C1206 accelerated mortar bar test are not applicable to concrete made with RCA [173].

2.5 Creep and Shrinkage Properties

Creep and shrinkage deformations of concrete occur primarily in the hydrated cement paste, while the coarse aggregate acts as a restraint against these deformations [7]. For concrete made with RCA, the hydrated cement paste includes the fresh paste as well as the residual mortar; both these paste fractions can contribute to creep and shrinkage. The lower elastic modulus and increased absorption of RCA can increase both creep and shrinkage. Creep and shrinkage can affect the level of warping, load transfer efficiency, and ultimately cracking in pavements [111,176].

2.5.1 Drying Shrinkage

Drying shrinkage is volume change due to loss of water from the concrete. Using RCA is generally accepted to increase the shrinkage of concrete, sometimes considerably [6,9,116]. Shrinkage values increase with increasing RCA replacement levels, though several researchers have suggested that RCA replacement levels less than 20% to 30% produce a negligible change in shrinkage values [10,33,66,177,178].

Higher shrinkage levels can lead to more mid-slab cracking in JPCP [114] due to a variety of mechanisms. Drying shrinkage affects built-in curl and warping levels and increased shrinkage can lead to decreased ride quality, cause slab corners to lift off of underlying layers, reduce load transfer efficiency by increasing crack width, and change the dominate cracking mode from transverse to longitudinal or corner cracking [121]. Even though concrete made with RCA has higher shrinkage levels, there is some evidence that this may not translate into higher cracking potential. Restrained shrinkage testing has found that concrete made with RCA takes longer to crack, indicating a lower cracking potential than concrete made with virgin aggregate. This has been attributed to the plastic deformation potential of RCA and reduced restraint compared to virgin aggregates [38].

Figure 2.6 shows the effect of RCA replacement level on drying for 6 mixes. The ordinate on this graph is the drying shrinkage ratio, which is the drying shrinkage of a given RCA replacement level divided by the control shrinkage where no RCA was used. All values plotted are taken from the literature and represent a wide range of mix designs, including different w/c ratios and supplementary cementitious material usage with the intent of capturing the range of potential results. The plotted shrinkage represents what the authors of each paper considered to be the final shrinkage value and therefor may correspond to shrinkage at different concrete ages. From this figure, it can be seen that the increase in drying shrinkage is often significant, particularly at high levels of RCA replacement. At low RCA replacement levels (<20%), the increase in drying shrinkage is small, but there are also few studies looking at these replacement levels. There are also a few studies which found considerable shrinkage at even low RCA replacement levels.

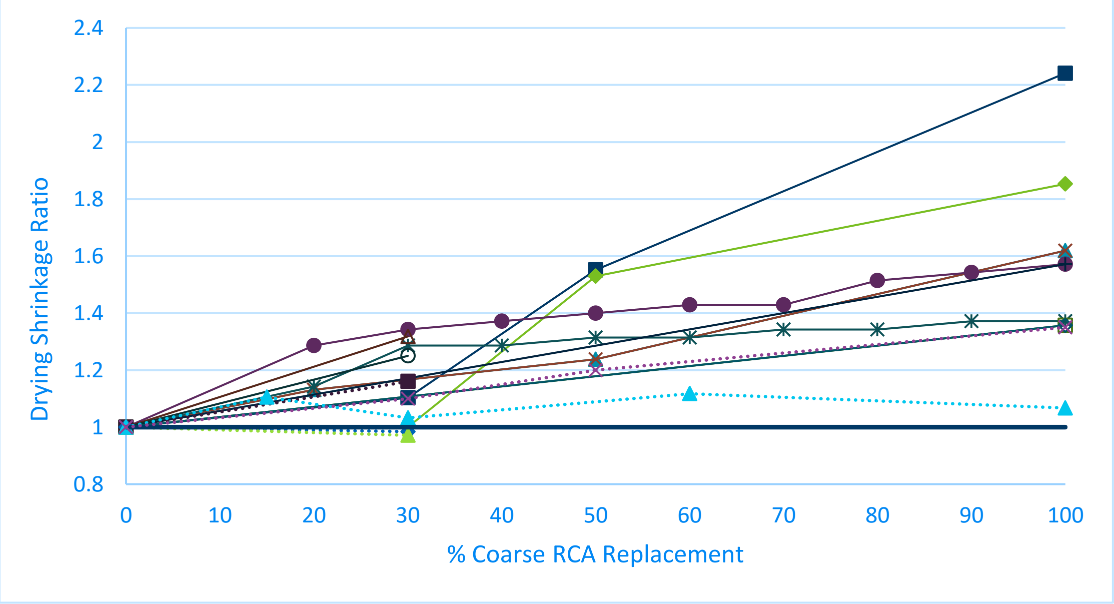

Figure 2.6: Effect of RCA replacement level on drying shrinkage [53,84,88–91]

The rate of shrinkage appears unaffected by the use of RCA, with concrete made with both virgin and RCA aggregates experiencing the majority of shrinkage within the first year [147]. While the total shrinkage is generally higher for concrete made with RCA, the percentage of drying shrinkage which is reversible is fairly similar for concrete made with virgin aggregates versus RCA aggregates [179]. It has been suggested that the extra water absorbed by the RCA could partially reduce the autogenous portion of shrinkage and therefore somewhat mitigate the additional shrinkage typically associated with RCA [88].

There are several factors which contribute to the increased shrinkage of concrete made with RCA. The higher porosity of RCA means that water can evaporate more easily from the concrete [77,88], this could also make concrete made with RCA more sensitive to changes in moisture conditions [88]. Because RCA itself is composed of a paste phase and an aggregate phase, there is more paste in the mix to undergo shrinkage [114]. This additional adhered mortar also means there is less of the stiffer aggregate phase to provide restrain against shrinkage [10,77]. Therefore, the mortar content of the RCA will have a big impact on shrinkage [30], with lower mortar content leading to lower shrinkage [111]. Additionally, the higher absorption capacity of RCA can prompt higher w/c ratios to maintain workability, and higher w/c ratios would cause increased shrinkage in the new paste [114].

Several techniques have been proposed to mitigate or reduce the effects of the additional shrinkage experienced by concrete made with RCA. Using a lower w/c ratio in new concrete made with RCA will result in less shrinkage than a higher w/c ratio [147]. To that end, the use of superplastizer to reduce overall water content can reduce shrinkage sufficiently in mixes made with RCA to compensate for the additional shrinkage associated with RCA use [127]. Pre-soaking aggregate has also been posited as a mitigation strategy. Concrete made with pre-soaked RCA developed less shrinkage in the first 90 days than concrete made with virgin aggregate, likely because water absorbed by the RCA during the pre-soak reduced autogenous shrinkage [147,155]. However, the total shrinkage after one year was still significantly higher for the concrete made with RCA [147]. From a pavement design perspective, changing joint spacing and using dowels can partially mitigate the effects of shrinkage [111].

2.5.2 Creep

Creep is deformation due to sustained loading. Creep in concrete is due mainly to deformation of the cement paste because it is much less stiff than the aggregates [6]. Creep is highly influenced by the paste content and paste properties; RCA concrete will be affected by both the new paste and the original paste adhered to the RCA. While creep values have been reported to be 70% [10] or even 84% [147] higher for concrete made with RCA, typical values for increased creep are given as 20-40% [114] or 30-60% [7], depending on the reference. Generally, higher RCA content results in more creep [147] and less reversible creep [180]. Higher values of creep may not be a concern for concrete pavements [114] and could actually be slightly beneficial because creep could counter residual stresses from curling, warping, and dowel and tie bar restraint [121].

Most creep was experienced within the first 200 days for concretes made with either virgin aggregates or pre-soaked RCA, but the concrete made with pre-soaked RCA incurred significantly more creep within the first 90 days than the concrete made with virgin aggregate.

This was attributed to slower strength development and therefore less creep resistance of the concrete made with RCA, potentially due to the effects of pre-soaking the aggregate [147].

It is generally accepted that the additional creep experienced by concrete made with RCA is because the RCA concrete has up to 50% more paste volume (due to the adhered paste on the aggregates) and the paste phase is what creeps [7,10]. The lower elastic modulus of concrete made with RCA also means there is less resistance to creep [147]. New concrete made with RCA and a higher w/c experiences a higher increase in creep than concrete made with RCA and a lower w/c as compared to concretes made with virgin aggregates [147].

2.6 Summary

The use of RCA as a replacement for some or all virgin coarse aggregate in concrete can affect almost all properties of interest to paving engineers. While it is possible to make concrete with RCA that does not have detrimental effects on mechanical and durability properties, it generally requires changes to the concrete mix design, especially for high RCA replacement levels. Adjusting the w/c, using supplementary cementitious materials (SCMs) such as fly ash, and incorporating admixtures can all help improve the performance of concrete made with RCA. However, if virgin aggregates are simply replaced with RCA, most concrete properties will suffer.

The majority of material property and performance issues caused by RCA are related to its high porosity due to the adhered mortar fraction. Generally, higher RCA replacement levels result in worse concrete performance because there is more adhered mortar present. The majority of research on RCA involves replacement levels of 50 and/or 100%. While many researchers have looked at other replacement levels, few have studied replacement levels less than 30%. The effects of using RCA at any level are quite variable and depend on both the properties of the concrete and the RCA. Further research is needed on how low RCA replacement levels (such as 5-20%) affect concrete properties.

Typical tests for fresh, mechanical, and durability properties can generally be applied to concrete made with RCA. For some newer tests, such as the box test and super air meter, there is little information in the research on whether the tests can be used with RCA, or how the use of RCA will affect the properties measured by these tests. Additional research is needed for RCA using these newer tests.

Chapter 3: Methods

One goal of this project was to ensure the research was as practical as possible and represented likely practices used in the field. The Technical Advisory Panel (TAP), the Aggregate Ready-Mix Association of Minnesota (ARM), and local producers were consulted during materials acquisition and methods development to determine how best to accomplish this goal.

3.1 Materials Selection

Materials selection focused on mainly on aggregates, but all mix materials were selected to be consistent with current industry practices to ensure realistic and representative results.

3.1.1 Control Aggregate

Limestone was selected as the control coarse aggregate with the thought that it would be representative of the aggregate type and quality common throughout the United States. According to the USGS Mineral Commodity Survey, 70% of crushed stone produced in US is limestone, and crushed stone is most common construction aggregate [181]. Additionally, limestone tends to be a lower quality aggregate compared to granite and crushed gravel typically available in the region, so any impacts the RCA content has on concrete made with limestone would likely be greater than if the concrete were made with higher quality aggregate.

The control aggregate was a limestone coarse aggregate sourced from Cemstone, a local ready-mix supplier, from their Faulkstone location (Trenhaile Quarry, Pit number 93401). Based on their typical use of this material, two different sizes of coarse aggregate from the same pit were blended to make the final coarse aggregate gradation, shown in Figure 3.1. This blend is composed of 76.4% aggregate meeting the #67 gradation, and 23.6% aggregate meeting the #4 gradation, with gradations defined by ASTM C33 [182].

The #4 as received had a significant amount of material retained on the 1in sieve, but very little retained on the 1¼ in sieve. To drastically reduce the amount of material needed for testing, all material retained on the 1¼ in sieve was removed from the control aggregate. This allowed 4 in (102 mm) diameter by 8 in (203 mm) high cylinders to be used instead of the larger 6 in (152 mm) diameter by 12 in (305 mm) high cylinders. The data shown in Figure 3.1 reflect the removal of this material.

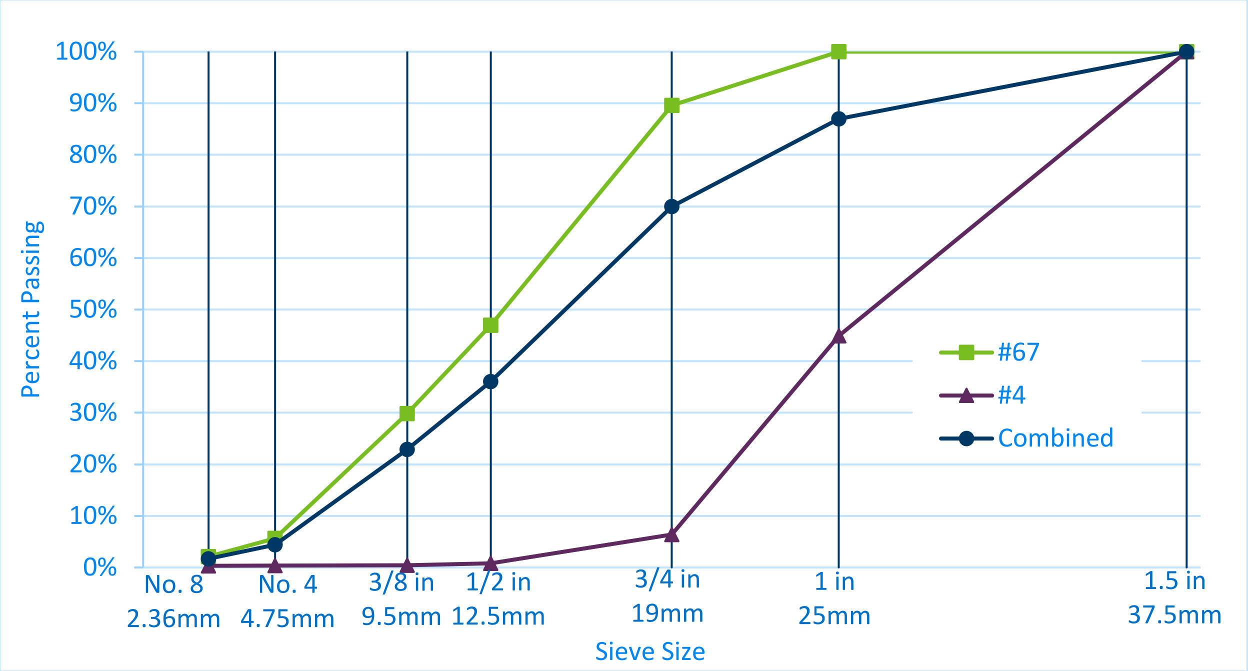

Figure 3.1: Control coarse aggregate gradation

Natural sand was selected as the fine aggregate and was sourced from the same supplier, from their Rosemont location (Pit number 19128). This sand was delivered in two separate batches, which were found to have slightly different gradations, as shown in Figure 3.2. The fineness moduli of sands A and B were 2.65 and 2.79 respectively, which is a 5.3% difference. Both sands met the ASTM C33 requirements for fine aggregate.

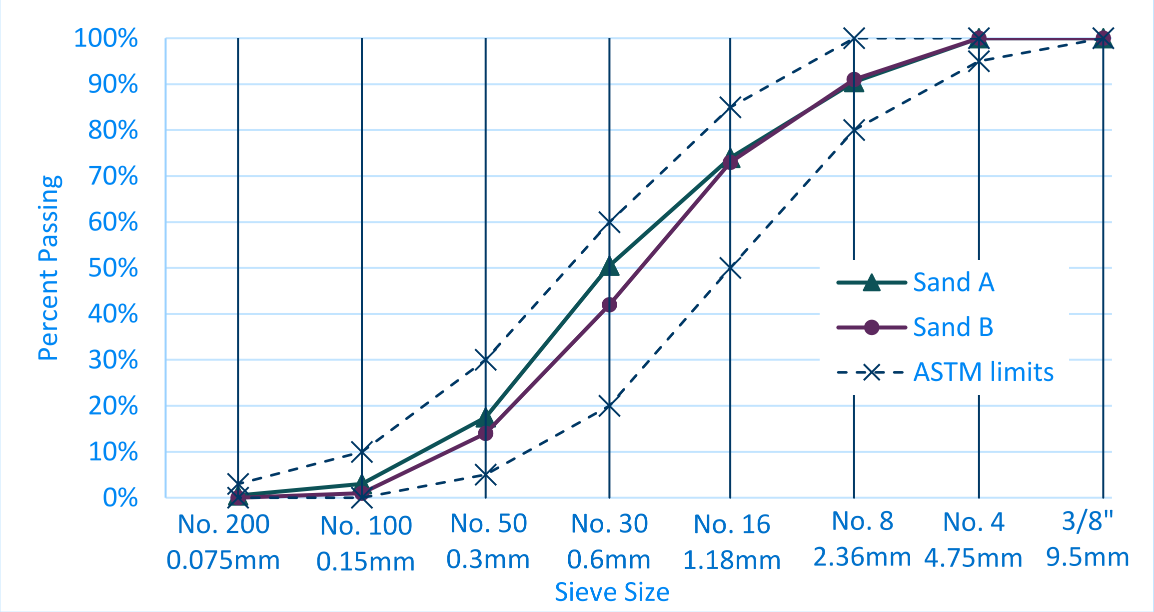

Figure 3.2: Control fine aggregate gradation (data provided by Cemstone)

The final aggregate blend was 45% sand and 55% blended coarse aggregate. This gradation meets the tarantula curve [183] for both sands A and B, as shown in Figure 3.3. This gradation also meets the tarantula curve requirements that coarse sand be greater than 15% and fine sand be between 24% and 34% for both sands A and B.

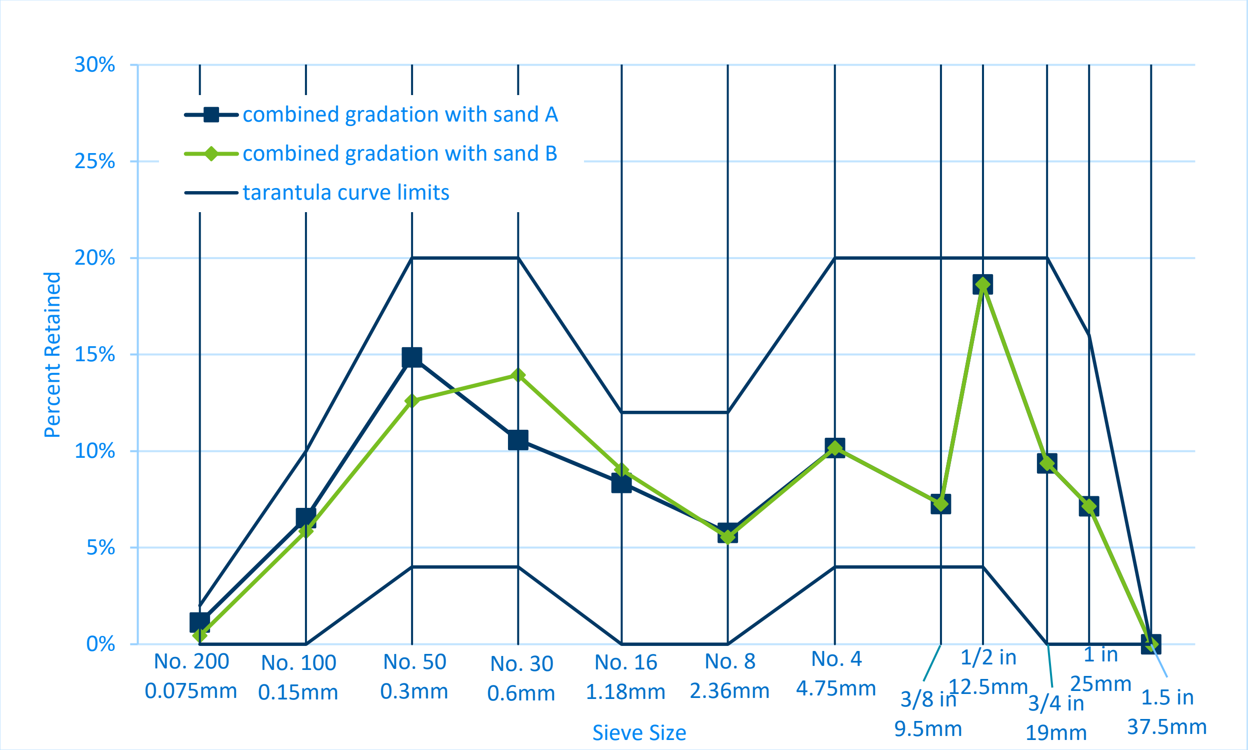

Figure 3.3: Control aggregate tarantula curve

3.1.2 Recycled Concrete Aggregate

Many concrete properties are dependent on RCA characteristics and quality, which are a function of the parent concrete properties and RCA crushing and processing. For the results of this study to be applicable over a wide range of potential RCA types, a wide range of RCA types must be considered. Working with the TAP, it was determined that both RCA of known high and low quality should both be considered, as well as RCA of unknown or mixed origin. Three materials were sourced from local ready-mix producers and the fourth was provided by the Missouri Department of Transportation (MoDOT). Materials were named based on their supplier.

The RCA materials sourced for this project are:

1. An uncontrolled RCA composed predominantly of leftovers and washout from a ready-mix plant with some concrete rubble of unknown provenance from Cemstone’s Henderson location.
2. A multi-source RCA from Aggregate Industries’ Empire plant produced by crushing and screening concrete from multiple origins, including demolition waste from curb & gutter, paving, and

sidewalks, washout from their ready-mix plant, and leftover concrete delivered directly to the crushing yard before trucks return to the ready-mix plant to wash out.

3. A very controlled source of returned concrete from AVR. This material was not specifically generated for use in new concrete but was the closest material available to the desired gradation.

4. An RCA produced by crushing the airfield concrete pavements from the Lambert Airport in St. Louis Missouri. While the composition of the parent concrete is not definitively known, it is suspected the original aggregate was sourced from a quarry of St. Louis limestone, which has a history of performing well in Missouri. This supposition is supported by the low value of Micro-Deval loss, as shown in Table 3.1. This material was supplied by the Missouri Department of Transportation (MoDOT)

The three materials sourced from Minnesota ready-mix suppliers will contain predominantly concrete made with relatively high-quality aggregates (ex. granite and gravel) because those aggregates are readily available in the market of these three companies. However, other areas of the country do not have aggregate of this quality. The MoDOT aggregate will show the effects of using an RCA made from a parent concrete with lower strength aggregate.

Aggregate gradation has many impacts on final concrete properties, so having a consistent gradation between the limestone control aggregate and the RCA was important. However, this needs to be balanced against having the results of the study provide meaningful information. While sieving the RCA to match the control gradation would ensure that gradation was not a factor in the final results of the study, this would not match with practices in the field if some level of RCA replacement were to be implemented. It has been shown that slight deviating from gradation limits does not have a significant effect on concrete properties [184]. Therefore, having the RCA and control aggregates both meet the same gradation requirements is a compromise that ensures the effects of gradation differences would be minimized while also ensuring the results are closer to how RCA replacement would occur in industry.

It was determined that most available RCA would meet an ASTM C33 [182] #67 gradation, so limestone meeting that same gradation was sourced. However, most concrete mixtures used for paving have larger aggregates than those which meet a #67 gradation. Again, there was a need to balance isolating the effects of the RCA replacement with standard industry practice to ensure the results of this research can easily be implemented. The ready-mix company supplying the control aggregate identified a mix design they use for paving which blends limestone aggregates meeting a #67 gradation with a larger size limestone aggregate meeting the ASTM C33 #4 gradation, as discussed in Section 3.1.1 .

The final gradation of the RCAs used in this project are shown in Figure 3.4. Upon testing, it was determined that none of the aggregates fully met the criteria of a #67 gradation, though they were all close. The material from Missouri was left over from a MoDOT research project and just happened to have a gradation very close to what this project required. Because this material was at least as close to a #67 as the material from the ready-mix suppliers, it was deemed to be of an acceptable gradation. The remainder of the aggregates are material that local producers supplied when asked for material that met a #67 gradation, and therefore is likely representative of what they would include in a mix calling for a #67 material. All of the ready-mix sources contain many different parent concretes. Even very controlled sources that contain only concrete made with aggregate from the producer's quarry will still have different mix designs and paste strengths. These will affect how the RCA crushes down [105]. RCA is also known to have high variability [10]. Therefore, it is possible that a ready-mix supplier may have tested the material and found it to meet a #67 gradation but that the material from a different part of their stockpile did not meet the criteria. The RCA from Henderson, Aggregate Industries, and MoDOT were all close to the bottom bound of the #67 gradation limit while the AVR material was close to the top bound.

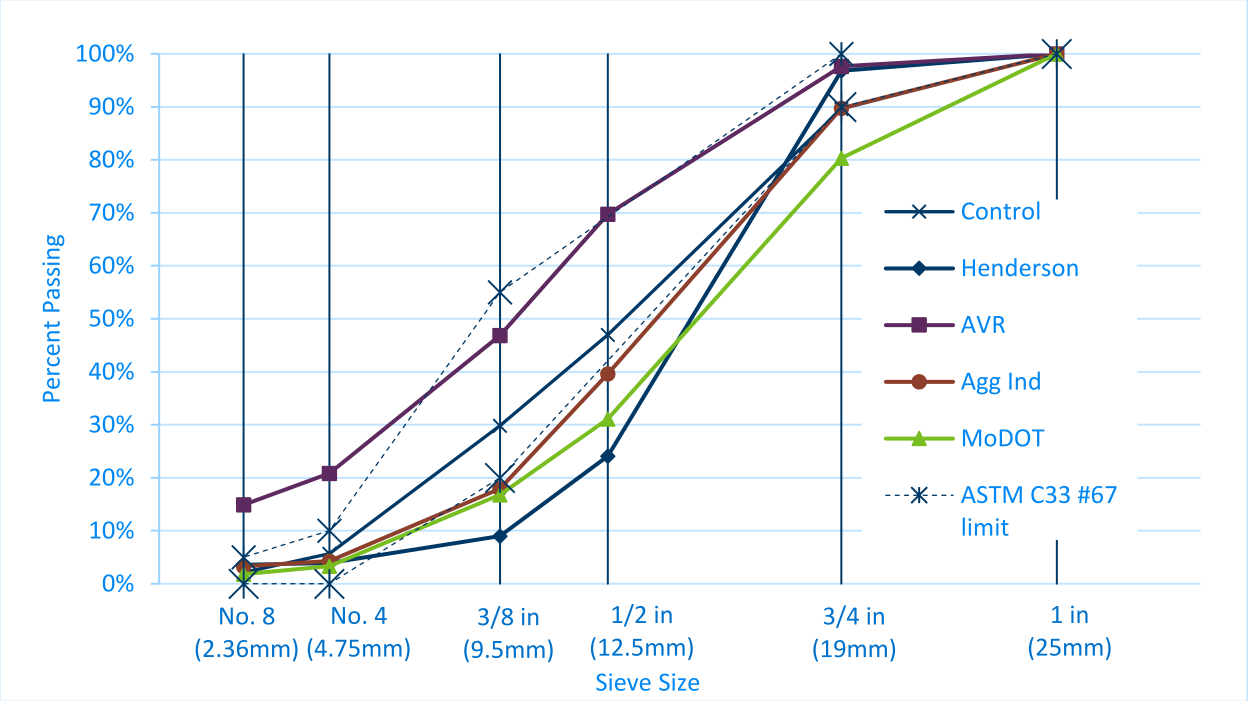

Figure 3.4: RCA and #67 control gradations

Washing of the RCA was another issue discussed with the TAP. The amount of fines in the RCA can have a large effect on the new concrete properties. While the TAP members stated a preference for washed RCA from an owner perspective, concern was also expressed that RCA producers may be reluctant to wash the RCA and that washed RCA may not always be available. Including only washed RCA in this study could limit the applicability of its results. The decision was made that the RCA used in this study would be held to standard limits on fines (ex. 1% from the MnDOT spec [185]), but the producer could achieve this through means of their choice, which may not include washing. Similar to the gradation requirement, not all of the materials met this requirement, but again are representative of what producers are interested in using as RCA. The percent passing the #200 sieve is shown in Table 3.1. The AVR material had significantly higher fines than the other RCA and was over the 1% limit. It should be noted that this material was not produced with the intent of being used for new concrete and was never intended to have low fines. However it was deemed useful to include to see the effect of a higher fines material on new concrete properties.

Table 3.1: Coarse Aggregate Properties

Aggregate Source	Specific Gravity	Absorption Capacity	P-200	FM	Micro-Deval
Control	2.68	1.06%	0.10%	3.78	10.4%
Henderson	2.32	5.32%	0.70%	3.77	21.4%
AVR	2.18	8.78%	2.89%	2.50	20.5%
Aggregate Industries	2.29	6.05%	0.67%	3.45	19.7%
MoDOT	2.40	3.50%	0.70%	3.67	14.4%

Aggregate specific gravity and absorption capacity [120] information was required to compute the aggregate substitution quantities. For the AVR sample, the RCA was split into coarse and fine fractions and the fine material was tested separately [186] and a weighted average was computed to account for the higher percentage of material passing the #4 sieve. Specific gravity and absorption capacity values for all of the RCA materials are provided in Table 3.1.

Table 3.1 also lists the Micro-Deval loss percentage and the fineness modulus (FM) of each aggregate. Micro-Deval testing was performed by MoDOT for all aggregates. Fineness modulus was determined from gradation data and was used as a proxy for gradation in the statistical analysis because the analysis required a single number to represent gradation. While it is theoretically possible to have two very different gradation curves with the same fineness modulus, generally fineness modulus can be used to give an idea of the relative coarseness of a gradation. In this case, Figure 3.4 shows that the Henderson, Aggregate Industries, and MoDOT aggregates have similar gradation curves while the AVR aggregate is much finer, and the fineness moduli presented in Table 3.1 supports this. Therefore, fineness modulus was deemed to be an acceptable, though admittedly imperfect proxy for gradation in analysis.

3.1.3 Cementitious Materials

The timeline of this project coincided with the rollout of Type 1L Portland Limestone Cement (PLC) [187] into the local market. Given that the industry is moving towards using PLC as the standard cement type, PLC was selected as the cement for this project. The cement was sourced from Continental Cement from their Davenport plant.

Fly ash was used as an SCM on this project because it is commonly used in paving mixes and because the sand sourced for this project has ASR concerns which require mitigation. The ready-mix producer supplying the sand found that 20% fly ash in a paving mix similar to the one developed for this project was sufficient for mitigation. The class F fly ash [188] sourced for this research was from a different supplier than the control aggregate supplier typically uses in their mixes, but was of the same class.

3.2 Mix Design Development

The mix design used for this project was based on a mix design from the ready-mix supplier who supplied the control aggregates and is one they use as a paving mix meeting MnDOT 3A21 criteria [185]. The mix uses the control aggregate blend and sand sourced for this research project. Changes to this mix include using PLC instead of standard Type I cement and determination of admixture dosages. This mix has a w/cm ratio = 0.4, a cementitious content of 560 lb/cy, 20% fly ash, a target slump of 1-3 in, and a target air content of 7%.

To achieve the target slump and air content for a standard MnDOT 3A21 mix, a mid-range water reducer (MRWRA) conforming to ASTM C494 [189] and an air entraining admixture (AEA) conforming to ASTM C260 [190] were used. The specific admixtures used were MasterPolyheed1020 and MasterAirAE90. Trial batching was used to determine admixture dosages. The final mix design for the control mix is provided in Table 3.2. The final slump and air content of the trial batch were 1.5in and 6.7% respectively.

Table 3.2: Final Control Mix Design

Ingredient	lb/cy
Water	224
Cement	448
Fly ash	112
#67 coarse aggregate	1323
#4 coarse aggregate	410
Sand	1376
Admixture	**oz/cwt**
MRWRA	0.37
AEA	2.6

3.3 Test Methods

3.3.1 Testing Plan

The testing matrix consisted of 13 total mixes: a control group and the four RCA materials, each at three different replacement levels. Based on the results of the literature review, it was determined that RCA replacement levels of 20% or more often have an effect on concrete properties, depending on the RCA properties. Therefore, replacement levels of 5, 10, and 15% were considered. The final testing matrix is shown in Table 3.3.

Aggregate replacement was done by volume, not weight, because RCA has a lower specific gravity than virgin aggregate due to the presence of the adhered paste. The #67 virgin material was replaced with RCA such that the total of virgin aggregate replaced was 5, 10, or 15%. This means that the replacement level of the #67 aggregate was greater than the RCA content of the mix because only the #67 aggregate was exchanged for RCA. The weight and volume of the #4 control aggregate in the mix was therefore constant.

Table 3.3: Testing Matrix

Aggregate Source and Type	Replacement Level (by volume)	Designation
Control – virgin limestone	N/A	Control
Henderson – returned concrete with some unknown concrete rubble	5%	Henderson 5
	10%	Henderson 10
	15%	Henderson 15
AVR – unwashed, crushed returned concrete	5%	AVR 5
	10%	AVR 10
	15%	AVR 15
Aggregate Industries – multi-source, demolition waste, returned concrete, washout	5%	Agg Ind 5
	10%	Agg Ind 10
	15%	Agg Ind 15
MoDOT – crushed airfield pavement with limestone aggregate	5%	MoDOT 5
	10%	MoDOT 10
	15%	MoDOT 15

As discussed above, the sand was delivered in two batches, which had slightly different gradations. The Control, Henderson, AVR, AggInd5, and AggInd10 batches were made entirely with sand A. The AggInd15 batch was made with 96.3% sand A in the beams and 95.3% sand A for fresh testing and all other samples, with the remainder of the sand coming from sand source B. The difference in the percent of each sand used comes from different amounts of sand being required for moisture corrections. All the MoDOT batches were made entirely with sand B.

3.3.2 Mixing

Concrete was mixed in the St. Thomas Civil Engineering Lab in accordance with ASTM C192 [191]. For each RCA replacement level, the concrete was mixed in two separate batches to accommodate the mixer capacity. All the concrete for the beams was mixed in one batch, and concrete for all other samples and fresh testing was mixed immediately afterwards. Generally there was sufficient concrete left from the beam batch to cast a few of the cylinders, with the remainder cast from the second batch. Due to mold availability, the control group beams were split into multiple batches instead of being cast from one single batch. Similarly, the shrinkage, freeze-thaw, and coefficient of thermal expansion samples for the control group and the shrinkage and freeze-thaw samples for the Henderson10 group were batched separately from the other samples.

Concrete samples for hardened testing were cast in accordance with their respective specifications and left covered in the lab for one day. Sample sizes were selected based on the nominal maximum aggregate size of 1¼ in. All cylinders were 4in diameter x 8in high. Concrete beams had a 6in x 6in cross section. Freeze-thaw prisms were 4in x 3in x 16in and length change prisms were 4in x 4in x 11.25in with an effective gauge length of 10in. Samples were demolded and placed in lime-water tanks to cure in accordance with ASTM C192 for the requisite number of days, depending on testing.

3.3.3 Fresh Properties

Fresh properties were tested immediately following mixing. Slump was tested in accordance with ASTM C143 [142]. Air content via the pressure method in accordance with ASTM C231 [138] with a Type B meter. Previous research has concluded that the pressure method can be used with RCA, though it does measure the total air content of the original and new pastes [113,192].

The SAM number was measured via the sequential pressure method in accordance with AASHTO TP118 [139], though the test often took longer than the specified 12 minutes to run. The same trained operator performed the SAM test on all mixes; this operator has a history of performing the test correctly.

The box test was run in accordance with AASHTO T396 [145]. Rather than evaluate the void rating immediately, photos were taken of each side of the concrete after the box sides were removed for later evaluation. Edge slump was evaluated on a binary of having occurred or not, rather than being measured. The threshold for edge slumping was 0.25in, as described in the test standard.

3.3.4 Hardened Properties

Compressive and flexural strength were tested in accordance with ASTM C39 [193] and C78 [194], respectively. Tests were conducted at 3, 7, 14, 21, 28, and 56 days after casting to investigate any effects on the rate of strength gain in addition to ultimate strength. The 21-day cylinders and 56-day beams for Henderson10 were inadvertently not tested. Results for compressive testing are reported as the average of four cylinders, except the 28 day strength, which is the average of five cylinders. The extra cylinder at 28 days was used for digital image correlation (DIC) testing. Results for the flexural test are the average of two beams.

The rate of compressive strength gain and flexural strength gain were also calculated. A trendline was fit to each data set and the derivative of this function was taken to determine the rate of strength gain. A logarithmic function was selected, providing an equation with the form y = m*ln(x) + b. This resulted in a rate with the form m/x. The value of m was used to represent the rate of strength gain.

Flexural strength is often estimated from compressive strength using a correlation. Mechanistic-empirical pavement design uses the correlation shown in Equation 1 [157], while other agencies use slightly different correlations. For example, ACI 318 [156] replaces the 9.5 multiplier with a value of 7.5 for structural applications.

$$f_r = 9.5\sqrt{f_c'} \tag{1}$$

Where:

f_r = flexural strength in psi

f_c' = compressive strength in psi

Using Equation 1, the 28-day flexural strength was estimated from the 28-day compressive strength. The ratio of estimated to actual flexural strength was also computed.

Surface resistivity was measured for all compressive test cylinders except those used for DIC testing because the paint needed for DIC testing blocked access to the surface. Resistivity testing was conducted in accordance with AASHTO T358 [163]. The recommended curing condition adjustment factor was applied to account for the fact that specimens were stored in a lime water bath instead of a moist cure room. Results are generally reported as the average of four cylinders. If any cylinder failed to meet the coefficient of variation criteria, that cylinder was excluded from the average. Based on the average resistivity value at a given concrete age, the qualitative risk of chloride ion penetration was estimated from the correlation provided in the test standard. The rate of increase in surface resistivity was also computed. A linear trendline was fit to each data set with the form y = mx + b. The derivative of this function, m, is the rate.

Elastic modulus and Poisson's ratio were measured at 28 days in accordance with ASTM C469 [195]. Results are reported as the average of two tests. Elastic modulus is often estimated in pavement design from the compressive strength. Mechanistic-empirical pavement design uses the correlation shown in Equation 2 to estimate elastic modulus from compressive strength [157]. Other forms of this correlation include the unit weight of the concrete, but that was not measured in this study and is often not available to pavement designers. Therefore, the simpler and more common form of the equation was selected.

$$E = 57\sqrt{f_c'} \tag{2}$$

Where:

E = elastic modulus in ksi
f_c' = compressive strength in psi

Using Equation 2, the 28-day elastic modulus was estimated from the 28-day compressive strength. The ratio of estimated to actual elastic modulus was also computed.

Coefficient of thermal expansion (CTE) was measured in accordance with AASHTO T336 [196] and is reported as the average of two cylinders tested. Because only one cylinder could be tested at a time and the test took an entire day, not all tests were conducted at 28 days. Generally the first cylinder in a batch was tested at 28 days and the second at 29 or 30 days. However, if more than one batch was cast on the same day, some cylinders had to be tested even later. All cylinders were tested within a week of reaching 28 days. For the MoDOT 10 batch, only one cylinder was tested and no cylinders were tested for the Aggregate Industries 5 batch.

Digital image correlation (DIC) is a non-contact full field optical imaging technique that can be used to visualize strain fields on a three-dimensional surface, such as a concrete cylinder. DIC was conducted on one cylinder per mix as part of the compression testing at 28 days. A speckle pattern was applied to a surface of the concrete using spray paint. The cylinder was then tested in compression following the standard ASTM C39 procedure [193]. During testing, the specimen was photographed using high speed cameras at a rate of one image per 0.2 seconds. The DIC system tracked the displacements of the speckles recorded in the images to provide measurements of displacements. A surface was fit across this field of displacement from which strains are then approximated [197–200].

For each test, the image just before failure and an image taken 50 frames (10 seconds) before that image were selected and the tensile strain fields in the lateral direction were computed. The time step just before failure was selected as the image before the image with a visible crack. For two of the tests (Control and AVR 5), there were no visible cracks on portion of the cylinder facing the camera. Instead, the before failure was selected as the image before the image corresponding to when the compression machine stopped applying load. A histogram of each strain field was constructed over a constant bin range. By superimposing these histograms for a given test batch, it is possible to see how the distribution of tensile strains changed as the specimen approached failure. The mean and maximum strain values were also computed for each strain field.

Unrestrained shrinkage testing was conducted by measuring length change in accordance with ASTM C157 [201]. Testing followed the specified regime except that all samples were tested three days after the 28-day moist cure period instead of four. Shrinkage strain was computed by dividing the measured length change by the gauge length of 10 inches. All specimens except Henderson 10, and MoDOT15 experienced an approximately four-day period of storage between 50% and 70% relative humidity instead of a constant 50% due to a malfunction of the cure chamber. A similar malfunction caused all specimens except MoDOT 15 to experience another 12-hour period of storage between 50 and 70% relative humidity and all specimens to experience an approximately 48 hour period of storage between 50 and 60% relative humidity and two separate approximately 12 hour periods of storage between 30 and 50% relative humidity. These periods of altered humidity occurred at different ages for each batch because they were mixed on different days. The ultimate shrinkage was reported as the average of three samples per mix. Values are reported at 252 days, but testing will continue and final values will be provided to the NRRA in a memo when testing is completed.

Freeze-thaw durability was tested in accordance with ASTM C666 with Procedure A [202]. Testing commenced after 14 days of curing in the lime water tanks. Because only five batches could be tested simultaneously, some samples had to be stored while others were tested. Samples were stored in a saturated, frozen state. A power outage in the testing room caused some samples to experience up to four days of storage at room temperature still in a saturated state during testing. This outage did not affect the freezer storing the samples awaiting testing. All samples were tested until 300 cycles because the relative dynamic moduli remained above 60% of the initial dynamic modulus for each sample. The Aggregate Industries 5 sample was tested at 310 cycles instead of 300, but the relative dynamic moduli for all samples of the batch were fairly consistent with measurements from several previous cycles, so it is unlikely this had a large impact on the results. The durability factor was reported as the average of three samples per batch.

3.4 Methods for Statistical Analysis

Statistical analysis was conducted in R [203], an open-source statistical analysis software package. A significance level of 5% (i.e. a p-value of 0.5) was selected in all cases; this significance level is standard in most statistical analyses.

3.4.1 Analysis of Variance

Analysis of variance (ANOVA) can be used to determine the likelihood that the property of interest is the same for all test batches considered (i.e. that there is no difference between the batches). However, this analysis results in comparing all batches, not just each batch to the control. If the ANOVA analysis identifies that at least one batch has different results for a given property, additional analysis can be conducted to determine which batches are different from each other. ANOVA analysis was run for each hardened property of interest. ANOVA analysis requires multiple replicates for any given property, so this analysis could not be conducted on fresh properties or digital image correlation (DIC) data.

Tukey's method (Tukey's honest significant difference) is a method that can be applied to the ANOVA analysis to compare each test batch to the others. This allows for consideration that random chance could cause differences that appear significant but are actually insignificant. This method is generally considered the most effective method of one-way ANOVA [204]. By examining the significance level of the control group compared to the other batches for each test, it is possible to determine which had significantly different results for each test. Tukey's method compares each batch to all of the other batches, but only comparisons between the control group and another batch were considered because the rest do not provide useful information for this study. The standard significance level of 5% was used. A p-value of less than 0.05 shows that the difference in test results between the control and the batch under consideration is significant. Tukey's method was applied to the ANOVA for each hardened property of interest where the ANOVA identified that there was a difference between at least one batch.

All hardened results were only considered at 28 days except for flexural strength, which was also considered at three, seven, and 56 days. The three and seven day flexural strength gives some indication on if using RCA would affect the time to open to traffic. In looking at the flexural strength with time, the 28-day flexural strength data for the control was lower than would be expected from following the trend established by the other time points. Therefore, the 56-day data was also considered in order to provide a more complete picture of the effect of RCA on long-term strength.

3.4.2 Linear Regression Analysis

ANOVA analysis is for categorical variables, so it allows for comparison of results between each batch to look for significance, but the analysis does not recognize that two batches with the same RCA source but different replacement levels are related. The factors that differentiate the different batches considered (ex. RCA replacement level or aggregate properties) are numeric variables. Linear regression analysis is a more suitable analysis tool for determining if there is a significant difference between concrete properties based on a numeric variable. Because linear analysis does not require multiple replicates, this analysis was conducted on both fresh and hardened properties.

Linear models were created for each concrete property and aggregate property. For these models, the control group was used as the 0% replacement value for each aggregate type. Aggregate properties were composite properties that accounted for the percent replacement. For absorption capacity, percent fines, fineness modulus, and Micro-Deval, these were computed as a weighted average of the control and RCA aggregate properties based on the percent replacement. For specific gravity, a harmonic average was used. The output of these models included the correlation coefficient, r, and the coefficient of determination, R^2. The correlation coefficient shows how the concrete property would change as the aggregate property increases. The analysis also shows if this correlation is significant. The coefficient of determination shows what percent of the variability in concrete property can be explained by the aggregate property.

Linear regression analysis only compares a single aggregate property to a single concrete property. However, the concrete properties could be influenced by multiple aggregate properties. Multiple linear regression analysis can be used to consider the effect of multiple aggregate properties simultaneously on a single concrete property. However, this analysis resulted in unstable models because the predictors (i.e. aggregate properties) are highly correlated. This makes sense because most of the changes we see in the aggregate properties are related to the mortar content of the RCA. The presence of the adhered mortar makes the aggregate more porous, resulting in a higher absorption capacity, lower specific gravity, and higher Micro-Deval. Because of the instability, these models were considered invalid.

Chapter 4: Results and Discussion

This section provides results and discussion of fresh and hardened testing as well as the statistical analysis. The statistical analysis is discussed before the results of individual tests because it shows that many of the measured properties of test batches containing RCA were not statistically significantly different from those of the control group. It is important to bear this in mind when examining the test results to avoid finding trends in the data that are not significant.

4.1 Results and Discussion of Statistical Analysis

Table 4.1 shows the results of the Tukey's honest significant difference analysis, which compares the results of each hardened property test to those of the control group for each batch separately. The adjusted p-values for compressive strength (f'c), flexural strength (MOR) at 28 days, elastic modulus E, coefficient of thermal expansion (CTE), and resistivity (Ω) are presented. An adjusted p-value of less than 0.05 shows that the difference in test results between the control and the batch under consideration is significant. To avoid misrepresentation, adjusted p-values are not provided if they are greater than 0.05 because they do not imply additional significance.

The ANOVA analysis showed that there were no significant differences between any of the different test batches for the results of the flexural strength test at 56 days or Poisson's ratio. Therefore, Tukey's analysis cannot be conducted, but also would provide no additional information. The ANOVA analysis did show a significant difference in some results of the flexural strength test at three and seven days, shrinkage, and freeze-thaw durability factor, but Tukey's method showed that none of these significant differences occurred when a test mix was compared with the control batch. Therefore, the three and seven day flexural strength, shrinkage, and freeze-thaw analyses results are omitted from Table 4.1.

Table 4.1: Results of Tukey's Analysis

Batch	f'c	MOR 28 day	E	CTE	Ω
Henderson 5	-	-	-	-	-
Henderson 10	0.00E+00	-	-	-	0.0003
Henderson 15	7.60E-05	-	-	-	0.0011
AVR 5	2.07E-04	-	-	0.048	0.0001
AVR 10	0.00E+00	-	0.003	0.017	0.0000
AVR 15	-	-	0.030	0.048	0.0008
Agg Ind 5	8.16E-05	0.037	-	N/A	0.0011
Agg Ind 10	0.00E+00	-	-		0.0019
Agg Ind 15	1.58E-04	-	-	-	-
MoDOT 5	0.00E+00	-	-	-	0.0126
MoDOT 10	1.00E-06	-	-	-	7.20E-06
MoDOT 15	1.00E-07	-	-	-	-

From this table, it can be seen that compressive strength and resistivity are the only properties that were significantly different from the control for most RCA types and replacement levels. For resistivity however, there was little practical significance to this difference because all resistivity values were associated with a moderate risk of chloride ingress except for the AVR 10 sample, which had a high risk. Elastic modulus and coefficient of thermal expansion were only significantly different from the control group for the mixes containing AVR RCA. The flexural strength at 28 days was only statistically significantly different from the control for the Aggregate Industries 5 sample. As will be discussed in 4.3.3 , this could be due to unexpectedly low values of the control specimens at 28 days. There was no significant difference in flexural strength between the control and the mixes containing RCA at any other concrete ages investigated.

Results of the linear regression analysis included correlation coefficients and coefficients of determination between concrete properties and aggregate properties, shown in Table 4.2 and Table 4.3 respectively. Compressive strength, flexural strength, and resistivity were investigated at 28 days and shrinkage was investigated at 252 days. These tables show only hardened concrete properties because none of the fresh properties were found to have any significant correlation with aggregate properties. The linear regression for fresh properties did show significant correlations between air content, slump, and box test score.

Table 4.2: Correlation Coefficients with Aggregate Properties

Property	Absorption capacity	Percent Fines	Fineness Modulus	Micro-Deval	Specific Gravity
Compressive Strength	-0.356	-0.238	Not Significant	-0.381	0.422
Flexural Strength	0.477	Not Significant	Not Significant	0.449	0.472
Elastic Modulus	-0.597	-0.653	0.564	-0.494	0.6
Poisson's Ratio	Not Significant	-0.409	0.38	Not Significant	Not Significant
CTE	0.765	0.543	-0.46	0.81	-0.799
Resistivity	-0.527	-0.466	0.403	-0.499	0.534
Shrinkage (252 day)	-0.272	-0.109	0.127	-0.334	0.254
Freeze-Thaw Durability	-0.448	-0.293	Not Significant	-0.496	-0.478

Table 4.3: Coefficients of Determination with Aggregate Properties

Property	Absorption capacity	Percent Fines	Fineness Modulus	Micro-Deval	Specific Gravity
Compressive Strength	0.127	0.057	Not Significant	0.145	0.178
Flexural Strength	0.228	Not Significant	Not Significant	0.202	0.223
Elastic Modulus	0.356	0.426	0.318	0.244	0.360
Poisson's Ratio	Not Significant	0.167	0.144	Not Significant	Not Significant
CTE	0.585	0.295	0.212	0.656	0.638
Resistivity	0.278	0.217	0.162	0.249	0.285
Shrinkage (252 day)	0.074	0.012	0.016	0.112	0.065
Freeze-Thaw Durability	0.201	0.086	Not Significant	0.246	0.228

The correlation coefficients from Table 4.2 indicate how a change in an aggregate property would affect the concrete property under consideration. These correlations will be discussed for each concrete property in Section 4.3 . Correlations are helpful when comparing results with expected trends and can provide a check on the validity of the results. However, this study was not large enough to produce predictive relationships between aggregate properties and concrete properties. Correlations should merely be used to consider general trends. When considering shrinkage particularly, recall that a lower shrinkage value is a more negative number (i.e. higher amount of shrinkage), so correlations appear to be the inverse of what is expected. Similarly, for resistivity, a higher resistivity value indicates lower risk or more resistance to chloride ion penetration.

The coefficients of determination shown in Table 4.3 show how much of the variability in a given concrete property can be explained by a specific aggregate property. For most of the concrete properties considered, absorption capacity, specific gravity and Micro-Deval had a larger impact than the percent fines or the fineness modulus, with the fineness modulus almost always having the lowest impact. While this data is insufficient to determine if any aggregate properties are predictors of concrete properties, it does help identify that those properties most related to RCA mortar content, such absorption capacity or specific gravity, would likely be better predictors of concrete properties than properties more related to gradation, such as fineness modulus. This could inform future work aimed at developing a specification for RCA which uses aggregate properties to determine if an RCA is acceptable or not.

4.2 Fresh Property Results and Discussion

4.2.1 Workability

The workability of the concrete was measured via the slump test [142] and the box test [145]. Results of these test are shown in Table 4.4. The target slump for this mix was ½” to 3”, based on a MnDOT 3A21 mix used for slip form paving [185]. Seven of the twelve mixes met the slump criteria. A box test score of two or less is considered suitable for slip form paving [141,183]. Nine of the test mixes met this criterion; however, the control mix did not. It should be noted none of the mixes which failed the slump test also failed the box test based on score, and vice versa. The box test also measures edge slumping, which is considered undesirable for paving mixes. The control mix and all but three of the test mixes experienced edge slumping.

Table 4.4: Workability Test Results

Batch	Slump (in)	Box test	
		Score	Edge slumping?
Control	1.25	2.75	yes
Henderson 5	1.75	1.75	yes
Henderson 10	3.75	1	no
Henderson 15	3	2.25	yes
AVR 5	2.5	1.5	yes
AVR 10	5.25	1	yes
AVR 15	1	2.25	yes
Agg Ind 5	2.75	2.5	yes
Agg Ind 10	3	1.5	no
Agg Ind 15	2.25	2	yes
MoDOT 5	3.5	1.25	yes
MoDOT 10	4.25	1.5	no
MoDOT 15	3.5	1.75	yes

The slump test results are shown graphically as a function of RCA replacement level in Figure 4.1. From this figure, it can be seen that slump increased in almost all cases, though there does not appear to be a definitive trend with respect to RCA content. This is contrary to the expected trend that slump decreases with RCA content [52,111]. It is recommended that the slump not vary more than 1in between trucks for a concrete pavement placement [205], so the level of variation seen when RCA is added may indicate that adjustments to the slump could be necessary. This project did not evaluate if the natural variability within a single RCA would result in slump that meets this uniformity criteria or not, so more work is needed in this area. However, if multiple sources of RCA were used at a low replacement level throughout the project, uniformity in slump could pose an issue. This concern must also be balanced with the fact that the consistency and accuracy of the slump test generally has also been questioned, with some research showing that slump measurements vary greatly between testers and also depends on when the test is performed relative to mixing [143].

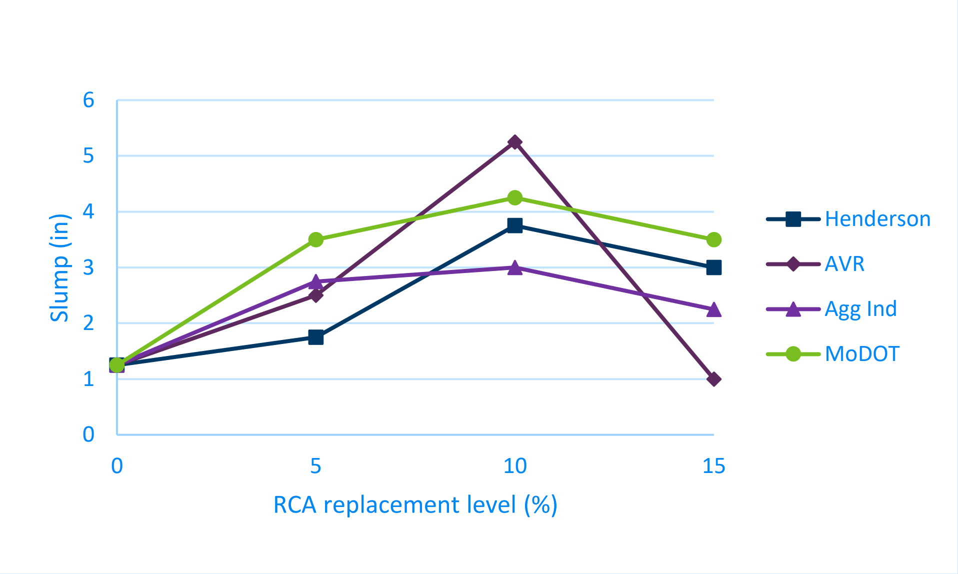

Figure 4.1: Slump versus RCA replacement level

Slump may have been higher when RCA was used because the higher absorption capacity of the RCA necessitated additional water be added during the moisture correction phase. There is no consensus on how quickly RCA absorbs water, with estimates ranging from 70% in 10 minutes [124], to 85% in 30 minutes [125], or 90% in either 5 minutes [88,123] or 24 hours [125]. If absorption time was longer than the time to mix and run the slump test, this water may have contributed to additional short term workability until it was absorbed.

Another factor influencing slump is air content, with higher air content leading to increased workability [9]. Most of the mixes containing RCA had higher air content, and the linear regression analysis identified a statistically significant correlation between air content and slump. This trend can also be seen in Figure 4.2. The higher air content may have been due to any additional workability from the additional water needed for moisture corrections influencing how the air entraining admixture worked. While aggregate properties including gradation, absorption, shape, and surface texture also influence the workability of the mix [9], the regression analysis did not find any statistically significant correlations between the aggregate properties examined and the slump, though it should be noted that this analysis did not include parameters for shape or surface texture.

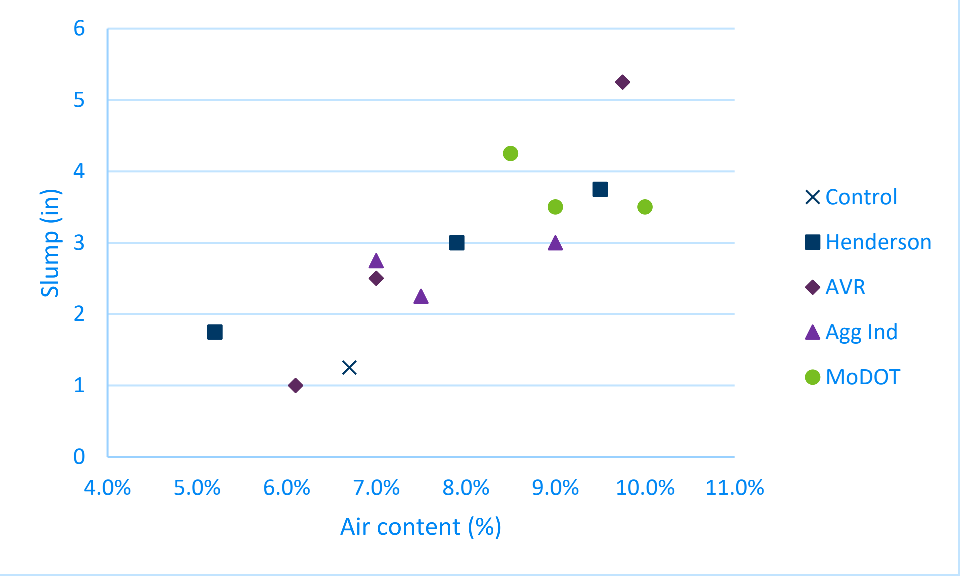

Figure 4.2: Slump versus air content

The results of the box test versus RCA replacement level are shown in Figure 4.3. From this figure, it can be seen that the control group actually had the highest box test score and all of the mixes containing RCA scored better than the control mix. There did not appear to be a trend relating the box test score to RCA replacement level and little research has been done on this topic to define an expected trend. Because the control group also experienced edge slumping, it cannot be said that the presence of RCA increased the likelihood of edge slumping. A previous study did find that the use of RCA increased edge slumping [192], but more research is needed in this area.

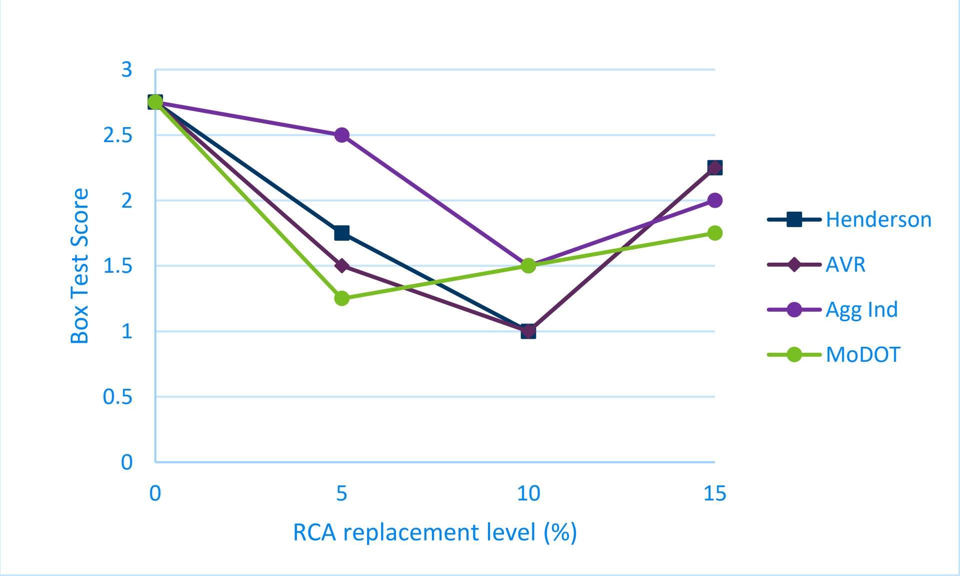

Figure 4.3: Box test score versus RCA replacement level

The lower box test scores in the mixes using RCA may be due in part to the increased air content of these mixes. The linear regression analysis identified a statistically significant correlation with air content, where higher air content resulted in a lower box test score, as shown in Figure 4.4. Air content is known to impact workability, as are aggregate properties such as gradation, absorption capacity, shape and surface texture [9]. However, here the linear regression analysis did not show any statistically significant correlation with the aggregate properties considered; this analysis did not consider aggregate shape or surface texture.

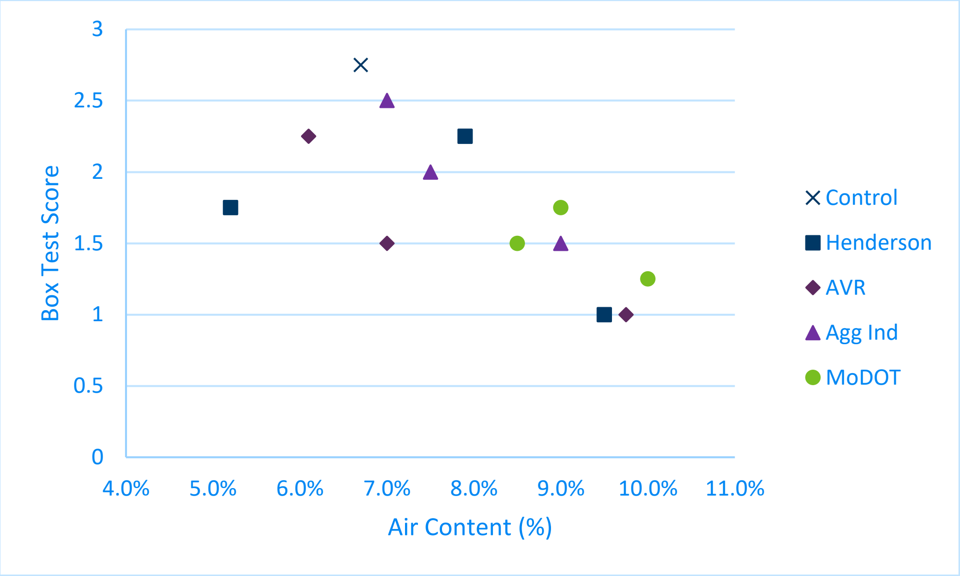

Figure 4.4: Box test score versus air content

The slump and box test score results were found to have a statistically significant correlation with each other; this correlation can be seen in Figure 4.5. In general, these results are not expected to be correlated because they are measuring different facets of workability [146]. The correlation observed in this research is likely due to the fact that both are well correlated with air content, which is known to impact workability [9].

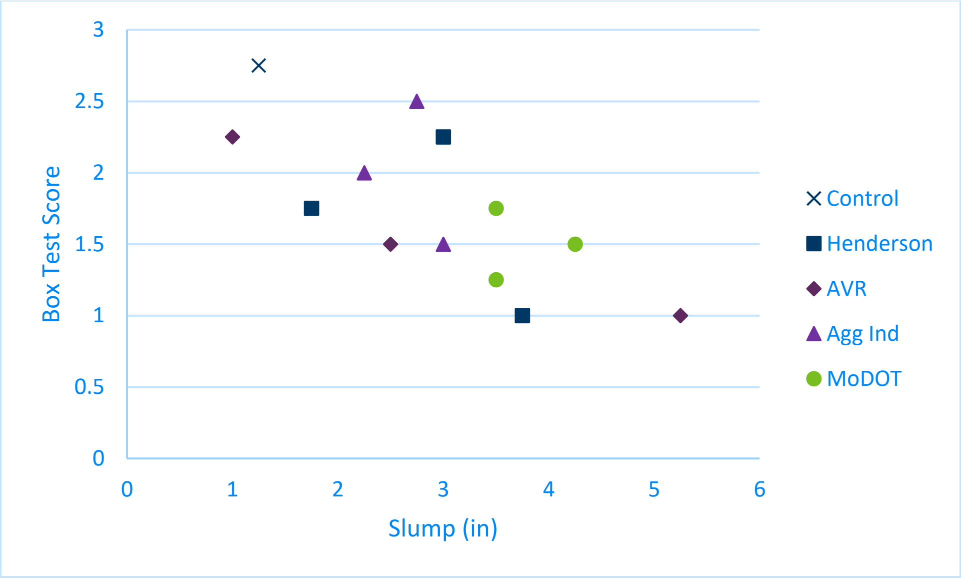

Figure 4.5: Box test score versus slump

4.2.2 Air Content and SAM

The air content of the concrete was measured via pressure meter. The super air meter (SAM) was used to measure the SAM number. Results of these tests are shown in Table 4.5. The target air content for this mix was 7% based on a MnDOT 3A21 mix used for slip form paving, with an allowable range of 5.5-9% [185]. This is slightly different than the range recommended by AASHTO of 5-8% [141]. There is no target for SAM number in the MnDOT standard spec, but it is generally recommended that the SAM number be less than or equal to 0.2 [206] and this is the criteria which has been adopted by AASHTO [141].

From Table 4.5, it can be seen that the air content was within the MnDOT allowable range for eight of the 12 test mixes and for the control batch. Air content was within the AASHTO allowable range for six mixes and the control batch. The air content is shown graphically as a function of RCA replacement level in Figure 4.6. From this figure, it can be seen that most mixes containing RCA had a higher air content than the control mix, though the lack of replicates means the statistical significance of this observation cannot be determined. There does not appear to be a discernable trend between RCA content or type and air content. This is supported by the linear regression analysis, which determined that there was not a statistically significant correlation between air content and any of the aggregate properties examined.

Table 4.5: Air Content and SAM Test Results

Batch	Air Content	Super Air Meter (SAM)	
		SAM number	Test Valid?
Control	6.70%	0.13	no
Henderson 5	5.20%	0.48	yes
Henderson 10	9.50%	0.11	no
Henderson 15	7.90%	0.17	yes
AVR 5	7.00%	0.07	no
AVR 10	9.75%	error	no
AVR 15	6.10%	0.04	no
Agg Ind 5	7.00%	0.19	yes
Agg Ind 10	9.00%	0.12	yes
Agg Ind 15	7.50%	0.21	N/A
MoDOT 5	10.00%	0.14	no
MoDOT 10	8.50%	0.28	N/A
MoDOT 15	9.00%	0.33	N/A

The higher air content of the mixes containing RCA could be due the fact that the air content test measures total air content, which includes any air content in the adhered mortar on the RCA [9,111,192]. Additionally, any extra moisture from water added for moisture corrections that was not absorbed by the RCA before testing could have influenced the slump of the mix, which can then influence the air content, as discussed in Section 4.2.1 .

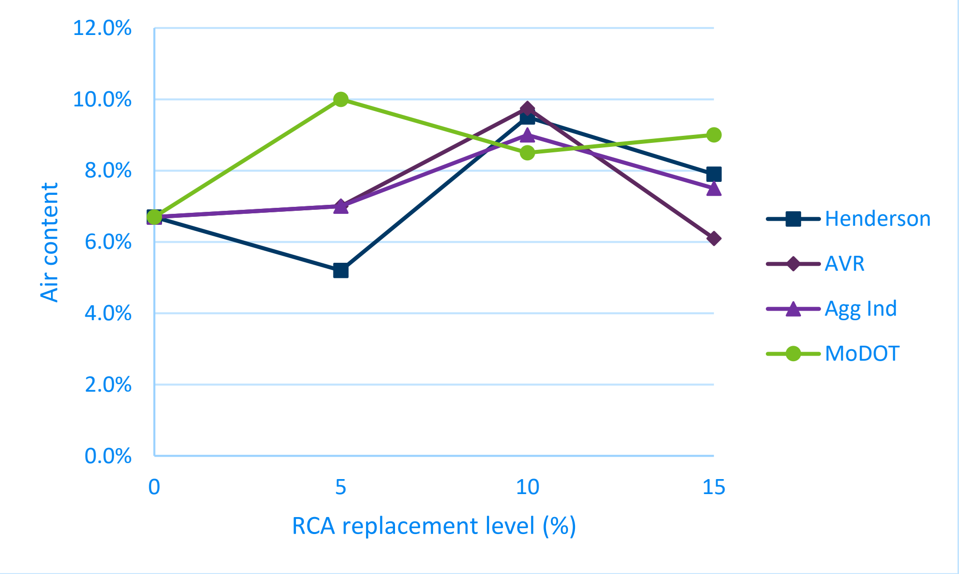

Figure 4.6: Air content versus RCA replacement level

The maximum recommended variation in air content between batches of concrete is 1% [205]. The majority of test batches containing RCA had air contents which deviated from the control batch air content by more than this amount. This research did not examine if air content would be consistent between batches made with the same type of RCA, but further work is necessary in this area to determine if the natural variation in RCA would affect the uniformity of the air content of the concrete. However, if project was using RCA from various sources, this work does show that uniformity in air content could be a concern.

From Table 4.5, it can be seen that the SAM number was below the recommended threshold of 0.2 in most cases. However the reliability of the SAM results is questionable. Of 13 total tests, 12 resulted in a SAM value and one resulted in an error. The results of tests that produced a valid SAM number were checked with a spreadsheet from the manufacturer that estimates if the test was likely run correctly or not. The intermediate values required to conduct this analysis were not recorded for the AggInd15, MoDOT 10 and MoDOT 15 batches. Of nine tests where the validity of the SAM test was checked, four showed that the test was likely run correctly. All tests were run by the same trained operator with a history of running tests correctly. This is a slightly higher failure rate than with other deployments of the SAM, such as where 46% of tests performed by trained operators were likely run incorrectly [140]. Of note, there was no indication when the tests were performed that the SAM number obtained was potentially incorrect and the values themselves were reasonable, giving no indication to the operator that values were suspect.

The variation in SAM number with respect to RCA replacement level is shown in Figure 4.7. From this figure, it can be seen that there is not a visible trend between RCA content and SAM number. Because of the unreliability of the SAM data, linear regression analysis was not conducted, so no statements regarding relation to the aggregate properties tested can be made.

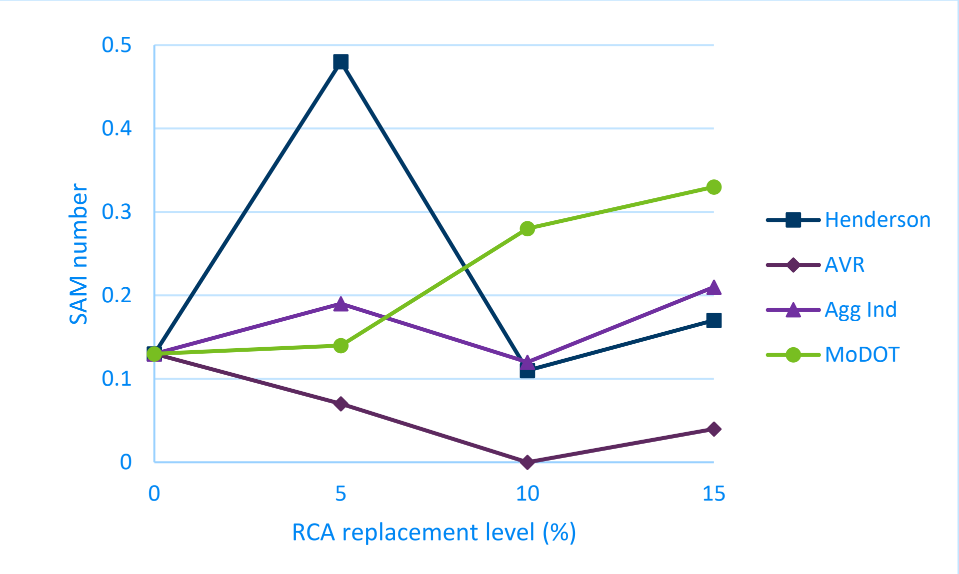

Figure 4.7: SAM number versus RCA replacement level

Correlations between the air content and freeze-thaw durability and between SAM number and freeze-thaw durability factor will be discussed in Section 4.3.8 .

4.3 Hardened Property Results and Discussion

Hardened properties measured at 28 days, including elastic modulus, Poisson's ratio, and coefficient of thermal expansion are shown in Table 4.6 . The values of compressive strength, flexural strength, and surface resistivity at 28 days are shown here for completeness and are also repeated later in discussion of those results with time. Values not measured at 28 days include the freeze thaw durability factor and shrinkage. Durability factor testing commenced at an age of 14 days for all samples (by either testing them immediately or storing them in the freezer until testing) but the age at the completion of testing (when the durability factor is calculated) varies depending on the length of the freeze-thaw cycles. For shrinkage, the value at 252 days is included. This test is ongoing and final values will be provided in a later memo.

Table 4.6: Hardened Property Results

Batch	Comp. Strength (psi)	Flexural Strength (ksi)	Elastic Modulus (ksi)	Poisson's Ratio	CTE (mm/ mm/° C)	Surface Resistivity (kΩ-cm)	Freeze Thaw Durability Factor	252 Day Shrinkage (με)
Control	5643	614	5576	0.22	8.93	15.9 (M)	103	430
Henderson 5	5516	572	5213	0.20	9.12	14.4 (M)	94	360
Henderson 10	3816	630	4647	0.21	9.43	13 (M)	92	417
Henderson 15	4756	685	4797	0.21	9.70	13.2 (M)	88	517
AVR 5	4802	704	4561	0.18	9.49	12.8 (M)	106	493
AVR 10	3662	679	4016	0.19	9.59	11.9 (H)	93	470
AVR 15	5221	675	4409	0.20	9.49	13.2 (M)	86	413
Agg Ind 5	4759	758	5089	0.21	N/A	13.3 (M)	89	457
Agg Ind 10	4217	704	4764	0.22	9.30	13.3 (M)	95	500
Agg Ind 15	4790	714	5436	0.21	9.70	14.3 (M)	90	470
MoDOT 5	3743	620	4575	0.22	9.39	13.7 (M)	91	370
MoDOT 10	4560	657	4730	0.19	8.87	12.3 (M)	88	360
MoDOT 15	4460	633	4904	0.20	9.40	15 (M)	101	427

4.3.1 Compressive Strength

The compressive strength with time is shown in Figure 4.8 and Table 4.7. Table 4.7 also shows the rate of strength gain *m*. The compressive strength of the concrete containing RCA was lower in most cases than that of the control group. This follows the expected trend [7,9,116,207] and was true for all ages tested. Not all mixes met the AASHTO criteria of 4000 psi at 28 days [141], but all mixes met this criteria by 56 days.

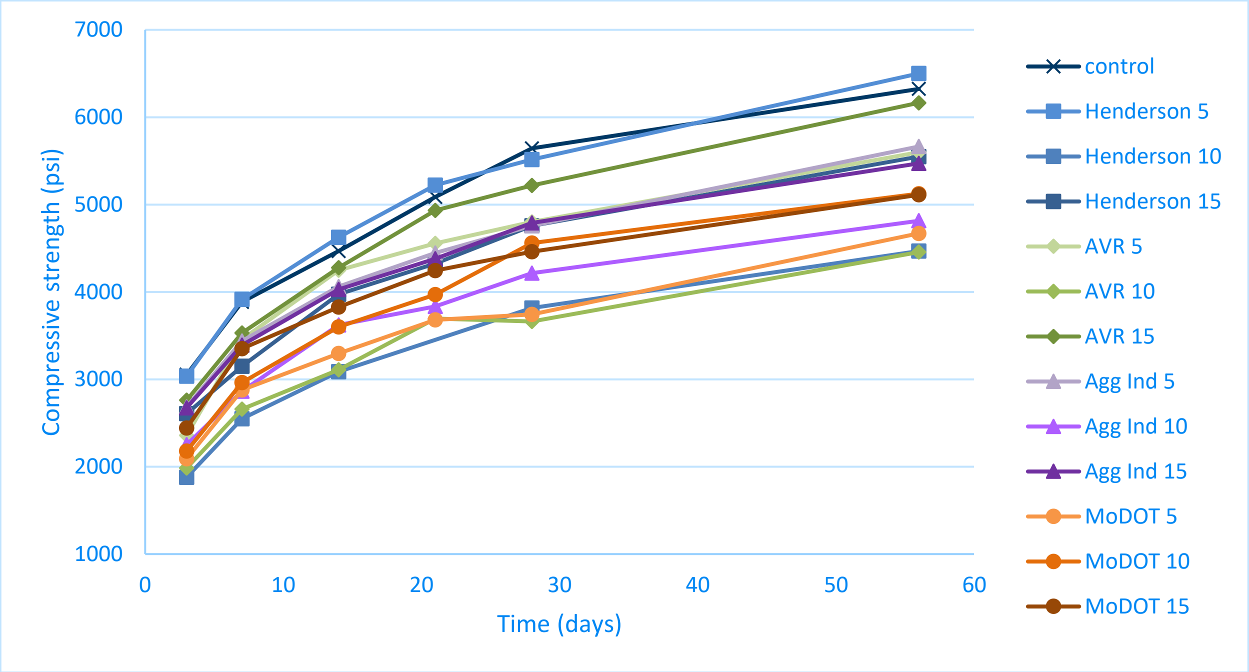

Figure 4.8: Compressive strength versus time

Table 4.7: Compressive Strength Results

Batch	**Compressive Strength (psi) at Day**						**Rate of strength gain *m* (psi/ln(day))**
	3	7	14	21	28	56	
Control	3054	3887	4468	5086	5643	6323	1137
Henderson 5	3036	3916	4624	5223	5516	6500	1175
Henderson 10	1879	2549	3088	N/A	3816	4468	888
Henderson 15	2606	3149	3973	4325	4756	5549	1021
AVR 5	2358	3459	4250	4557	4802	5599	1083
AVR 10	1985	2658	3109	3697	3662	4456	831
AVR 15	2760	3529	4278	4933	5221	6165	1172
Agg Ind 5	2684	3441	4062	4446	4759	5665	995
Agg Ind 10	2251	2864	3621	3835	4217	4814	886
Agg Ind 15	2674	3393	4029	4382	4790	5472	956
MoDOT 5	2091	2879	3295	3679	3743	4671	830
MoDOT 10	2178	2962	3600	3971	4560	5125	1022
MoDOT 15	2444	3351	3828	4245	4460	5111	893

The 28-day compressive strength versus RCA replacement level is shown in Figure 4.9. From this figure, it can be seen that inclusion of the RCA did reduce the compressive strength, and the statistical analysis of the 28-day data showed this reduction to be statistically significant in all cases except for Henderson 5 and AVR 15.

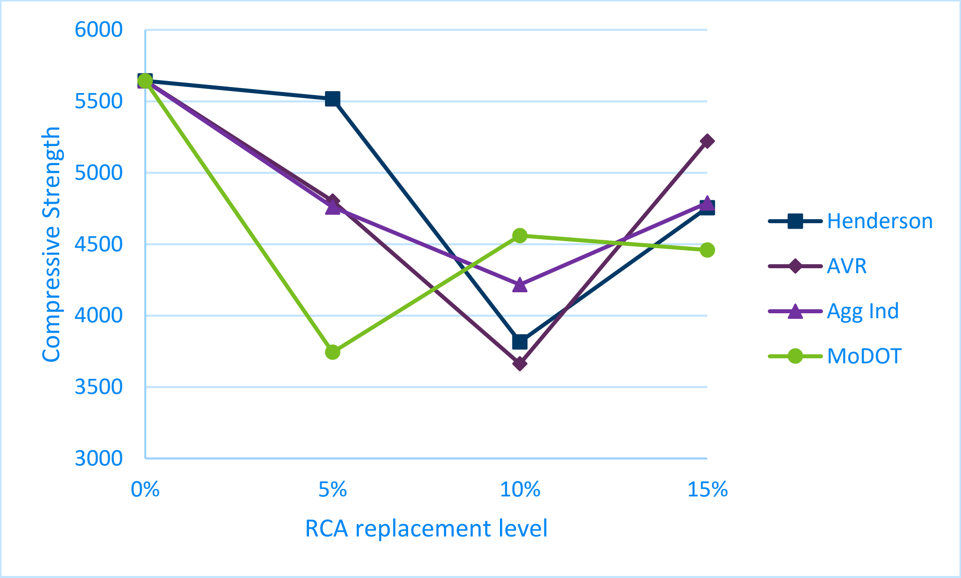

Figure 4.9: 28-day compressive strength versus RCA replacement level

There are many theories as to why the inclusion of RCA can reduce compressive strength. In this study, the reduced strength observed in the RCA concrete could be due to lower bond force between recycled aggregates and new cement paste compared to that between virgin aggregate and new cement paste [151], higher air content [114] as was discussed in Section 4.2.2 , the higher porosity of the RCA [10], and changes to the interfacial transition zone due to the porosity of the RCA [10,40,110]. It has also been suggested that the inclusion of RCA results in a larger volume fraction of paste, which has less strength than aggregate [114]. However, this effect is likely low in this case because of the low RCA replacement levels. The strength of the RCA versus that of natural aggregate can also be a contributing factor to lower concrete strength [151]. However, the control aggregate used in this research is limestone while three of the four RCAs likely contained granite or gravel because those are the predominate aggregates in the region from which the RCA was sourced. While the presence of the adhered paste would reduce the strength of the RCA [116], the strength disparity between the RCA and the virgin aggregate was likely lower than normal because the RCA parent concrete was made with stronger aggregates than the virgin aggregate.

The linear regression analysis explored the connection between compressive strength and absorption capacity, percent fines, fineness modulus, specific gravity, and Micro-Deval. It was determined that absorption capacity, percent fines, and Micro-Deval all had significant inverse correlations with compressive strength, while specific gravity had a significant positive correlation with compressive strength, see Table 4.2. These correlations fit with the theories on the reduction in compressive strength when RCA is used because the porosity of the adhered mortar causes the higher absorption capacity, higher percent fines, higher Micro-Deval and lower specific gravity of RCA and these characteristics are responsible for the changes in bond and interfacial transition zone and the changes to air content that cause lower strengths. The coefficients of determination for these properties show that absorption capacity, specific gravity, and Micro-Deval likely explain more of the variation seen in compressive strength than percent fine.

Differences in aggregate gradation likely played a minimal role in strength differences because both the RCA and the virgin aggregate it replaced had similar gradations. This is supported by the linear regression, which did not find a significant correlation between the fineness modulus and compressive strength. Research on the effect of gradation variation found little effect on compressive strength when the gradations were within or just outside the bounds of a single gradation band [184], which is the case with the gradations seen here.

The rate of compressive strength gain was also investigated. This can be seen by comparing the curvature of each line in Figure 4.8 and also by examining the computed rate of strength gain versus RCA replacement level shown in Figure 4.10. From these figures, it can be seen that the rate of strength gain was generally lower with RCA replacement level. ANOVA analysis could not be conducted on the rate of strength gain due to a lack of replicates, so it is not possible to tell if there is a statistically significant difference between the rate of gain of the control and mixes containing RCA.

Linear regression analysis showed a strong and statistically significant correlation between 28-day compressive strength, and the rate of strength gain, which is to be expected. There was no statistically significant correlation between compressive strength gain and any of the aggregate properties investigated. It has been suggested that concrete made with RCA has initially lower strengths but that the strength could be recovered by 120 days [96]. While the results presented here only run to 56 days, the rates of strength gain do not seem to suggest any recovery of strength is likely. This fits with trends observed by others [108].

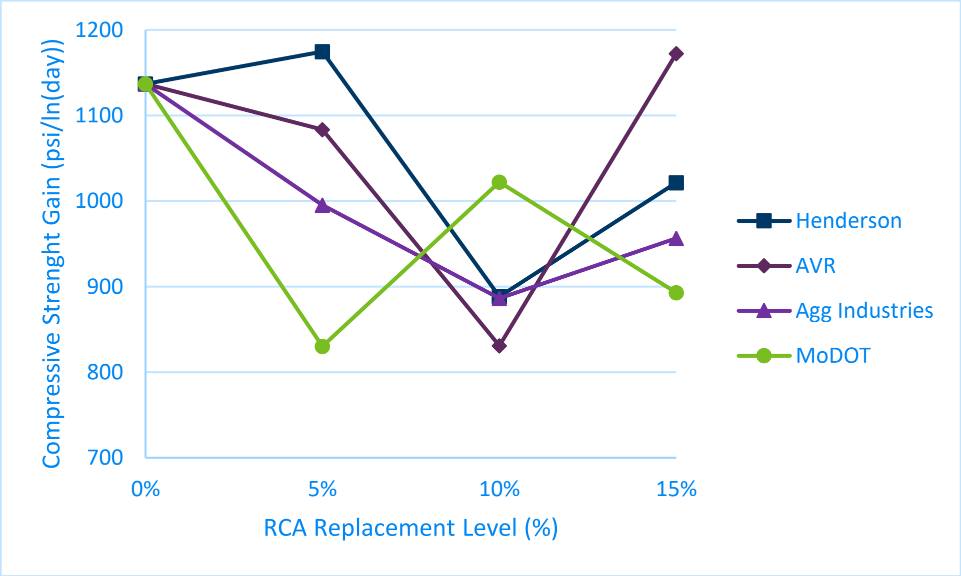

Figure 4.10: Rate of compressive strength gain versus RCA replacement level

Mechanisms for the RCA to affect the strength gain of the new paste, such as internal curing [8,96] or hydration of any unhydrated cement in the RCA [88,109], have been suggested. However, given that the compressive strength itself was found to be correlated with aggregate properties but the rate of compressive strength gain was not, the reduction in compressive strength is likely a function of the RCA itself, suggesting that the presence of the RCA is not affecting the hydration reaction of the new paste.

4.3.2 Strain Fields from Compression Testing

Digital image correlation (DIC) was used to help visualize the strain fields from compression testing for one cylinder from each mix. When considering this data, it is important to note that it represents a strain field over an area, rather than an aggregate response. Figure 4.11 shows a series of images from the DIC data collected for the Aggregate Industries 10 batch; images from other batches were similar. Going from left to right, these images show the tensile field strain in the x-direction (horizontal) as the cylinder approaches a compression failure induced by axial load and ultimately fails. The color scale is constant across these images and strain units on the scale bar are ε (in/in). The crack can be seen forming and the strain can be seen to increase in the region of the crack before failure.

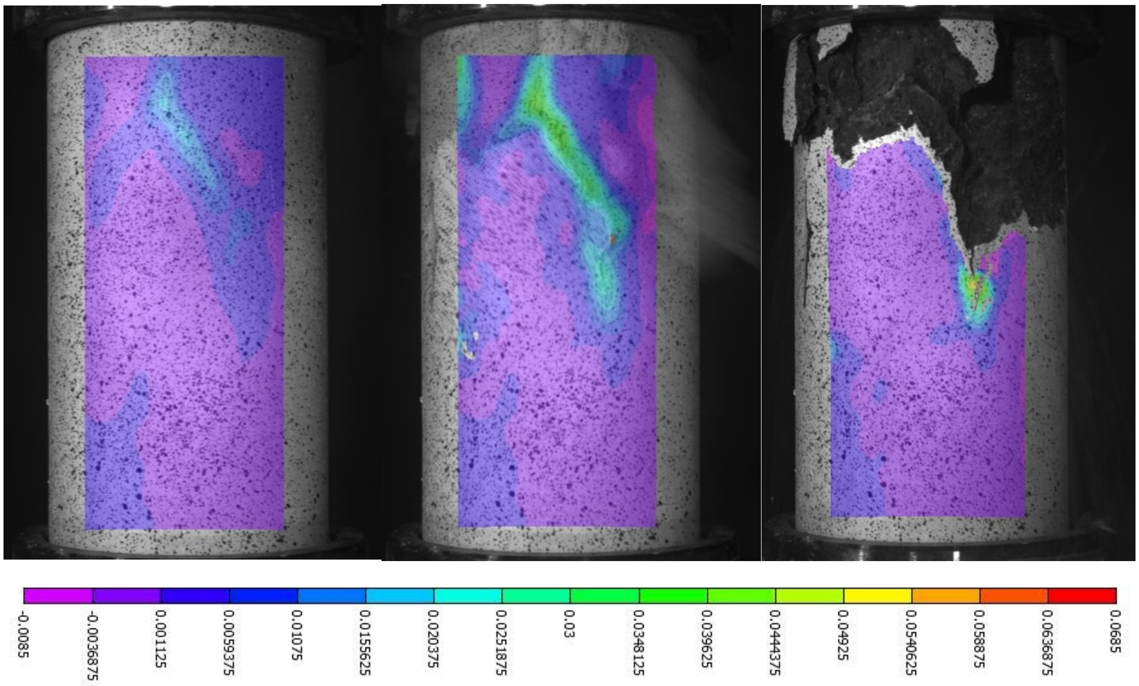

Figure 4.11: Tensile strain field before failure (left), at failure (center) and after failure (right)

Histograms of the tensile field strain were generated for DIC camera images 50 frames (10 seconds) before failure and right before failure. Superimposing these histograms for a given test shows how the tensile strains change as the sample approaches failure. These histograms are shown in Figure 4.12 through Figure 4.15 for the various RCAs tested. The control histogram is repeated in each figure for reference. In these histograms, the blue color is the histogram 50 frames before failure and the orange histogram is the diagram right before failure. Where these histograms overall, the color appears brown.

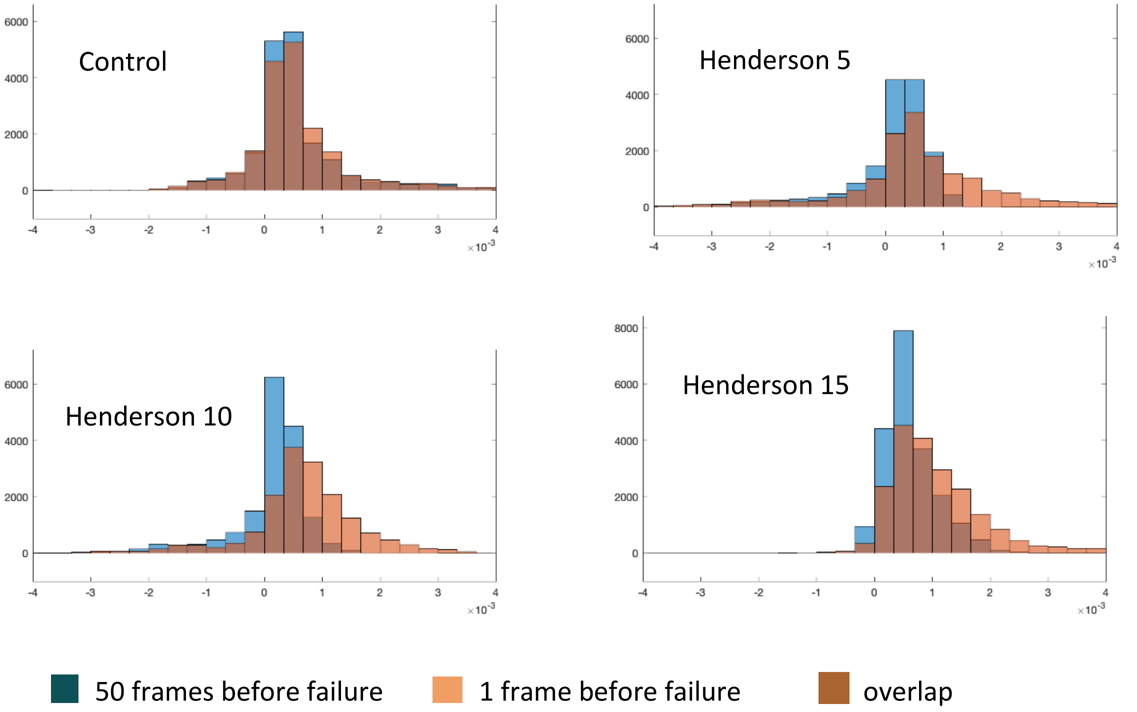

Figure 4.12: Superimposed histograms of frequency of tensile strain values (mε) for the control and Henderson test batches at 50 frames before failure and just before failure

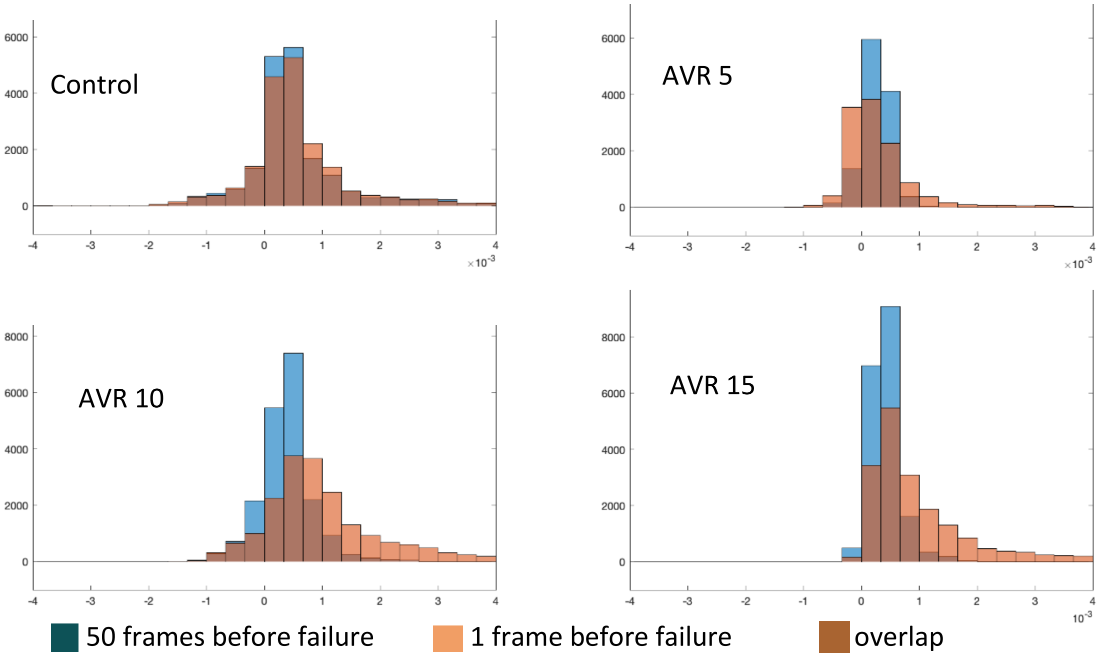

Figure 4.13: Superimposed histograms of frequency of tensile strain values (mε) for the control and AVR test batches at 50 frames before failure and just before failure

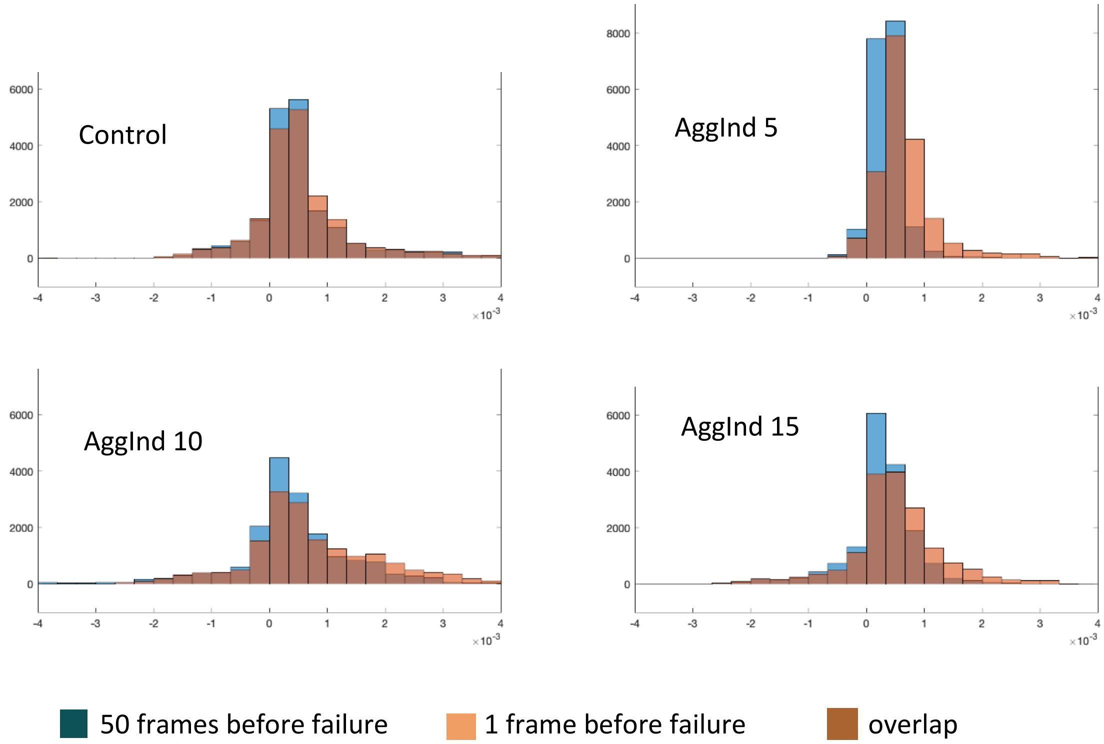

Figure 4.14: Superimposed histograms of frequency of tensile strain values (mε) for the control and AggInd test batches at 50 frames before failure and just before failure

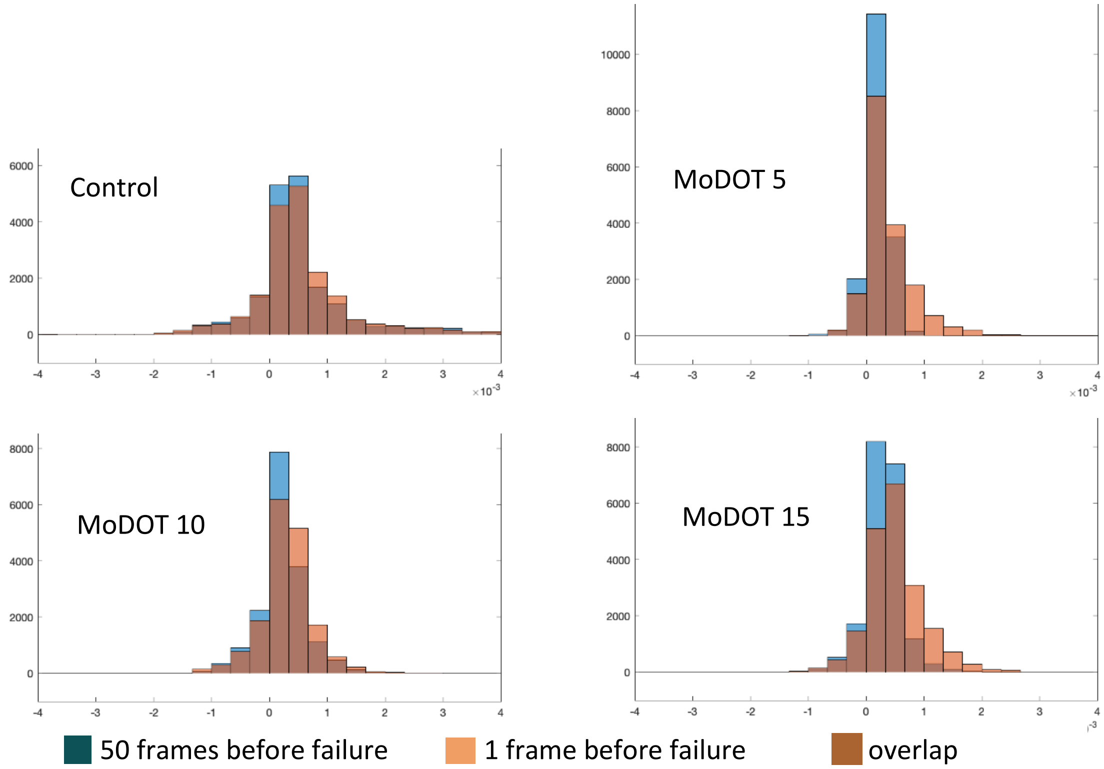

Figure 4.15: Superimposed histograms of frequency of tensile strain values (mε) for the control and MoDOT test batches at 50 frames before failure and just before failure

From these figures, it can be seen that the samples containing RCA show a distinct shift in the distribution of the tensile strain histogram to the right as the sample approached failure, while the strain in the control histogram increased only slightly as the sample approached failure. Mean and maximum strains in the field also increased in the RCA samples but did not in the control sample. This suggests an increase in the deformation in the samples containing RCA right before failure. The new paste was of the same composition for all mixes, but the RCA aggregate itself contains both an aggregate and an adhered mortar phase. The adhered mortar is less stiff than the aggregate and its presence contributes to a lower overall fraction of aggregate in the concrete. These factors could be responsible for the higher level of deformation observed before failure. The aggregate in the parent concrete from the AVR, Henderson, and Aggregate Industries batches is likely made from granite or gravel based on the region from which it was sourced. These aggregates are likely to be as stiff or stiffer than the limestone aggregate used as the control, which further suggests that the adhered mortar is responsible for the higher tensile strains observed. The presence of the adhered mortar is also a contributing factor to the lower compressive strength of samples containing RCA, as discussed in Section 4.3.1 .

4.3.3 Flexural Strength

The flexural strength with time is shown in Figure 4.16 and Table 4.8. Table 4.8 also shows the rate of strength gain *m*. From Figure 4.16, it can be seen that the flexural strengths of the test mixes containing RCA were grouped around the control mix, with some test batches having higher strength and some having lower strength. The statistical analysis found that there was no statistically significant difference between the 28 day flexural strength of the control batch and any of the test mixes except the Aggregate Industries 5 batch, which had a higher strength than the control mix. However, Figure 4.16 also shows that the average 28 day flexural strength was lower than would be expected from the trend of the breaks at other ages. Looking at the data from other ages can provide further insight.

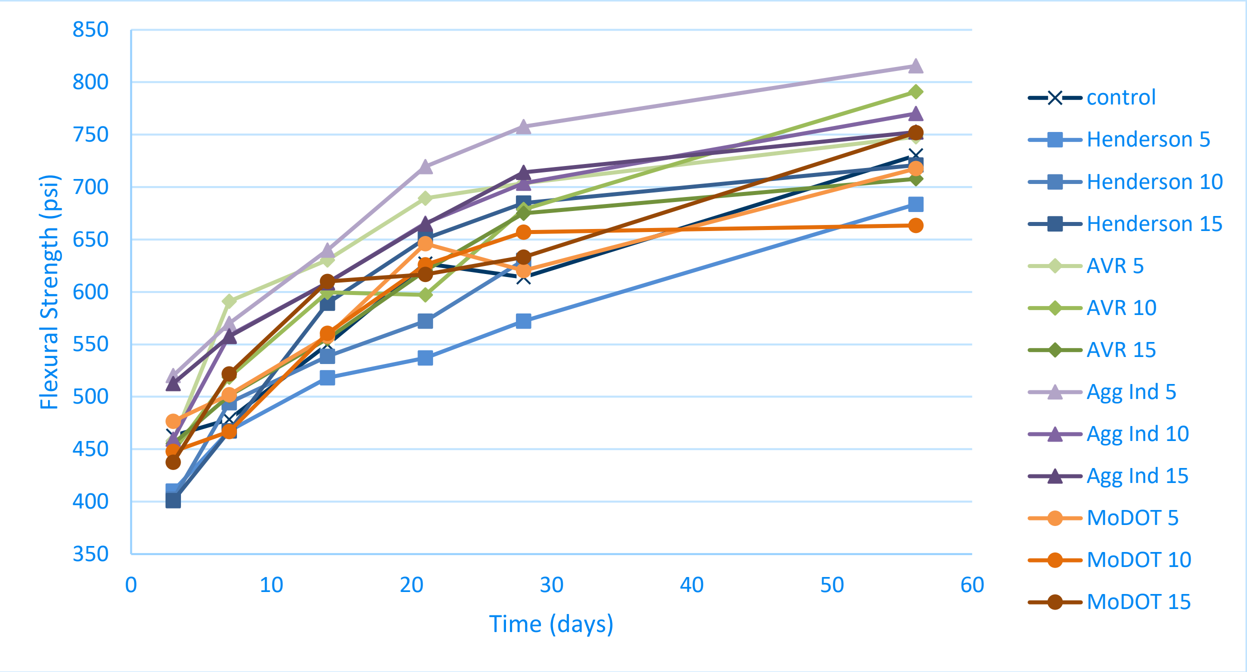

Figure 4.16: Flexural strength versus time

The flexural strength at three and seven days show the early age strength, which is important for determining opening to traffic. There was no statistically significant difference at early ages between the control batch and the test mixes made with RCA. The flexural strength at 56 days gives a better indication of the long-term behavior, and again, there was no statistically significant difference between the control batch and the mixes containing RCA.

Table 4.8: Flexural Strength Results

Batch	Flexural Strength (psi) at Day						Rate of strength gain, *m* (psi/ln(day))
	3	7	14	21	28	56	
Control	463	479	550	627	614	730	93
Henderson 5	410	467	518	537	572	684	87
Henderson 10	403	494	539	572	630	N/A	94
Henderson 15	401	468	589	651	685	721	120
AVR 5	458	591	630	689	704	748	98
AVR 10	448	519	600	597	679	791	112
AVR 15	455	501	555	620	675	708	93
Agg Ind 5	520	570	640	719	758	816	108
Agg Ind 10	460	558	609	666	704	770	106
Agg Ind 15	513	557	609	665	714	753	87
MoDOT 5	477	502	558	646	620	718	84
MoDOT 10	448	467	561	626	657	663	87
MoDOT 15	438	522	610	617	633	752	101

The flexural strength versus RCA replacement level is shown in Figure 4.17 for 3-, 28- and 56-day strengths. The 7-day strength values are not included for clarity of the graph, but they follow a similar trend as the 3-day results. The reader should exercise caution in interpreting this figure given that most of the results are not statistically significant. Therefore, this data should be interpreted as not showing a trend between RCA replacement level and flexural strength. The presence of RCA is not generally considered to change flexural strength significantly [7], so the results follow the expected trend. The literature review also showed that increasing RCA content was associated with higher decreases in flexural strength but that these decreases are also modest. Flexural strength decreases at low RCA replacement levels, such as those used here were mostly negligible, which again fits the data seen here.

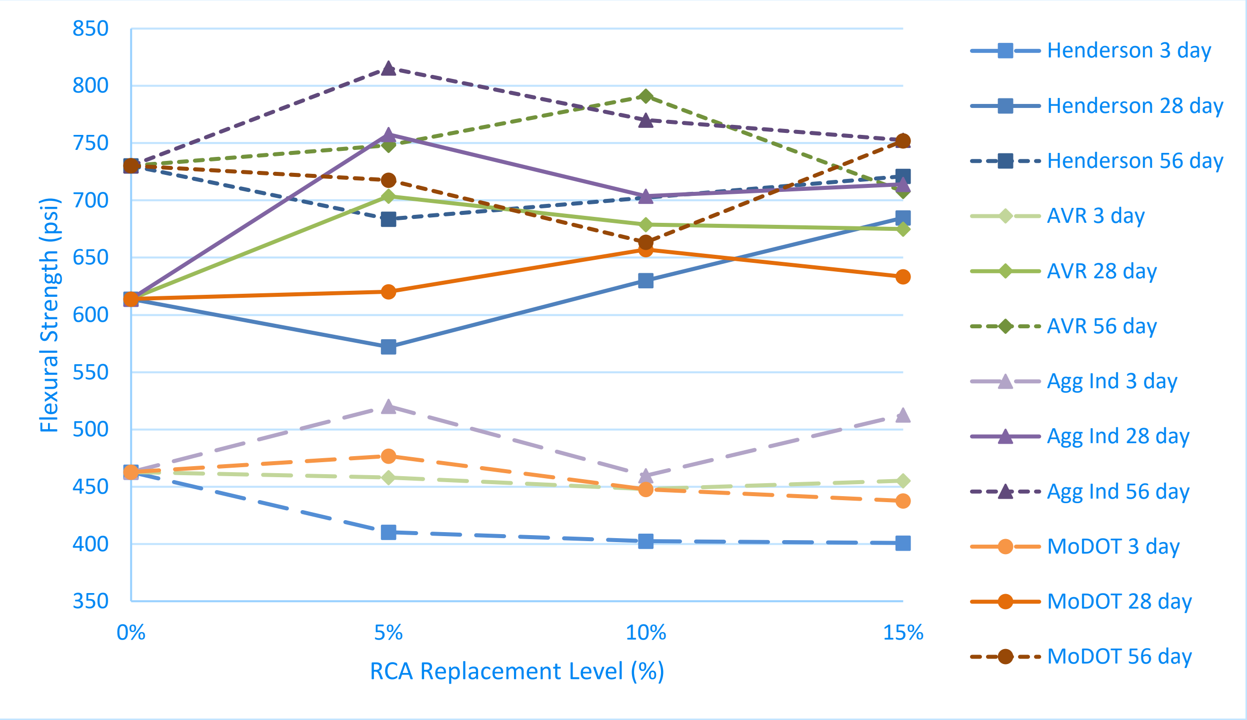

Figure 4.17: Flexural strength versus RCA replacement level

AASHTO criteria for performance engineered concrete mixes for pavements requires a flexural strength of 600 psi at 28 days [141]. All mixes in this study met this criterion except Henderson 5, which had a 28-day flexural strength of 572 psi. All mixes exceeded this criterion by 56 days.

Linear regression analysis was used to explore any potential correlations between flexural strength and the aggregate properties of absorption capacity, percent fines, fineness modulus, specific gravity, and Micro-Deval. No significant correlations were found between any of the aggregate properties and the 3-, 7-, or 56-day strengths. The 28-day flexural strength was found to be positively correlated with absorption capacity and Micro-Deval, and inversely correlated with the specific gravity. The coefficients of determination were similar for these three properties. No significant correlations were found between 28-day flexural strength and either the percent fines or the fineness modulus. However, the 28-day data for the control group was lower than expected, as previously discussed. The linear regression analysis uses the control group as the 0% replacement level for all mixes. If this data point is removed and the analysis is repeated for only the 5, 10, and 15% replacement levels, then there are no significant correlations between 28-day flexural strength and any aggregate properties. It is likely, therefore that the correlations between 28-day flexural strength and aggregate properties are only a function of lower 28-day flexural strength of the control group. This data point should be repeated to confirm this hypothesis.

The rate of flexural strength gain was also investigated by examining the curvature of each line shown in Figure 4.16. These computed rates of strength gain are shown versus RCA replacement level in Figure 4.18. This figure shows no easily discernable trend between RCA replacement level and the rate of flexural strength gain. ANOVA analysis could not be conducted on the rate of strength gain due to a lack of replicates, so it is not possible to tell if there is a statistically significant difference between the rate of gain of the control and mixes containing RCA. Linear regression analysis showed a statistically significant correlation between the 28-day flexural strength, and the rate of strength gain, which is to be expected. There was no statistically significant correlation between flexural strength gain and any of the aggregate properties investigated.

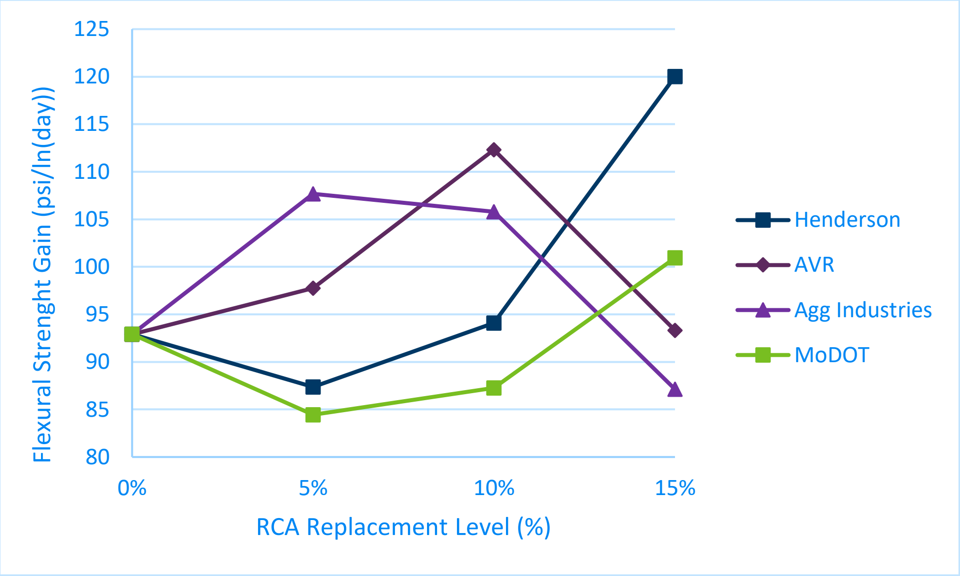

Figure 4.18: Rate of flexural strength gain versus RCA replacement level

The values of actual and estimated 28-day flexural strength are shown in Table 4.9. The ratio of the estimated to actual strength is also provided. This correlation over-estimated the flexural strength of the control group but underestimated the flexural strength of the batches containing RCA in most cases, with an overall average underestimation of 4%. This is likely acceptable from a pavement design perspective because some error would be expected when using a correlation to estimate flexural strength, regardless of if RCA were used or not. Indeed, the control group had a larger estimation error. Future studies should look at this correlation for a larger sample group of RCA types to see if it still holds.

Table 4.9: Actual Versus Estimated Flexural Strength

Batch	Actual 28-day flexural strength (psi)	Estimated 28-day flexural strength (psi)	Estimated/Actual
Control	614	714	1.16
Henderson 5	572	706	1.23
Henderson 10	630	587	0.93
Henderson 15	685	655	0.96
AVR 5	704	658	0.94
AVR 10	679	575	0.85
AVR 15	675	686	1.02
Agg Ind 5	758	655	0.87
Agg Ind 10	704	617	0.88
Agg Ind 15	714	657	0.92
MoDOT 5	620	581	0.94
MoDOT 10	657	642	0.98
MoDOT 15	633	634	1.00

4.3.4 Elastic Modulus

The elastic modulus of concrete containing RCA was found to decrease in all cases when compared with the control group, as shown in Figure 4.19. Results can also be found in Table 4.6. However, this decrease was only found to be statistically significant for the AVR 10 and AVR 15 mixes. Therefore, this figure should not be used generally to look for trends between RCA replacement level and elastic modulus.

A decrease in elastic modulus when RCA is included in a concrete mix is generally expected [10,106,114]. The literature review found that this decrease is modest for moderate replacement levels and increases with increasing RCA replacement levels. Of the few studies that used low replacement levels similar to those used in this research, little to no change in elastic modulus was observed [26,29,34], which matches the data seen here.

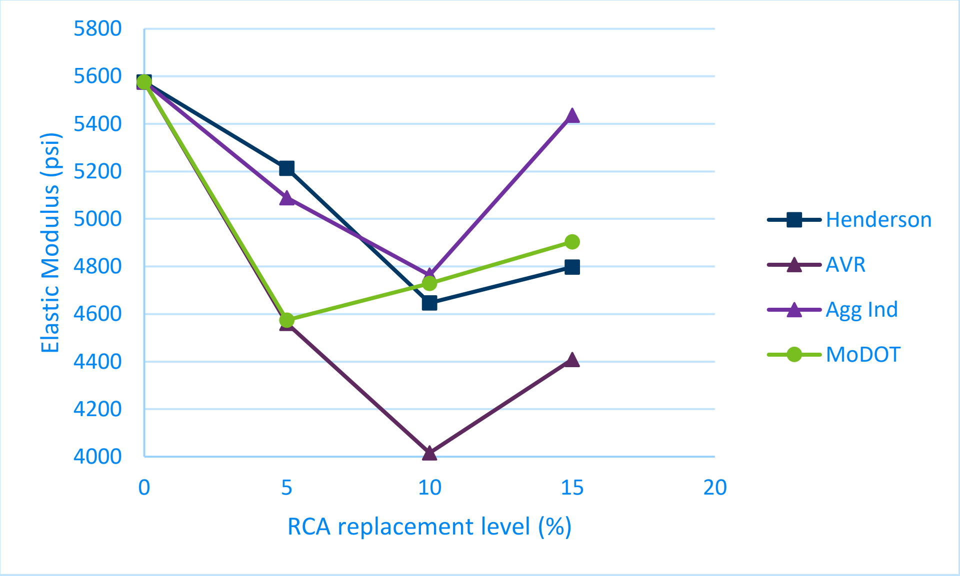

Figure 4.19: Elastic modulus versus RCA replacement level

Linear regression analysis showed statistically significant correlations between the elastic modulus all aggregate properties investigated. Elastic modulus decreased as absorption capacity increased, which is as expected. Increased absorption capacity is associated with higher mortar content in the RCA [107] which is in turn associated with lower concrete stiffness [10]. Elastic modulus was also found to increase as the aggregate specific gravity increased. This also matches the expected trend because a higher specific gravity means less adhered mortar [107], which should result in a higher concrete stiffness [10]. Increases in fineness modulus (indicating a coarser gradation) were found to be correlated with higher concrete stiffness. It is possible that the coarse gradation is indicative of less particle breakdown during the RCA crushing process, which may point to a stronger, stiffer aggregate particle. This would be expected to lead to stiffer concrete [8]. An increase in the percent fines in the aggregate was found to decrease the elastic modulus. The RCA aggregates contained higher amounts of fines compared to the control aggregate, and these fines are likely composed mainly of mortar from the parent concrete, which would be less stiff than the control aggregate. Replacing a portion of the control aggregate with these fines would therefore be expected to result in lower concrete stiffness. Similarly, the elastic modulus was found to decrease as the Micro-Deval value increased. A higher Micro-Deval value is associated with more particle breakdown, which could indicate higher amounts of adhered mortar and more fines, leading to lower concrete stiffness.

The coefficients of determination show that percent fines was largest determiner of elastic modulus and Micro-Deval was the smallest. Absorption capacity, fineness modulus, and specific gravity had similar values of R^2, and they were between the values for percent fines and Micro-Deval.

The values of actual and estimated 28-day elastic modulus are shown in Table 4.10. The ratio of the estimated to actual modulus is also provided. In all cases, the correlation overestimated the elastic modulus. For the control group, the elastic modulus was overestimated by 30% while the average overestimate for the batches containing RCA was 25%. Given that the correlation used assumes a standard concrete unit weight and that concrete containing RCA may have lower unit weight, it is possible that the longer form correlation which includes a unit weight term may produce more accurate results. However, it is highly unlikely that the pavement designer would know the RCA type and specific gravity during the pavement design phase, so the use of unit weight in any estimation of elastic modulus is impractical. Future research with a large range of RCA types should further investigate this correlation to see if other improvements are possible.

Table 4.10: Actual Versus Estimated Elastic Modulus

Batch	Actual 28-day Elastic Modulus (psi)	Estimated 28-day Elastic Modulus (psi)	Estimated/Actual
Control	5576	4282	1.30
Henderson 5	5213	4233	1.23
Henderson 10	4647	3521	1.32
Henderson 15	4797	3931	1.22
AVR 5	4561	3950	1.15
AVR 10	4016	3450	1.16
AVR 15	4409	4118	1.07
Agg Ind 5	5089	3932	1.29
Agg Ind 10	4764	3701	1.29
Agg Ind 15	5436	3945	1.38
MoDOT 5	4575	3487	1.31
MoDOT 10	4730	3849	1.23
MoDOT 15	4904	3807	1.29

4.3.5 Poisson’s Ratio

There was found to be no statistically significant difference between the value of Poisson’s ratio for the control mix and the mixes containing RCA at any replacement level. Values of Poisson’s ratio versus RCA content are shown in Figure 4.20. Results can also be found in Table 4.6. The reader should not attempt to determine trends in how RCA content changes Poisson’s ratio because there is no significant trend. The literature is also inconclusive on the effects of RCA use on Poisson’s ratio, with some studies finding values increased [96,113] and others finding a decrease [27]. The range of values observed in this study is within the typical range of 0.15 to 0.25 expected for concrete and close to the commonly stated value of 0.20 to 0.21 [9].

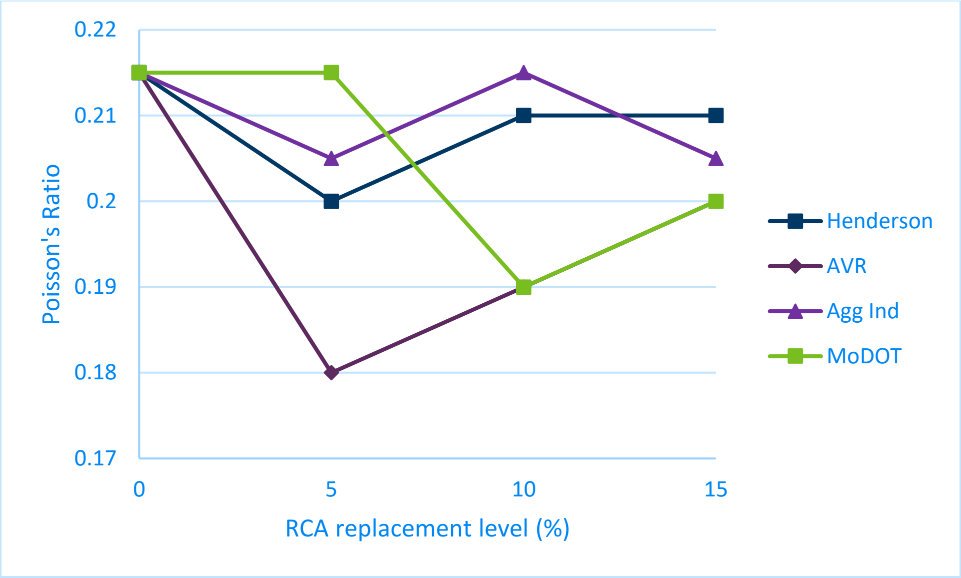

Figure 4.20: Poisson's ratio versus RCA replacement level

The linear regression analysis found no significant correlation was found between Poisson’s ratio and absorption capacity, specific gravity, or Micro-Deval. A significant positive correlation was found between Poisson’s ratio and the fineness modulus and a significant inverse correlation was found with percent fines. These properties had similar coefficients of determination. There is little information in the literature on why these properties may have an influence on Poisson’s ratio. However, that influence was insufficient to cause enough change for the values of Poisson’s ratio to be statistically significant between mixes and variations in Poisson’s ratio have not been found to significantly alter predicted pavement performance [157], so these correlations may be of little practical importance.

4.3.6 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) was generally found to increase when RCA was included in the mix. However, the differences in CTE between the control group and the concrete containing RCA were only found to be statistically significant for the mixes containing AVR aggregate. Values of CTE versus RCA replacement level are shown in Figure 4.21. Results can also be found in Table 4.6. All values measured were within the standard range for concrete of 6 to 13 mm/mm/°C [9]. The literature is generally inconclusive about the effect of RCA on concrete CTE, with the use of RCA generally expected to decrease CTE [57,86,159,160] but with several studies also finding an increase [82,111,161], which fits the results seen here.

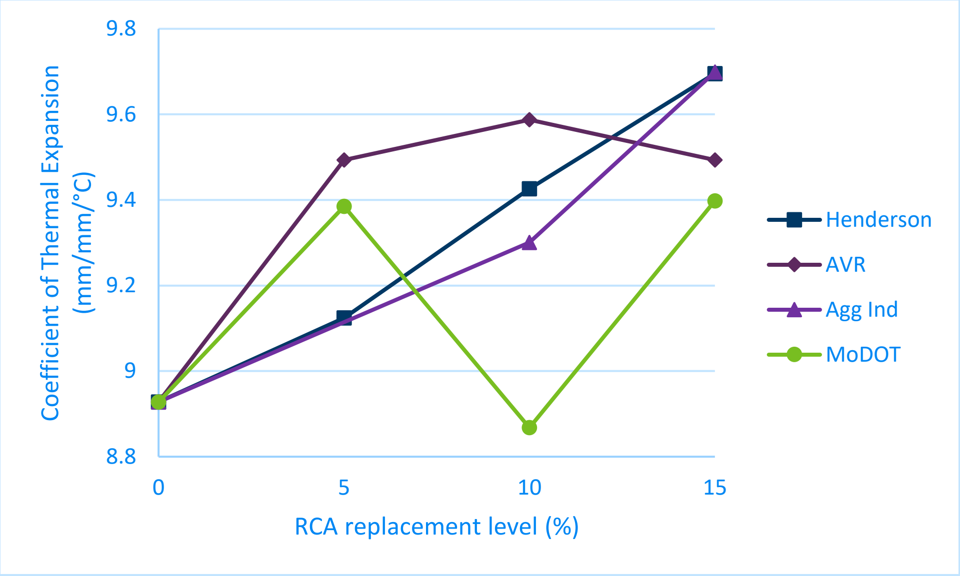

Figure 4.21: Coefficient of Thermal Expansion versus RCA replacement level

The linear regression analysis showed that all aggregate properties investigated were significantly correlated with CTE. CTE increased as absorption capacity, Micro-Deval, and percent fines increased. Increases in these properties are associated with higher mortar content in the RCA, which would be expected to increase CTE [111]. Similarly, the inverse correlation between CTE and specific gravity would also indicate higher mortar contents. The fineness modulus was found to be inversely correlated with CTE, and a smaller fineness modulus, associated with smaller aggregate particles, could also indicate a higher mortar content and therefore higher CTE. Absorption capacity, specific gravity and Micro-Deval had much higher coefficients of determination than fineness modulus and fines.

4.3.7 Surface Resistivity

The surface resistivity with time is shown in Figure 4.22 and Table 4.11. From this figure, it can be seen that the surface resistivity was lower for all batches containing RCA compared to the control at all ages except seven days, with lower values indicating less durability. Use of RCA is typically expected to reduce resistivity [113,152], so these results are as expected. The values of 28-day resistivity were found to be statistically significantly different from the control batch for all RCA mixes except Henderson 5, Aggregate Industries 15 and MoDOT 15. However, the decrease in resistivity was not sufficient to change the qualitative assessment of chloride ion penetration risk in most cases. At 28 days, all mixes exhibited a moderate risk of chloride ion penetration except AVR 10, which had a high risk. An increase in resistivity with age is expected [57] and by 56 days, several samples had high enough values of resistivity to be categorized as low risk for chloride ion penetration.

The presence of RCA reduces resistivity because the resultant concrete is more permeable due to the increased porosity of the RCA [88]. While resistivity is generally correlates well with the results of the rapid chloride permeability test for concrete containing RCA, this correlation may not be valid for mixes containing both RCA and fly ash [113]. Therefore, future work may be necessary to conduct rapid chloride permeability testing on these mixes to determine both their susceptibility to chloride ingress and if the resistivity testing can be considered valid for these mixes. Previous research has shown that concrete made with RCA can have low [113,152] or even very low [12] risk to chloride ion penetration, so ways to decrease the chloride ingress risk of the concrete mixes tested here could also be explored.

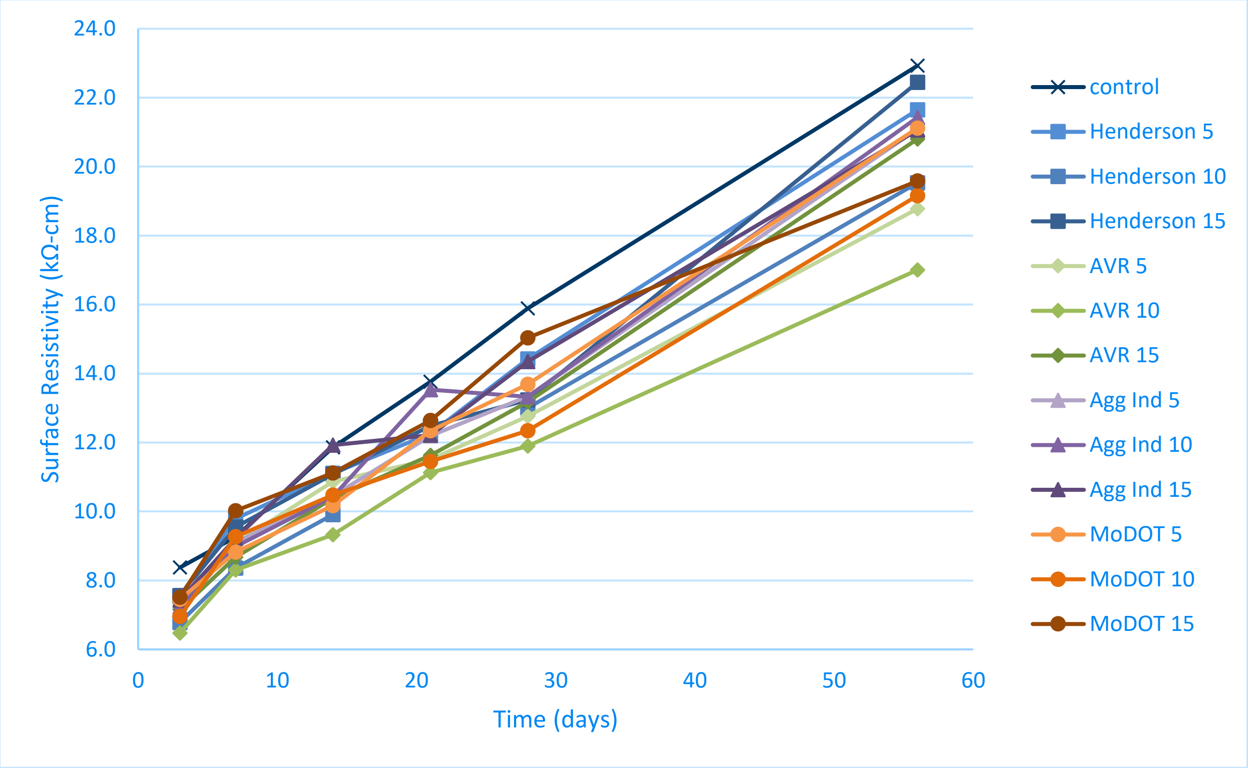

Figure 4.22: Surface Resistivity versus time

Linear regression analysis found significant correlations between resistivity and the aggregate properties of absorption capacity, specific gravity, Micro-Deval, percent fines, and fineness modulus. The positive correlation with absorption capacity and inverse correlation with specific gravity are likely due to the increased porosity of the RCA stemming from the adhered mortar, which results in less resistance to chloride ingress [88]. A higher Micro-Deval value associated with higher adhered mortar content would similarly decrease resistivity, and an inverse correlation between resistivity and Micro-Deval was also found. Resistivity was found to increase as fineness modulus increased and decrease as the percent fines increased. A coarser gradation indicated by the higher fineness modulus and a lower percent fines could indicate less particle breakdown and therefore lower adhered mortar content, both of which would also result in higher resistivity and less risk of chloride ingress. The R^2 values for absorption capacity, specific gravity and Micro-Deval were much larger than those for percent fines and fineness modulus.

Table 4.11: Surface Resistivity Results

Batch	Surface Resistivity (kΩ-cm) and Associated Risk Level at Day						Rate of Resistivity Gain (kΩ-cm/day)
	3	7	14	21	28	56	
Control	8.4 (H)	9.3 (H)	11.9 (H)	13.8 (M)	15.9 (M)	22.9 (L)	0.277
Henderson 5	7.6 (H)	9.8 (H)	11.1 (H)	12.3 (M)	14.4 (M)	21.6 (L)	0.255
Henderson 10	6.8 (H)	8.4 (H)	9.9 (H)	0 (H)	13 (M)	19.5 (M)	0.234
Henderson 15	7.6 (H)	9.6 (H)	11.1 (H)	12.5 (M)	13.2 (M)	22.4 (L)	0.268
AVR 5	7.4 (H)	9.1 (H)	10.9 (H)	11.5 (H)	12.8 (M)	18.8 (M)	0.204
AVR 10	6.5 (H)	8.3 (H)	9.3 (H)	11.1 (H)	11.9 (H)	17 (M)	0.189
AVR 15	7.2 (H)	8.7 (H)	10.4 (H)	11.6 (H)	13.2 (M)	20.8 (M)	0.251
Agg Ind 5	7.5 (H)	9.1 (H)	10.5 (H)	12.2 (M)	13.3 (M)	21.1 (L)	0.249
Agg Ind 10	7.2 (H)	9 (H)	10.4 (H)	13.5 (M)	13.3 (M)	21.4 (L)	0.259
Agg Ind 15	7.4 (H)	9.2 (H)	11.9 (H)	12.2 (M)	14.3 (M)	21.1 (L)	0.246
MoDOT 5	7.4 (H)	8.8 (H)	10.2 (H)	12.3 (M)	13.7 (M)	21.1 (L)	0.255
MoDOT 10	7 (H)	9.3 (H)	10.5 (H)	11.5 (H)	12.3 (M)	19.2 (M)	0.214
MoDOT 15	7.5 (H)	10 (H)	11.1 (H)	12.6 (M)	15 (M)	19.6 (M)	0.217

The rate of resistivity gain was investigated by examining the slope of each line shown in Figure 4.22. These computed rates of resistivity gain are shown versus RCA replacement level in Figure 4.23. This figure shows no easily discernable trend between RCA replacement level and the rate of resistivity gain other than that all mixes made with RCA had lower values of resistivity than the control group. ANOVA analysis could not be conducted on the rate of strength gain due to a lack of replicates, so it is not possible to tell if there is a statistically significant difference between the rate of gain of the control and mixes containing RCA. Linear regression analysis showed a statistically significant correlation between the 28-day resistivity, and the rate of resistivity gain, which is to be expected. There was no statistically significant correlation between resistivity gain and any of the aggregate properties investigated.

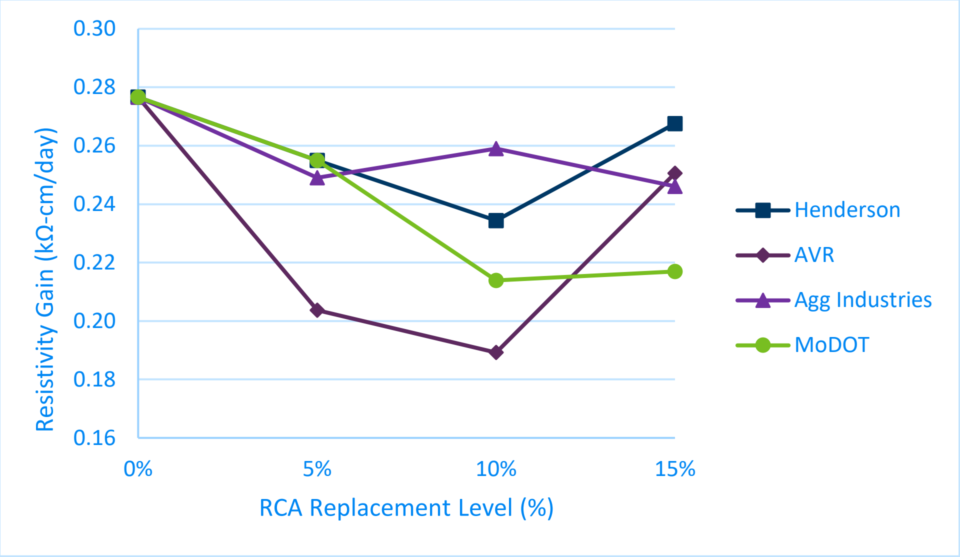

Figure 4.23: Rate of resistivity gain versus RCA replacement level

4.3.8 Freeze-Thaw Durability

The freeze-thaw durability factor was not found to be statistically significantly affected by the inclusion of RCA at any replacement level investigated. Results of durability factor versus RCA replacement level are shown in Figure 4.24, but the reader should use caution in looking for trends in these results because of the lack of statistical significance. Results can also be found in Table 4.6. A durability factor greater than 70 is commonly recommended for concrete pavements [141,205] and all samples exceeded this value. While there is no consensus on the effects of RCA on freeze-thaw durability, the results observed here match with the expectations of the American Concrete Institute that RCA does not influence freeze-thaw durability [7].

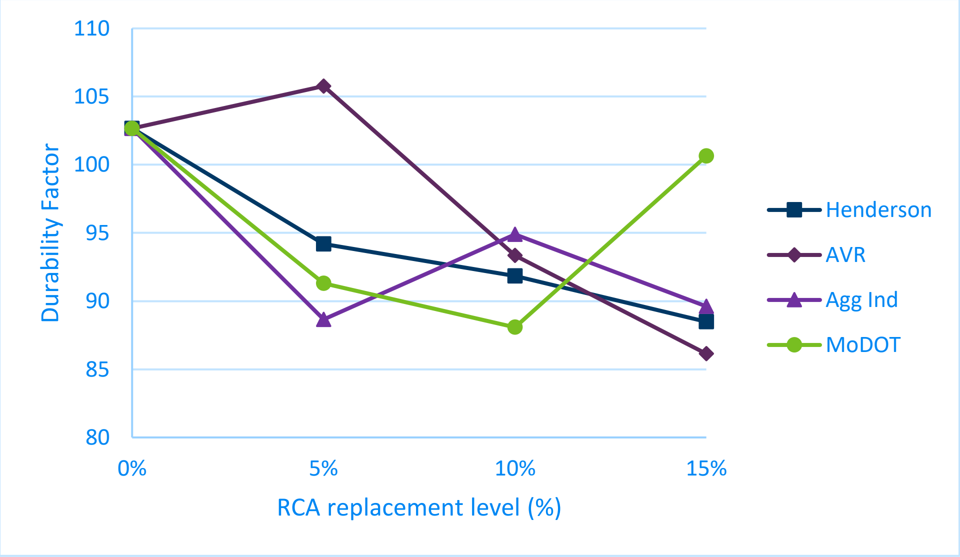

Figure 4.24: Freeze-thaw durability factor versus RCA replacement level

The linear regression analysis showed significant correlations with all aggregate properties investigated except fineness modulus. There was an inverse correlation between freeze-thaw durability factor and absorption capacity and a positive correlation between durability factor and specific gravity. These are to be expected because higher absorption capacity and lower specific gravity indicate a more porous aggregate due to higher adhered mortar content, which would allow greater water movement within the concrete [9]. Similarly, there were inverse correlations between the durability factor and both Micro-Deval and percent fines. These could both indicate a higher adhered mortar content, which would again be expected to result in lower durability. The coefficients of determination for absorption capacity, Micro-Deval, and specific gravity were all similar and much larger than the coefficient of determination for percent fines.

Freeze-thaw durability cannot be measured until after the concrete is already placed; fresh tests like air content and SAM are often used to predict freeze-thaw durability while the concrete is still plastic and for quality control. There is some concern that the standard air content test may not be as useful in concrete containing RCA because it is measuring total air content instead of just the air content in the new paste [111], though others claim the test is still valid [113]. Figure 4.25 shows the durability factor from freeze-thaw testing versus the air content measured via the pressure meter. Any tests with an air content above 5.5% should have acceptable freeze-thaw durability [185] and any durability factor above 70% indicates acceptable performance on the freeze-thaw test [141,205]. Therefore, any tests in the upper right quadrant show agreement between these two tests that the concrete will have good freeze-thaw resistance. As seen in Figure 4.25, almost all of the tests fall into this quadrant. There is one test below the 5.5% air content threshold set by MnDOT (for which the mix was designed), but this test still met the 5% threshold set by AASHTO [141] and had acceptable performance on the freeze that test. This supports the idea that the standard air pot is an acceptable air content test for concrete containing RCA at replacement levels up to 15%. However, additional data is needed to make a definitive claim.

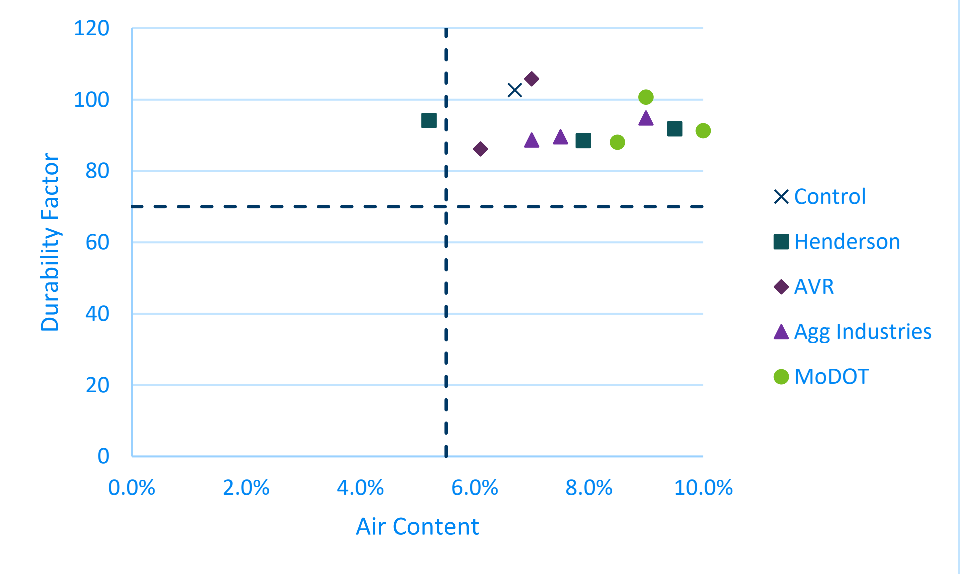

Figure 4.25: Durability factor versus air content as measured via the pressure meter

There has been little work in literature on the applicability of the SAM test to concrete made with RCA. A SAM number no greater than 0.2 is recommended to ensure freeze-thaw durability [141]. Figure 4.26 shows the freeze-thaw durability factor versus SAM number. Any points in the upper left quadrant of the graph meet the criteria for both SAM number and durability factor. From this figure, it can be seen that all but two batches met both criteria. This indicates that the SAM test may be valid for concrete containing up to 15% RCA, though the data should be treated with some caution because several of the SAM tests were indicated as likely having been run incorrectly, as discussed in Section 4.2.2 . Additional data and a larger number of tests would be required to definitively state that the SAM test is valid for concrete containing RCA.

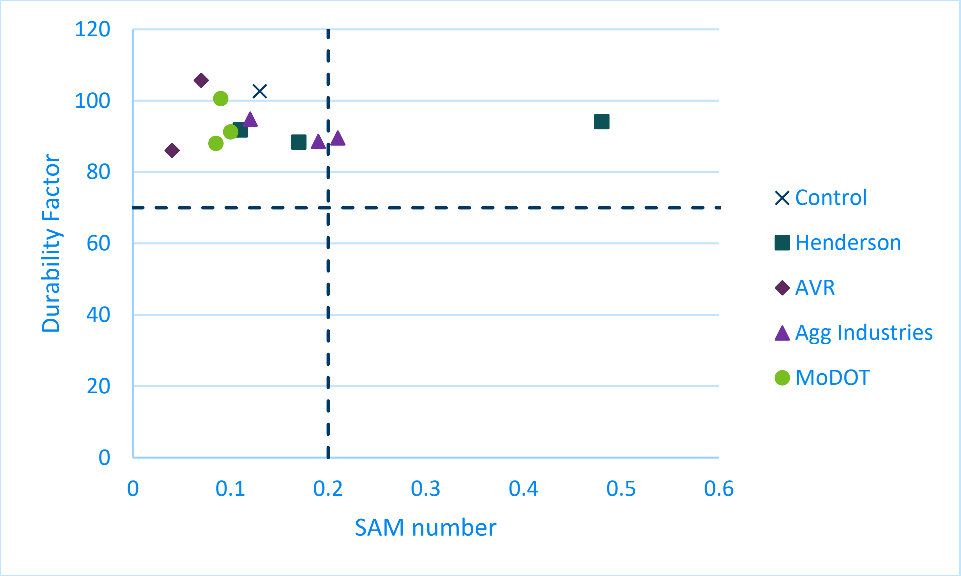

Figure 4.26: Durability factor versus SAM number

4.3.9 Shrinkage

The shrinkage at 252 days was found to increase in some cases and decrease in others when RCA was used. Shrinkage at 252 days versus RCA replacement level is shown in Figure 4.27 and results with time are shown in Figure 4.28. However, none of the shrinkage results for the batches containing RCA were found to be statistically significantly different than the control concrete. Therefore, the shrinkage results presented in Figure 4.27 should not be used to look for trends. Results can also be found in Table 4.6. While it is generally accepted that the use of RCA in concrete causes increased shrinkage [9,116,207], it has also been shown that low replacement levels (less than 20 to 30%) can produce negligible changes in shrinkage [10,33,66,177,178]. Therefore, the results shown here are not unexpected. Shrinkage values will be expected to increase as the concrete continues to age, though the value of shrinkage strain appears to be stabilizing as shown in Figure 4.27. Ultimate shrinkage values upon completion of shrinkage testing will be provided in a memo but the established trends are not expected to change.

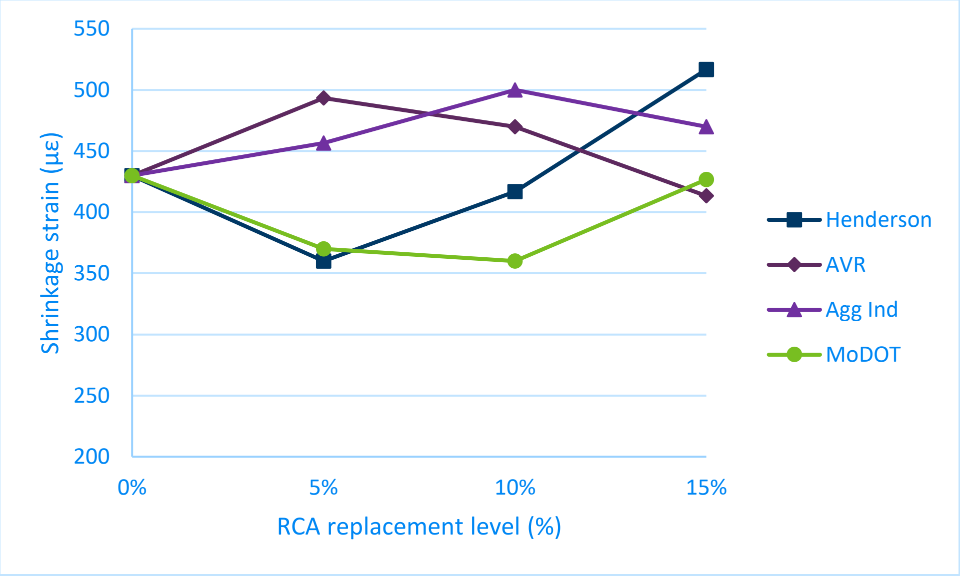

Figure 4.27: Shrinkage at 252 days versus RCA replacement level

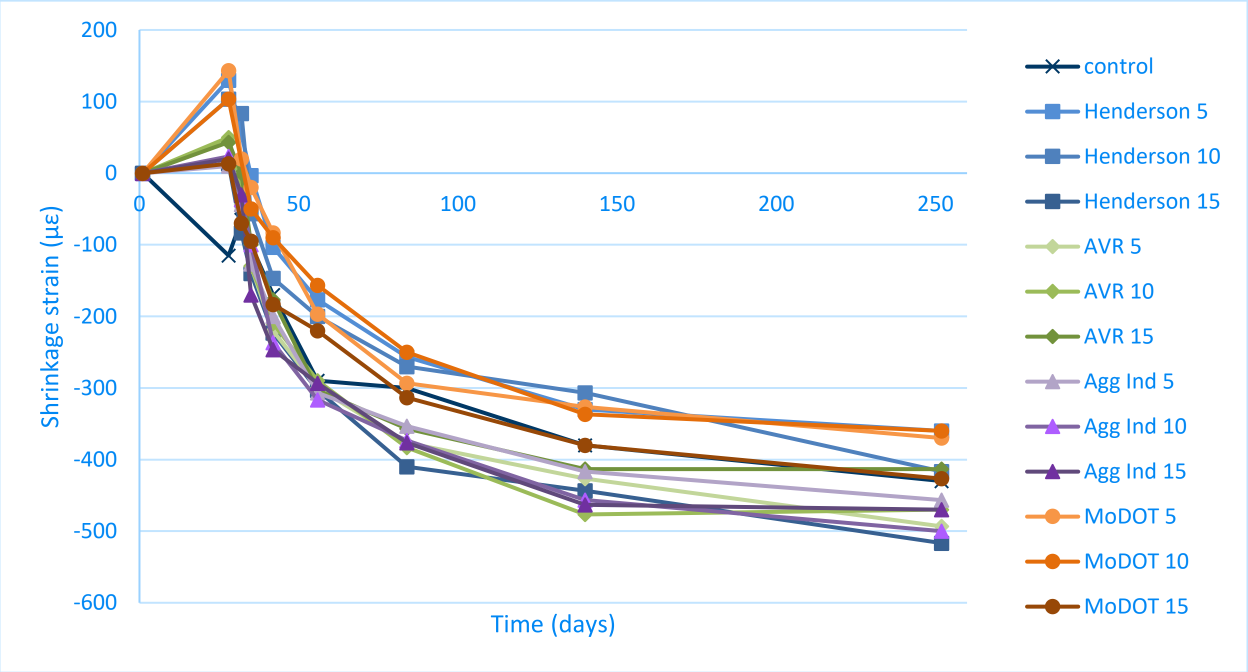

Figure 4.28: Shrinkage strain with time up to 252 days

The AASHTO T160 [208] and ASTM C157 [201] both provide test methods to determine shrinkage strain but they specify soaking samples for a different amount of time and measurements at different time intervals. This research was conducted using ASTM C157, which calls for 28 days of storage in a lime water bath before moving to drying conditions. The AASHTO test uses only a seven day period of soaking, which would result in higher values of shrinkage. The AASHTO criteria for performance engineered concrete mixes for pavements limits shrinkage at 91 days to 480 microstrain [141]. The ASTM test measures shrinkage at 84 and 140 days, but not 91. These two differences make direct comparisons between the data and the AASHTO criteria difficult. All mixes had a 140 day shrinkage less than the 480με limit and most mixes met this criteria at 252 days. While this information cannot be used to say that the shrinkage strain meets the AASHTO performance engineered concrete mix criteria, it does show that all shrinkage values are within a reasonable range and that the presence of RCA at the replacement levels investigated is not causing excessive shrinkage.

Linear regression analysis showed that shrinkage had significant correlations with all aggregate properties investigated. More shrinkage occurred in samples with higher absorption capacity and lower specific gravity. This is as expected because higher absorption capacity and lower specific gravity are associated with higher adhered mortar content [107], which is associated with higher shrinkage [111]. This can be due to increased moisture mobility within the concrete [77,88], increased paste content [114], and/or lower stiffness to restrain shrinkage [10,77]. Similarly, a higher Micro-Deval value and higher percent fines could also indicate higher mortar content and therefore increased shrinkage. Both values were found to be correlated with higher shrinkage levels. Aggregates provide restraint from shrinkage and concrete made with larger aggregate is typically expected to shrink less [8]. Here, aggregates with a higher fineness modulus, indicating coarser gradations and more large particles, were found to be correlated with less overall shrinkage. This may be due to the aggregate size generally or the fact that larger RCA particles tend to have lower mortar content [109], or a combination of both factors. The coefficients of determination were of similar level for all aggregate properties investigated except Micro-Deval, which had a larger coefficient of determination.

Chapter 5: Conclusions and Recommendations

This study investigated the effect of using low replacement levels of RCA on the properties of concrete for paving applications. Replacement levels of 5, 10, and 15% were compared to a control group containing only virgin aggregate. Four RCA sources were tested, representing a variety of RCA properties. Fresh and hardened tests were conducted, and results were analyzed to determine if the use of RCA caused any statistically significant differences between the test batches and the control group.

5.1 Conclusions

This research found that using RCA with reasonable characteristics at replacement levels of up to 15% would likely not adversely affect many of the concrete properties of interest to pavement design. Three of the four aggregates tested would likely be considered reasonable based on generally accepted limits on properties like absorption capacity and percent fines: Henderson, Aggregate Industries, and MoDOT. However, this research was not intended to define the limits of what is reasonable and future work is still needed in this area.

The following conclusions on the effects of using low levels of RCA on specific concrete properties were found:

- Most of the test mixes considered experienced a statistically significant decrease in compressive strength, even at low RCA replacement levels. While the difference between the 28-day compressive strength of the control group and mixes containing RCA ranged from a 3% gain to a 38% reduction, most mixes experienced a 15-25% reduction.

- The rate of compressive strength gain showed that the concrete made with RCA was unlikely to gain sufficient long-term strength to eventually achieve a similar strength level as concrete made with virgin aggregate.

- The compressive strength itself was found to be correlated with aggregate properties but the rate of compressive strength gain was not. This suggests that the reduction in compressive strength was a function of the RCA itself and that the presence of the RCA did not affect the hydration reaction of the new paste.

- The flexural strength of the concrete was not impacted by the presence of RCA in a statistically significant way at 3, 7, or 56 days. At 28 days, one sample containing RCA had a statistically significantly larger flexural strength than the control group, and all other test mixes were unaffected by the inclusion of RCA. The control group's 28-day flexural strength was lower than expected when compared to the other ages tested, so this result should be treated tentatively. Looking at the flexural strength data as a whole, it appeared to be unaffected by the inclusion of RCA.

- There was a statistically significant decrease in the elastic modulus of the concrete made with the AVR aggregate at the 10 and 15% replacement levels versus the control group. None of the other batches tested had elastic moduli significantly different from that of the control.

- There was a statistically significant increase in the CTE of the concrete made with the AVR aggregate at all replacement levels versus the control group. None of the other batches tested had CTEs significantly different from the control.
- There was no statistically significant difference in the values of Poisson's ratio, shrinkage at 252 days, and freeze-thaw durability factor between the control group and any of the mixes containing RCA.
- The inclusion of RCA was found to decrease the value of surface resistivity in a statistically significant way for almost all the test batches compared to the control batch. However, the control and all mixes containing RCA, except the AVR 10 mix, were considered to have a moderate risk of chloride ingress at 28 days. Therefore, this result may not have much practical significance.
- Incorporating RCA into the concrete generally increased the slump, which could be due to the additional water added to the mix as part of the moisture correction process. The short amount of time between batching the concrete and taking the slump measurement may have been insufficient to allow all the water to be absorbed by the RCA, resulting in temporarily increased workability.
- The standard air content test and SAM number correlated well with freeze-thaw durability and are therefore likely still valid predictors of freeze-thaw durability at the RCA replacement levels investigated.

Compressive strength was the property that experienced the largest negative impact from using RCA, even at low replacement levels. This matches trends observed in the literature, albeit for only a few studies since there has been limited work on RCA replacement at low levels [29,35]. The decrease in compressive strength is likely due to the presence of the adhered mortar on the RCA, which results in the RCA itself potentially having lower strength, forming a lower-quality bond with the new concrete paste, and/or a reduction in the actual amount of aggregate present in the concrete because a certain fraction of aggregate was replaced by paste. These hypotheses are supported by digital image correlation (DIC) analysis of compression testing, which showed an increase in tensile strain before failure. This was likely due to the adhered mortar on the RCA, which was both less stiff than the virgin aggregate and the aggregate phases of the RCA and which occupied space in the concrete that would normally be devoted to aggregate.

While compressive strength is the most commonly tested concrete property, its main purpose in pavement design is to be correlated with properties that are less commonly measured directly at the time of design, such as flexural strength and elastic modulus. Flexural strength was found to be underestimated by an average of 4% when RCA was used, while elastic modulus was found to be overestimated by an average of 25%

Statistical analysis investigated the relationship between aggregate properties and hardened concrete properties. The aggregate properties investigated were absorption capacity, specific gravity, Micro-Deval, percent fines, and fineness modulus. Properties were computed as composite properties based on the percent of RCA versus virgin aggregate in the mix. Most concrete properties were found to be correlated with aggregate properties. The coefficient of determination R^2 shows how much of the variability in a given concrete property could be explained by an aggregate property. The R^2 values for fineness modulus were generally not significant or were lower than the R^2 values for absorption capacity, specific gravity, and Micro-Deval. Percent fines had high R^2 values for elastic modulus and Poisson's ratio, but low values for all other concrete properties. This indicates that properties related to RCA mortar content may be more likely to be predictors of the behavior of concrete made with RCA than properties related to gradation. It also supports the idea that replacing virgin aggregate with RCA from within the same gradation band even if the gradations are not identical is not problematic.

5.2 Recommendations for Future Research

The study presented here was intended as a first step toward implementation of low levels of RCA in new concrete pavements. An ideal goal would be to find a quantity of RCA that could be included in standard paving concrete without concern for how properties would be affected, similar to how recycled asphalt pavement (RAP) is currently used in new asphalt pavements at low levels. To accomplish this goal, additional work will be needed to build off the conclusions from this study. The following areas for further research were identified:

- Adding RCA, even at low levels, was found to change the slump and air content enough that uniformity between batches made with and without RCA or with different types of RCA could be a concern for meeting acceptance criteria and constructability. More testing is needed to determine if the natural variation within a stockpile of a single RCA type would create uniformity concerns or not. Work is also needed to identify when an RCA is different enough from another RCA to count as a different material, both in terms of when the effect on concrete properties would be different and when the specific gravity would be different enough to affect volume-based replacement, given that producers will likely calculate the volume but measure the weight during production.

- Slump and box test scores were both found to have a statistically significant correlation with air content but not with any of the aggregate properties examined. This suggests that controlling air content may be an important aspect to ensuring the proper level of workability for paving applications. The variation in air content and slump values for several different batches of concrete made from the same RCA stockpile should be investigated.

- Compressive strength is typically an input in pavement design in that it is used to estimate the flexural strength and elastic modulus. The relationship with elastic modulus in particular was found to overestimate the measured value. Future research should consider improvements to this correlation. One challenge is that the correlation is based in part on unit weight, which will change with RCA source.

- This research only looked at the risk of chloride ingress as measured by surface resistivity. There is some concern that the correlation between this risk as measured by surface resistivity versus the rapid chloride permeability test may be questionable if the concrete includes both RCA and fly ash [113], which this concrete did. Rapid chloride permeability testing should also be conducted to determine if the risk levels seen here are reasonable.

- RCA was found to lower the rate of surface resistivity gain of the concrete, meaning it takes longer for the concrete to reach a higher level of resistance to chloride ingress. Future work should investigate if concrete made with RCA requires additional time before chlorides are applied and if some time requirement would be appropriate to ensure deicing salts are not applied too soon after paving. This is likely only a concern for late season paving.

- While the SAM test results correlated well with freeze-thaw durability, many of the SAM test results were not valid. This testing should be repeated to ensure the trend holds. A larger data set will also be required to determine if both the air content and/or SAM number are good estimates of freeze-thaw durability.

- This research conducted the shrinkage test under ASTM procedures, which differ from those of AASHTO. Shrinkage testing should be repeated with AASHTO methods to ensure that the shrinkage values obtained meet AASHTO performance mix design criteria.

- Current data was insufficient to determine if any RCA properties can be used as predictors of the effect using RCA will have on concrete properties. But it does indicate that aggregate properties related to mortar content are more likely to be useful predictors than properties related to gradation.

Future work in several of the areas identified above will be needed before RCA can be implemented at low levels with confidence. Of particular importance will be identifying parameters that can be used to specify RCA. This research has identified several aggregate characteristics that would be good starting points for future work in this area.

5.3 Recommendations for Future Implementation

Before RCA can be included in concrete mixes, there will need to be a specification with property limits that define if a specific RCA is allowable. This work showed that three of the four RCA sources tested resulted in concrete that would likely be acceptable, while one did not. The AVR aggregate was the only RCA that resulted in statistically significant changes in E and CTE. It also was the most different from the other aggregates in many of the properties tested, likely because it was not produced with the intent of being used in new concrete. While this research did not test a large enough number of RCA sources with varied properties to definitively determine RCA property criteria, it can give suggestions for which properties are likely candidates for such an investigation in the future.

The linear regression analysis showed that absorption capacity and specific gravity both explain a portion of the variation seen in all concrete properties tested except Poisson’s ratio. Absorption capacity and specific gravity have been found to have similar effects on concrete properties [38], but absorption capacity is more directly related to adhered mortar content while specific gravity of the RCA will also be influenced by the density of the aggregate in the parent concrete. Therefore, absorption capacity is likely a better parameter to investigate. A limit on absorption capacity of 5% has been suggested when specifying RCA [107]. The Henderson and Aggregate Industries RCAs had absorption capacities of 5.32% and 6.05%, respectively, which were above this 5% limit, but both aggregates produced concrete that did not vary significantly from the control concrete in most properties tested. This was in contrast to the

AVR aggregate, which had an 8.78% absorption capacity and a larger impact on concrete properties. This suggests a limit on absorption capacity close to 5% is a good starting point for future work defining a specification.

The linear regression analysis showed that percent fines may be an important property to consider with respect to elastic modulus and Poisson's ratio, but not any of the other concrete properties. Many DOT specifications already limit the percent fines, and the technical advisory panel for this project, comprised of DOT personnel from several agencies, expressed strong support for requiring either that the RCA be washed or meet the limits on percent fines to which virgin aggregates are held. While the RCA suppliers contacted in this study expressed reluctance to wash their material, most felt confident they could meet a 1% fines limit without washing. Future work to define a specification should likely consider a limit on the percent fines and 1% may be an initial limit to consider because it is achievable by producers, acceptable by agencies, and aggregates meeting this limit had positive results in this research. The AVR RCA also differed from the other RCA material tested in having a much higher percent fines, with 2.89% of material passing the #200 sieve. This was in contrast to the other three sources, which all had fewer than 1% fines.

Micro-Deval was identified by the linear regression analysis as an important aggregate property when considering the effects of RCA on compressive strength, CTE, resistivity, shrinkage, and freeze-thaw durability. However, unlike absorption capacity and percent fines, the Micro-Deval value of the AVR aggregate was not very different from that of the other RCA sources. The AVR Micro-Deval loss value of 20.5% was similar to the values for Henderson and Aggregate Industries of 21.4% and 19.7%, respectively. The MoDOT RCA had a lower Micro-Deval loss value of 14.4%, which was closer to the 10.4% value of the control aggregate. Given that the AVR aggregate was the only RCA source that resulted in statistically significant changes to CTE and produced the only concrete with a high chloride penetration risk at 28 days, this suggests that Micro-Deval may not be a useful predictor of these concrete properties even though the linear regression analysis showed it can explain some of the variation seen in test results.

Micro-Deval may be useful in eliminating RCA with aggregate from parent concrete with low-quality aggregates, which could have a negative impact on other properties. This parallels the use of Micro-Deval as a soundness test in other areas of highway construction. For example, the Missouri Department of Transportation currently limits percent loss via Micro-Deval for aggregates used in asphalt to 18 or 20%, depending on the aggregate grade [209]. While they do not currently have a similar limit for aggregates in concrete, they are exploring a limit of 22% based on past experience. Given that the aggregates in the parent concrete of the AVR, Aggregate Industries, and Henderson aggregates were likely sourced from areas of Minnesota with high-quality aggregates, it is unsurprising that the RCA produced by these parent concretes exhibited reasonable values of loss via Micro-Deval. Similarly, the MoDOT RCA from the St. Louis airport was suspected to contain aggregate from a formation of limestone known for strong performance. Any future work aimed at developing a specification should investigate RCA with parent concrete containing aggregate with lower-quality aggregate to determine if Micro-Deval is an appropriate test to control for aggregate soundness. The 22% limit proposed by the Missouri DOT would be a suggested starting point for a specification based on the DOT's experience.

Fineness modulus was used to represent gradation in the linear regression analysis. This analysis showed that fineness modulus had a low or insignificant coefficient of determination in all cases. While the AVR aggregate did have a fineness modulus that was far from that of the other three RCA types considered, this wa because AVR had a gradation slightly finer than the #67 gradation while the other three RCA sources had gradations slightly coarser than the #67 gradation. All RCAs were outside the target gradation limits but very close to them. The linear regression analysis here supports previous findings in the literature that replacing aggregate within or close to a single gradation band does not have a significant impact on concrete properties [184]. From a practical standpoint, specifying that the RCA must meet the same gradation band as the virgin aggregate it is replacing is the most realistic option that can easily be accomplished by producers. Thus, it is recommended that this be the future specification requirement related to gradation.

A specification for RCA could also consider other properties not investigated here, such as aggregate porosity or soundness. As discussed in the literature review, these are not without challenges, but could also prove useful for specification development.

Once a sample specification has been developed, test projects can use this specification to provide field data. Test sections will also help inspire confidence in the sample specification if they perform well.

5.4 Research Benefits

Potential benefits of this research include construction savings, environmental impacts, reduced risk, and increased technical knowledge. The conclusion that there is likely a way to incorporate up to 15% RCA into new concrete allows these benefits to be realized. While the benefits of using RCA related to construction savings and the environment are smaller for lower levels of aggregate replacement than they would be for 100% RCA concrete, it is important to note that agencies are often not willing to use or able to produce concrete with high RCA levels. Low levels of RCA replacement may also serve as a bridge to higher replacement levels in the future, which will further increase benefits. Quantification of the value of these benefits was outside the scope of this project.

5.4.1 Construction Savings

As quality aggregates become scarcer in major metropolitan areas [2], they will become more expensive. The ability to replace a portion of the virgin aggregates in a concrete paving mix with RCA will reduce the amount of virgin aggregate required, which will in turn reduce costs associated with the material itself. Transportation costs may also be decreased because virgin aggregates will generally need to be transported longer distances from the places where they are still available, while RCA is typically generated within metropolitan areas. This study showed that RCA replacement of up to 15% may be viable as long as the RCA has reasonable aggregate properties, which could result in a decrease in virgin aggregate consumption of up to 15%. Contractors are also generally reluctant to use untested materials on projects because they often must warranty their work. Increased knowledge related to the use of RCA could result in additional construction savings by reducing risk (discussed in Section 5.4.3).

Quantifying the actual construction savings realized from using RCA would require project specific information, such as if the RCA is being crushed on site, if the concrete is being mixed on site, and haul distances for the RCA and virgin aggregates. Given that an existing concrete pavement generally does not produce enough RCA to be used as both the base and aggregate in a new pavement [12], there may be a need to import additional RCA for the concrete, depending on replacement level.

5.4.2 Environmental Aspects

The use of RCA in concrete to replace virgin aggregates is environmentally friendly because it eliminates both the need to landfill the parent concrete of the RCA and the need to quarry as much virgin aggregate [4]. Using 15% RCA in concrete reduces the use of virgin aggregate by approximately 15%, though the actual reduction will be slightly different because replacement is based on volume, but aggregate is typically measured based on weight. Additionally, transportation distances for RCA are likely to be shorter as virgin aggregates sources closer to metropolitan areas become depleted and virgin aggregates must be sourced from farther away; in contrast, most RCA is generated in metropolitan areas. Reduced transportation distances results in reduced emissions from hauling trucks.

Project specific information would be required to fully quantify the environmental benefits of using RCA. Benefits would also depend on where the boundary of the analysis is drawn, for example, if cradle-to-gate, cradle-to-grave, or cradle-to-cradle criteria are considered. Additional details needed for an analysis would include haul distances, equipment types, and construction information. One interesting consideration that merits future investigation is how the benefits of carbon sequestration via carbonation change if the RCA is crushed on site and used fairly quickly versus if it sits in a stockpile before being used.

5.4.3 Reduced Risk

One of the main reasons agencies are disinclined to use RCA in paving concrete is the risk associated with using a material that will have unknown effects on the quality and life of the pavement [14]. Previous poor experience with concrete containing RCA has further increased the hesitancy to use RCA [11]. While much research has examined the effects of using high levels of RCA, there is less knowledge regarding the effects of low RCA replacement levels. Additional knowledge specific to these levels of RCA will help agencies make more informed decisions, which results in lower risk that the pavement will not perform as desired. Risk to the contractor is also reduced by both increased knowledge of the effects RCA may or may not have on the pavement.

5.4.4 Technical Outcomes

The main technical outcomes of this project are an increased knowledge of the effect of RCA on concrete properties when used a low replacement levels and guidance for future work that will inform next steps.

Compressive strength was found to decrease for all RCA types and replacement levels and this reduction was generally statistically significant. Surface resistivity was also found to decrease in a statistically significant way, but for the majority of mixes, the decrease was insufficient to change the chloride penetration risk category of the concrete, so these changes may not have practical significance. Flexural strength, Poisson's ratio, 252-day shrinkage, and freeze-thaw durability factor did not experience any statistically significant changes for any of the mixes tested. Elastic modulus and coefficient of thermal expansion were found to decrease only for the mixes containing the AVR aggregate; changes were not statistically significant for any of the other RCA types.

Another technical outcome is providing additional data on fresh testing of concrete containing RCA. There is little information in the literature on tests such as the box test [145] or the super air meter (SAM) [139] being used on concrete containing RCA. While this research cannot verify that the box test is valid for concrete containing RCA, it does provide documentation in the literature of using the box test on concrete containing RCA. For the SAM test, good agreement was found between concrete that met the SAM number limit of ≤ 0.2 and concrete that met the freeze-thaw durability factor recommendation of ≥ 70. While several of the SAM tests run in this study were found to have likely been run incorrectly, those that were correctly run did accurately predict freeze-thaw durability. This indicates that the SAM test may be valid for concrete containing RCA at replacement levels up to 15%. However, to definitively say that the SAM test is valid to predict freeze-thaw durability for concrete containing RCA, a larger study that includes some mixes that are not durable would be required.

Linear regression analysis was used to identify how much of the variation between a test mix and the control group could be attributed to aggregate properties of absorption capacity, specific gravity, percent fines, Micro-Deval, and fineness modulus. While this research was not designed to specifically identify aggregate property limits for use in a specification, it can provide a roadmap for future work to produce a specification.

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