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

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Task 5: Data Analysis

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TASK 5: Data Analysis

In this task, the data gathered in Task 4 was analyzed. Some of the results presented in Task 4 are repeated here for the reader's convenience. A statistical analysis was conducted of the hardened properties test results. Results and discussion of both the statistical analysis and the concrete property testing are provided.

5.1. Methods for Statistical Analysis

Statistical analysis was conducted in R [1], an open-source statistical analysis software package. A significance level of 5% was selected in all cases; this significance level is standard in most statistical analyses.

5.1.1. Analysis of Variance

The analysis of variance (ANOVA) analysis 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 [2]. 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 0.05 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 slightly 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.

5.1.2. 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. SAM number was not included in the analysis because so many of the test values were determined to be unreliable during testing.

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.

5.2. Results and Discussion of Statistical Analysis

Table 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), shrinkage, resistivity (Ω), and freeze-that durability (F/T) 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 1.

Table 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 no 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 5.4.3, this could be due to unexpectedly low values of the control specimens at 28 day 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 2 and Table 3 respectively. Compressive strength, flexural strength, and resistivity were investigated at 28 days and shrinkage was investigated at 140 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 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 (140 day)	-0.441	-0.328	0.391	-0.373	0.399
Freeze-Thaw Durability	-0.448	-0.293	not significant	-0.496	-0.478

Table 3: Coefficients of Determination with Aggregate Properties

	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 (140 day)	0.194	0.108	0.153	0.139	0.159
Freeze-Thaw Durability	0.201	0.086	Not Significant	0.246	0.228

The correlation coefficients from Table 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 5.4. 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 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 then 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.

5.3. Discussion of Fresh Property Results

5.3.1. Workability

The workability of the concrete was measured via the slump test [3] and the box test [4]. Results of these test are shown in Table 4. The target slump for this mix was ½" to 3", based on a MnDOT 3A21 mix used for slip form paving [5]. Seven of the twelve mixes met the slump criteria. A box test score of two or less is considered suitable for slip form paving [6,7]. 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. All but three of the test mixes and the control mix experienced edge slumping.

Table 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 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 [8,9]. It is recommended that the slump not vary more than 1in between trucks for a concrete pavement placement [10], 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 [11].

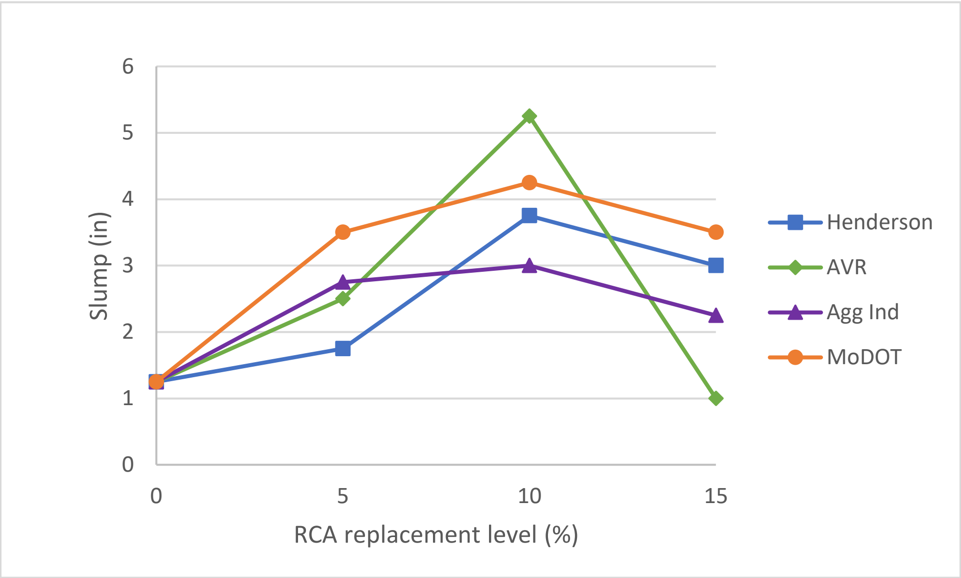

Figure 1: Slump versus RCA replacement level

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 [12], to 85% in 30 minutes [13], or 90% in either 5 minutes [14,15] or 24 hours [13]. 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 [16]. 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 . 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 [16], 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.

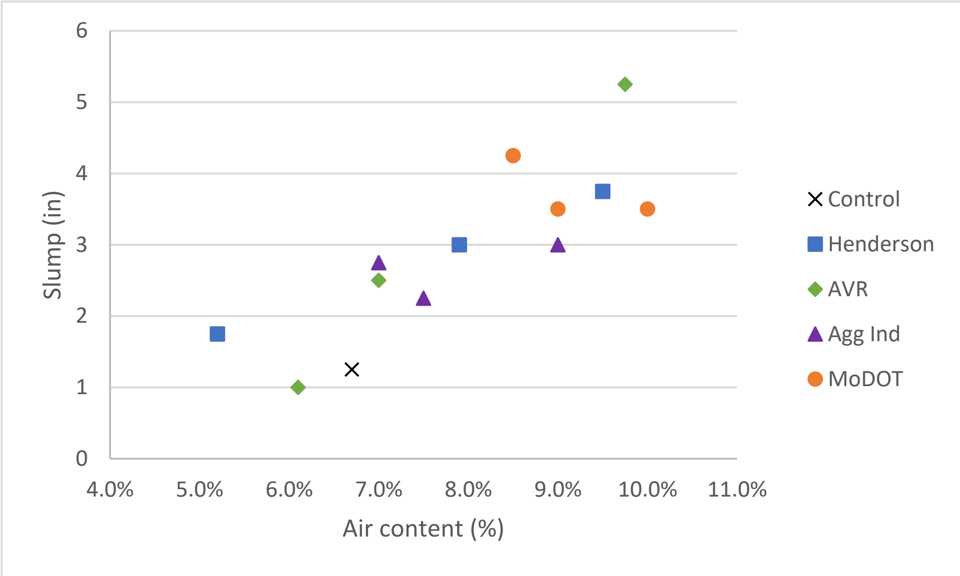

Figure 2: Slump versus air content

The results of the box test versus RCA replacement level are shown in Figure 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 [17], but more research is needed in this area.

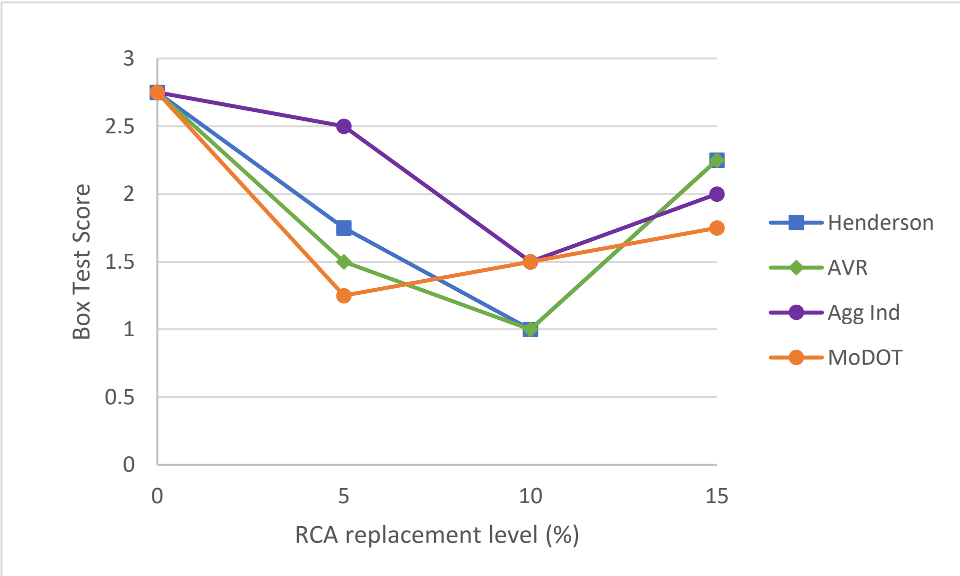

Figure 3: Box test score versus RCA replacement level

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. Air content is known to impact workability, as are aggregate properties such as gradation, absorption capacity, shape and surface texture [16]. However, here the linear regression analysis did not show any statistically significant correlation with the aggregate properties considered.

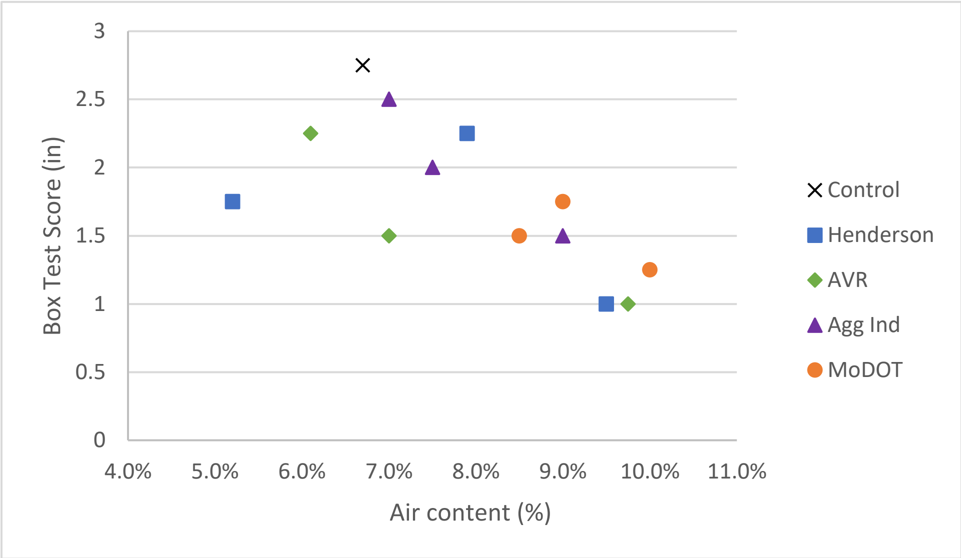

Figure 4: Box test score versus air content

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 5. In general, these results are not expected to be correlated because they are measuring different facets of workability [18]. 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 [16].

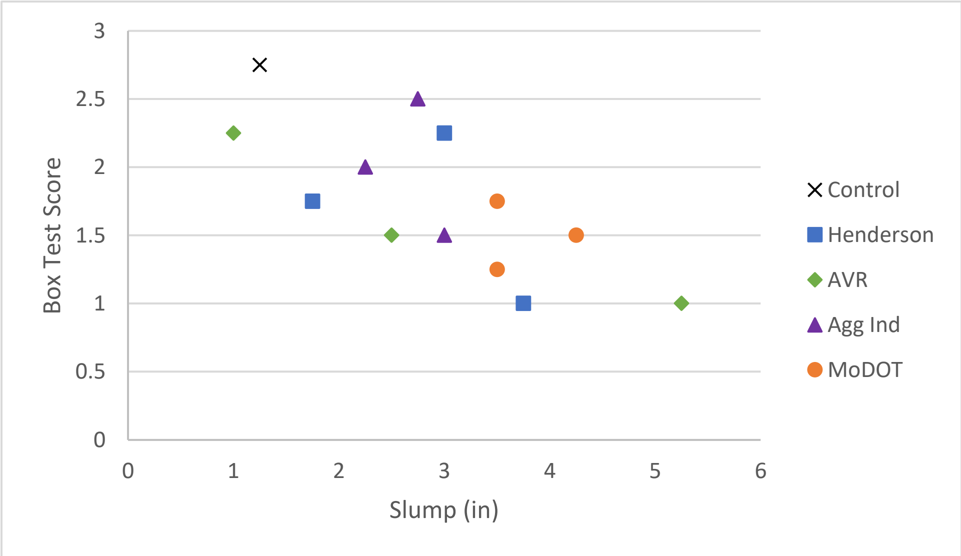

Figure 5: Box test score versus slump

5.3.2. 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 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% [5]. This is slightly different than the range recommended by AASHTO of 5-8% [7]. 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 [19] and this is the criteria which has been adopted by AASHTO [7].

Table 5: Air Content and SAM Test Results

Batch	Air Content	Super Air Meter	
		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

From Table 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 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.

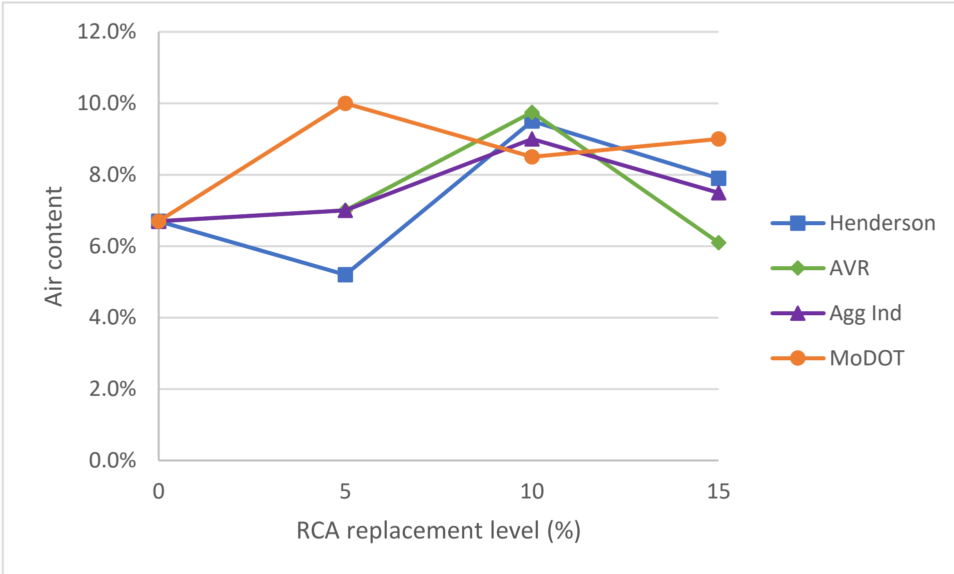

Figure 6: Air content versus RCA replacement level

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 [9,16,17]. 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 5.3.1.

The maximum recommended variation in air content between batches of concrete is 1% [10]. 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 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 [20]. 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 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 conducted, so no statements regarding relation to the aggregate properties tested can be made.

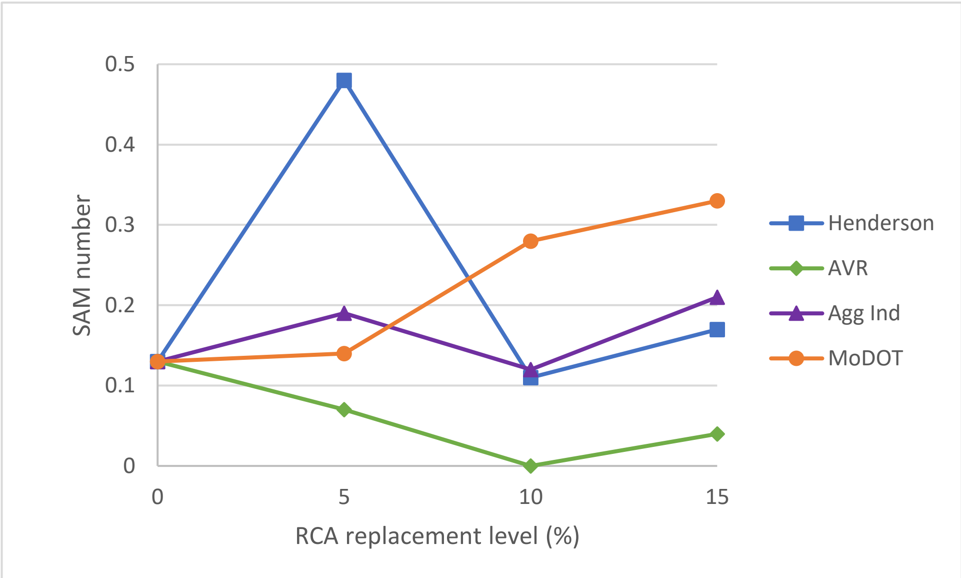

Figure 7: SAM number versus RCA replacement level

Correlations between the air content and freeze-thaw durability and between SAM number and freeze-thaw durability factor will be discussed in Section 5.4.8.

5.4. Discussion of Hardened Property Results

5.4.1. Compressive Strength

The compressive strength with time is shown in Figure 8. The compressive strength of the concrete containing RCA was lower in most cases than that of the control group. This follows the expected trend [16,21–23] and was true for all ages tested. Not all mixes met the AASHTO criteria of 4000 psi at 28 days [7], but all mixes met this criteria by 56 days.

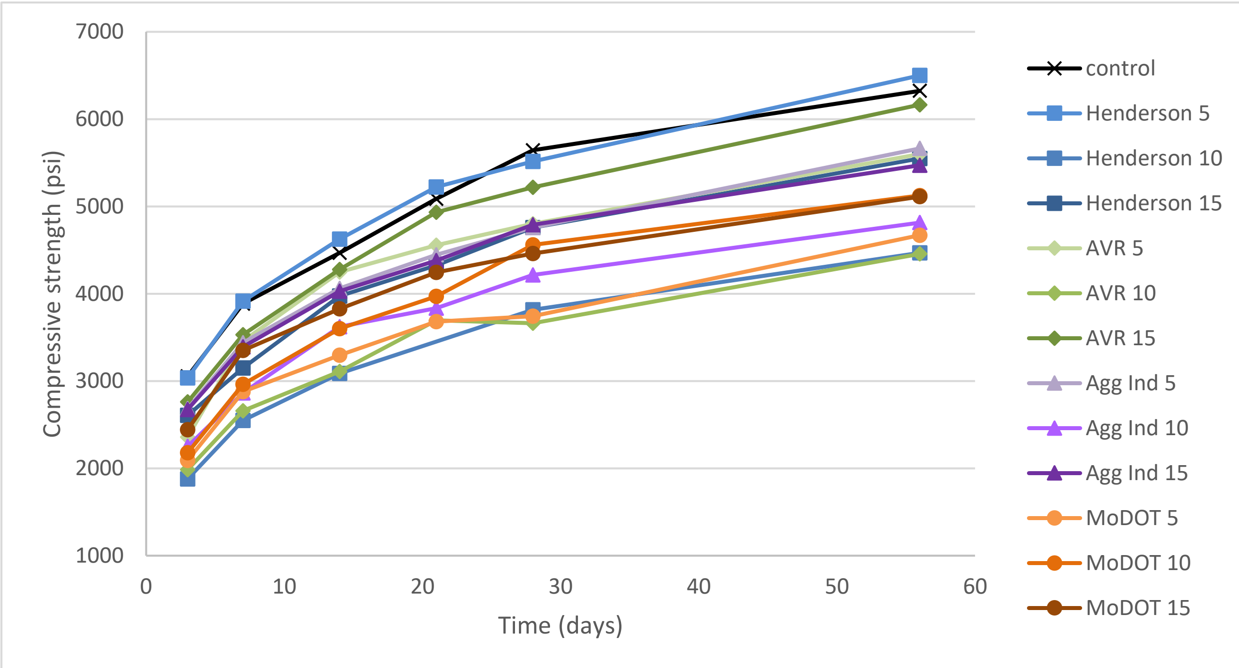

Figure 8: Compressive strength versus time

The 28-day compressive strength versus RCA replacement level is shown in Figure 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 (which experienced a small gain in strength) and AVR 15.

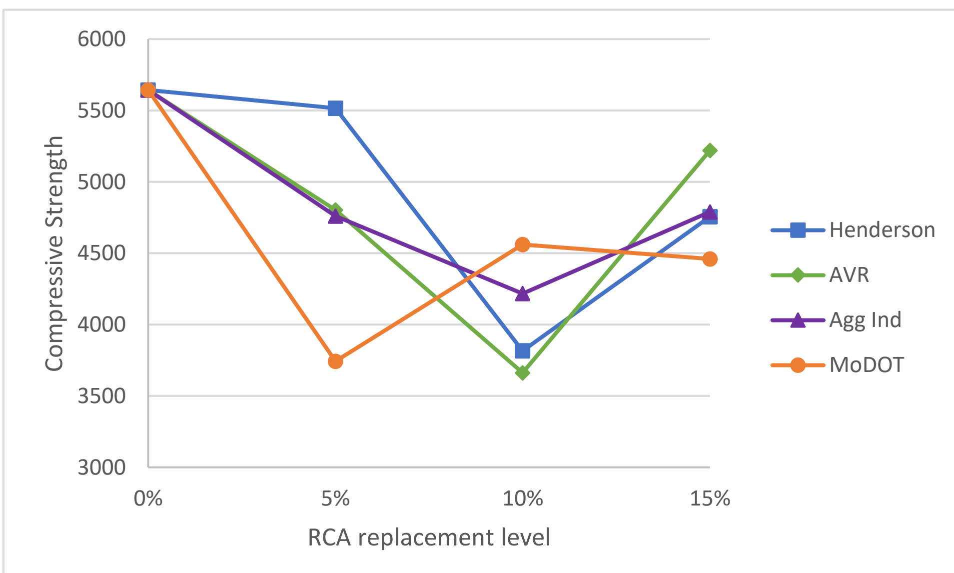

Figure 9: 28-day compressive strength versus RCA replacement level

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 [24], higher air content [25] as was discussed in Section 5.3.2, the higher porosity of the RCA [26], and changes to the interfacial transition zone due to the porosity of the RCA [26–28]. It has also been suggested that the inclusion of RCA results in a larger volume fraction of paste, which has less strength than aggregate [25]. 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 [24]. 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 [22], 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 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 same 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 [29], 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 8 and also by examining the computed rate of strength gain versus RCA replacement level shown in Figure 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 is mainly recovered by 120 days [30]. 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 [31].

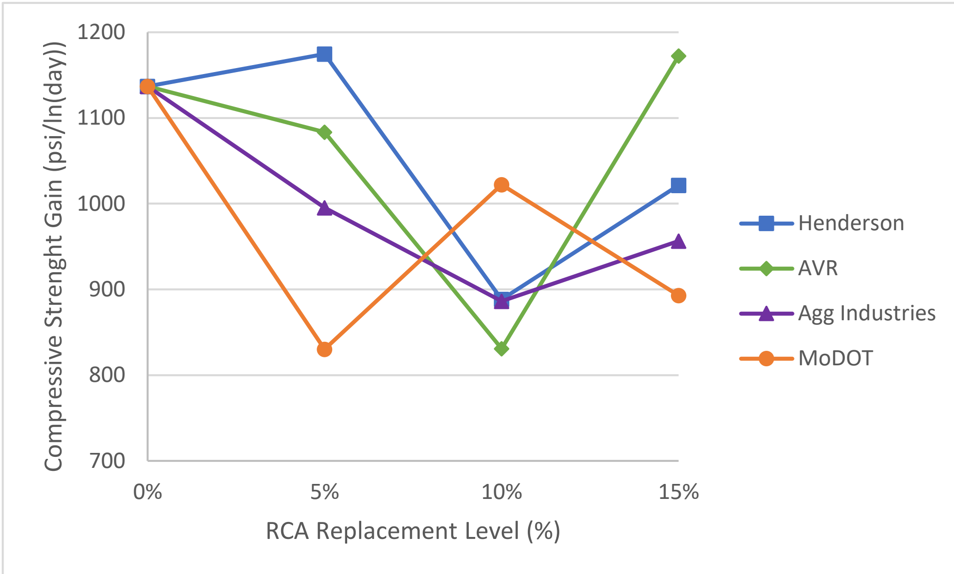

Figure 10: Rate of compressive strength gain versus RCA replacement level

Mechanisms for the RCA to affect the strength gain of the new paste, such as internal curing [30,32] or hydration of any unhydrated cement in the RCA [14,33], 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 and that the presence of the RCA is not affecting the hydration reaction of the new paste.

5.4.2. 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 11 shows a series of images from the DIC data collected for the AggInd 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 increasing in the region of the crack before failure.

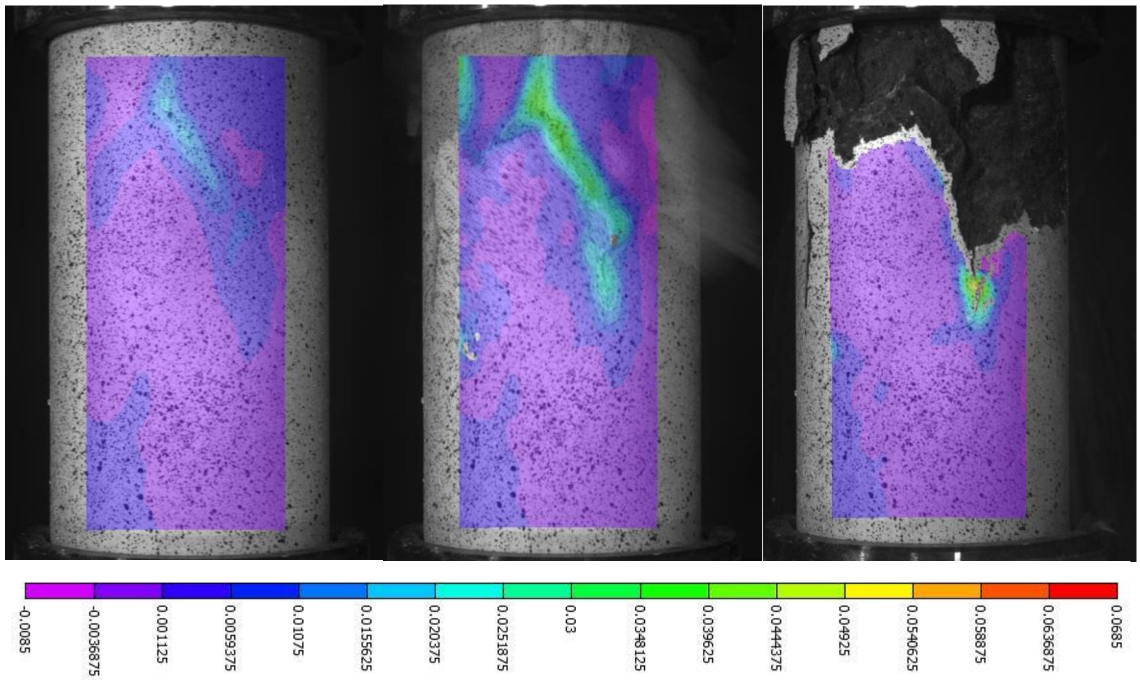

Figure 11: Tensile strain field before failure (left), at failure (center) and after failure (right)

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 12 through Figure 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.

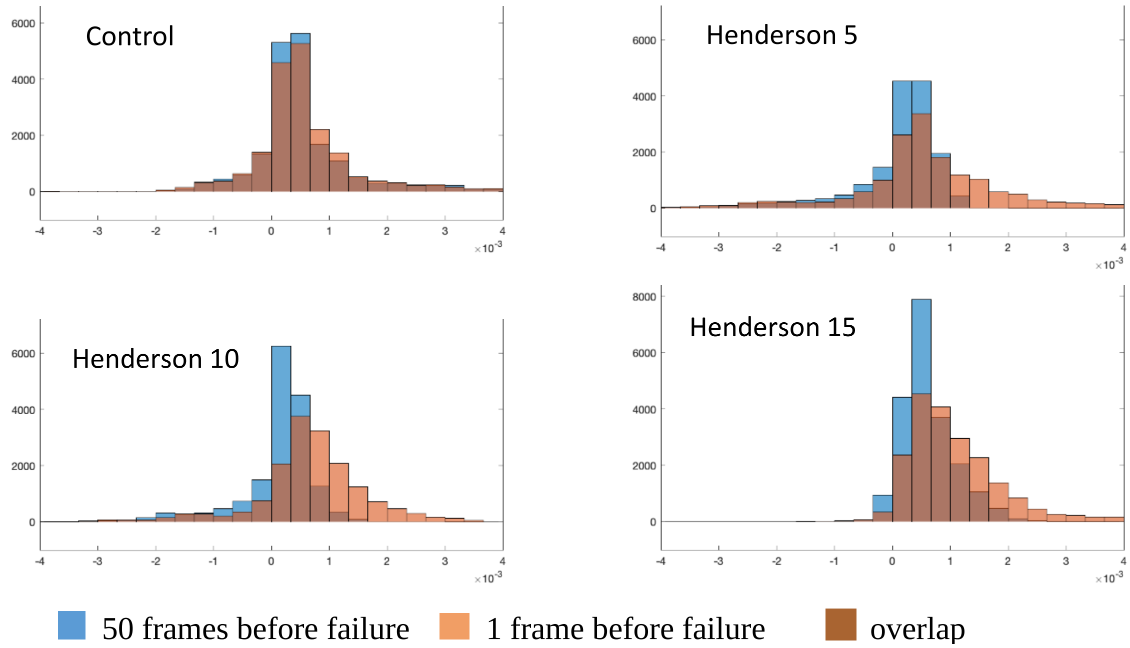

Figure 12: Superimposed histograms of frequency of tensile strain values (mε) for the control and Henderson test batches at 50 frames before failure and just before failure

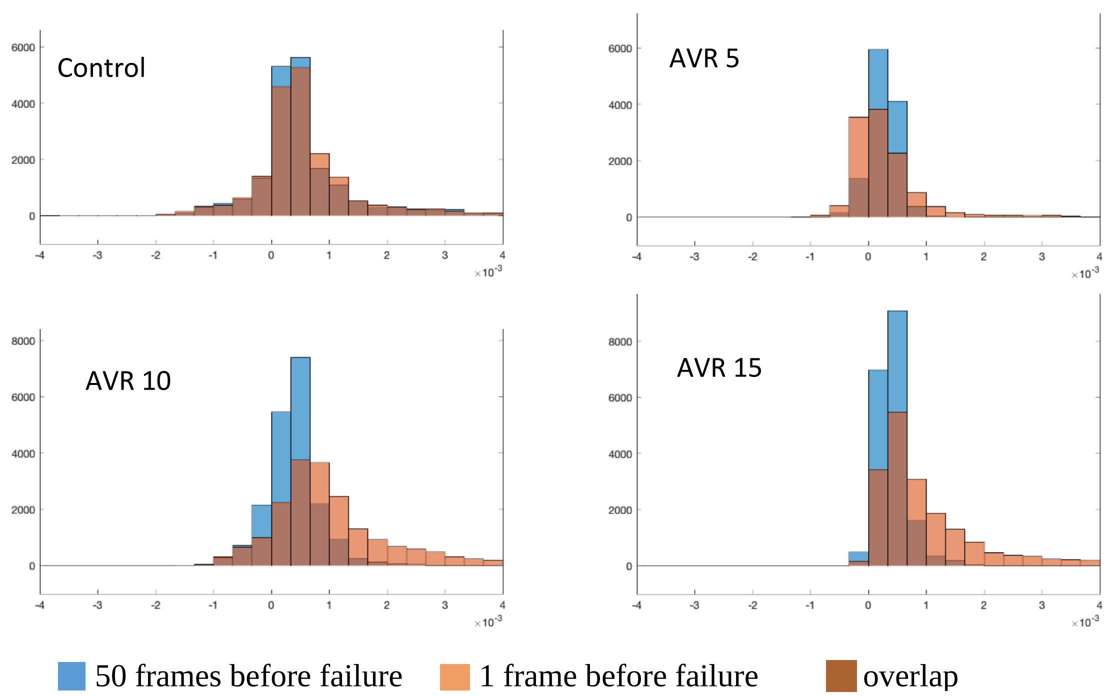

Figure 13: Superimposed histograms of frequency of tensile strain values (mε) for the control and AVR test batches at 50 frames before failure and just before failure

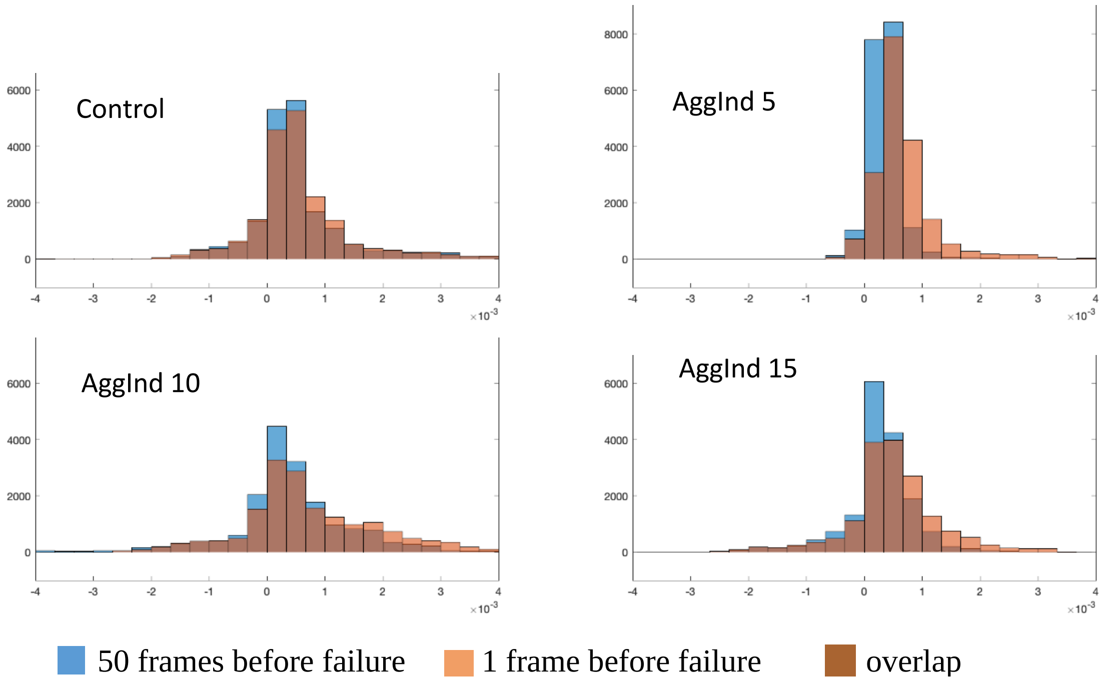

Figure 14: Superimposed histograms of frequency of tensile strain values (mε) for the control and AggInd test batches at 50 frames before failure and just before failure

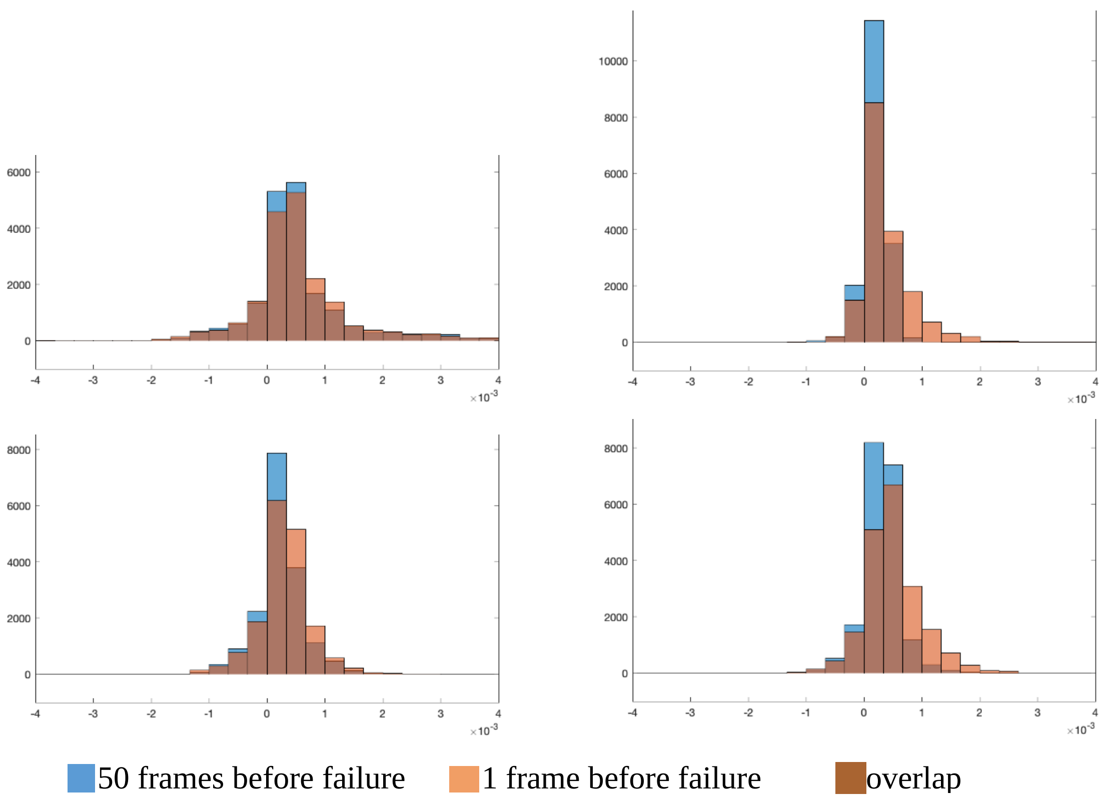

Figure 15: Superimposed histograms of frequency of tensile strain values (mε) for the control and MoDOT test batches at 50 frames before failure and just before failure

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 5.4.1.

5.4.3. Flexural Strength

The flexural strength with time is shown in Figure 16. From this figure, 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 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.

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 text 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.

The flexural strength versus RCA replacement level is shown in Figure 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 [23], 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 trend seen here.

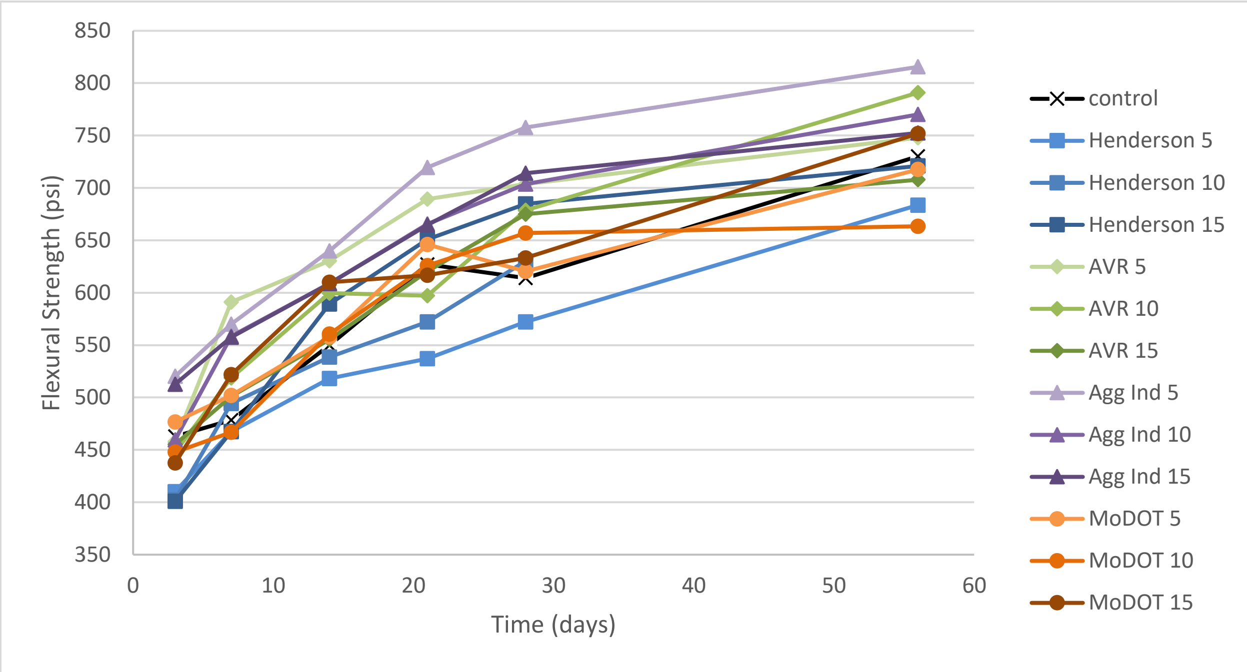

Figure 16: Flexural strength versus time

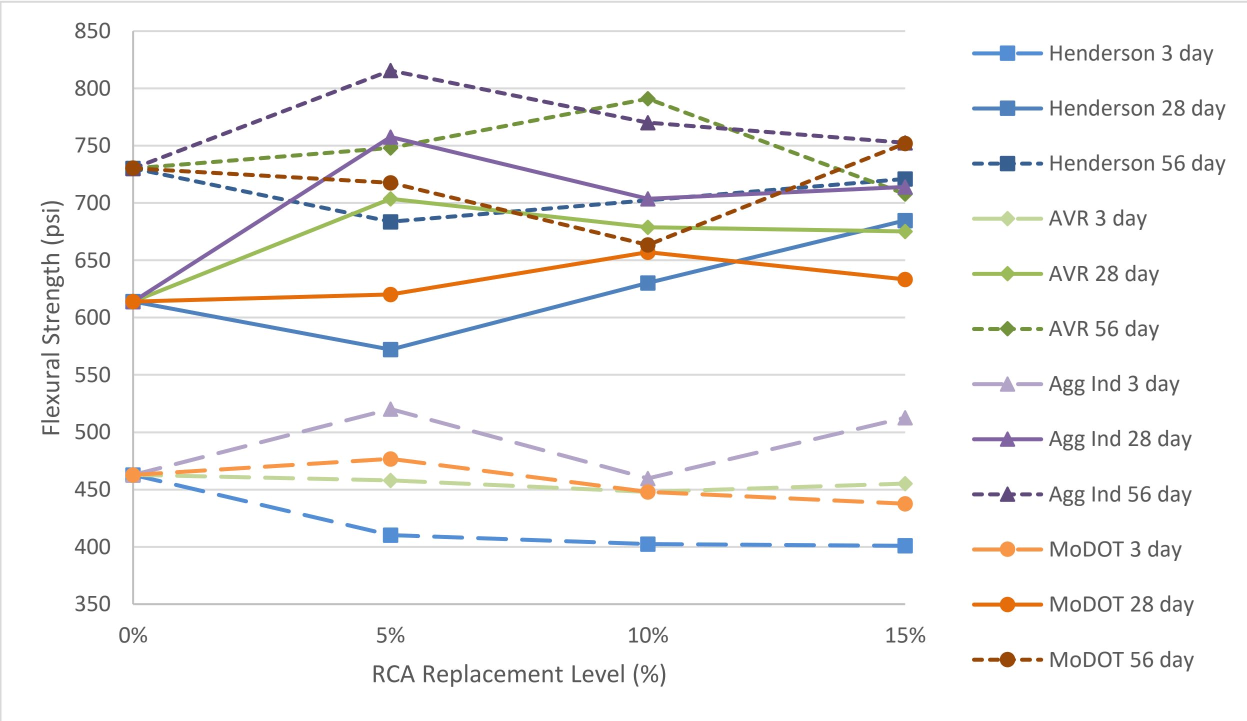

Figure 17: Flexural strength versus RCA replacement level

AASHTO criteria for performance engineered concrete mixes for pavements requires a flexural strength of 600 psi at 28 days [7]. 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 16. These computed rates of strength gain are shown versus RCA replacement level in
Figure 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.

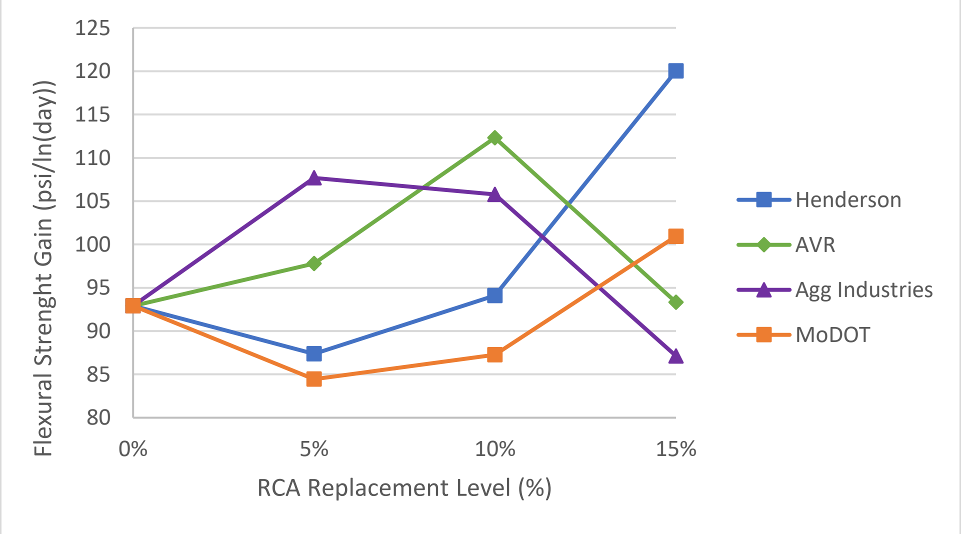

Figure 18: Rate of flexural strength gain versus RCA replacement level

5.4.4. *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 19. 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.

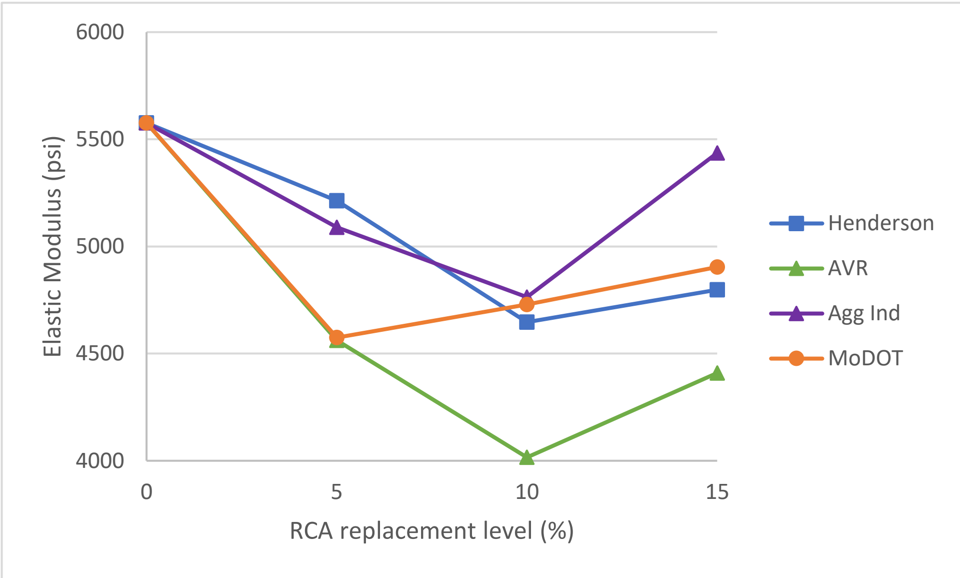

Figure 19: Elastic modulus versus RCA replacement level

A decrease in elastic modulus when RCA is included in a concrete mix is generally expected [25,26,34]. 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 [35–37], which matches the trend seen here.

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 [38] which is in turn associated with lower concrete stiffness [26]. 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 [38], which should result in a higher concrete stiffness [26]. 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 [32]. 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.

5.4.5. 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 20. 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 [30,39] and others finding a decrease [40]. 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 [16].

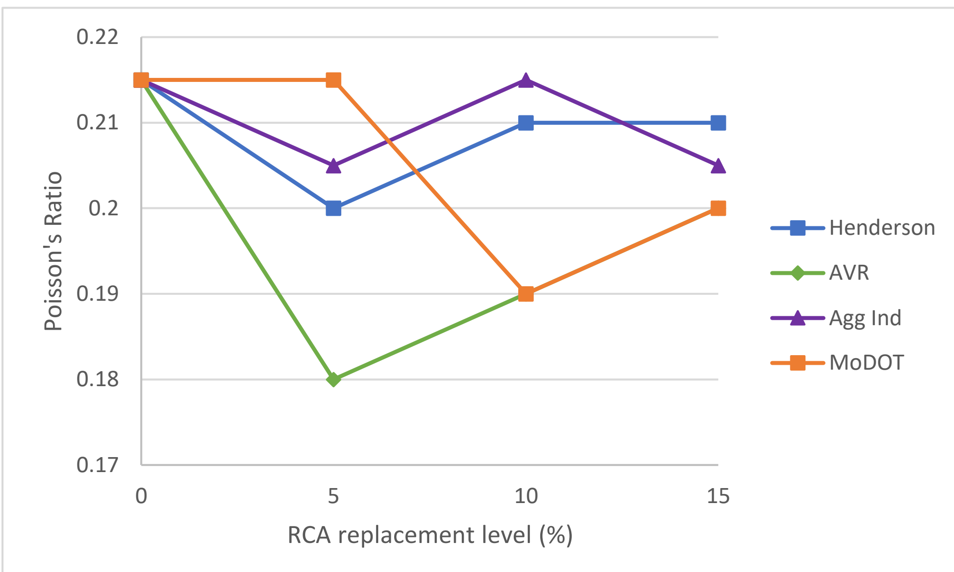

Figure 20: Poisson's ratio versus RCA replacement level

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 [41], so these correlations may be of little practical importance.

5.4.6. 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 21. All values measured were within the standard range for concrete of 6 to 13 mm/mm/°C [16]. The literature is generally inconclusive about the effect of RCA on concrete CTE, with the use of RCA generally expected to decrease CTE [42–45] but with several studies also finding an increase [9,46,47], which fits the results seen here.

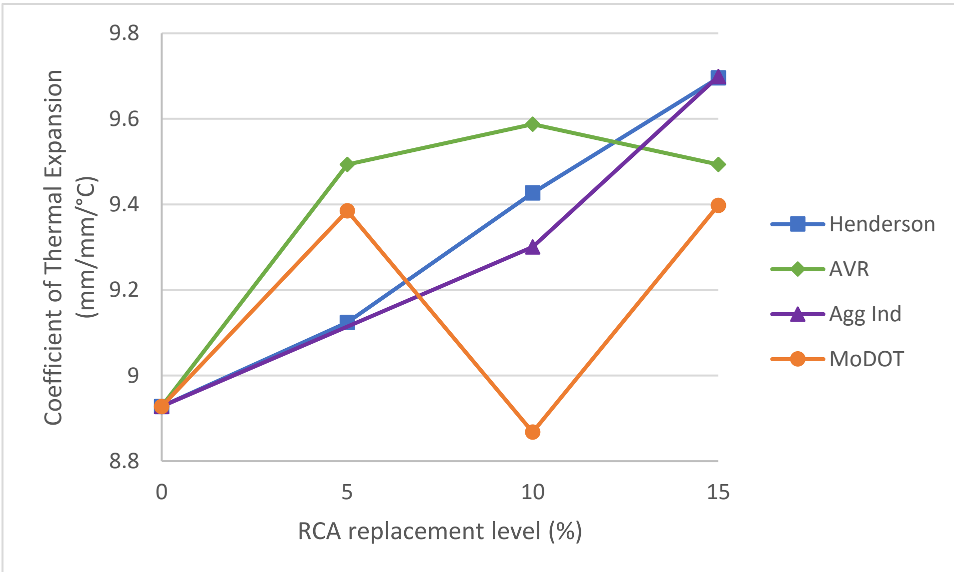

Figure 21: Coefficient of Thermal Expansion versus RCA replacement level

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 [9]. 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.

5.4.7. Surface Resistivity

The surface resistivity with time is shown in Figure 22. 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 [39,48], 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 as expected [45] and by 56 days, several samples had high enough values of resistivity to be categorized as low risk for chloride ion penetration.

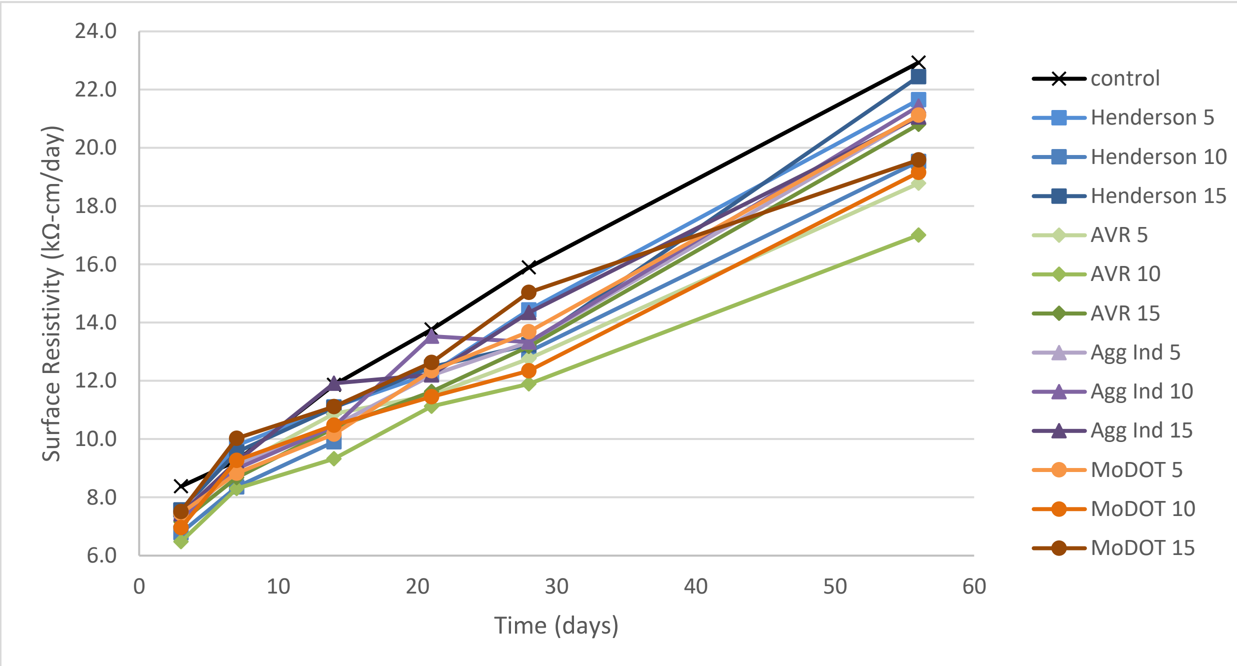

Figure 22: Surface Resistivity versus time

The presence of RCA reduces resistivity because the resultant concrete is more permeable due to the increased porosity of the RCA [14]. 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 [39]. 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 [39,48] or even very low [49] risk to chloride ion penetration, so ways to decrease the chloride ingress risk of the concrete mixes tested here could also be explored.

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 [14]. 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.

The rate of resistivity gain was investigated by examining the slope of each line shown in Figure 22. These computed rates of resistivity gain are shown versus RCA replacement level in Figure 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.

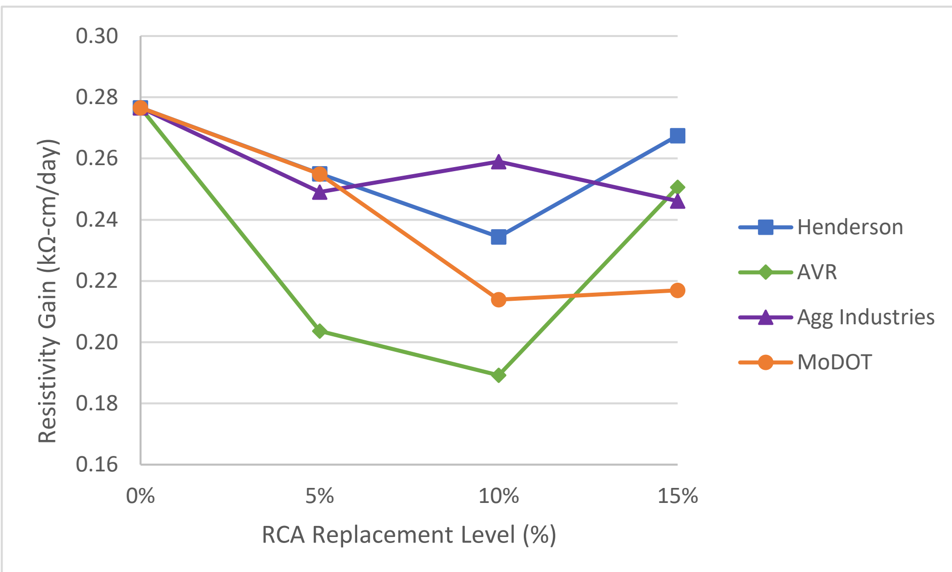

Figure 23: Rate of resistivity gain versus RCA replacement level

5.4.8. 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 24, but the reader should use caution in looking for trends in these results because of the lack of statistical significance. A durability factor greater than 70 is commonly recommended for concrete pavements [7,10] 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 ACI that RCA does not influence freeze-thaw durability [23].

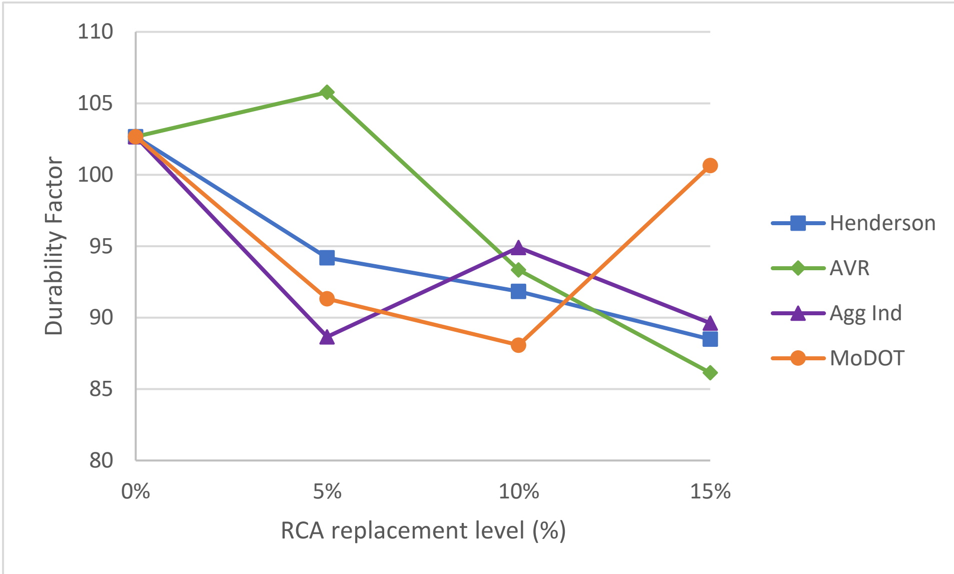

Figure 24: Freeze-thaw durability factor versus RCA replacement level

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 [16]. 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 [9], though others claim the test is still valid [39]. Figure 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 [5] and any durability factor above 70% indicates acceptable performance on the freeze-thaw test [7,10]. 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 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 [7] and had acceptable performance on the freeze that test. This shows that the standard air pot is probably an acceptable air content test for concrete containing RCA at replacement levels up to 15%.

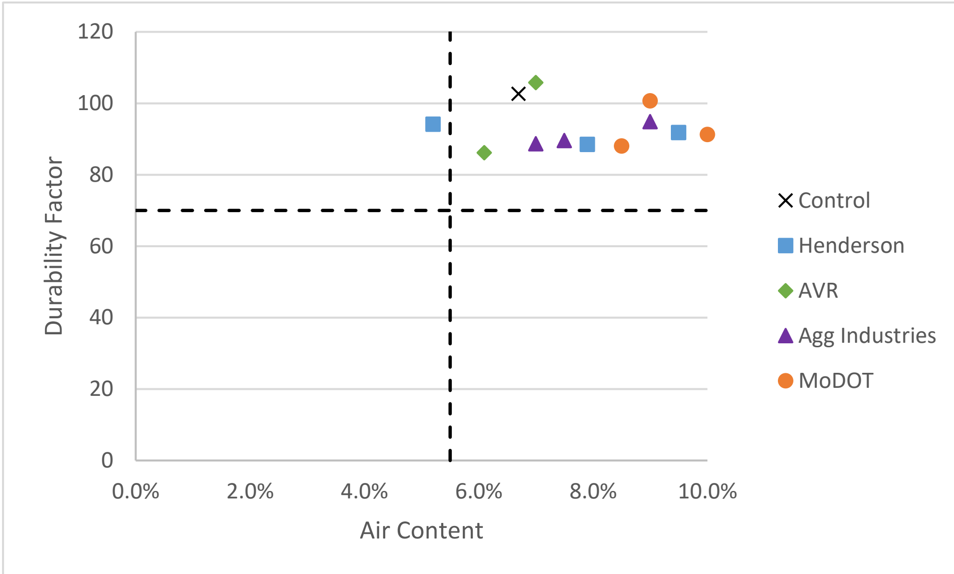

Figure 25: Durability factor versus air content as measured via the pressure meter

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 [7]. Figure 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 likely can be used 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 5.3.2.

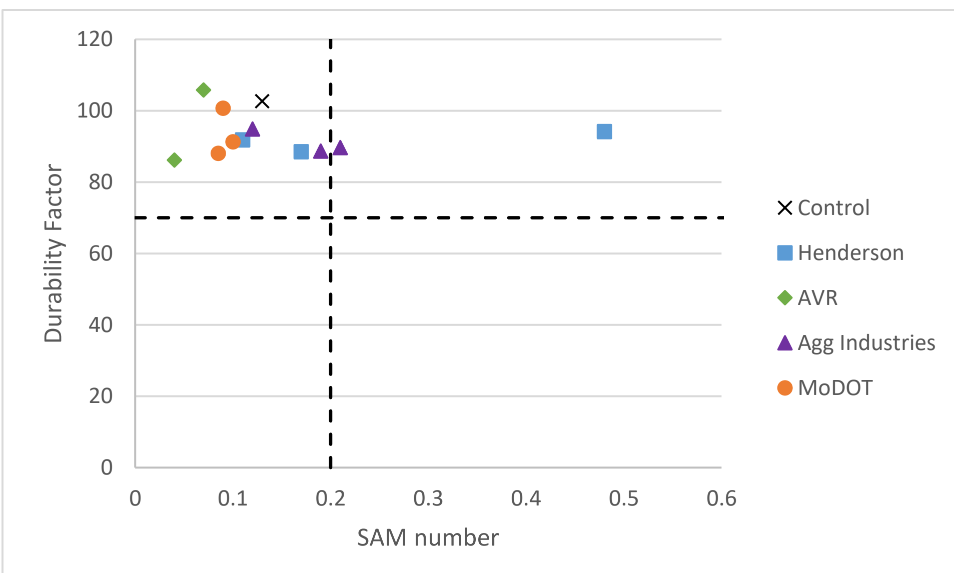

Figure 26: Durability factor versus SAM number

5.4.9. Shrinkage

The shrinkage at 140 days was found to increase in some cases and decrease in others. 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 27 should not be used to look for trends. While it is generally accepted that the use of RCA in concrete causes increased shrinkage [16,21,22], it has also been shown that low replacement levels (less than 20 to 30%) can produce negligible changes in shrinkage [26,50–53]. 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 27. The final report for this project will contain updated shrinkage data at a later age.

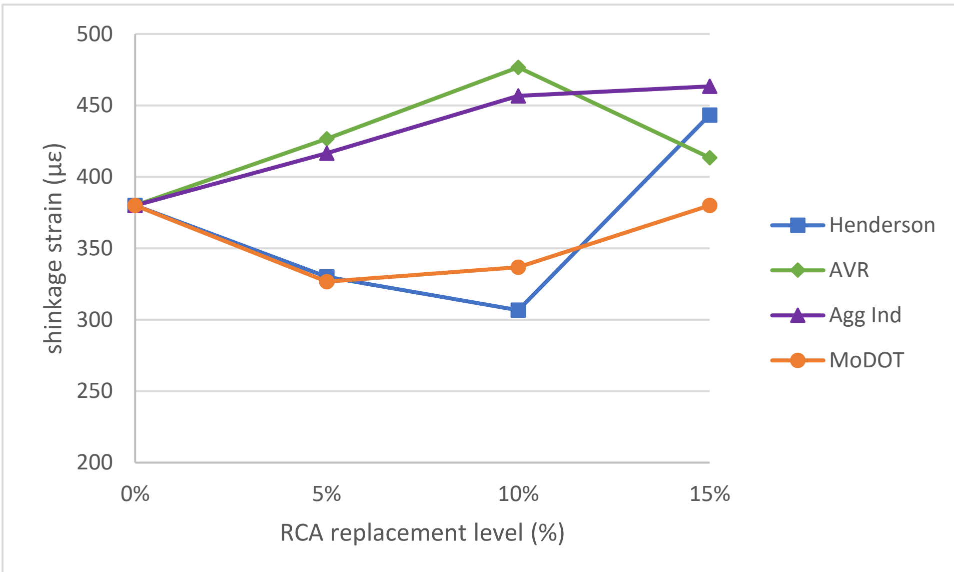

Figure 27: Shrinkage at 140 days versus RCA replacement level

The AASHTO T160 [54] and ASTM C157 [55] 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 [7]. 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. 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.

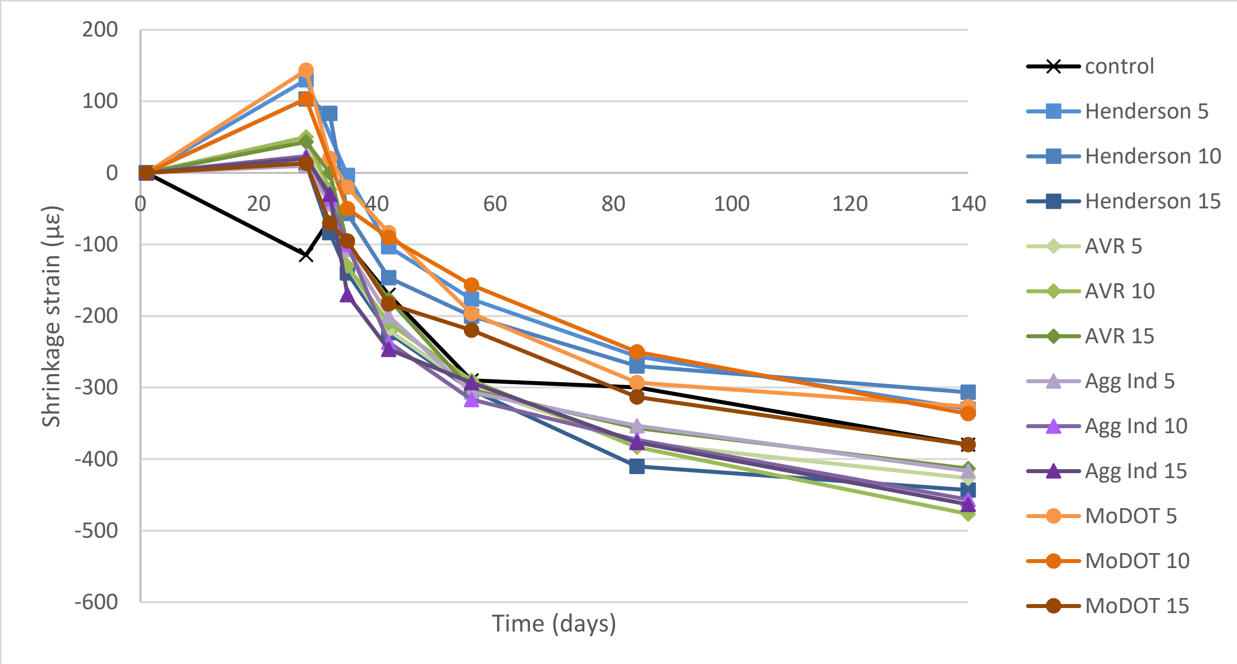

Figure 28: Shrinkage strain with time

The AASHTO T160 [54] and ASTM C157 [55] 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 [7]. 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. 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 [38], which is associated with higher shrinkage [9]. This can be due to increased moisture mobility within the concrete [14,56], increased paste content [25], and/or lower stiffness to restrain shrinkage [26,56]. 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 [32]. 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 [33], or a combination of both factors. The coefficients of determination were of similar level for all aggregate properties investigated.

5.5. 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 and represent 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.

5.5.1. 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 work is not able to define the limits of what is reasonable.

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. 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 at 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 achieve a similar strength level as the 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 is a function of the RCA itself and that the presence of the RCA is not affecting 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 that of 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 appears 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 percent 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 that of the control.
- There was no statistically significant difference in the values of Poisson's ratio, shrinkage at 140 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 of 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 of 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 [35,57]. 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 is 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 is likely due to the adhered mortar on the RCA, which is both less stiff than the virgin aggregate and the aggregate phases of the RCA and which occupies 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. Because compressive strength was found to decrease but the flexural strength and elastic modulus were not, this suggests that concretes using RCA should consider directly measuring flexural strength and elastic modulus rather than relying on traditional correlations with compressive strength. If compressive strength correlations are used, they may result in a more conservative design because the compressive strength would be lower, resulting in lower predictions, but the flexural strength and elastic modulus would likely be unaffected in reality

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 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.

5.5.1. Recommendations for Future Research

The study presented here was intended as a first step towards 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.
- 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. However, the flexural strength and elastic modulus did not decrease with the use of RCA the same way that compressive strength did. Further investigation into predictive relationships between compressive strength and other properties for concrete containing RCA is needed to determine if existing equations are valid or require modification.
- 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 [39], 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 to soon after 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.
- 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.

5.5.2. 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 was likely acceptable, and 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. 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 AVR aggregate had a much larger absorption capacity and consequently much lower specific gravity than the other aggregates considered. Absorption capacity and specific gravity have been found to have similar effect on concrete properties [58], 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 [38]. The Henderson and Aggregate Industries RCAs had absorption capacities of 5.32% and 6.05% respectively, which are above this 5% limit, but both aggregates produced concrete that did not vary significantly from the control concrete in most properties tested. This is 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 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 is in contrast to the other three sources, which all had fewer than 1% fines. 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.

Micro-Deval was identified by the linear regression analysis as an important aggregate property when considering the affects of RCA on compressive strength, CTE, resistivity, 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 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 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 concrete performance even though the linear regression analysis showed it can explain some of the variation seen in test results. Future work should still consider investigating Micro-Deval as a specification parameter, but this work did not result in guidance on a preliminary value to consider.

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 very far from that of the other three RCA types considered, this is 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 of 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 [29]. 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. 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.

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5.7. References

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