REDUCING SHRINKAGE THROUGH ADMIXTURES

AND AGGREGATE GRADATION

By

ERINN MCARTOR

Bachelor of Science in Civil Engineering

Oklahoma State University

Stillwater, OK

2019

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2021

REDUCING SHRINKAGE THROUGH ADMIXTURES

AND AGGREGATE GRADATION

Thesis Approved:

Dr. M. Tyler Ley

Thesis Adviser

Dr. Norbert Delatte

Dr. Deb Mishra

ACKNOWLEDGEMENTS

I would like to acknowledge funding from the Oklahoma Department of Transportation and Wisconsin Department of Transportation. I would also like to thank Dr. Tyler Ley for giving me a chance to work with him during my Masters. He played a large role in helping me further my leadership skills, as well as my technical skills. Thank you to Dr. Norb Delatte and Dr. Deb Mishra for agreeing to serve on my defense committee. Michael Dickey, Loren Emerson, Hope Becker, Chad Staffileno, and Bret Robertson: it was a pleasure to work will all of you at the lab and I can confidently say that we formed lifelong friendships here at Oklahoma State. A huge thank you to all of the undergraduate students I worked with at Bert Cooper Engineering Laboratory. Their hard work and dedication to providing quality research is much appreciated.

Name: ERINN MCARTOR

Date of Degree: MAY, 2021

Title of Study: REDUCING SHRINKAGE THROUGH ADMIXTURES AND AGGREGATE GRADATION

Major Field: CIVIL ENGINEERING

Abstract: A study was conducted into the impacts of shrinkage reducing admixtures (SRAs) and larger nominal maximum coarse aggregate sizes on the properties and performance of concrete mixtures. Bridge deck concrete mixtures with different dosages of SRA were prepared and tested. The influence of the SRA on fresh properties, compressive strength, electrical resistivity, mass change, and shrinkage strain is examined. Pavement concrete mixtures with a 1.5-in. nominal maximum coarse aggregate size were prepared and tested. The Tarantula Curve design method was used to vary the amount of coarse aggregate while keeping the amount of fine aggregate constant. The influence of the percent retained on the 1-in. sieve size on the workability performance, compressive strength, electrical resistivity, mass change, and shrinkage strain is examined.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION TO THE IMPACTS OF SHRINKAGE REDUCING ADMIXTURES AND LARGER COARSE AGGREGATE SIZES ON CONCRETE

1.0 INTRODUCTION

Concrete is one of the most widely used construction materials in the world. There is a large emphasis on designing concrete mixtures to be long-lasting and durable. Increasing the durability performance of concrete mixtures can be done in several ways, including incorporating different admixtures and adjusting the aggregate gradation in a mixture. One of the biggest concrete durability issues is cracking. Cracks provide pathways for water, sulfates, and other corrosive chemicals to enter the concrete and cause premature deterioration. Several phenomena can cause cracking, such as loads, moisture loss, temperature variation, and chemical reactions [1]. Drying shrinkage, or moisture loss in hardened concrete, is one of the primary causes of bridge deck cracking; however, this type of cracking can be reduced by using a shrinkage reducing admixture (SRA). Previous studies have found that SRAs can reduce drying shrinkage strains by up to 50 percent [2]. Cracking occurs when the internal tensile stresses exceed the tensile capacity of the concrete. SRAs decreases the surface tension of water in the mixture, thus decreasing the capillary tensile stresses formed in the porous microstructure of the concrete [3]. This is beneficial for preventing premature cracking. Despite the improved shrinkage performance that SRAs allow, some negative side effects have been reported. They have been known to reduce the rate of cement hydration, reduce the compressive strength, and cause instability of the air void system of concrete [3-6].

Many concrete durability issues arise due to phenomena related to the cement paste. Aggregate gradation determines the void content within the structure of aggregate and consequently the amount of cement paste that is required to fill the void space between the aggregate and ensure a workable concrete [7]. Optimizing the aggregate gradation of a concrete mixture is one of the best ways to reduce the volume of paste. Since Portland cement is the most expensive ingredient in concrete, this is a desirable approach to creating more economical concrete. Optimized aggregate gradation can also improve the workability, mechanical properties, and durability of concrete [8]. Reducing the amount of paste in a concrete mixture can reduce the durability issues that arise in the paste of concrete mixtures, such as shrinkage and freeze-thaw.

Incorporating larger coarse aggregate sizes has been thought to improve the performance of concrete mixtures. Common concrete mixture design methods, such as the ACI 211 [9], use the nominal maximum coarse aggregate size as an input into the workability of the mixture. One benefit of a using larger nominal maximum aggregate size was that it allows for a higher number of sieve sizes to be utilized. This allows the gradation to be spread over a larger number of sieves, and thus reducing any high amounts on any one sieve.

1.1 RESEARCH OBJECTIVES

The main objective of this research was to understand how shrinkage reducing admixtures (SRAs) and larger coarse aggregate sizes impact the overall performance of concrete by performing laboratory tests on concrete mixtures. To achieve this goal, different SRA dosages and aggregate gradations were investigated in Chapters 2 and 3, respectively.

CHAPTER II

REDUCING DRYING SHRINKAGE IN BRIDGE DECK CONCRETE WITH LOW DOSAGES OF SHRINKAGE REDUCING ADMIXTURES

2.0 INTRODUCTION

Cracking is a significant issue in concrete. Cracks allow water and other chemicals to penetrate into the concrete and reach the reinforcement. This can lead to durability issues, such as corrosion and freeze-thaw damage. These durability issues can reduce the service life of concrete structures, particularly bridge decks. As concrete loses water from the pores from drying then it will shrink. If the shrinkage is restrained, then this will cause internal tensile stresses and this will cause cracking.

One way to help minimize the shrinkage cracking potential within the concrete has been to incorporate a shrinkage reducing admixture (SRA). This admixture decreases the surface tension of water in the mixture, thus decreasing the capillary stresses formed in the porous microstructure of the concrete [3]. The hydrogen-bonding interactions between the polar units of the SRA cause a reduction in the surface tension of the pore solution, which reduces the tensile stresses within the pores [10]. This is beneficial for preventing unwanted cracking in concrete.

Despite the shrinkage performance improvements that SRAs allow, some negative side effects have been reported. SRAs have been known to reduce the rate of cement hydration and reduce the compressive strength [3, 4, 5]. Another negative side effect occurs when SRAs are used in tandem with air-entraining admixtures (AEAs). Surfactant-based AEAs also reduce the surface tension of water, which promotes the formation of bubbles during mixing [11]. When an SRA and AEA are used together, the combined effect on surface tension in plastic concrete may result in larger air voids than desired and instability of the air-void system [6]. This can contribute to lower freeze-thaw durability and scaling resistance of the concrete.

The objective of this research is to assess the effectiveness of SRA for reducing drying shrinkage strains in bridge deck concrete. This was accomplished by performing laboratory tests on typical bridge deck concrete mixtures with SRA dosages of 0%, 1%, 2%, and 4% by weight of cementitious material. Another goal of the research is to study the effects that SRA had on the fresh properties of Slump (ASTM C143) [12], Unit Weight (ASTM C138) [13], and Air Content (ASTM C231) [14], and the hardened properties of Drying Shrinkage testing (ASTM C157) [15], Compressive Strength testing (ASTM C39) [16], and Electrical Resistivity testing (AASHTO T358).

2.1 EXPERIMENTAL METHODS

2.1.1 Materials

All of the mixtures in this research used a Type I ordinary Portland cement that met the requirements of ASTM C150. A Class C fly ash that met the requirements of ASTM C618 was used at a 20% cement replacement by weight. The oxide analyses for the cement and fly ash, as well as the Bogue calculations for the cement, are shown in Table 2-1. All mixtures used aggregates that were locally available and used in commercial concrete. The coarse aggregate used was crushed limestone with a nominal maximum aggregate size of 3/4", and the fine aggregate used was natural sand. Both aggregates met ASTM C33 specifications. Depending on the different mixture designs, a shrinkage-reducing admixture (SRA) meeting ASTM C494 was used.

Table 2-1 - Chemical Composition of Type I Portland Cement and Class C Fly Ash

	Oxide (%)								**Phase Concentrations**			
Material	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**	**C_3S**	**C_2S**	**C_3A**	**C_4AF**
Cement	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	48	24	8.1	7.9
Fly Ash	25.3	19	5.2	33	7.8	2.6	3.4	0.6	-	-	-	-

2.1.2 Concrete Mixture Design

Four different mixture designs were investigated and are shown in Table 2-2. The mixtures were designed to have 6.5 sacks (611 lbs) of cementitious material per cubic yard of concrete, a paste volume of 29%, and a water-to-cementitious materials ratio (w/cm) of 0.45. This is a typical bridge deck mixture design for the state of Oklahoma. Three of the mixtures had a different dosage of SRA added to them during the mixing process. The SRA dosages investigated by each of the four concrete mixtures include 0%, 1%, 2%, and 4% by weight of cementitious material. The concrete mixture with 0% SRA added was used as a control mixture to compare the results of the mixtures with SRA.

Table 2-2 - Concrete Mixture Proportions at Saturated Surface Dry (SSD)

Mixture	**Cement** (lbs/yd^3)	**Fly Ash** (lbs/yd^3)	**Coarse** (lbs/yd^3)	**Fine** (lbs/yd^3)	**Water** (lbs/yd^3)	**Additive** (lbs/yd^3)	**Additive Used**
No SRA	489	122	1835	1195	275	0	-
1% SRA	489	122	1835	1195	275	6.11	SRA

2% SRA	489	122	1835	1195	275	12.22	SRA
4% SRA	489	122	1835	1195	275	24.44	SRA

2.1.3 Concrete Mixing Procedure

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 73°F for at least 24 hours before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was started and the admixtures were added. If the SRA was added, then it was added and the concrete was mixed for three minutes.

2.1.4 Sample Preparation and Testing

After preparing the mixture, fresh properties of the concrete were tested, which included Slump (ASTM C143) [12], Unit Weight (ASTM C138) [13], and Air Content (ASTM C231) [14]. Then samples were prepared for Drying Shrinkage testing (ASTM C157) [15], Compressive Strength (ASTM C39) [16], and Electrical Resistivity (AASHTO T358). The number of samples with the test method can be summarized in Table 2-3 and additional information about the sample preparation and testing can be found in the proceeding subsections.

Table 2-3 - Concrete Testing Information

Test Property	Test Method	Sample Size	Sample Count
Slump	ASTM C143	---	1
Unit Weight	ASTM C138	---	1
Air Content	ASTM C231	---	1
Drying Shrinkage	ASTM C157	3” x 3” x 11.25”	4 (2 for mass, 2 for length)
Compressive Strength	ASTM C39	4” x 8”	12 (3 at 3, 7, 28, and 56 d)
Electrical Resistivity	AASHTO T358	4” x 8”	12 (3 at 3, 7, 28, and 56 d)

2.1.5 Shrinkage Testing

2.1.5.1 Sample Preparation for Shrinkage Testing

Four 3 x 3 x 11.25 in. beam samples were prepared for drying shrinkage testing. Two of the samples were used for mass change measurements, while the other two samples were used to measure length change (ASTM C157). The two length change samples contained vibrating wire strain gauges that were cast into the samples during concrete placement. The strain gauges allowed strain measurements to be taken as the concrete was hydrating, which is not possible when using the ASTM C157 standard procedure for shrinkage measurements. To keep the gauges centered in the beam forms, two holes were drilled in the forms and thin wires were loosely wrapped around each end of the gauge and each wire was strung through each hole in the wooden sides.

2.1.5.2 Curing and Drying Conditions for Shrinkage Testing

After casting, all four samples were demolded and an initial mass reading was taken for the two mass change samples. Then, all four samples were wet cured for 7 d in an environmentally-controlled room that was kept at a temperature of 73°F and 100%

relative humidity. After the curing period, the four samples were removed, another mass reading was taken, and the samples were stored in the drying room, which was kept at a temperature of 73°F and 50% relative humidity.

2.1.5.3 Shrinkage and Mass Measurements

Four beam samples were prepared for drying shrinkage testing according to ASTM C157. Two of the samples were used for mass change measurements, while the other two samples were used to measure length change via vibrating wire strain gauges. All four beams were demolded after one day, and initial mass measurements were recorded. Then, the mass loss of each sample was measured at the time intervals specified in ASTM C157 with an accuracy of 0.1 g (0.00022 lbs). The gauges recorded strain measurements from the samples every hour. Since strain measurements were being recorded for two samples, the measurements were averaged and plotted with error bars showing one standard deviation.

2.1.6 Compressive Strength Testing

From each mixture, twelve 4 x 8 in. concrete cylinders were made and cured according to ASTM C192 for compressive strength testing (ASTM C39) and electrical resistivity testing (AASHTO T358). The cylinders were cured in the environmentally-controlled room at a temperature of 73°F and 100% relative humidity. The cylinders were kept in this room in their molds until compressive strength testing at 3, 7, 28, and 56 d as per ASTM C39. The maximum peak load and stress were recorded for all three samples.

2.1.7 Electrical Resistivity Testing

The same 12 samples used for compressive strength testing were tested for electrical resistivity according to AASHTO T358 before breaking the cylinder. These samples were cured in the environmentally-controlled room at a temperature of 73°F and 100% relative humidity according to ASTM C192 and kept in their molds until testing. Four lines were marked on the circular face of each concrete cylinder at 0, 90, 180, and 270 degrees and measured in terms of kΩ-cm over those lines. These four measurements were averaged for each cylinder.

2.2 RESULTS AND DISCUSSION

As summarized in Table 2-4, the fresh concrete properties of each mixture were tested using Slump (ASTM C143), Unit Weight (ASTM C138), and Air Content (ASTM C231). The slump increased at least 1 inch with SRA being added to the concrete mixture. Based on previous research, the addition of SRA is known to slightly improve the workability of concrete [5, 10, 17-19]. This increase in slump may occur because SRA decreases the surface tension of the water [5].

Table 2-4 - Fresh Concrete Properties

Mixture	Slump (in)	Unit Weight (lbs/ft^3)	Air Volume (%)
No SRA	4.25	153.0	1.3
1% SRA	5.5	151.5	2.0
2% SRA	5.25	151.3	1.9
4% SRA	6.25	151.4	1.9

For the hardened testing, the results are provided based on the Drying Shrinkage (ASTM C157), Compressive Strength (ASTM C39), and Electrical Resistivity (AASHTO T358).

2.2.1 Drying Shrinkage Results

2.2.1.1 Mass Change

The mass change over time for all four mixtures is shown below in Figure 2-1. The mass change results show that all of the samples gained mass during the hydration and curing period and then began to lose mass after the samples were placed in the drying room, which was kept at a temperature of 73°F and 50% relative humidity.

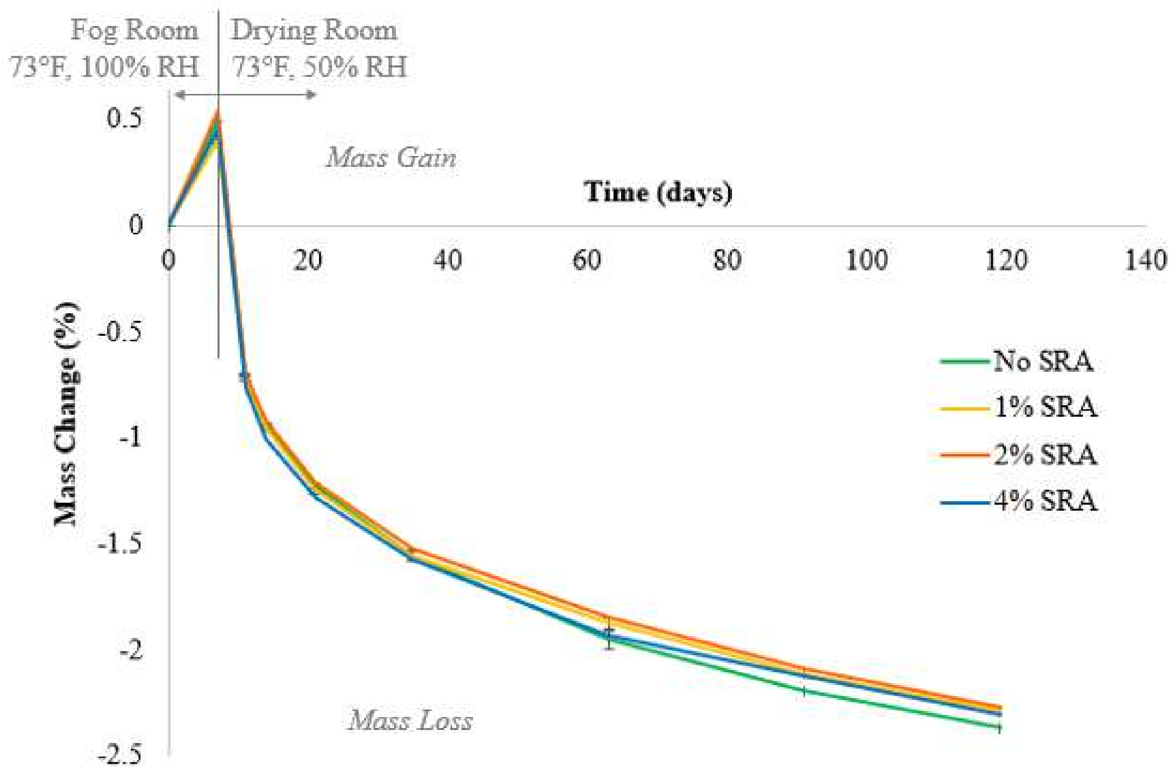

Figure 2-1 – Mass change for all mixtures over time.

According to a Student t-test, there is no significant statistical difference in the mass change between all four mixtures after the beams were subjected to drying. This likely means that there was no significant difference in the drying rate of mixtures with different doses of SRA. Although there was no difference in mass change, the beams did experience different amounts of shrinkage. This difference in shrinkage without noticeable weight loss has been seen before in studies conducted by Shah et al. and Chaunsali et al. [19, 2]. This means the effectiveness of SRAs is related to changes in the surface tension of the water within the pores [19, 20]. The results from the mass change t-testing are summarized in Table A-1 in the appendix.

2.2.1.2 Shrinkage Strain

The shrinkage strain over time as measured by the strain gauges is shown in Figure 2-2. The gauges measure initial strains within the concrete that occur as it is being placed in the molds and during hydration. After the initial strains, the gauges continue measuring the strains over time during the curing process and the drying process. The strain gauge readings show that all of the samples expanded during the hydration and curing period, and then began to shrink after the samples were placed in the drying room, which was kept at a temperature of 73°F and 50% relative humidity.

During the hydration and curing period, all of the samples exhibited similar expansion strain values and there was no statistical difference between the strain values of the four mixes during the hydration and curing period. Due to the similarity in the early age strains, this study focuses on the shrinkage strains during the drying period. A figure showing the strain values during the hydration and curing period is included in Appendix A. In Figure 2-2, the shrinkage strain for all four concrete mixtures during the drying period is presented. Also, Table 2-5 summarizes the comparisons between the shrinkage strain values of the mixture with No SRA and the mixtures containing SRA.

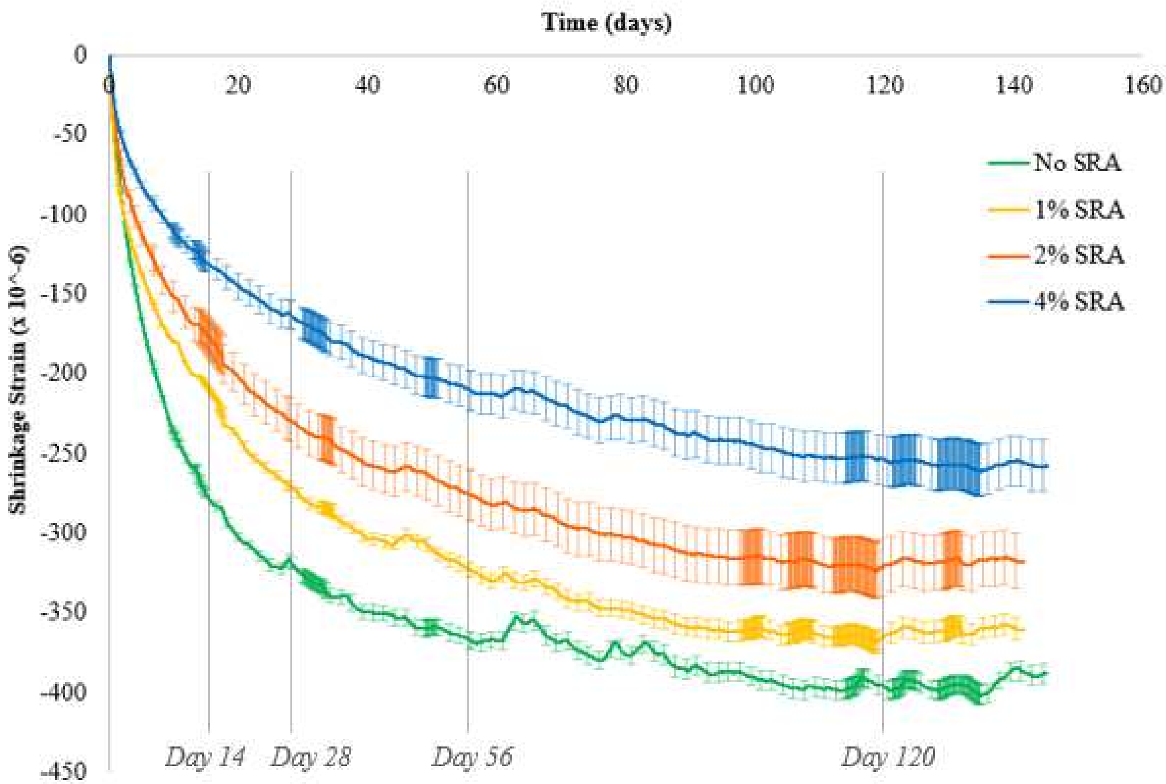

Figure 2-2 – Strain readings for all mixtures during the drying period

Table 2-5 – Shrinkage reduction at highlighted days of interest

Day	1% SRA	2% SRA	4% SRA
14	28%	44%	72%
28	16%	32%	65%
56	12%	28%	54%
120	12%	23%	50%

[1]Percent difference = $\frac{|V1-V2|}{\left(\frac{V1+V2}{2}\right)} \times 100$; V_1 = initial value, V_2 = new value

The values in Table 2-5 denote the percent reduction in shrinkage strain between the mixture with No SRA and the mixtures containing SRA at the highlighted days of interest. These values were determined by calculating the percent difference[1] between the strain values of the mixture with No SRA and the mixtures containing SRA at each day.

The results presented in Figure 2-2 and Table 2-5 show that the mixture with 4% SRA dosage experienced the least amount of shrinkage, while the mixtures with No SRA and 1% SRA experienced the most shrinkage. It is apparent that as the SRA dosage increases, the amount of shrinkage reduction increases. Previous research conducted by Shah et al also confirms this conclusion; as more SRA is added, less free shrinkage occurs in the concrete [19]. They compared the shrinkage performance of mixtures with No SRA and mixtures with SRA after 42 d of drying, and their results are shown in Table 2-6. These values are comparable to the results presented in this work. Table 2-6 presents the shrinkage reduction for each SRA dosage of this to work and the results from Shah et al [19].

Table 2-6 – Comparing shrinkage reduction after 42 d of drying

SRA Dosage	This Work	Shah et al [19]
1%	14%	28%
2%	30%	38%
4%	58%	54%

The mixtures with SRA show significant shrinkage performance during the first 14 d of drying. These results correlate to the rate of shrinkage being less (i.e. flatter initial slope) for mixtures with SRA added to them. After 14 d of drying, the rate of shrinkage begins to decrease (i.e. the slope begins to flatten) in all 4 mixtures. After 120 d of drying, all 4 mixtures have reached their ultimate strains and are no longer shrinking. These results seem to show that the improved shrinkage performance caused by the addition of SRA is not as significant in later ages. This finding is supported by a study conducted by Weiss et al., which determined that concrete demonstrates a lower initial rate of shrinkage (i.e. flatter initial slope) with the addition of SRA [21]. This study [21] researched the effects that different SRA dosages had on the shrinkage performance of concrete mixtures. Weiss's results show that the mixtures with 1% and 2% SRA exhibited lower initial rates of shrinkage (i.e. flatter initial slopes) than the mixture with No SRA. The shrinkage strains in this study [21] also began to flatten after 14 d of drying, which reinforces the results shown in this work.

A study conducted by Chaunsali et al. determined that an SRA of 1.5 gal/yd^3 can yield approximately 50% reduction in shrinkage [2]. The high SRA dosage used in the study [2] was 1.5 gal/yd^3 and is similar to the 2% SRA dosage in this work, which equates to 1.58 gal/yd^3. They were able to achieve 50% less shrinkage at this dosage, which is nearly 2 times more shrinkage reduction than what was found in this work. The mixture designs and shrinkage test methods from research conducted by Chaunsali et al. are very comparable to this work. In their study [2], the concrete mixtures were designed to have a w/cm of 0.44 and a maximum nominal coarse aggregate size of 0.75 inches, but the type of aggregate that they used was not reported. They made concrete prisms 3 x 3 x 11.25 in. in size to measure the drying shrinkage and mass change of the mixtures. They kept their prisms in the same environmental conditions as done in this work; they were cured in limewater for 7 days and then kept in drying conditions of 73°F and 50% relative humidity for the remainder of the testing. The only noticeable difference in methodology is that they followed the ASTM C 157 length change methods to calculate the percentage of shrinkage, whereas in this work, embedded vibrating wire gauges were used to directly collect the change in strain over time. Also, the type of aggregate used in the study [2] could be different than the aggregate used in this work. This could be important, as the stiffness of aggregates plays an important role in restraining shrinkage, and a difference in stiffness will impact the shrinkage performance.

2.2.2 Compressive Strength Results

In Figure 2-3, the compressive strength data for all four concrete mixtures is presented. Also, Table 2-7 presents the comparisons between the compressive strength values of the mixture with No SRA and the mixtures containing SRA.

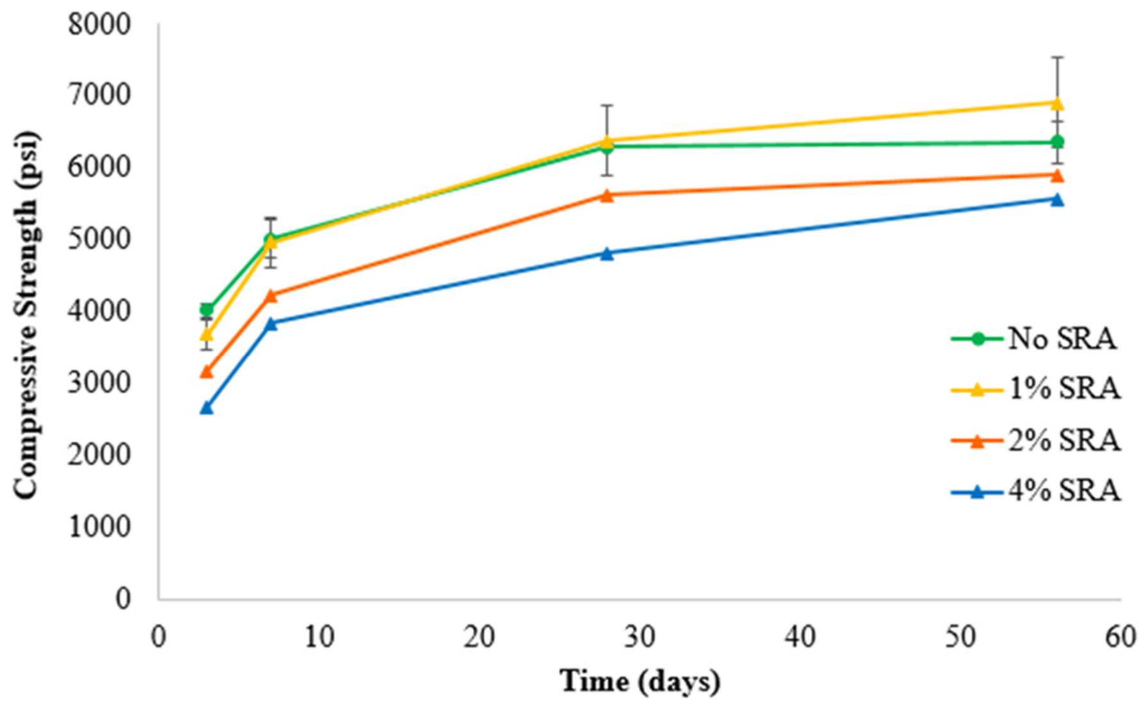

Figure 2-3 – Time versus Compressive Strength for all concrete mixtures.

Table 2-7 – Compressive strength change compared to No SRA mixture

Day	1% SRA	2% SRA	4% SRA
3	No difference	23%	40%
7	No difference	17%	26%
28	No difference	No difference	27%
56	No difference	No difference	13%

[1]Percent difference = $\frac{|V1-V2|}{\left(\frac{V1+V2}{2}\right)} \times 100$; V_1 = initial value, V_2 = new value

The values in Table 2-7 denote the percent reduction in compressive strength between the mixture with No SRA and the mixtures containing SRA at each day of interest. These values were determined by calculating the percent difference[1] between the mixture with No SRA and the mixtures containing SRA. The term “No difference” in the table means no statistical difference according to a Student T-test was found between the mixture with no SRA and the mixture in question. More details can be found in Appendix A.

According to Figure 2-3, the mixture with 4% SRA dosage shows the lowest compressive strength values, while the mixtures with no SRA and 1% SRA dosage show the highest compressive strength values. In previous studies, SRA has been known to decrease the compressive strength of concrete mixtures [4, 22, 23]. At each measurement day, there was no significant statistical difference between the compressive strength of the mixtures with 1% SRA dosage and No SRA. This matches previous work that shows that SRA used at 1% does not significantly alter the compressive strength of concrete [19].

The results in Table 2-7 show that the impact of the SRA on compressive strength reduces over time. For example, on day 3, the strength reduction for the mixture with 4% SRA is 40%; however, by day 56, the strength reduction is only 13%. This same trend also occurs for the mixture with a 2% SRA dosage. This seems to show that SRA has a lower impact on strength reduction at later ages.

2.2.3 Electrical Resistivity Results

In Figure 2-4, the resistivity data for all four concrete mixtures is presented. Also, Table 2-8 presents the comparisons between the resistivity values of the mixture with No SRA and the mixtures containing SRA.

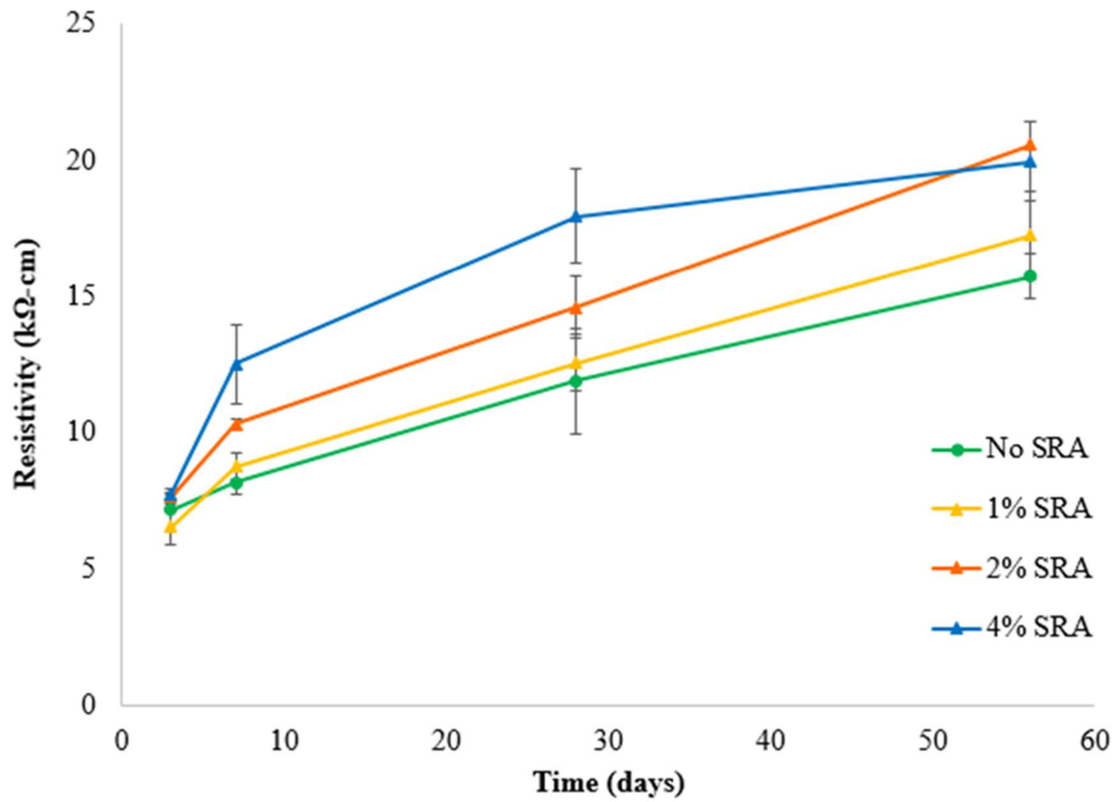

Figure 2-4 – Time versus Resistivity for all concrete mixtures.

Table 2-8 – Resistivity increase based on SRA dosage

Day	1% SRA	2% SRA	4% SRA
3	No difference	No difference	No difference
7	No difference	23%	42%
28	No difference	No difference	41%
56	No difference	27%	24%

[1]Percent difference = $\frac{|V1-V2|}{\left(\frac{V1+V2}{2}\right)} \times 100$; V_1 = initial value, V_2 = new value

In Table 2-8, the comparisons between the resistivity values of the mixture with No SRA and the mixtures containing SRA are presented. The values in Table 2-8 were determined by calculating the percent difference[1] between the mixture with No SRA and the mixtures containing SRA. The term “No difference” in the table means no significant statistical difference from a Student t-test between the resistivity measurements. More details can be found in Appendix A.

According to Figure 2-4, the mixture with 4% SRA dosage shows the highest resistivity values, while the mixtures with No SRA and 1% SRA dosage show the lowest resistivity values. At each measurement day, there is no significant statistical difference between the electrical resistivity of the mixtures with No SRA and 1% SRA dosage. The results presented in Figure 2-4 seem to show that for the 2% and 4% SRA dosages that the resistivity increases. Studies conducted by Hatami et al. and Maia et al. also determined that concrete electrical resistance is increased when SRA is used [5, 24]. This increase in electrical resistance is thought to be attributed to the effect that SRA has on reducing electrical conductivity of concrete pore solution but it could be related to the microstructure [24, 25].

From Table 2-8, there is a difference in resistivity values for the 4% SRA mixture at 7 and 28 d, and this difference decreases with time. This supports the idea that there is a temporary change in the pore solution chemistry of the concrete that reduces after 28 d.

As previously presented, there was also no significant statistical difference in mass change for all four concrete mixtures. Since the electrical resistivity increased with higher SRA dosages, and the mass change for all the mixtures was similar, this suggests that there is not a large difference in the connectivity of the pore structure. This again supports the idea that the SRA temporarily alters the pore solution chemistry within the concrete mixture. This assumption is supported by the conclusion made by Shah et al.; the effectiveness of SRAs is related to other factors, such as impacting the microstructure of the cement paste or reducing the surface tension of the mixing water [19].

2.4 PRACTICAL SIGNIFICANCE

Knowing how to reduce the effects of drying shrinkage can significantly improve the performance of concrete. The research conducted in this paper shows that an SRA dosage of 1% by weight of the cement offered a shrinkage reduction of nearly 30% after 14 d of drying. It should also be noted that no statistical decrease in early-age compressive strength occurred with the addition of SRA at a dosage of 1%. This significant improvement in shrinkage performance with a low dosage of admixture is an important finding because it is an economical way to improve shrinkage performance without impacting the other properties of the concrete. This would provide a practical solution to improve the durability of concrete without substantially increasing the cost.

Higher dosages of SRA, such as 2% and 4%, showed improved shrinkage reduction and electrical resistivity performance; however, the compressive strength was negatively affected by these higher dosages. If reduced shrinkage performance is necessary, this reduction of compressive strength could be offset by decreasing the water-to-cementitious materials ratio (w/cm) of the concrete. Since the SRA increases the workability of concrete mixtures, this will help with placement at lower w/cm ratios.

2.5 SUMMARY

In this work, an investigation into the impact that different dosages of SRA have on fresh and hardened properties of bridge deck concrete mixtures was conducted. This research shows that adding a shrinkage reducing admixture (SRA) can significantly improve the shrinkage performance of concrete without affecting construction practices. Using SRA at a dosage of 1% by weight of cementitious materials improved shrinkage performance without impacting the compressive strength or electrical resistivity.

Based on the information provided in this paper, the following conclusions can be drawn:

- In every property test, the mixture with 1% SRA performed the same as the mixture with No SRA.
- At early ages (i.e. 14 d of drying), mixtures with SRA show significant shrinkage performance; however, the reduction in shrinkage seems to be less significant in later ages.
    - After 14 d of drying, the mixtures with 1%, 2%, and 4% SRA exhibited 28%, 44%, and 72% less shrinkage than the mixture with no SRA, respectively.
    - However, after 120 d of drying, the mixtures with 1%, 2%, and 4% SRA exhibited 12%, 23%, and 50% less shrinkage than the mixture with no SRA, respectively.
- No significant difference in mass change was found between all of the concrete mixtures with different dosages of SRA. Also, the electrical resistivity increased with the addition of SRA. These results seem to show that the pore solution within the concrete is altered by the SRA up until 28 d.
- The two higher SRA dosages (i.e. 2% and 4%) reduced the compressive strength of the concrete. However, this reduction in strength seems to be larger at early ages and smaller at later ages.

This work shows that low dosages of SRA can provide useful reductions in shrinkage with minimal impact on strength. These types of uses should be used more widely to reduce concrete cracking.

CHAPTER III

PERFORMANCE IMPACTS ON PAVEMENT CONCRETE USING LARGER NOMINAL MAXIMUM COARSE AGGREGATE SIZE

3.0 INTRODUCTION

Materials and the mixture design of concrete have a large effect on the performance. The concrete industry has gone to great lengths to better understand the relationships of a variety of materials in concrete. One challenging material to understand has been the aggregate, due to the large variability from place to place. It has been stated in much literature about how larger coarse aggregate sizes have been thought to improve the performance of a concrete mixture. Common concrete mixture design methods, such as the ACI 211, ACI 302, ACI 318 [9], use the nominal maximum coarse aggregate size as an input into the workability, durability, and/or compressive strength of the mixture. Most literature suggests as the nominal maximum size increases, the workability of the mixture is predicted to increase [26, 27, 28].

Many think that these larger aggregates can decrease the shrinkage, and ultimately improve the overall performance of concrete mixtures [29]. The Wisconsin Department of Transportation requires the use of 1.5-in. nominal coarse aggregate in concrete mixtures. Yet, research using the Tarantula Curve design method [30] has shown that using a larger nominal maximum coarse aggregate size can reduce the workability of the concrete in several situations. Also, drying shrinkage is more a function of the paste volume than the nominal maximum coarse aggregate size. The Tarantula Curve is a technique using the combined gradation of aggregates to aid in the proportioning of mixtures to highlight workability issues [30, 31]. Unfortunately, there was only a limited amount of work completed in the research [30].

This work focuses on evaluating how using a 1.5-in. nominal maximum coarse aggregate size impacts the overall performance of pavement concrete. The Tarantula Curve design method was used to investigate different combined gradations and their effects on the fresh and hardened properties of pavement concrete mixtures. In these mixtures, the fine aggregate proportions were held constant, while the coarse aggregate proportions were varied to allow the impact of the larger coarse aggregate sizes on the workability and the hardened properties to be investigated.

3.1 EXPERIMENTAL METHODS

3.1.1 Materials

All the concrete mixtures in this research were prepared using a Type I ordinary Portland cement that meets the requirements of ASTM C150. A Class C fly ash that met the requirements of ASTM C618 was used at a 20% cement replacement by weight. The oxide analyses for the cement and fly ash, as well as the Bogue calculations for the cement, are shown in Table 3-1. All mixtures used an ASTM C494 mid-range water reducer (MRWR) Type A. One 1.5-in. nominal size coarse aggregate, one 3/4-in. nominal size coarse aggregate, and one fine aggregate were used in the mixtures. The coarse aggregates used were river gravel obtained from the same source, and the fine aggregate was a locally produced natural river sand. A sieve analysis for each of the aggregates was completed per ASTM C136. Absorption and specific gravity of each aggregate followed ASTM C127 for a coarse aggregate or ASTM C128 for a fine aggregate. The properties of and sieve analysis of each aggregate are shown in Table 3-2 and Figure B-1 in the appendix.

Table 3-1 **-** Chemical Composition of Type I Portland Cement and Class C Fly Ash

Material	Oxide Percentages								Phase Concentrations			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	C_3S	C_2S	C_3A	C_4AF
Cement (%)	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	48	24	8.1	7.9
Fly Ash (%)	25.3	19	5.2	33	7.8	2.6	3.4	0.6	-	-	-	-

Table 3-2 **-** Properties and Sieve Analysis of Each Aggregate Type

		Aggregate Properties & Sizes		
		Coarse		Fine
		1.5" NM Coarse	3/4" NM Coarse	River Sand
Properties	Bulk Specific Gravity (SSD)	2.72	2.73	2.65
	Absorption (%)	0.88	1.14	0.55
Percent Passing the Sieve Number	1.5"	87%	100%	100%
	1"	20%	100%	100%
	3/4"	3%	99%	100%
	1/2"	1%	66%	100%
	3/8"	0%	41%	100%
	#4	0%	5%	98%
	#8	0%	2%	92%
	#16	0%	2%	74%
	#30	0%	2%	41%
	#50	0%	2%	10%
	#100	0%	2%	1%
	#200	0%	2%	0%
	Pan	0%	0%	0%

3.1.2 Concrete Mixture Design

To evaluate and compare the performances of multiple concrete mixtures, the paste content and water-to-cementitious materials ratio (w/cm) were held constant. The mixtures were designed to have 5.5 sacks (517 lbs) of cementitious material per cubic yard of concrete, a paste volume of 23.2%, and a w/cm of 0.42. A total of 6 concrete mixtures were produced to determine the influence of gradation on specific properties of the concrete. The mixture designs for all 6 mixtures are shown in Table 3-3.

The Tarantula Curve was used to design the concrete mixtures. All the mixtures were designed to intentionally hold the paste and mid-range WR dosage constant and vary the gradations of the mixtures. Additionally, the fine aggregate proportions were held constant, while the coarse aggregate proportions were varied. This allowed the impact of the larger coarse aggregate sizes on the workability and the hardened properties to be investigated and measured. The workability was evaluated with the AASHTO TP 137 Box Test results. The Box Test measures how responsive a concrete mixture is to vibration, specifically for slip-form applications. The combined aggregate gradations of all mixtures for every aggregate type were plotted in a percent retained chart and will be presented in the results section.

Table 3-3 - Concrete Mixture Proportions at Saturated Surface Dry (SSD)

Mix	**1.5" NM Coarse (lbs/yd^3)**	**3/4" NM Coarse (lbs/yd^3)**	**Fine (lbs/yd^3)**	**Cement (lbs/yd^3)**	**Fly Ash (lbs/yd^3)**	**Water (lbs/yd^3)**
1	0	2050	1350	362	155	217
2	250	1800	1350	362	155	217
3	500	1550	1350	362	155	217

4	750	1300	1350	362	155	217
5	1000	1050	1350	362	155	217
6	1250	800	1350	362	155	217

3.1.3 Concrete Mixing Procedure

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 73°F for at least 24 hours before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was started, and the water reducer was added, and the concrete was mixed for three minutes.

3.1.4 Sample Preparation and Testing

After preparing the mixture, fresh properties of the concrete were tested, which included Slump ASTM C143 [12], Box Test (AASHTO TP-137), Unit Weight ASTM C138 [13], and Air Content ASTM C231 [14]. Then samples were prepared for Drying Shrinkage testing ASTM C157 [15], Compressive Strength ASTM C39 [16], and Electrical Resistivity (AASHTO T358). The number of samples with the test method can be summarized in Table 3-4 and additional information about the sample preparation and testing can be found in the proceeding subsections.

Table 3-4 - Concrete Testing Information

Test Property	Test Method	Sample Size	Sample Count
Slump	ASTM C143	---	2
Box Test	AASHTO TP-137	---	2
Unit Weight	ASTM C138	---	1
Air Content	ASTM C231	---	1
Drying Shrinkage	ASTM C157	4 x 4 x 11.25 in.	4 (2 for mass, 2 for length)
Compressive Strength	ASTM C39	6 x 12 in.	8 (3 at 7 and 28 d, plus reserve)
Electrical Resistivity	AASHTO T358	4 x 8 in.	6 (3* at 3, 7, 14, 28, 56, 90, and 120 d, plus reserve)

*These samples were reused at each day of interest for their respective test

3.1.4.1 Slump Test

The Slump test was used to help provide insight into the consistency of workability of the concrete mixtures. The Slump Test ASTM C143 [12] has been the most specified workability test; however, it simply measures the ability of a cone of concrete to deflect after removing forms [32]. This test is not sensitive enough to accurately predict the workability of mixtures with low flowability, such as pavement mixtures [33]. During placement, pavement mixtures are vibrated and extruded through side forms, and the slump test is not capable of mimicking the vibration energy applied during paving.

3.1.4.2 Box Test

The Box Test (AASHTO TP-137) was used to measure the workability performance of the mixtures in this study. It is a useful tool for evaluating the response of a concrete mixture to vibration, while also holding an edge [30]. The Box Test was conducted as follows: 1) freshly mixed concrete was placed into temporarily fixed wood forms, 2) a hand-held vibrator with a specified size and speed was used to consolidate the concrete at a fixed time with a controlled entry and exit location, 3) the forms were removed, 4) the concrete was visually inspected to assess if the sides were properly consolidated, and 5) a straight edge is used to measure edge slumping [30]. The results of the Box Test are determined by ranking the surface characteristics and edge slumping of the concrete block. The visual ranking system used for the Box Test is shown below in Figure 3-1. For this testing, a mixture was assumed to have good workability performance if the edge slumping was less than 0.25 inches and the sides had less than 30% surface voids measured visually. This performance criterion will be referred to as “passing the Box Test.” These requirements are discussed in a past publication by Cook et al. [31].

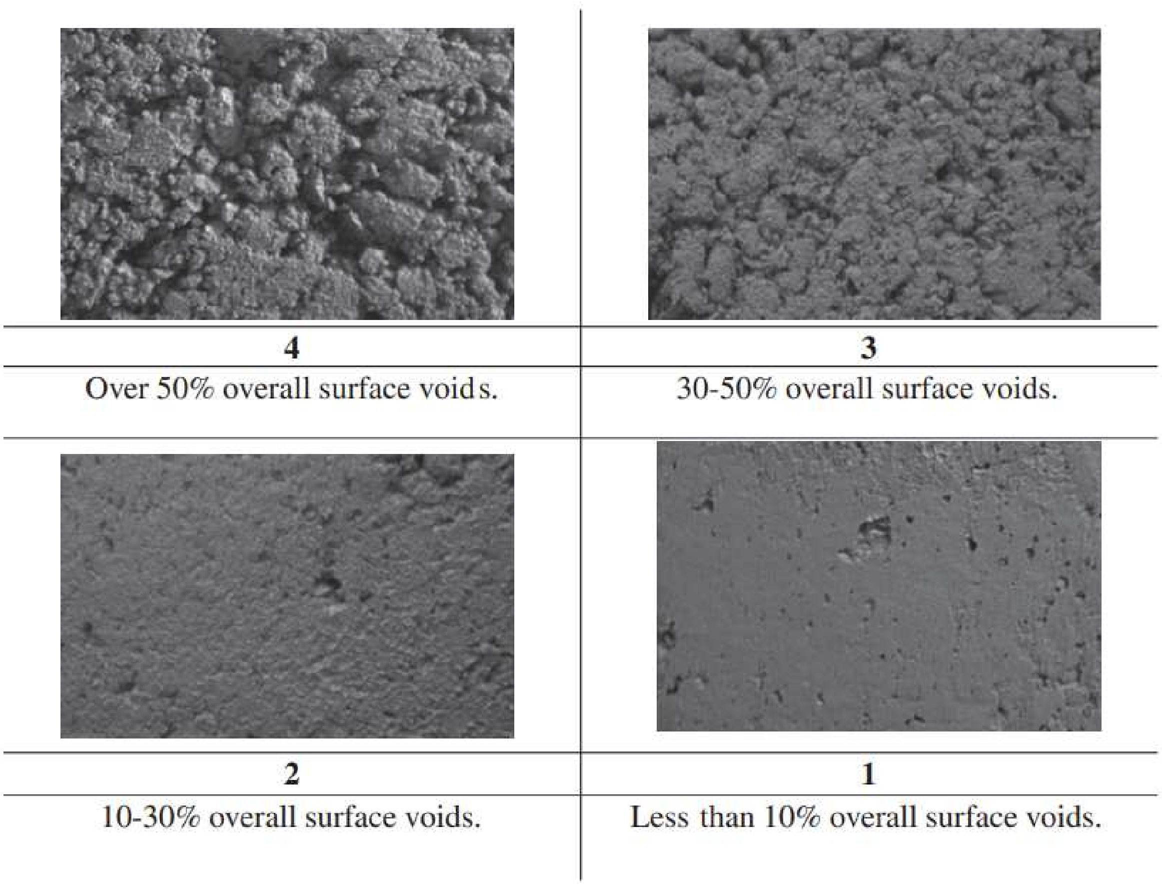

Figure 3-1 - Visual ranking system for the Box Test

3.1.4.4 Shrinkage Testing

3.1.4.4.1 Sample Preparation for Shrinkage Testing

Four 4 x 4 x 11.25 in. beam samples were prepared for drying shrinkage testing. Two of the samples were used for mass change measurements, while the other two samples were used to measure length change (ASTM C157). The two length change samples contained vibrating wire strain gauges that were cast into the samples during concrete placement. The strain gauges allowed strain measurements to be taken as the concrete was hydrating, which is not possible when using the ASTM C157 standard procedure for shrinkage measurements. To keep the gauges centered in the beam forms, two holes were drilled in the forms and thin wires were loosely wrapped around each end of the gauge and each wire was strung through each hole in the wooden sides.

3.1.4.4.2 Curing and Drying Conditions for Shrinkage Testing

After casting, all four samples were demolded, and an initial mass reading was taken for the two mass change samples. Then, all four samples were wet cured for 7 d in an environmentally controlled room that was kept at a temperature of 73°F and 100% relative humidity. After the curing period, the four samples were removed, another mass reading was taken, and the samples were stored in the drying room, which was kept at a temperature of 73°F and 50% relative humidity.

3.1.4.4.3 Shrinkage and Mass Measurements

Four beam samples were prepared for drying shrinkage testing according to ASTM C157 [15]. Two of the samples were used for mass change measurements, while the other two samples were used to measure length change via vibrating wire strain gauges. All four beams were demolded after one day, and initial mass measurements were recorded. Then, the mass loss of each sample was measured at the time intervals specified in ASTM C157 with an accuracy of 0.1 g (0.00022 lbs). The gauges recorded strain measurements from the samples every hour. Since strain measurements were being recorded for two samples, the measurements were averaged and plotted with error bars showing one standard deviation.

3.1.4.5 Compressive Strength Testing

From each mixture, six 6 x 12 in. concrete cylinders were made and cured according to ASTM C192 for compressive strength testing ASTM C39, and an additional two cylinders were made and kept as reserve. The cylinders were cured in the environmentally controlled room at a temperature of 73°F and 100% relative humidity. The cylinders were kept in this room in their molds until compressive strength testing at 7 and 28 d as per ASTM C39.

3.1.4.6 Electrical Resistivity Testing

From each mixture, three 4 x 8 in. concrete cylinders were made and cured according to ASTM C192 for electrical resistivity testing AASHTO T358, and an additional 3 were kept as reserve. These samples were curried in the environmentally controlled room at a temperature of 73°F and 100% relative humidity according to ASTM C192 and kept in their molds until testing. Four lines were marked on the circular face of each concrete cylinder at 0, 90, 180, and 270 degrees and measured in terms of kΩ-cm over those lines. These four measurements were averaged for each cylinder.

3.2 RESULTS AND DISCUSSION

The combined individual percent retained gradations of all 6 mixtures are plotted in the Tarantula Curve and are shown below in Figure 3-2. The fine aggregate was held constant with a fine sand volume of 31% and a coarse sand volume of 24%. The total volume of coarse and intermediate aggregate was held constant in each mixture but the relative proportion of the two was changed for each mixture. Since the mixture has to sum to a cubic foot, this means that when the larger coarse aggregate is reduced then the intermediate aggregate must be increased. This allowed mixtures to be created with very high amounts of larger coarse aggregate and low amounts of intermediate aggregates and vice versa. By systematically changing the amount of each of these materials the changes in workability or hardened properties can be determined.

As shown in Figure 3-2, the combined gradations of mixtures 2, 3, and 4 are within the limits set by the Tarantula Curve. Mixtures 5 and 6 both exceed the 16% limit on the 1-in. size, and mixture 1 exceeds the 20% limit on the #4 size and contains no rock larger than 3/4-in. This mixture with only 3/4-in aggregate is expected by some to be less workable because of the decrease in the maximum nominal aggregate size.

It should be noted the legend in the figure denotes the mixture number followed by the percent retained on the #4 sieve size and the percent retained on the 1-in. sieve size. This code will be used in the legends of all remaining figures shown in this work. The legend also denotes the mixtures that passed the Box Test with a solid line and the mixtures that failed the Box Test with a dotted line.

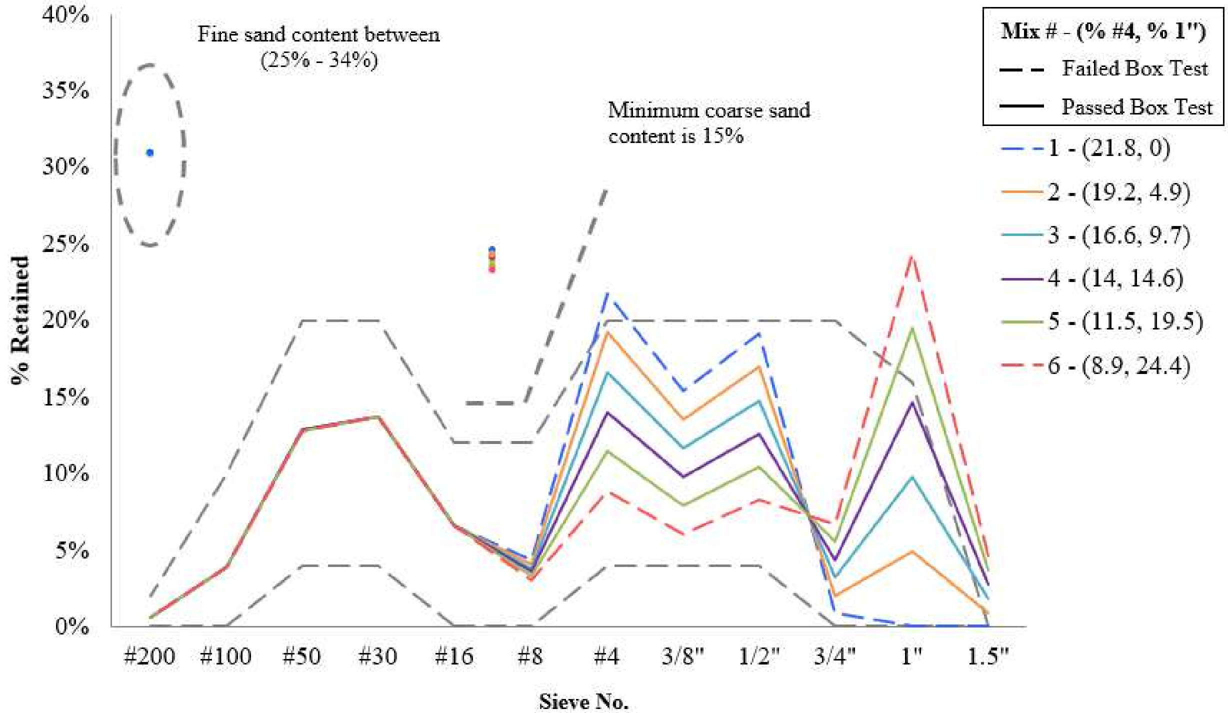

Figure 3-2 - Tarantula Curves for all mixtures.

3.2.1 Summary of Fresh Property Results

The fresh concrete properties of each mixture are summarized in Table 3-5. The average (Ave.) and standard deviation (S.D.) for the Slump Test and Box Test.

Table 3-5 - Fresh Concrete Properties

Mix	Slump (inches)		Box Test Rating		
	Ave.	S.D.	Ave.	S.D.	Edge Slump
1	0.25	0	3.5	0.6	NO
2	0.5	-	1.88	0.75	NO
3	1	-	1.88	0.25	NO
4	1.5	-	1	0	NO
5	2	-	1.75	0.5	NO
6	1.75	0.71	2.44	0.5	YES

3.2.1.1 Box Test Performance

The Box Test results for the mixtures are displayed in Figure 3-3 below. According to Figure 3-3, mixtures 2 through 5 passed the Box Test, and mixtures 1 and 6 did not. Table 3-5 also states that mixture 6 was the only mixture that exhibited edge slumping during the Box Test.

In Figure 3-2, the combined gradation for mixture 1 shows that the #4 size had more than 20% retained, which exceeds the limit for this size. From previous research by Cook et al., if a single sieve size of coarse aggregate (#4 and larger) retained more than 20%, the workability performance of the concrete would decrease [30]. Thus, the Box Test performance for mixture 1 reinforces this idea from the Tarantula Curve design method. Mixtures 5 and 6 exceeded the limit on the 1-in. size, which is known to create workability issues in a given concrete mixture. From Cook et al.'s previous research, the Tarantula Curve limit for the 1-in. sieve size was found to be 16% [30]. As previously shown in Figure 3-2, mixture 5 had 19.5% retained on the 1-in. size, while mixture 6 had 24.4% retained on the 1-in. size. Mixture 5 passed the Box Test, but mixture 6 did not. This means that for this material, there is a limit for the 1-in. size that is between 19.5% and 24.4% retained.

The 1-in. sieve size limit was determined to be 16% by Cook et al., but there was limited work done to fine-tune the limit. Cook et al. studied the workability performance of one mixture with a 1.5-in. nominal maximum coarse size. The aggregate used in the study [30] was a crushed limestone, and the percent retained on the 1-in. size was 16%. The results of Cook et al.'s study showed that the mixture exhibited good workability performance, but no additional mixtures were tested with this aggregate size in order to find the actual limit in which the workability performance started to decrease. The aggregate studied in this work was river gravel, which has a different shape and different surface texture and angularity than crushed limestone. Different aggregate characteristics can impact the workability of concrete mixtures. River gravel is much smoother and less angular than crushed limestone. This difference could allow for improved workability performance with higher amounts retained on the 1-in. size as shown in this work. Also, Cook et al. studied mixtures with a paste content of 24.2% and a w/cm of 0.45. These differences in aggregate type and mixture design could be the reason for the different workability performances observed for this work and the study conducted by Cook et al.

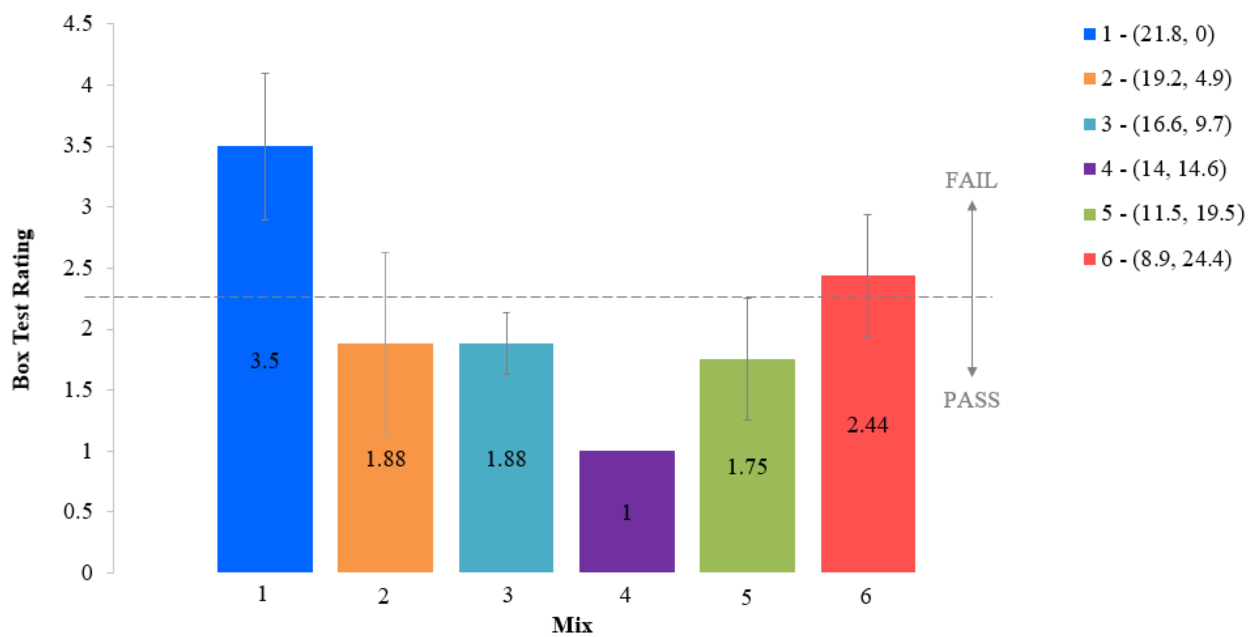

Figure 3-3 - Average Box Test results of all mixtures.

3.2.1.2 Slump Test Performance

The Slump Test results for the mixtures are displayed in Figure 3-4 below. Standard deviation error bars are also shown for each mixture. As stated in Table 3-5, the standard deviations for the slump results were only reported for mixtures 1 and 6. This is due to the lack of slump measurements collected for the other 4 mixtures. The standard deviation for mixture 1 is zero, which is why no error bar is shown in Figure 3-4. According to the results presented above in Table 3-5 and below in Figure 3-4, mixtures 1, 2, and 3 had the lowest slump values. When looking at the combined gradations in Figure 3-2, these three mixtures had the highest amount of intermediate aggregate out of all 6 mixtures. Mixtures 2 and 3 are approaching the limit for the #4 size, and mixture 1 exceeds the #4 size limit. According to the Tarantula Curve design method, excessive amounts of intermediate sizes decrease the workability and promote segregation [30]. This is evident when looking at the slump results in Figure 3-4; mixture 1 had the lowest slump values (0.25 in.) and it contained an excessive amount of #4 size rock. Similarly, mixtures 2 and 3 had the next lowest slump values (0.5 in. and 1 in., respectively) and contained amounts of #4 size rock that approached the limit. Mixture 6 had an average slump of 1.75 in., but had a larger standard deviation than the other mixtures (0.71 in.). This large standard deviation could have been the result of the concrete mixture segregating due to having a high amount on the 1-in. size and smaller amounts on the intermediate sizes. Research done by Sokhansefat et al. found that when there is greater than 20% of coarse aggregate retained on a single sieve size, it will increase the potential for segregation of the concrete [34]. The results of their study [34] showed that concrete mixtures with 20% coarse material retained on a sieve size showed higher internal spacing of aggregates and regions where no aggregate was present. This poor spacing and distribution of coarse aggregate suggest that segregation occurred within the mixture. The results shown in Figure 3-4 also show that the slump of the concrete mixtures increased as the percent retained on the 1-in. sieve size increased. However, past research by Cook et al. has shown that the slump of concrete does not accurately represent how it will consolidate and finish in the field, which are both important aspects for pavement concrete [30, 31]. If the Slump Test was the primary test method to assess the workability of concrete mixtures in this work, mixture 2 would be expected to have poor workability performance; however, it passed the Box Test. Similarly, mixture 6 would be expected to have good workability performance according to the Slump Test results, but it failed the Box Test.

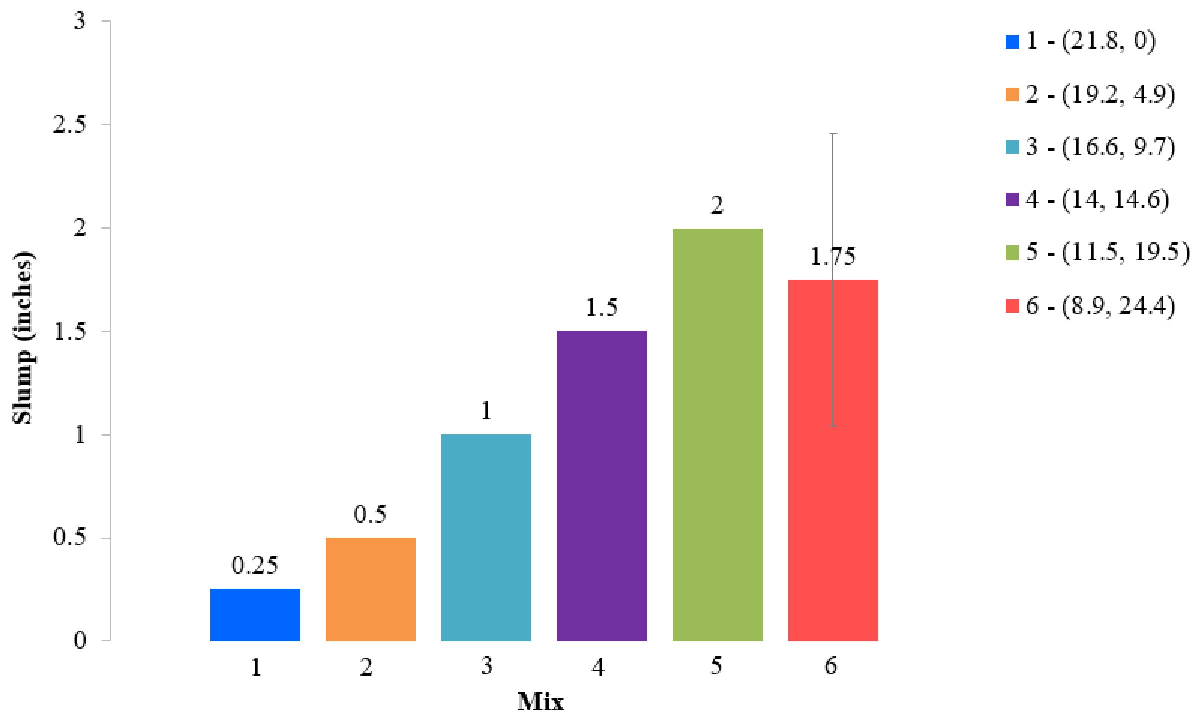

Figure 3-4 - Average Slump Test results for the mixtures.

3.2.2 Summary of Hardened Property Results

The hardened concrete properties of each mixture are presented in the following sections. The hardened property results include compressive strength, electrical resistivity, mass change, and shrinkage strain.

3.2.2.1 Compressive Strength

The compressive strength results for the mixtures are displayed below in Figure 3-5. The average strength of all 6 mixtures was calculated for each day, and these results are also shown in Figure 3-5. According to the legend in the figure, the average strength value (of all 6 mixtures) is depicted as a solid black line, and the average plus or minus the standard deviation (of all 6 mixtures) is depicted as a dotted gray line.

A Student t-test was used to determine which mixtures had compressive strength values that were statistically different than the average strength value at each day of interest. The results of the t-test are shown in Table B-1 in the appendix. From Figure 3-5, mixture 1 had the highest 7-d strength, and mixtures 5 and 6 had the lowest strengths. At 28 d, mixtures 1 through 3 had the highest strengths, and mixture 6 had the lowest strength. According to Figure 3-5 and the results from the t-test, the compressive strength of mixtures 1 and 5 are statistically different than the average compressive strength at 7 d; the strength of mixture 1 is statistically higher, while the strength of mixture 5 is statistically lower. At 28 d, the strength of mixtures 1 through 5 are statistically the same as the average, and mixture 6 is statistically lower.

In Figures 3-5, all 6 mixtures exhibited very similar compressive strength performance at 7 d. This is most likely due to the paste being weaker at these early ages, and since all 6 mixtures had the same paste content they all exhibited similar performance. At 28 d, the paste in the mixtures was more mature, so the compressive strength performance was dominated by the aggregates in the mixtures.

From Figures 3-2 and 3-5, it can be observed that as the amount of large aggregate (1-in. sieve size) increased, compressive strength decreased. When looking at Figure 3-2, the combined gradations of mixtures 1, 2, and 3 show higher amounts of intermediate sizes and smaller amounts of 1-in. size. Conversely, the combined gradations of mixtures 5 and 6 show high amounts of 1-in. size and smaller amounts of intermediate sizes. A study by Issa et al. also found that as the nominal maximum coarse aggregate size in concrete mixtures increased, the compressive strength decreased [35]. The lower compressive strengths exhibited by these mixtures could be the result of the larger aggregates having thicker transition zones surrounding them [36]. The transition zone is a layer that forms around the aggregates in fresh concrete where the microstructure of the cement paste is modified [37]. Before setting, the concrete mixture bleeds and this leads to an accumulation of water under the aggregates, which leads to a gradient of water and a higher localized w/cm. [37]. According to Myers and Carrasquillo (1998), the thickness of the transition zone is dependent on aggregate size and w/cm; larger aggregates cause the transition zone to be thicker, and this is a weak link for concrete mixtures [36]. The higher localized w/cm in the transition zone causes the formation of large Calcium Hydroxide (CH) crystals. Calcium Hydroxide is one of the more soluble phases in Ordinary Portland Cement, so its dissolution creates large voids in the cement paste and increases the porosity [36]. This phenomenon negatively affects the paste-to-aggregate bond, which leads to reductions in compressive strength. The results from Figure 3-5 seem to reinforce this idea.

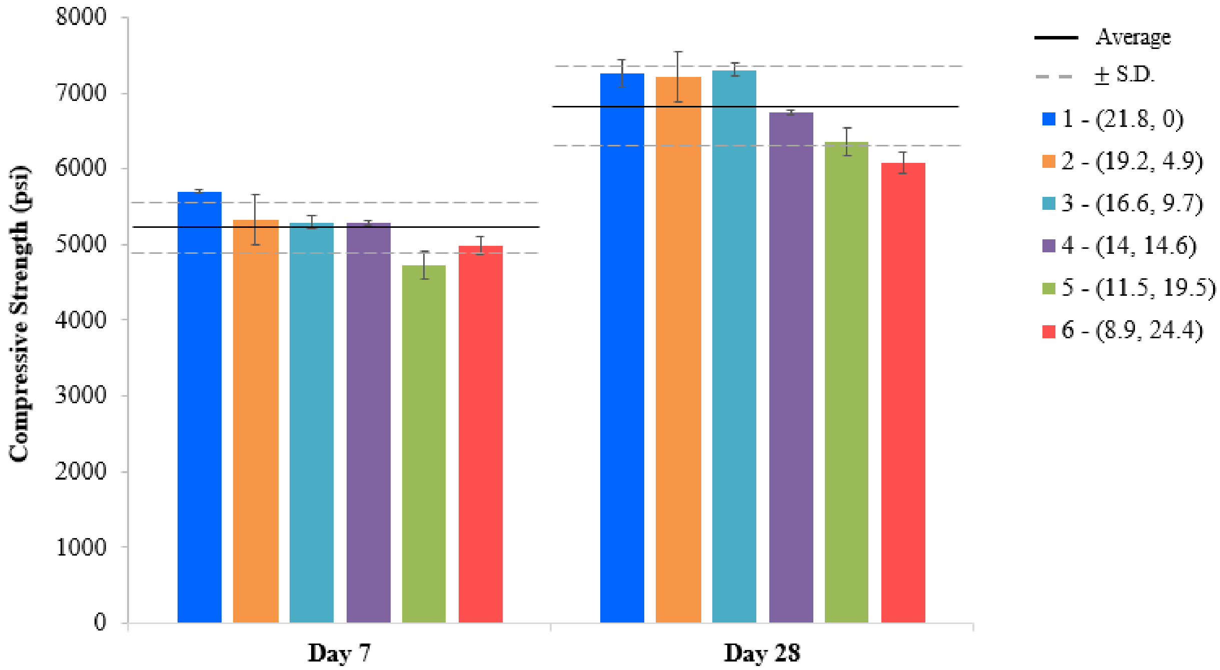

Figure 3-5 - Average compressive strength of the mixtures at each day of interest.

3.2.2.2 Electrical Resistivity

The electrical resistivity results for the mixtures are displayed below in Figure 3-6. The average resistivity value of all 6 mixtures was calculated for each day, and these results are also shown in Figure 3-6. According to the legend in the figure, the average resistivity value (of all 6 mixtures) is depicted as a solid black line, and the average plus or minus the standard deviation (of all 6 mixtures) is depicted as a dotted gray line.

A Student t-test was used to determine which mixtures had electrical resistivity values that were statistically different than the average resistivity value at each day of interest. The results of the t-test are shown in Table B-2 in the appendix.

According to Figure 3-6 and the results from the t-test, all 6 mixtures exhibited similar resistivity values for the first 14 d, meaning there was no significant statistical difference between the resistivity of the average and the 6 mixtures. At 28 d, mixtures 1 and 6 exhibited slightly higher resistivity values than the other mixtures and were found to be statistically different than the average. Mixture 1 has high amounts retained on the intermediate sizes, which could be causing the higher resistivity values. As stated before, higher amounts of intermediate sizes allow for more aggregate interlock and greater packing density in concrete mixtures. However, by this logic, mixtures 2 and 3 should also exhibit this behavior since they have higher intermediate percentages. Mixture 5 has a low intermediate amount and it exceeds the 1-in. limit, so it should be exhibiting lower resistivity values than mixtures 2 and 3, but this is not the case.

Another mixture of interest at 28-d is mixture 6, which exhibited lower resistivity values. As previously discussed, the combined gradation of mixture 6 shows a high amount retained on the 1-in. size and low intermediate sizes. Mixture 5 has a very similar gradation but is exhibiting nearly 23% higher resistivity values at 28 d. The resistivity performance of mixture 6 could be the result of the mixture segregating and creating empty void spaces in the concrete. This is caused by having more than 20% retained of coarse aggregate retained in a single sieve size [34].

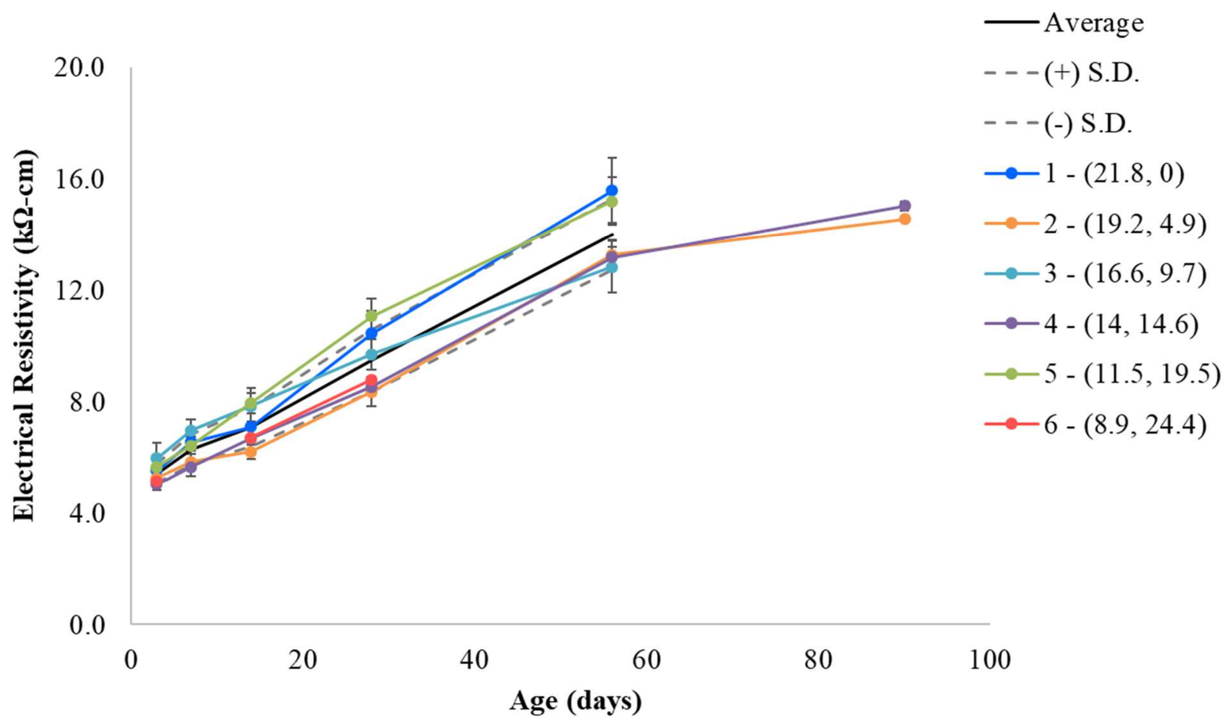

Figure 3-6 - Average resistivity measurements for mixtures at each day of interest.

3.2.2.3 Mass Change

The mass change over time for the mixtures, as well as the average mass change of all 6 mixtures, is presented below in Figure 3-7. According to Figure 3-7, a majority of the mixtures are experiencing the same amount of mass change over time. A Student t-test was used to compare the mass change of each mixture to the average mass change of all 6 mixtures over time. The results of the t-test analysis can be found in Table B-3 in the appendix. The results of the t-test show that at each day of interest, mixture 4 was found to be statistically different than the average mass change of 6 mixtures, but this difference was very small. Mixture 4 also had about the same amount of coarse and intermediate aggregates. The results presented in Figure 3-7 seem to show that changing the gradation of a given concrete mixture had little to no impact on the mass change due to drying.

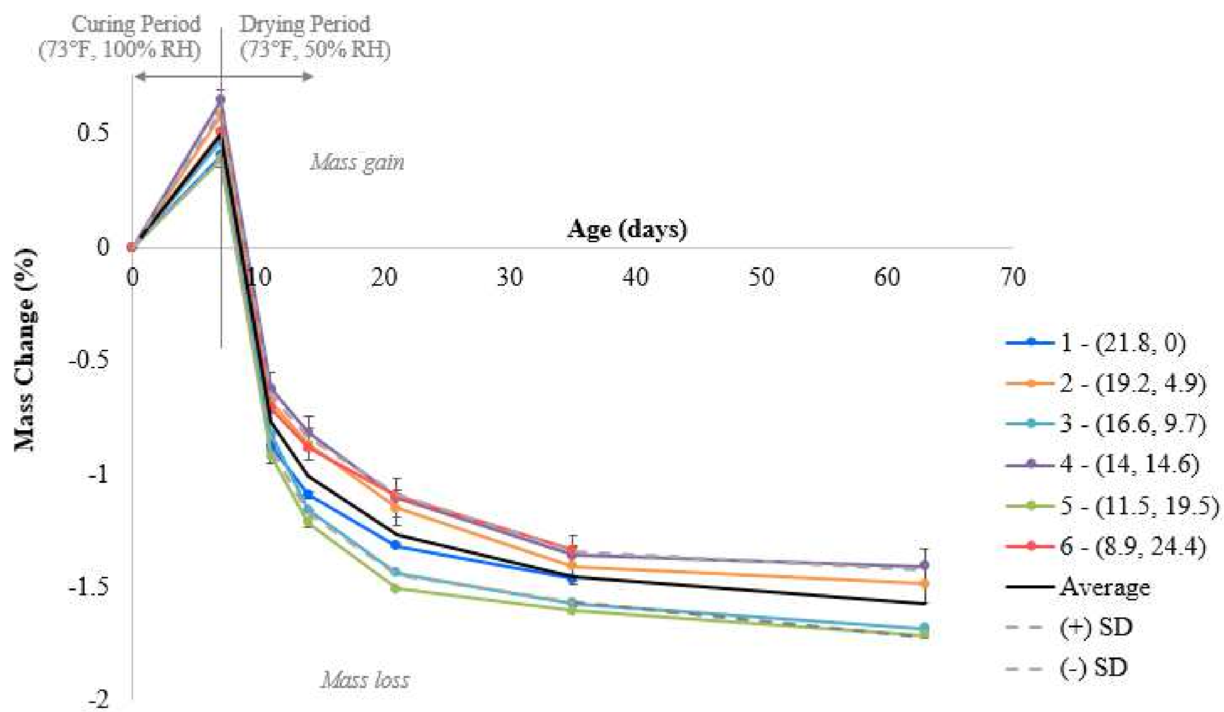

Figure 3-7 **-** Mass change values of the mixtures at each day of interest.

3.2.2.4 Shrinkage Strain

The shrinkage strain over time was measured by the strain gauges is shown in Figure 3-8. The gauges measure initial strains within the concrete that occur as it is being placed in the molds and during hydration. After the initial strains, the gauges continue measuring the strains over time during the curing process and the drying process. The strain gauge readings show that all of the samples expanded during the wet curing period, and then began to shrink after the samples were placed in the drying room. The drying room is maintained at 73°F and 50% relative humidity.

During the hydration and curing period, all of the samples exhibited similar expansion strain values and there was no statistical difference between the strain values of the 6 mixtures during the hydration and curing period. Similarly, no statistical difference between strain values of the mixtures was observed during the drying period. The results in Figure 3-8 seem to show that changing the gradation of a given concrete mixture had no impact on the shrinkage performance. This occurred because there was no change in the paste content or w/cm of the mixture.

The mass change and shrinkage results from Figures 3-7 and 3-8 seem to show that increasing the maximum nominal coarse aggregate size alone does not improve the shrinkage performance of concrete mixtures. This is because the paste content was not altered for any mixture, and shrinkage is a paste-related mechanism. The Wisconsin Department of Transportation currently requires a 1.5-in. nominal coarse aggregate size in their concrete mixtures because it is believed that it can improve shrinkage performance. The results from this study show that this is not the case; increasing the aggregate size without reducing the paste content does not improve the shrinkage performance of pavement concrete mixtures.

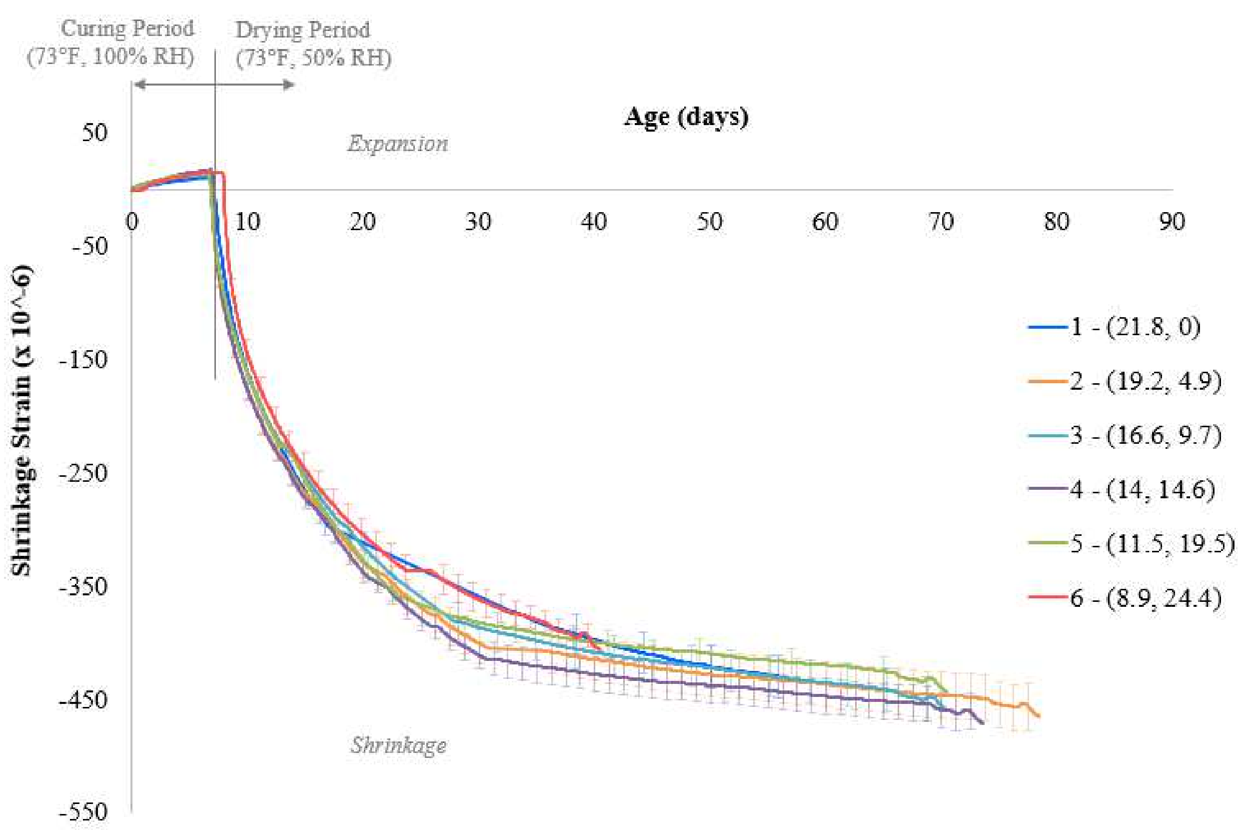

Figure 3-8 - Average shrinkage strains from mixtures during curing and drying periods.

3.3 SUMMARY

This work provided additional insights into the 1-in. sieve size with the Tarantula Curve. The following conclusions were made from this work:

- Good workability performance from the Box Test was achieved in mixtures with 19.5% coarse aggregate on the 1-in. sieve size, which exceeded the Tarantula Curve limit.
- Using more than 20% coarse aggregate on the #4 and 1-in. sieve sizes created mixtures with poor Box Test performance.
- The slump of concrete mixtures increased as the percent retained on the 1-in. sieve size increased, but slump is a questionable indicator of workability for paving applications
- The compressive strength of the concrete was improved when the percent retained on the #4 sieve size was higher than 16% in a mixture. Mixtures with higher percentages (>19%) retained on the 1-in. sieve experienced lower compressive strengths.
- Dramatic changes with gradation did not seem to affect the electrical resistivity of the concrete mixtures at early ages (< 14 d). However, a slight increase in resistivity performance was observed in mixtures 1 and 5 after 28 d.
- No significant differences between mass change or drying shrinkage was observed with different aggregate gradations.

CHAPTER IV

CONCLUSION

4.0 SUMMARY

The main objective of this research was to understand how shrinkage reducing admixtures and larger coarse aggregate sizes impact the overall performance of concrete by performing laboratory tests on concrete mixtures. To achieve this goal, different SRA dosages and aggregate gradations were investigated in Chapters 2 and 3, respectively. The following conclusions have been drawn from Chapter 2:

- At early ages (i.e. 14 d of drying), mixtures with SRA show significant shrinkage performance; however, the reduction in shrinkage seems to be less significant in later ages.
    - After 14 d of drying, the mixtures with 1%, 2%, and 4% SRA exhibited 28%, 44%, and 72% less shrinkage than the mixture with no SRA, respectively.
    - However, after 120 d of drying, the mixtures with 1%, 2%, and 4% SRA exhibited 12%, 23%, and 50% less shrinkage than the mixture with no SRA, respectively.

- No significant difference in drying rate was found between all of the concrete mixtures with different dosages of SRA. Also, the electrical resistivity increased with the addition of SRA. These results seem to show that the pore solution within the concrete is altered by the SRA up until 28 d.
- The two higher SRA dosages (i.e. 2% and 4%) reduced the compressive strength of the concrete. However, this reduction in strength seems to be larger at early ages and smaller at later ages.

This work shows that low dosages of SRA can provide useful reductions in shrinkage with minimal impact on strength. These types of uses should be used more widely to reduce concrete cracking.

Conclusions from Chapter 3:

This work provided additional insights into the 1-in. sieve size with the Tarantula Curve. The following conclusions were made from this work:

- Good workability performance from the Box Test was achieved in mixtures with 19.5% coarse aggregate on the 1-in. sieve size, which exceeded the Tarantula Curve limit.
- Using more than 20% coarse aggregate on the #4 and 1-in. sieve sizes created mixtures with poor Box Test performance.
- The slump of concrete mixtures increased as the percent retained on the 1-in. sieve size increased, but slump is a questionable indicator of workability for paving applications
- The compressive strength of the concrete was improved when the percent retained on the #4 sieve size was higher than 16% in a mixture. Mixtures with higher

percentages (>19%) retained on the 1-in. sieve experienced lower compressive strengths.

- Dramatic changes with gradation did not seem to affect the electrical resistivity of the concrete mixtures at early ages (< 14 d). However, a slight increase in resistivity performance was observed in mixtures 1 and 5 after 28 d.
- No significant differences between mass change or drying shrinkage was observed with different aggregate gradations.

REFERENCES

[1] Nair, H., Ozyildirim, C., & Sprinkel, M. M. *Reducing Cracks in Concrete Bridge Decks Using Shrinkage Reducing Admixture* (No. FHWA/VTRC 16-R13, VTRC 16-R13). Virginia Transportation Research Council, 2016.

[2] Chaunsali, P., Lim, S., Mondal, P., Foutch, D. A., Richardson, D., Tung, Y., & Hindi, R. *Bridge decks: mitigation of cracking and increased durability*. Illinois Center for Transportation (ICT), 2013.

[3] Quangphu, N., Linhua, J., Jiaping, L., Qian, T., & Tienguan, D. *Influence of shrinkage-reducing admixture on drying shrinkage and mechanical properties of high-performance concrete.* Water Science and Engineering, 2008. 1(4): p. 67-74.

[4] Cope, B. L., Ramey, G. E. *Reducing drying shrinkage of bridge-deck concrete.* Concrete International, 2001. 23(8): p. 76-82.

[5] Hatami, B., Ramezanianpour, A. M., & Daryan, A. S. *Investigation on the Effect of Shrinkage Reducing Admixtures on Shrinkage and Durability of High-Performance Concrete.* Journal of Testing and Evaluation, 2017. 46(1): p. 141-150.

[6] Pendergrass, B., Darwin, D., Feng, M., & Khajehdehi, R. *Compatibility of Shrinkage-Reducing and Air-Entraining Admixtures*. American Concrete Institute, 2017.

[7] Quiroga, P. N. *The effect of the aggregates characteristics on the performance of Portland cement concrete.* PhD diss., 2003.

[8] Rached, M. M., De Moya, M., & Fowler, D. W. *Utilizing aggregates characteristics to minimize cement content in portland cement concrete*, 2009.

[9] ACI Committee 211. *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. American Concrete Institute. Farmington Hills, MI: ACI, 1991.

[10] Zhan, P. M., He, Z. H. *Application of shrinkage reducing admixture in concrete: A review.* Construction and Building Materials, 2019. 201: p. 676-690.

[11] Mindess, S., Young, F. J., & Darwin, D. *Concrete 2nd Edition*. Technical Documents, 2003.

[12] ASTM, *ASTM C143-03 Standard test method for slump of hydraulic-cement concrete*. ASTM, West Conshohocken, PA, 2003.

[13] ASTM, *C138 Standard test method for density (unit weight), yield, and air-content (gravimetric) of concrete*. ASTM International, West Conshohocken, PA. 2013.

[14] ASTM, *ASTM C231 Standard test method for air content of freshly mixed concrete by the pressure method*. ASTM International, West Conshohocken, PA, 1997.

[15] ASTM, *ASTM C 157 Standard test method for length change of hardened hydraulic-cement mortar and concrete*. ASTM, 1999.

[16] ASTM, *ASTM C39 Standard test method for compressive strength of cylindrical concrete specimens*. ASTM, 2010.

[17] Yoo, D.Y., Banthia, N., & Yoon, Y.S. *Effectiveness of shrinkage-reducing admixture in reducing autogenous shrinkage stress of ultra-high-performance fiber-reinforced concrete.* Cement and Concrete Composites, 2015. 64: p. 27-36.

[18] Yoo, D.Y., et al., *Mitigating shrinkage cracking in posttensioning grout using shrinkage-reducing admixture.* Cement and Concrete Composites, 2017. 81: p. 97-108.

[19] Shah, S., Karaguller, M., & Sarigaphuti, M. *Effects of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete.* Materials Journal, 1992. 89(3): p. 289-295.

[20] Villani, C., et al. *Neutron radiography evaluation of drying in mortars with and without shrinkage reducing admixtures*. in American Concrete Institute Fall Meeting, Washington, DC. 2014.

[21] Weiss, W.J., Yang, W., & Shah, S.P. *Shrinkage cracking of restrained concrete slabs.* Journal of Engineering Mechanics, 1998. 124(7): p. 765-774.

[22] Weiss, J., et al., *Performance of shrinkage-reducing admixtures at different humidities and at early ages.* ACI Materials Journal, 2008. 105(5): p. 478.

[23] Yoo, D.Y., et al., *Effect of shrinkage-reducing admixture on biaxial flexural behavior of ultra-high-performance fiber-reinforced concrete.* Construction and Building Materials, 2015. 89: p. 67-75.

[24] Maia, L., et al., *Influence of shrinkage reducing admixtures on distinct SCC mix compositions.* Construction and Building Materials, 2012. 35: p. 304-312.

[25] Sant, G., et al., *Influence of shrinkage-reducing admixtures on moisture absorption in cementitious materials at early ages.* Journal of Materials in Civil Engineering, 2010. 22(3): p. 277-286.

[26] Richard, D. N., *Aggregate Gradation Optimization- Literature Search*. Missouri Department of Transport. RDT 05-001. Jefferson, Missouri: MDOT; 2005.

[27] National Stone, Sand, and Gravel Association. *The Aggregates Handbook. 2nd ed*. Alexandria, Virginia: Sheridan Books, Inc; 2013.

[28] Fuller, W., Thompson, S. *The Laws of Proportioning Concrete*. Transactions of ASCE. New York, NY: ASCE; 1907.

[29] Parry, J., personal communication, November 2, 2020.

[30] Cook, M. D. *Aggregate proportioning for slip formed pavements and flowable concrete*. Diss. Oklahoma State University, 2015.

[31] Cook, M. D., Ghaeezadah A., Ley M. T. A *Workability Test for Slip Formed Concrete Pavements*. Construction and Building Materials. 68. Elsevier; 2014, p. 376-383

[32] Shilstone, J. M. *A hard look at concrete*. Civil Engineering 59.1: 47, 1989.

[33] Powers, T. C. *Properties of Fresh Concrete*, John Wiley and Sons Inc., New York, 301, 1968.

[34] Sokhansefat, G., Ley, M. T., Cook, M. D., Alturki, R., & Moradian, M. *Investigation of concrete workability through characterization of aggregate gradation in hardened concrete using X-ray computed tomography*. Cement and Concrete Composites, 98, 150-161. 2019.

[35] Issa, S.A., Islam, M., Issa, M.A. and Yousif, A.A. *Specimen and aggregate size effect on concrete compressive strength*. Cement, concrete and aggregates, 22(2), pp.103-115. 2000.

[36] Myers, J. J., & Carrasquillo, R. L. *Production and Quality Control of High Performance Concrete in Texas Bridge Structures* (No. FHWA/TX-05/9-580/589-1), 1998.

[37] Ollivier, J. P., Maso, J. C., & Bourdette, B. *Interfacial transition zone in concrete*. Advanced cement based materials, 2(1), 30-38. 1995.

APPENDICES

Appendix A

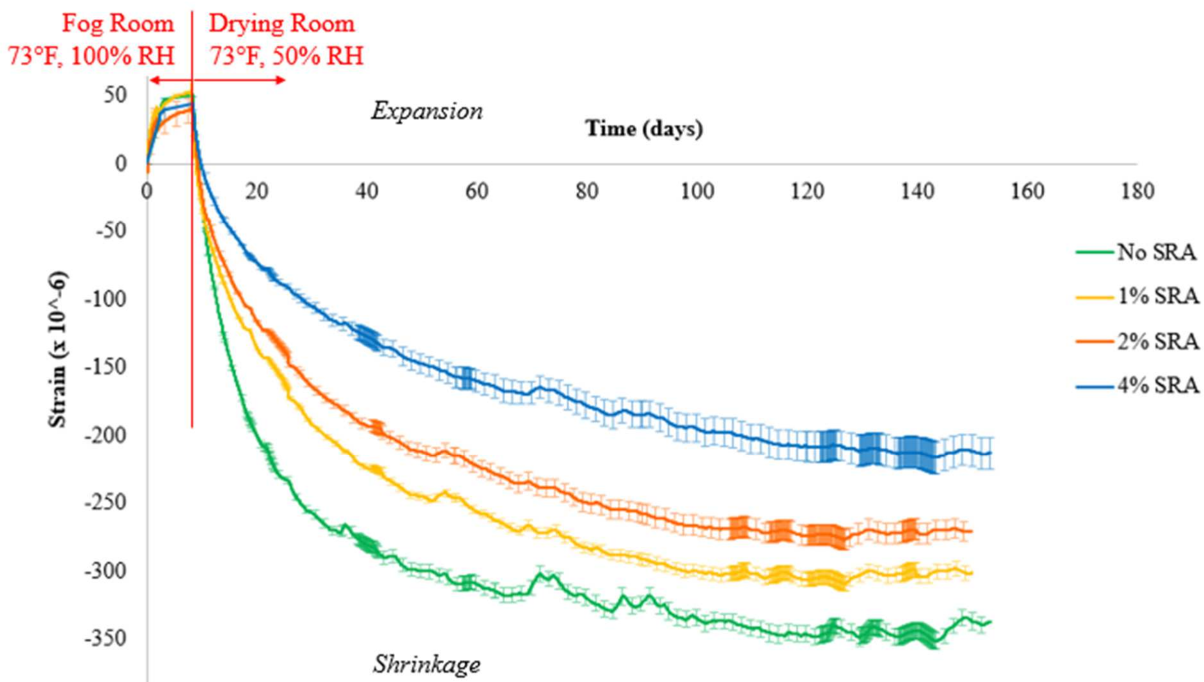

Figure A-1 – Strain readings for all four mixtures during curing and drying periods.

Student t-testing was used to determine if there was a significant difference between the mass change of all five mixtures. Table A-1 reports the t-statistics for each day of interest and each combination of means for the mass change of the mixtures. If a t-statistic was calculated to be greater than 0.05, there was no significant statistical difference between the two means of interest.

Table A-1 – Student t-testing results for mass change at days of interest

Day 7			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.0404	-	-
2% SRA	0.0838	0.0044	-
4% SRA	0.3660	0.2466	0.1647
Day 11			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.1732	-	-
2% SRA	0.9421	0.2396	-
4% SRA	0.4106	0.5525	0.4083
Day 14			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.4574	-	-
2% SRA	0.1342	0.1491	-
4% SRA	0.4609	0.5193	0.3789
Day 21			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.6043	-	-
2% SRA	0.2716	0.3015	-
4% SRA	0.5734	0.6720	0.4655
Day 35			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.9245	-	-
2% SRA	0.2339	0.2351	-
4% SRA	0.8563	0.8308	0.5485
Day 63			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.1823	-	-
2% SRA	0.1602	0.3543	-
4% SRA	0.7974	0.6137	0.4822
Day 91			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.3706	-	-
2% SRA	0.3057	0.4044	-
4% SRA	0.5100	0.8595	0.6498
Day 119			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.3027	-	-
2% SRA	0.2553	0.4393	-

4% SRA	0.5288	0.8433	0.6802
Day 147			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.3083	-	-
2% SRA	0.2781	0.5234	-
4% SRA	0.5604	0.6648	0.5594

Student t-testing was used to determine if there was a significant difference between the compressive strength of all five mixtures. Table A-2 reports the t-statistics for each day of interest and each combination of means for the compressive strength of the mixtures. If a t-statistic was calculated to be greater than 0.05, there was no significant statistical difference between the two means of interest.

Table A-2 – Student t-testing results for compressive strength at days of interest.

Day 3			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.0940	-	-
2% SRA	0.0050	0.0316	-
4% SRA	0.0004	0.0034	0.0192
Day 7			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.8760	-	-
2% SRA	0.0294	0.0652	-
4% SRA	0.0048	0.0143	0.0962
Day 28			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.7938	-	-
2% SRA	0.1562	0.1420	-
4% SRA	0.0002	0.0274	0.1138
Day 56			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.2720	-	-
2% SRA	0.1067	0.0928	-

4% SRA	0.0230	0.0583	0.1448

Student t-testing was used to determine if there was a significant difference between the electrical resistivity of all five mixtures. Table A-3 reports the t-statistics for each day of interest and each combination of means for the electrical resistivity of the mixtures. If a t-statistic was calculated to be greater than 0.05, there was no significant statistical difference between the two means of interest.

Table A-3 – Student t-testing results for electrical resistivity at days of interest.

Day 3			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.3252	-	-
2% SRA	0.1136	0.1361	-
4% SRA	0.0031	0.1321	0.7080
Day 7			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.2599	-	-
2% SRA	0.0073	0.0298	-
4% SRA	0.0414	0.0536	0.1584
Day 28			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.6868	-	-
2% SRA	0.1755	0.1407	-
4% SRA	0.0294	0.0275	0.0946
Day 56			
	No SRA	**1% SRA**	**2% SRA**
1% SRA	0.3279	-	-
2% SRA	0.0046	0.0820	-
4% SRA	0.0334	0.1537	0.6317

Appendix B

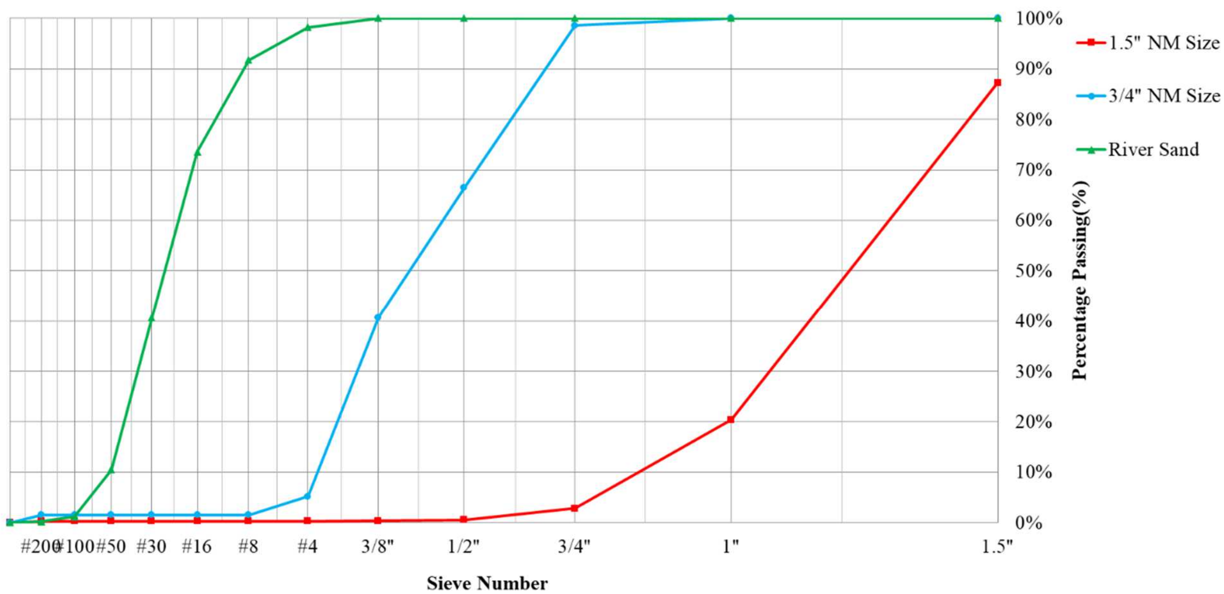

Figure B-1 - Percent Passing chart for all aggregates used.

Table B-1 – Student t-test results for compressive strength of mixtures.

	Day 7	Day 28
Mix	**Average**	**Average**
1	0.016	0.113
2	0.714	0.273
3	0.642	0.111
4	0.666	0.744
5	0.027	0.089
6	0.156	0.016

Table B-2 – Student t-test results for electrical resistivity of mixtures.

	Day 3	Day 7	Day 14	Day 28	Day 56
Mix	**Average**	**Average**	**Average**	**Average**	**Average**
1	0.626	0.430	0.980	0.307	0.140
2	0.610	0.310	0.104	0.080	0.299
3	0.219	0.168	0.176	0.709	0.188
4	0.064	0.056	0.416	0.092	0.230

5	0.336	0.673	0.046	0.030	0.169
6	0.136	N/A	0.256	0.044	N/A

Table B-3 – Student t-test results for mass change of mixtures

Day	**7**	**11**	**14**	**21**	**35**	**63**
	Average	**Average**	**Average**	**Average**	**Average**	**Average**
Mix 1	0.35	0.17	0.16	0.25	0.57	0.42
Mix 2	0.05	0.13	0.08	0.15	0.32	0.16
Mix 3	0.62	0.33	0.08	0.07	0.05	0.23
Mix 4	0.06	0.03	0.03	0.02	0.02	0.15
Mix 5	0.14	0.09	0.27	0.53	0.86	N/A
Mix 6	0.85	0.25	0.14	0.06	0.04	N/A

VITA

Erinn McArtor

Candidate for the Degree of

Master of Science

Thesis: REDUCING SHRINKAGE THROUGH ADMIXTURES AND AGGREGATE GRADATION

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2021.

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2019.