DURABILITY EVALUATION OF CONCRETE WITH HIGH-VOLUME RECYCLED MATERIALS

By

MOHAMMAD ZARE BANADKOKI

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Islamic Azad University

Karaj, Tehran

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DURABILITY EVALUATION OF CONCRETE WITH

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Thesis Approved:

Dr. Julie Ann Hartell

Thesis Adviser

Dr. Steven Cross

Dr. Yongwei Shan

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Abstract: This work aims to analyze the durability of concrete with high replacement percentages of virgin materials with recycled concrete as a coarse aggregate and class-C fly ash as a supplementary cementitious material. More specifically, frost resistance of the mixtures were investigated by performing cyclic freezing and thawing testing (ASTM C666) and salt scaling resistance following a method based on the BNQ NQ 2621-900 method. In addition, the electrical resistivity and rate of absorption of the mixtures were determined, along with their tensile and compressive strengths, to aid in the comparative analysis. A total of 19 mixtures containing different combinations of recycled concrete aggregate (0%, 25%, 50%, 75% and 100%) and Class-C fly ash (0%, 20%, 40%, 50%, 60%) were investigated. Results demonstrate promising use of the evaluated materials for concrete mixtures.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Concrete production yields a remarkable amount of natural non-renewable material and greenhouse gases every year. In order to minimize this problem, cement and aggregates need to be properly investigated as two important components of concrete. Recycled concrete, which is currently used widely as aggregate, could itself reduce a huge portion of construction waste. As a result, the demand for virgin aggregates could decrease significantly. On the other hand, replacing cement with supplementary cementitious material such as fly ash, zeolite and slag can use less cement in order to reduce greenhouse gas production.

Based on research from The Federal Highway Administration, 2 billion tons of new aggregates are produced annually in the US [1]. Experts anticipate the demand for new aggregate is going to increase exponentially by 2.5 to year 2020. With respect to this growing trend, experts worry that current resources of the aggregates will end and access to natural aggregates would be difficult. However, construction waste in the US will continue to grow. Construction demolition, on average, produces around 123 million tons of construction waste alone [1], in which 2/3 of its weight consists of concrete [2]. Currently, concrete waste accounts for the largest portion of the landfills. In order to deal with the growing demand for new aggregates and excessive waste production, experts in the US contemplate the feasibility of using concrete waste as aggregate in concrete production. There are many states in the US that have started to use recycled coarse aggregates in their construction process. In the US, 41 states have recognized the use of RCA in rip-rap, pipe bedding, consolidation of soil and even landscape material [1]. Among them, 38 states go a step further to use RCA as base aggregates in their pavement design systems. However, only 11 states have begun to use RCA in their concrete pavement construction.

Cement production is the most reactive component in concrete, creating a large amount of greenhouse gases. The cement production process alone accounts for about 4.5% of total greenhouse gases emissions [3]. The Word Business Council for Sustainable Development has stated, "to produce a pound of cement, 0.73 to 0.99 lbs. of CO_2 gases would be emitted into the atmosphere" [4]. Furthermore, they go on to anticipate that cement production will reach up to 4 million tons by 2040 [4]. One of the best solutions to produce less greenhouse gases is to replace a major part of cement with supplementary cementitious materials (SCMs). It should be noted that most current standards have limited the use of SCMs in concrete. According to Oklahoma's Department of Transportation (ODOT), it is estimated that 6,400 miles of highways need to be rehabilitated between 2015-2040, requiring a large volume of concrete to be made in order to meet their pavement demands. Using this new approach of creating concrete containing high percentages of fly ash (FA) class C and recycled concrete aggregates (RCA) could bring many benefits to the state of Oklahoma. Some of these benefits include lower greenhouse gas emissions, lower production of construction waste, preserving natural sources, and less taxpayer expenses for construction. The present research attempts to maximize the simultaneous use of RCA and class C fly ash in concrete, such that the resulting mix design could have the ability to meet serviceability requirements for both normal climates as well as severe climate conditions.

CHAPTER II

REVIEW OF LITERATURE

2.1 Introduction

Based on Oklahoma's Department of Transportation (ODOT) long-term transportation plan, 6,400 miles of the Oklahoma state's highways need to be rehabilitated [5]. By developing a coherent concrete pavement design, ODOT can minimize the carbon footprint of its highway systems, diminish the waste materials entering landfills, and preserve virgin material sources. Subsequently, this approach can provide economic benefits to ODOT as well as the taxpayers of Oklahoma. The use of high percentages of FA and RCA can greatly contribute to this goal.

RCA typically consists of two sections: original aggregates and the adhered cement paste. When RCA is used in concrete, two internal transition zones (ITZ) are formed within the concrete. The first ITZ is considered as the transition zone between original aggregate and its adhered mortar into the RCA and the second ITZ is between RCA and the new cement paste. Having two ITZs will have many impacts on the behavior of concrete that contains RCA, in both fresh or hardened mode [1,6]. Due to having high volumes of adhered cement paste, RCA has high water absorption, lower unit weight, and higher porosity than normal aggregates [6]. Due to breaking and crushing in their production, recycled coarse aggregate and recycled fine aggregate have higher angularity than the normal aggregates. This can cause some problems when RCA is used in concrete. By using RCA in concrete mix designs, researchers and experts could face many problems, such as: high porosity, unstable quality of product, sulfates, chloride, and other impurities, weaker transition zones between cement and aggregates, and cracks due to RCA's production process. In general, the properties of concrete containing RCA are highly dependent upon the source from which the RCA is coming. The new composition, mixing process, and RCA demolishing process are other important factors need to be taken into consideration.

Regarding fresh concrete, when the percentage of RCA increases, unit weight and workability of the concrete decrease [7,8]. The decrease in unit weight can be attributed to having higher percentages of cement paste in concrete containing RCA. The decrease in workability is related to higher angularity of RCA aggregates than the normal ones.

It should be noted that the presence of finer recycled aggregate could have more negative effects on concrete workability [7,9]. Hence, removing fine recycled aggregates from the mix design, can improve the workability of concrete greatly. Regarding hardened property, the results are different among researchers. Generally, using higher percentages of RCA can cause compression strength, splitting tensile strength, fracture energy, modulus of elasticity and rapture modulus to decrease, while shrinkage and creep will increase [6-14]. In recent research, it has been found that using RCA in percentages less than 50% can slightly change the mechanical properties of concrete compared to the control sample. The decrease in above mentioned properties could relate to having two transition zones when RCA is used. At the same time, the decrease in modulus of elasticity and the increase in creep and shrinkage can be attributed to the presence of more cement paste in mixes containing RCA.

Research done on fatigue of RCA concrete show variability and scattered data in this topic. Fatigue was evaluated in compression or RCA concrete mixtures, and it was reported that there is no significant change in fatigue performance in replacement of less than 20% while at higher replacement ranges, the increase of RCA caused fatigue performance to decrease [15].

Arora and Singh [16] investigated flexural fatigue and based on their results, the increase of RCA percentage led to decrease of fatigue performance; Sobhan [17] introduced comparable results to ordinary concrete. Regarding durability, the findings are different among researchers. Some researchers have found that with increase in the percentages of RCA, the freezing and thawing resistance of concrete will decline [8,18] while a group of them believe using RCA doesn't make significant difference [19-21]. Movaseghi [22] has reported that salt scaling resistance would increase when age of RCA source used in concrete increases, while Spear and Ben Othman [23] haven't observed a significant difference when age of RCA source used in concrete increases.

In the 1980s and 1990s, some states in the US used RCA in their pavement projects. The Federal Highway Administration investigated the long-term performances of those pavements in Connecticut, Minnesota, Wisconsin, Kansan and Wyoming [24]. According to the results, RCA pavements showed an acceptable overall performance compared to ordinary concrete [24]. However, RCA pavements having higher amount of cement paste indicated more cracks rather than normal concretes [24]. Based on the results of a number of cores taken from the pavements, it was indicated that compressive strength and tensile strength have not changed significantly, but modulus of elasticity decreased [24].

Supplementary cementations material (SCMs) has been used in concrete for a long time. Green gas emission and the loss of natural sources made through cement production process have caused researcher to make an effort to use SCMs in a large scale. Various researchers have found out that replacing high percentages of cement (up to 75%) with class C or F fly ash can increase the workability of concrete, while the hardened properties have shown reduction in their results [25-30]. The use of some additives such as gypsum and limestone can retrieve part of the mentioned decrease. Based on their results, mix designs containing high percentages of fly ash (higher than 50 percent) have shown comparable freezing and thawing resistance compared to normal concrete while salt scaling resistance of those mixes have experience a decrease in their values. Naik [30] investigated the long-term performance of concrete pavements containing high percentages of fly ash and it was reported that FA mixtures have relatively equal salt scaling resistance compared to natural aggregate mixtures.

There has been no research on the composition of high percentages of fly ash and recycled concrete aggregates on concrete mixtures. The purpose of the present research project is to test the properties of concrete aggregates with high percentages of fly ash and recycled concrete aggregates.

CHAPTER III

EXPERIMENTAL METHODOLOGY

3.1 Introduction

This research study investigated the effect of using fly ash and recycled concrete aggregates on concrete. The research team, consisting of Masters and Doctoral students as well as faculty from Oklahoma State University and the University of Oklahoma, was responsible for making two series of mix designs with different water-to-cement ratios. Additionally, these mix designs contained different percentages of class C fly ash and recycled concrete aggregate to meet strength and durability requirements of class (A) concrete. According to Oklahoma Department of Transportation special provisions for Portland cement concrete, the maximum of water-to-cement ratio for concrete Class (A) is 0.48 and the minimum of the 28-day compressive strength for concrete Class (A) is 3000 psi. This research was done in two phases. In the first phase, which started on May 15^{th} 2016, concrete mixes containing either natural or recycled concrete aggregates and concrete mixes containing either ordinary cement or fly ash were studied and compared to concrete mixes made of the combination of RCA and FA. Five different mix designs were investigated for the effect of RCA replacement on concrete. The first mix design was the control sample containing no fly ash and recycled concrete aggregates and the other four ones had 25%, 50%, 75% and 100% RCA replacement. The second set of mix designs contained natural aggregates and 20%, 40% and 60% of fly ash. The combination effect of FA and RCA was investigated by adding 40%, 50% and 60% of fly ash to concrete mixes with 100% of RCA replacement.

RCA material came from Metro Materials, a sand & gravel supplier in Norman, Oklahoma while the fine and coarse aggregates were provided from Dolese Bros, a ready mix concrete supplier in Oklahoma. The cement used was ASTM C 150 [31] type I/II (Low Alkali) and the fly ash was ASTM C 618 [32] Class C. The specific gravity and absorption of recycled concrete aggregates and natural aggregate were measured in accordance to ASTM C 127 [33]; the result are shown in Table 1. The chemical analysis and physical properties of the cement and the fly ash is represented in Table 2.

Table 1: Properties of the aggregates

	Absorption (%)	Specific gravity
Fine aggregate	0.7	2.51
Fine RCA	6.48	1.932
Coarse aggregate	0.86	2.67
Coarse RCA	4.47	2.01

Table 2: Physical properties and chemical composition of cement and fly ash

	Cement	Fly ash
SiO_2 (wt%)	20.76	31.86
Al_2O_3 (wt%)	3.77	20.44
Fe_2O_3 (wt%)	2.95	5.86
SO_3 (wt%)	2.92	2.96
CaO (wt%)	63.89	2.96
MgO (wt%)	1.87	28.31
Na_2O (Wt%)	0.19	7.21
Specific gravity	3.11	2.72

Based on sieve analysis results, RCA supply consists of 26% fine RCA and 74% coarse RCA. Figure 1 represents the sieve analysis results for the coarse aggregates used in this research. The mixture proportion is presented in Table 3 (values are in terms of cubic yard). All mixtures had a water/cementitious materials ratio of 0.48.

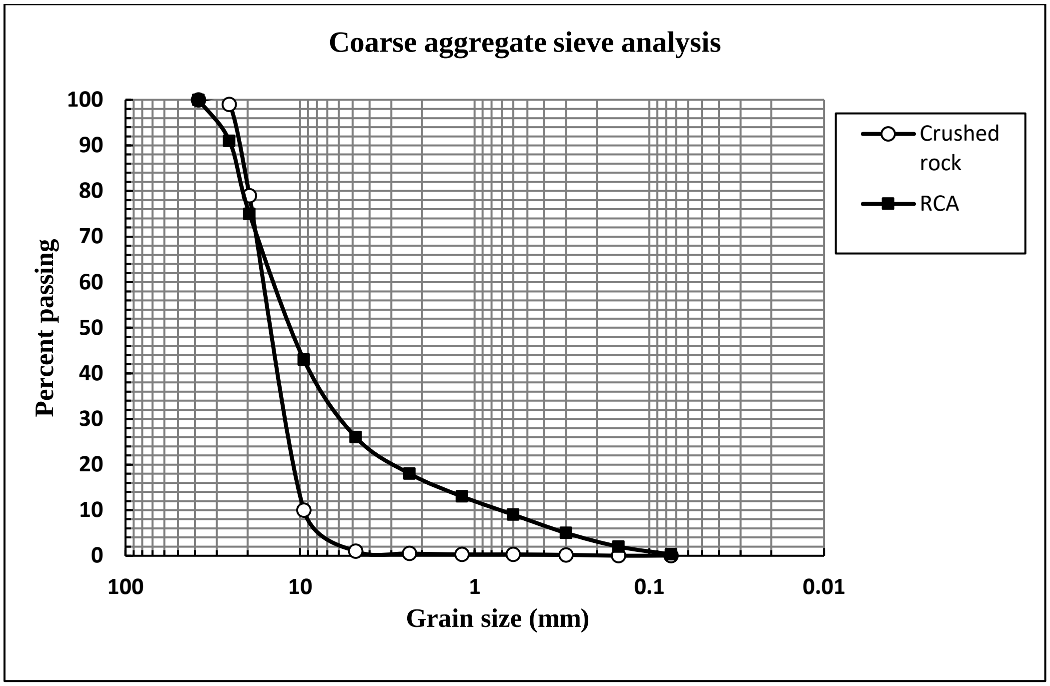

Figure 1: Sieve analysis of coarse aggregate

Table 3. Mix proportions in

	Cement (lb)	Fly Ash (lb)	CA (lb)	FA (lb)	RCA (lb)	Water (lb)	MB AE 90 (oz)
OPC 0RCA 0FA	517	0	1880	1177	0	243.7	11
OPC 25RCA 0FA	517	0	1410	1030	466	243.7	1
OPC 50RCA 0FA	517	0	940	883	933	243.7	1
OPC 75RCA 0FA	517	0	469	735	1399	243.7	1
OPC 100RCA 0FA	517	0	0	588	1865	243.7	1
OPC 0RCA 20FA	414	103	1880	1177	0	243.7	1
OPC 0RCA 40FA	310	207	1880	1177	0	243.7	1
OPC 0RCA 60FA	207	310	1880	1177	0	243.7	1
OPC 100RCA 40FA	310	207	0	588.6	1816.08	297	0.6
OPC 100RCA 50FA	258.5	258.5	0	588.6	1816.08	297	0.6
OPC 100RCA 60FA	207	310	0	588.6	1816.08	297	0.6

3.2 Mixing procedure:

One day before mixing, samples were taken from natural and recycled aggregates for moisture correction and the concrete was mixed in Fears lab, located at University of Oklahoma. First, the natural and recycled aggregates were wet blended for three minutes. Cement and or fly ash plus water were then added and blended for another three minutes followed by two minutes of rest. Afterward, the combination was blended again for the final three minutes and the total time of mixing was 8 minutes. All mixtures were cast and consolidated in accordance with ASTM C 192 [34].

Table 4 presents the properties of the fresh concrete measured by the Air Content (ASTM C231) [35], Unit Weight (ASTM C138) [36] and the Slump test (ASTM C143) [37].

Table 4: Properties of the fresh concrete

	Slump (inch)	Unit weight (lb/ft^3)	Air content (%)
OPC 0RCA 0FA	4.25	146.4	6.6
OPC 25RCA 0FA	7.5	143.2	4.1
OPC 50RCA 0FA	5	143.2	4.2
OPC 75RCA 0FA	2	143.2	3.6
OPC 100RCA 0FA	0.25	140.8	2.9
OPC 0RCA 20FA	1.75	148.8	4.6
OPC 0RCA 40FA	2.5	147.2	5
OPC 0RCA 60FA	3.5	146.4	6
OPC 100RCA 40FA	4.5	141.1	3.1
OPC 100RCA 50FA	4.25	141.5	2.9
OPC 100RCA 60FA	5.75	140.8	2.4

3.3 Samples preparation and casting

3.3.1 Cylindrical samples

For each mix design, fifteen 4”x8” cylinders were made for Sorptivity test (ASTM C1585-13) [38], compressive strength (ASTM C39) [39], splitting tension (ASTM C496) [40] and electrical resistivity (AASHTO TP95) [41]. All cylinder specimens were filled in three layers of concrete followed by 25 times of rodding for each layer. In order to provide consolidation, all samples were pounded by hand until there were no air bubbles left to come to the surface. After the completion of the casting, samples were kept under a damp canvas for 24 hours. The next day, concrete cylinders were transferred to Bert Cooper Lab at Oklahoma State University.

3.3.2 Salt scaling slabs

Based on modified BNQ NQ 2621-900 [42] method, two slabs measuring 200mm × 300mm were cast for each mix design in wooden molds. Two days prior to casting, the wooden molds were oiled lightly. Concrete was placed within the wooden forms in one layer and rodded every two inches so that the thickness of the slab was 90 mm. Afterward, the sides of the wooden molds were tapped with a rubber hammer to better consolidate the mixture. The surface of the concrete slabs was screed off with a soft wooden trowel so that the trowel was moistened properly in order to minimize the possibility of water absorption of the trowel. After bleeding appeared on the surface of the slab, samples were kept under a damp canvas and a plastic sheet in order to minimize the evaporation of the specimens, for a total of 24 hours.

3.3.3 Freezing and thawing slabs

Based on ASTM C 666/C 666M [43], Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, two beam specimens were cast in metal molds. One day prior to casting, the metal molds were lightly oiled, taking care to remove the excess oil from the internal surface of the molds. Each specimen was made with two layers of concrete. Each layer poured was followed by 25 rough taps and tamping the sides for better consolidation. Next, the excess concrete on the surface of the samples was removed and finished using a smooth metal trowel.

All freezing and thawing prisms were made at the civil engineering laboratory of the University of Oklahoma. After 24 hours of being covered by plastic sheets, all specimens were transferred to Oklahoma State University for demolding and preparation of the test.

3.4 Curing Methods:

3.4.1 Cylindrical samples curing method

The cylinders were cured for 28 days in a water tank in the curing room under a controlled condition. The temperature was always 73 °F, while the relative humidity was 100%.

The additional curing condition necessary for the Sorptivity test is as follows. The cylinders were cut form the top 50mm, and then rinsed. Based on ASTM C1585-13, samples were placed in a wrapped desiccator and then were moved to a chamber with a temperature of 50 ± 2v °C. A solution of 80.2 g/100 water of a potassium bromide was used to control the relative humidity at 80 ± 3 %. After 3 days of curing in the chamber, all specimens were sealed with paraffin, and were kept inside a sealable container for another 15 days at temperature of 23 ± 2°C.

3.4.2 Salt scaling slab's curing method

After 24 hours, all slabs were demolded from the wooden forms shown in Figure 7 and then were moist cured for 14 days with a relative humidity of 100% at 25 °C. This curing regime was followed by another 14 days of curing in drying room at 50% relative humidity. After the 28 days of curing and prior to running the respective tests, all concrete slabs were placed in foam dikes so that all edges were insolated and then the specimens were conditioned with 5 mm of saline solution (3% NaCl) for 7 days.

3.4.3 Freezing and thawing beam's curing method

All test specimens were stored in saturated limewater for 14 days while the relative humidity of the fog room was 100% and the temperature was 25 °C.

3.5 Test methods

3.5.1 Compressive strength

After 28 days of curing, based on ASTM C39/39M, the compressive strength test was administered to three concrete cylinders per mix. Both end sides of concrete cylinders were grinded to maximize the distribution of the load. Before the test, surface water on samples were removed to provide SSD condition. The compression machine shown in Figure 2, applies load at the rate of 35 ± 7 psi/s. After breaking the concrete cylinders, the peak loads were recorded and the average of the values are shown in Graphs 1, 2, and 3. The compressive strength of cylindrical specimen can be calculated form Equation 1:

$$\mathrm{C} = \frac{P}{A}$$

Where:

C = compressive strength

P = maximum load carried by specimen

A = average cross section area

Figure 2: Loading machine for compressive strength test

3.5.2 Splitting tensile test

Splitting tensile strength of cylindrical concrete specimens is obtained by applying a diametrical compressive load on the longitudinal axis of cylindrical concrete samples until failure occurs. The rate of loading must be in the range 0.7 to 1.4 MPa/min. In order to have a better load distribution along the length of samples, thin plywood bearing strips were placed between the loading plate and both side of cylindrical samples. Figure 3 shows the loading machine used for tensile strength test. The magnitude of the splitting tensile strength can be calculated from Equation 2:

$$T = \frac{2\mathrm{P}}{\pi \mathrm{Ld}}$$

Where:

T = splitting tensile strength

P = maximum applied load indicated by the testing machine

L = length in mm

d = diameter of the sample.

Figure 3: Splitting loading machine

Graphs 4, 5, and 6 present the results for splitting tensile strength test. The final reported numbers are the result of averaging the results from breaking three samples.

3.5.3 Electrical resistivity test

Electrical resistivity of concrete can be explained as the resistance of concrete against ions transfer while it is subjected to an electrical field. Electrical resistivity is a ratio between the applying voltage and the output flow so that resistivity is independent of sample geometry [44]. Concrete resistivity varies in a range of 10^6 Ωm for oven-dried samples to 10 Ωm for the saturated ones [45]. Electrical resistivity of concrete is attributed to the microstructure characteristics such as porosity, pore solution properties, the amount of moisture present in pore structure [46, 47, 48] and the temperature of the sample [49]. The rapid chloride permeability test used to be employed to measure electrical resistivity of concrete. In this method, a constant voltage is applied to the concrete sample and the electrical current passed from the sample is measured in saturated condition. However, this method has limitations. For example, it is destructive. Additionally, the process results in heat production, which can cause variation in results. Currently, researchers attempted to discover a new method of testing electrical resistivity without these limitations. With the development of this new method, testing electrical resistivity has become more rapid, cost-effective, and able to perform large-scale testing [50, 51, 52]. In the present study, the electrical resistance of concrete was measured by two techniques including four point (Wenner probe) and two-point uniaxial method.

3.5.3.1 Surface electrical resistivity test

In four point (Wenner probe) method, the surface electrical resistivity of concrete samples were measured. Each sample was divided by four, for surface area, and then is marked. As such, every time the test is performed on the same spots and, as a result, it provides a reasonable trend for following the results. Once the samples are marked, they were placed on a solid support, ensuring stability while performing the measurements. The surface resistivity was measured by placing the Wenner probe vertically on the surface of the concrete samples and then pushing it for a second so that the screen shows the related number. This device consists of four electrodes in which the exterior probes are generating an alternative current while the inner probes assess the electrical potential. It is important to note that being samples in SSD condition is the vital parameter needs to be taken into consideration. This test was done in the drying room in a relative humidity of 50%. In this research, Resipod Proceq probe was used. The Resipod Proseq is capable of giving the electrical surface resistivity directly in terms of K-ohm-cm.

Figure 4: Surface electrical resistivity test

3.5.3.2 Bulk electrical resistivity test

In uniaxial technique, the concrete sample is set between two metal parallel electrodes covered by a clammy sponge to guarantee an appropriate electrical contact. The plates were connected to an alternative current source. By turning the battery on, an alternative current, (AC) was applied to the concrete and then the drop in the potential was measured in between the two plates. This method is highly dependent on the moisture content of the sponge. Therefore, the sponge must be kept completely wet. The application of this test takes only a few seconds and due to its non-destructive characteristics, this test can be performed on the same cylindrical samples prepared for other tests. The device used for this experiment is called GIATEC RCON2™.

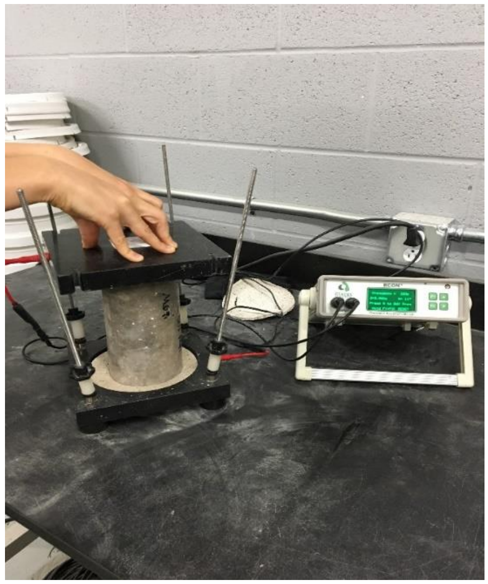

Figure 5: Bulk electrical resistivity test

3.5.4 Sorptivity

The rate of absorption of water in concrete specimens can be measured by the Sorptivity test. Sorptivity is one of the most important properties of concrete attributed to its durability [53, 54, 55]. Based on McCarter research [56], minimizing the Sorptivity can result in decrease of the penetration of water containing chloride and sulfate agents into concrete.

In the Sorptivity test, only one surface of concrete specimen is exposed to water and with the passing of time, the increase of mass is assessed which occurs due to capillary suction. After finishing the curing process, the samples are removed from the storage container and their mass and diameter were recorded. Afterward, the side surface and end surface of each sample was sealed by paraffin as the sealing material and they were weighed to the nearest 0.01 g. This measurement was considered the initial mass for the experiment. Next, two pieces of wood strip (support device) were placed at the bottom of a container and then the containers were filled with water so that approximately 3 mm of water was at the top of the wood strips as shown in Figure 6. Since this test is a function of time, a timer was used for the whole process of the test. When we started the test, the samples were immediately placed on the support device and their mass was recorded at a specific timeline introduced by ASTM C1585. For each mass determination, the samples were removed from the container and water surface was blotted off by a dampened towel. Equation 3 is used for calculation of Sorptivity:

$$I = \frac{m_t}{a * d}$$

Where:

I = the absorption

m_t = the change in mass of samples in grams, at the time t

a = the area of the sample exposed to water in mm^2

d = the density of water in g/mm^3.

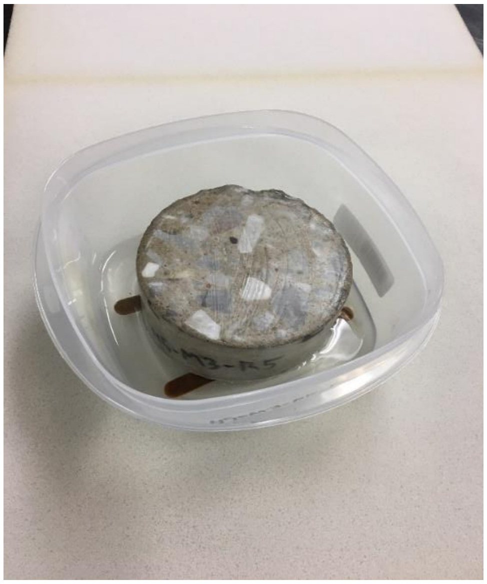

Figure 6: Sample preparation for Sorptivity test

3.5.5 Salt scaling

In wintertime, de-icer salt is commonly used in order for removal of the snow from the surface of the road and highways. This can cause concrete scaling. Unfortunately, the repair and replacement process of concrete pavements damaged in scaling cost highway agencies a lot of money. Salt scaling is defined as superficial damage caused by freezing and thawing a saline solution on the surface of a concrete specimen [57]. This results in progressive damage through the removal of small chips or flakes from the concrete surface [57,58]. There are many different parameters that can affect the rate and degree of scaling. This includes water-to-cement ratio, curing, maturity, air entrainment, finishing, and type and concentration of saline solution.

Yet, various scaling test methods have been developed around the world such as ASTM C672 [59] test method in North America, The RILEM TC 117-FDC/CDF [60] test method in Germany, Borᾰs test method known as standard SS 13 72 44 [61] used in Sweden, MTO LS-412 [62] test method in Ontario, and BNQ NQ 2621-900 test method developed in Quebec. It has been recommended that in the case of using supplementary cementitious materials in concrete, ASTM C672 could not be reliable, and as such this test cannot accurately simulate the field condition. Therefore, the present research, ASTM WK 9367, which is known as modified BNQ test, was implemented for the evaluation of concrete mixtures salt scaling resistance.

The proposed ASTM WK 9367 procedure requires 50 rounds of a 24-hour of freezing and thawing cycle, where each cycle consists of 16 ± 1 h of freezing followed by 8 ± 1h of thawing. During the test procedures, the surface of the slabs were covered by plastic sheet to prevent evaporation. After each five cycles the mass loss of the specimens were recorded while the surface of the specimens were rinsed and filled with new saline solution to continue the test. In order for measuring the mass loss of the specimens, a 80µm filter was used which was placed in the oven prior to weight measurements. After 50 cycles, the cumulative mass loss of each specimen is measured and an average mass loss of 0.5 kg/m^2 is the passing limit. Figure 7 shows the salt scaling sample before demolding, and Figure 8 represents using a foam frame for isolating the edges of the sample.

Figure 7: Salt scaling specimen before demolding

Figure 8: Using foam frame for isolating the edges

3.5.6 Freezing and thawing

In cold weathers, while the temperature drops, water existing in capillary pores of saturated concrete elements can freeze and cause expansion of concrete (approximately 9%). If this process is followed by successive thawing and refreezing cycles, cumulative damage occurs as the result of the repeated cycles. In each cycle, water can penetrate places, like cracks, and when it freezes, enlarge the dimension of the cracks. The severity of the damage could range from superficial to complete disintegration of the concrete structure. Road slabs located in cold regions are vulnerable to this issue, hence, precautions need to be taken into consideration prior to paving roads in order to minimize the probable rehabilitation expenses in the future. Oklahoma is susceptible to cold climates during winter. In the winter months between November and February, the temperatures sometimes reach below 0 °C, and there is always possibility of freezing and thawing for concrete pavements. Considering that Oklahoma is considered an F1 in exposure classification (meaning Moderate Freezing and Thawing), 7 different mix designs in addition to the control sample were cast, and their resistance to freezing and thawing was evaluated.

Immediately after the curing period, the specimens were brought to a cold-water chamber, which was set to mimic the target thaw temperature (-2 °F and +4 °F) of the freeze-thaw cycle and afterward the fundamental transverse frequency and the initial mass were determined.

The relative dynamic modulus of elasticity is obtained from Equation 4:

$$P_c = \left({n_1}^2 / n^2 \right) \times 100$$

Where:

P_c= relative dynamic modulus of elasticity, after c cycles of freezing and thawing, percent

n = fundamental transverse frequency at 0 cycles of freezing and thawing

n_1= fundamental transverse frequency after c cycles o freezing and thawing

The durability factor of each specimen is calculated from Equation 5:

$$\text{DF} = {}^{PN}/_{M}$$

Where:

DF = durability factor of the test specimen

P = relative dynamic modulus of elasticity at N cycles, %

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be determined, whichever is less, and

M = specified number of cycles at which the exposure is to be determined

Figure 9 shows the freezing and thawing chamber used for this test. This apparatus consists of sixteen connected aluminum containers in which concrete samples can be exposure to freezing and thawing cycles. The chamber has been calibrated so that every freezing and thawing cycle takes approximately 252 minutes to be accomplished. In every cycle, the chamber alternately lowers the temperature from 40 °F to 0 °F and then heightens the temperature from 0 °F to 40°F. Based on ASTM C 666/C 666M, the specimens must be removed from the chamber at intervals not exceeding 36 cycles. By the end of the last cycle, the chamber is turned off and samples were removed out of the containers for transverse frequency and mass measurements.

Figure 9: Freezing and thawing chamber

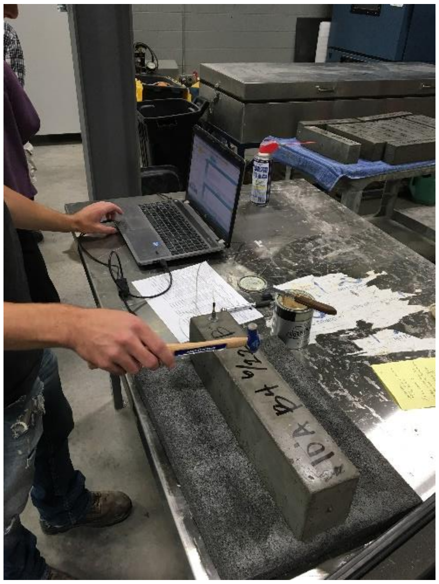

Figure 10: Transverse frequency measurements

3.5.7 Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) is categorized as a non-destructive testing method. Because it is quick, direct, inexpensive, reliable, and non-invasive, UPV provide a great opportunity of investigation into damaged concrete structure [63,64,65]. When an ultrasonic pulse is traveling through a concrete element, the density and elastic properties of the concrete would have an impact on the velocity of the pulse. Many researchers believe that UPV test can be used as a means of evaluating the overall quality of the concrete element [66]. Based on transducers set up, UPV test can be conducted by direct transmission, semi-direct transmission and indirect transmission. As direct formation in the most sensitive among all, this set up was used for UPV evaluation. The 4’’× 8’’ cylinders already made and cured for compressive strength test was used for this non-destructive test. UPV device consists of two sensors connected to a control box equipped by a pulse generator and a digital screen shown in Figure 11. In order to provide a better connection between sample and sensors (transducer and receiver), a liquid gel was applied as a layer between them. The transducer sends a pulse with a frequency of 54 kHz throughout the concrete sample and the digital display shows the wave travel time between the sensors with a known distance. The velocity of the wave can be measured using Equation 6:

$$\nu = \frac{L}{t}$$

Where:

ν = speed of the pulse

L = length of the specimen between two sensors

t = travel time of the wave

Figure 11: Proceq ultra-sonic instrument used for measurements

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction

As it was stated before, in the first phase of this study, 10 different mix designs plus the control sample were made to test FA's and RCA's ability to improve the mechanical and durability properties of concrete. In order to better understand the independent effects of RCA and FA on concrete, the diagrams are depicted in the following manner. In the section for each test, there are three diagrams or graphs. The first diagram shows the lone impacts of RCA, the second diagram shows the lone impacts of FA, and the third diagrams shows the concurrent impacts of RCA and FA. Two phases of research were completed in the present study. Phase I of the research included the compressive strength test, splitting tensile test, resistivity test, and sorptivity. Phase II of the research included the compressive strength test, splitting tensile test, ultrasonic pulse velocity test, salt scaling durability test, and freeze-thaw test.

4.2 Fresh concrete properties

As can be seen in Table 4 (Section 3.1), by adding RCA, the slump value decreases compared to the control sample. Due to having adhered cement paste, RCA is more porous than the natural aggregate and has this ability to absorb more water in the mixture. Moreover, angularity of the angularity of the RCA will emphasis this issue as well. On the other hand, adding fly ash increases the workability of concrete [67]. Due to its finer structure compared to cement, using fly ash will increase the thinness in concrete mixture, which will lead to having a more workable concrete compared to ordinary concrete. As shown in Table 4, slump values in mixes containing FA were less than those of the control sample due to their lower water demand. In order to have higher slumps, using superplasticizer is recommended.

4.3 Compressive Strength

The present study found that the use of RCA improves the compression strength of concrete (see Figure 12). The use of 25%, 50%, and 75% RCA did not significantly change compression strength of the concrete when compared with the control sample. However, the compression strength increased by 25% when using 100% RCA, while the water to cement ratio and the mount of cement was equal. The results obtained in this study are contradictory to the results of the Xuping Li study. [68] In 2011, Butler et al [69] reported that the compressive strength of RCA concrete is higher than conventional concrete while in 2012, Xiao et al [70] found that the compressive strength of recycled concrete is generally lower than the ordinary concrete. This reduction could be attributed to having more porosity and weak aggregate bond to the matrix.

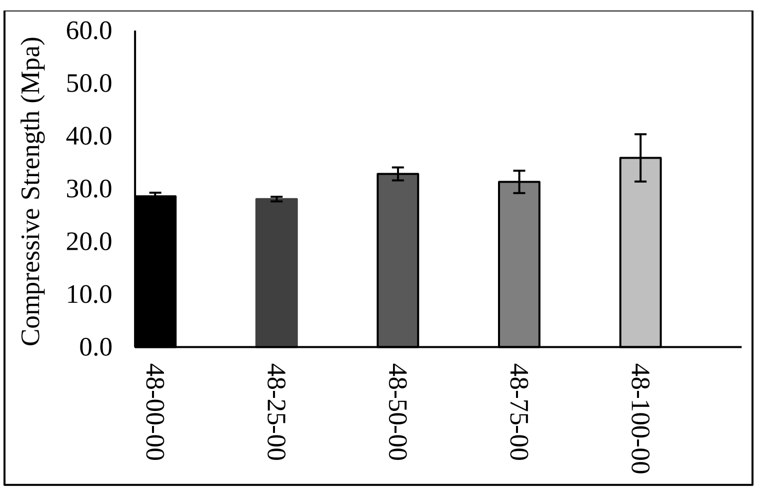

Figure 12: Compressive strength for samples containing varying levels of RCA

All tests using varying levels of FA showed an increase in compression strength for the concrete samples (see Figure 13). When using 20% FA, compression strength increased by 23% as compared to the control sample. When using 40% FA, compression strength increased by 42% as compared to the control sample. However, when using 60% FA, compression strength increased by 10% as compared to the control sample. Thus, to go above 40% FA decreases the ability of the material to affect improvement of compression strength. Therefore, the present study showed that 40% is the optimal value for using FA in concrete. As previous researchers have reported, fly ash increases the later-ages compressive strength of concrete which is approved by the findings of this research [71,72,73].

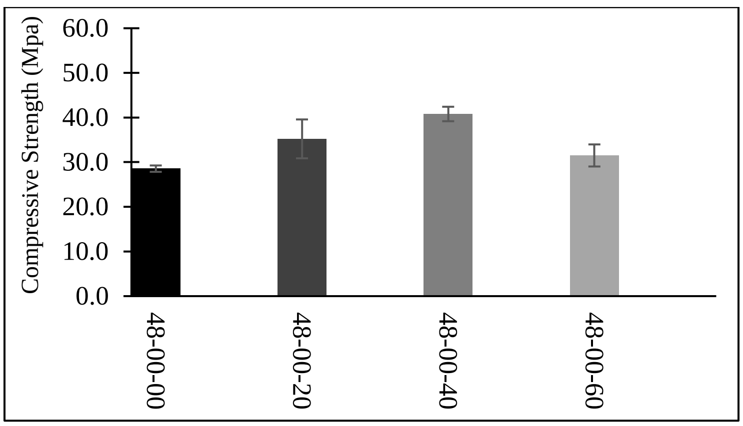

Figure 13: Compressive strength for samples containing varying levels of FA

When combining levels of FA paired with 100% RCA, no significant changes are seen in the compression strength of the sample (see Figure 14). There are only minor and insignificant increases in compression strength when using 40% and 50% FA paired with 100% RCA, and in fact, using 60% FA with 100% RCA decreases the compression strength by approximately 20% when compared to the control sample.

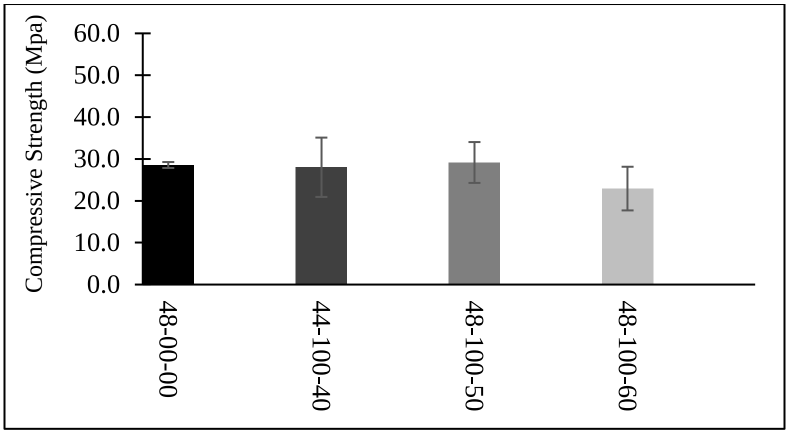

Figure 14: Compressive strength for samples containing a combination of varying levels of FA and 100% RCA

The use of RCA has improved the compressive and splitting tensile strength; while in general, the use of RCA leads to decreases in the mechanical properties of concrete. The effect of RCA on concrete is highly dependent to the original concrete quality and the mix proportion. As shown, the microstructure properties of the interfacial transition zone between RCA and cement can affect concrete strength [74, 75]. For this study, the obtained results are not comparable to that of other researchers' [76, 77, 78], thus the quality of the RCA material may have been a contributing factor.

4.4 Splitting Tensile Strength

All RCA mixtures showed an increase of some kind in the splitting tensile strength of concrete (see Figure 15). The 25% of RCA increased splitting tensile strength by 9%, the 50% of RCA increased splitting tensile strength by 18%, the 75% of RCA increased the splitting tensile strength by 0%, and the 100% of RCA increased the splitting tensile strength by 6%, all as compared to the control sample. Therefore, the 50% of RCA resulted in the highest splitting tensile strength.

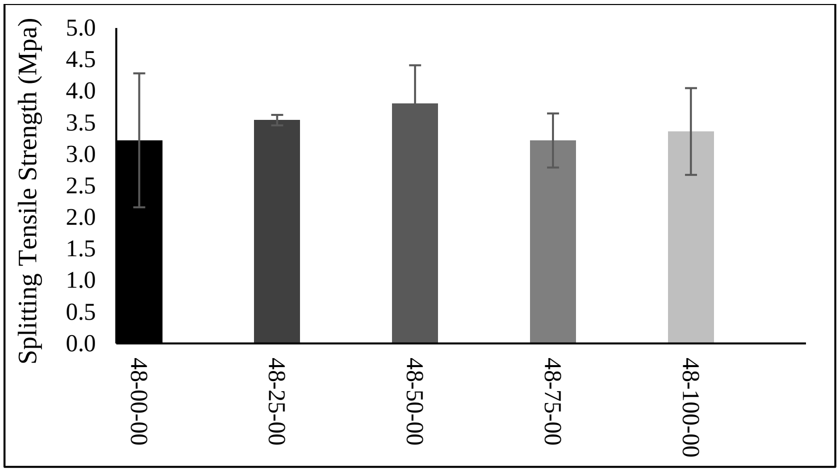

Figure 15: Splitting tensile strength test for samples containing varying levels of RCA

When analyzing the data for splitting tensile strength, the 20% FA did not have an impact (see Figure 16). However, similar to the compression test, the 40% FA resulted in the most significant increase in splitting tensile strength at 34.4% increase, compared to the control sample. While the 60% FA had a 9% increase in strength, which was still lower than the 34.4% increase seen with 40% FA. This further supports the idea that 40% FA is the optimum value to be used in concrete. These results are supported by previous literature, which was attributed to the high absorption of adhered mortar in RCA and the effectiveness of the new formed ITZ. [79]

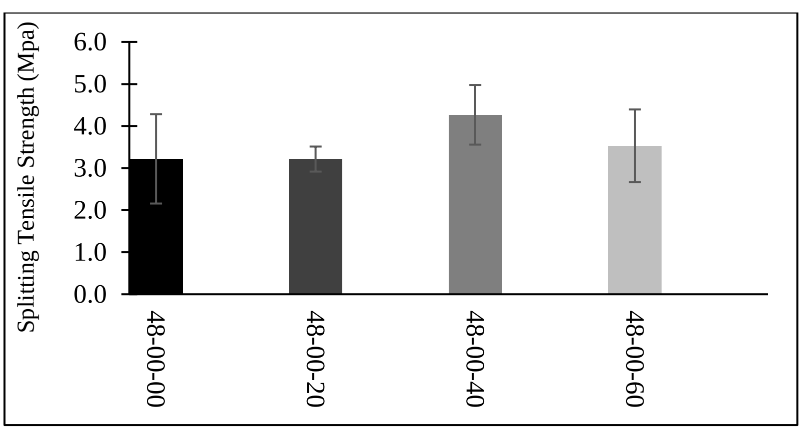

Figure 16: Splitting tensile strength test for samples containing varying levels of FA

When 100% RCA is paired with different percentages of FA, no significant changes were observed (Figure 17). Though the compression test value decreased when combining 100% RCA and 60% FA, that sample did not change significantly in the splitting tensile test.

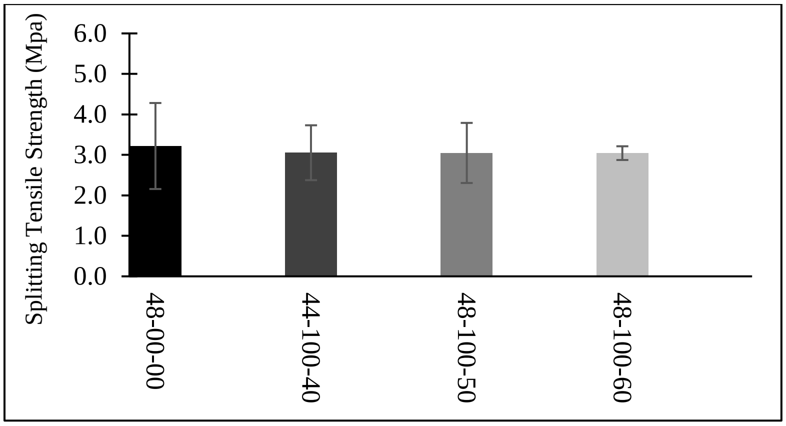

Figure 17: Splitting tensile strength for samples containing a combination of varying levels of FA and 100% RCA

As previously reported, fly ash replacement is known to decrease the mechanical properties of concrete in the early ages due to weak bonding of fly ash particles to cement matrix [80,82]. However, as evident in the results of this study, after 28 days all mixtures containing fly ash gained greater compressive and tensile strength, compared to the control sample. The increase in compressive strength could be attributed to the pozzolanic reaction and the filler effect of fly ash, which gives the cement matrix a denser microstructure and a higher compressive strength gain.

It should be noted that fly ash has variable chemical and physical properties depending on the source and that could be a reason for the variability of what we have found compared to general knowledge about fly ash effect on concrete. Moreover, another reason for the better results obtained in this study could be due to a good compatibility between dosage of cement, fly ash, RCA and admixtures.

4.5 Surface Electrical Resistivity

Surface electrical resistivity decreased when using all percentages of RCA (see Figure 18). There was no significant difference between 25% RCA and 50% RCA, both decreasing by 29%. However, 75% RCA and 100% RCA both decreased more to 37.5% and 42%, respectively. Therefore, there may be more decrease in surface electrical resistivity with an increase in percentage of RCA.

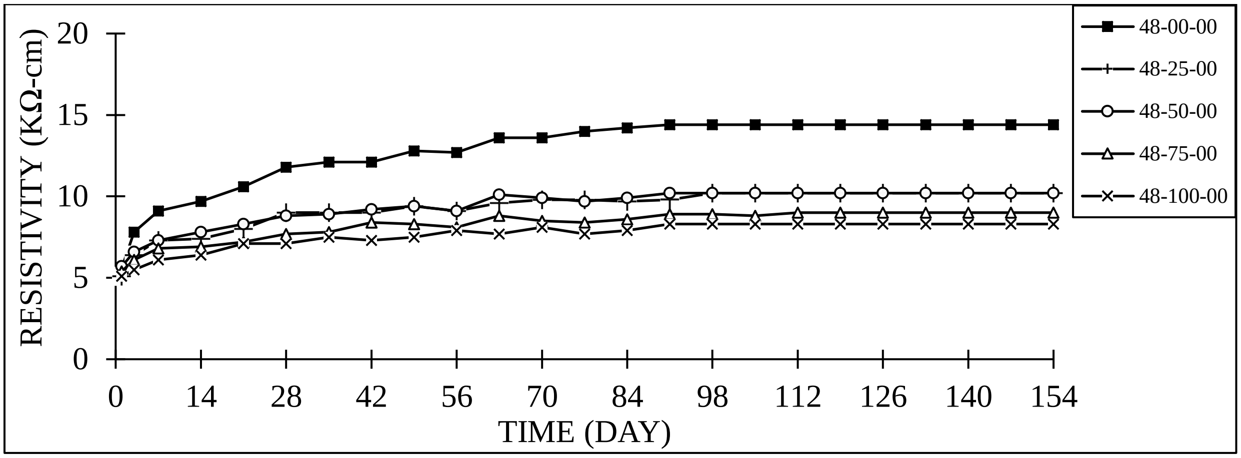

Figure 18: Surface electrical resistivity for samples containing varying levels of RCA

Electrical resistivity is investigated at two stages when using FA (see Figure 19). In early ages (0-14 days), the more percentage of FA that is used, the values for electrical resistivity are lower. However, that trend is not confirmed in the late ages (14+ days). When analyzing the data after 154 days, 20% FA resulted in 91% increase in electrical resistivity, 40% FA resulted in 270% increase in electrical resistivity, and 60% FA resulted in 200% increase in electrical resistivity. 40% FA shows higher values of electrical resistivity than 60%, which confirms the aforementioned idea that 40% is the optimum percentage of usage of FA.

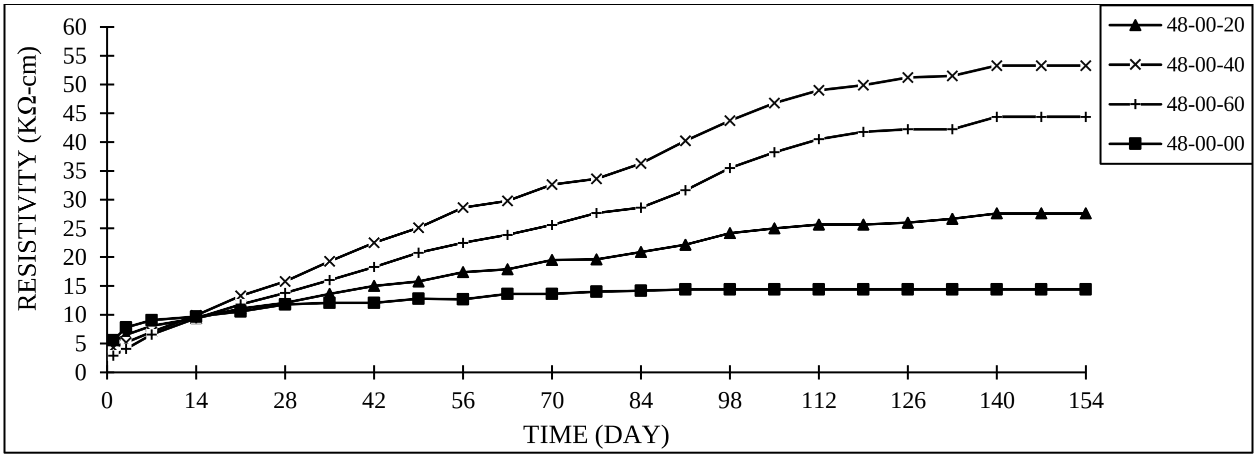

Figure 19: Surface electrical resistivity for samples containing varying levels of FA

As shown in Figure 20, all combinations of 100% RCA and different percentages of FA decrease the electrical resistivity compared to the control sample within the early ages (0-14 days). In the late ages (14+ days), all combinations increased the electrical resistivity. Using 100% RCA with 40% FA showed a 19.4% increase in electrical resistivity compared to the control group. Using 100% RCA with 50% FA showed a 44.4% increase in electrical resistivity compared to the control group. Using 100% RCA with 60% FA showed a 13% increase in electrical resistivity compared to the control group. According to the present findings, 100% RCA combined with 50% FA yield the highest increase in electrical resistivity.

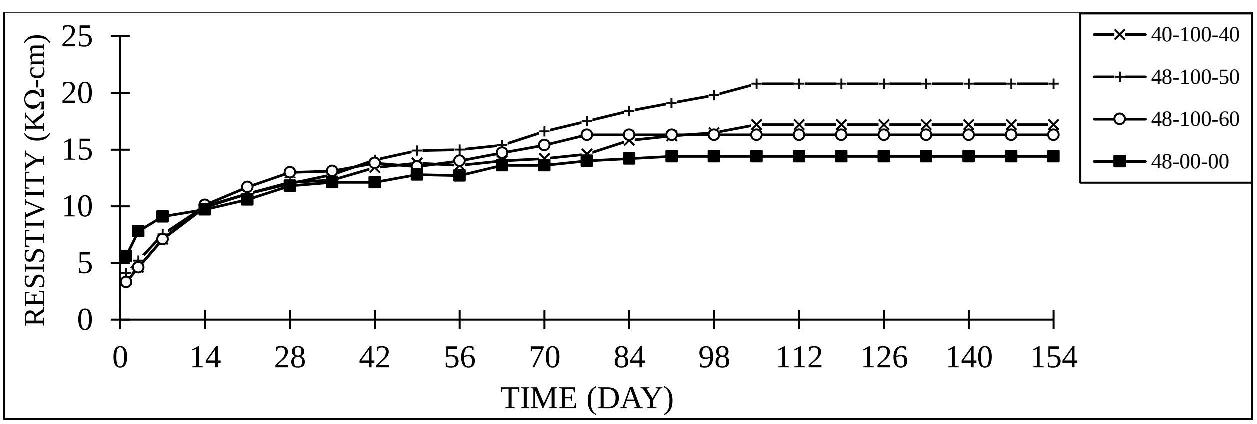

Figure 20: Surface electrical resistivity for samples containing a combination of varying levels of FA and 100% RCA

According to on AASHTO TP95, researchers can use electrical resistivity to measure concrete's resistance to chloride penetration. Furthermore, electrical resistivity can be used to evaluate ionic mobility within the pore solution of concrete, which is a leading factor of corrosion. Table 5 shows the chloride penetrability levels in terms of electrical resistivity. For mixtures evaluated containing FA, they would be classified as moderate resistance to chloride ion penetrability which is superior to mixtures containing no supplementary cementitious materials. The latter mixtures would be classified as highly susceptible to chloride ion penetrability. The addition of class-C FA to mixtures containing 100% RCA does provide long-term potential for resistivity gain. After 56 days, these mixtures surpass the control reaching moderate classification.

Table 5: Chloride penetrability based on AASHTO TP 95

Chloride ion penetrability	AASHTO TP 95 (KΩ.cm)
High	< 12
Moderate	12 to 21
Low	21 to 37
Very Low	37 to 254
Negligible	> 254

4.6 Bulk Electrical Resistivity

Figure 21 shows the results of the bulk electrical resistivity for samples with varying values of RCA. The samples were quick to rise in value during the early days (0-14 days). The results for the late days follow the same trend developed early on, with the control sample having the highest resistivity values. The samples decrease roughly in order, with the 50% RCA sample being the next highest after the control (yet still notably less), then the 25% RCA sample, and then the 75% RCA sample. Finally, the 100% RCA sample reports the lowest values in resistivity.

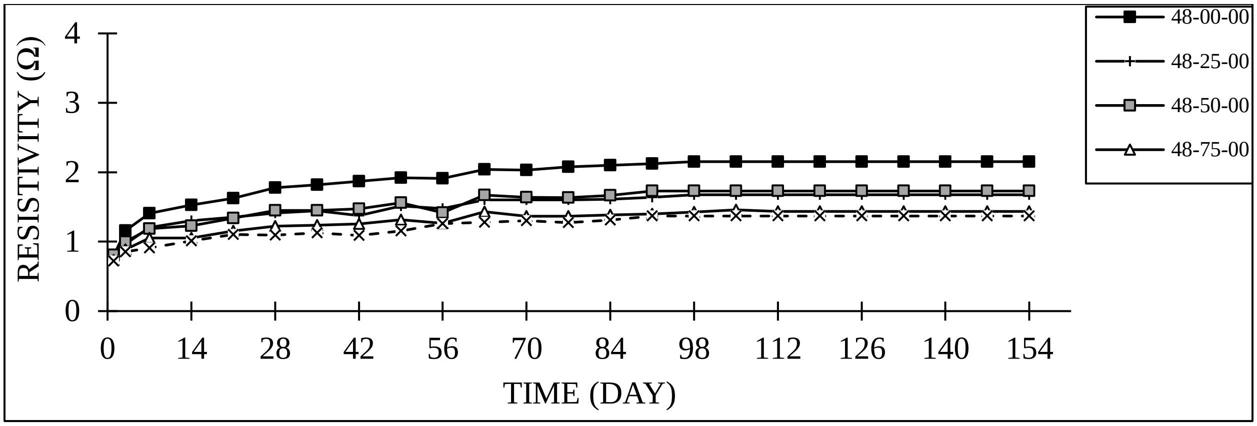

Figure 21: Bulk electrical resistivity for samples with varying levels of RCA.

The results for bulk electrical resistivity for samples with varying levels of FA can be found in Figure 22 below. In the early days (0-14 days), the trend of all the samples fell below the control sample. However, in the late ages (14+ days) all the samples' trends fell above the control sample. Specifically, the 40% FA sample shows the highest resistivity, then the 60% FA, and lastly the 20% FA sample. This change shows that the pozzolanic reaction is completing in fly ash. As shown with the graph, with the increase of time, the pozzolanic reaction is completing in fly ash, thus causing the resistivity values to increase over time.

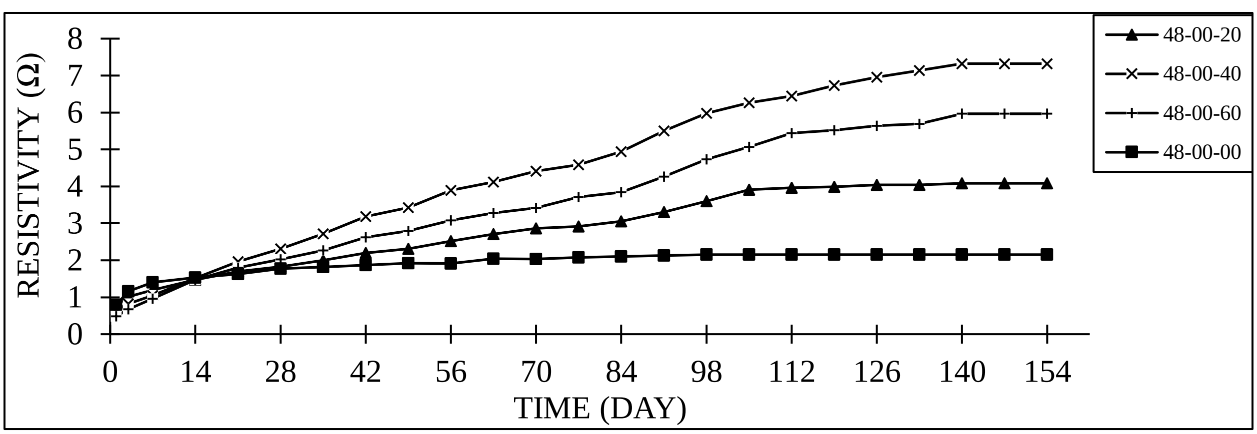

Figure 22: Bulk electrical resistivity for samples with varying levels of FA

Figure 23 shows the bulk electrical resistivity results for samples with a combination of varying levels of FA and 100% RCA. Much like the above results for varying levels of FA, the current results show that the control sample has a higher resistivity than the other samples in the early days (0-14 days). However, there is no significant difference between any of the samples during days 14-42. However, as time increases (49+ days), it is evident that the 50% FA paired with 100% RCA sample has the highest electrical resistivity. By these later ages, the control groups show the least resistivity, with 40% FA + 100% RCA and 60% FA + 100% RCA falling in the middle.

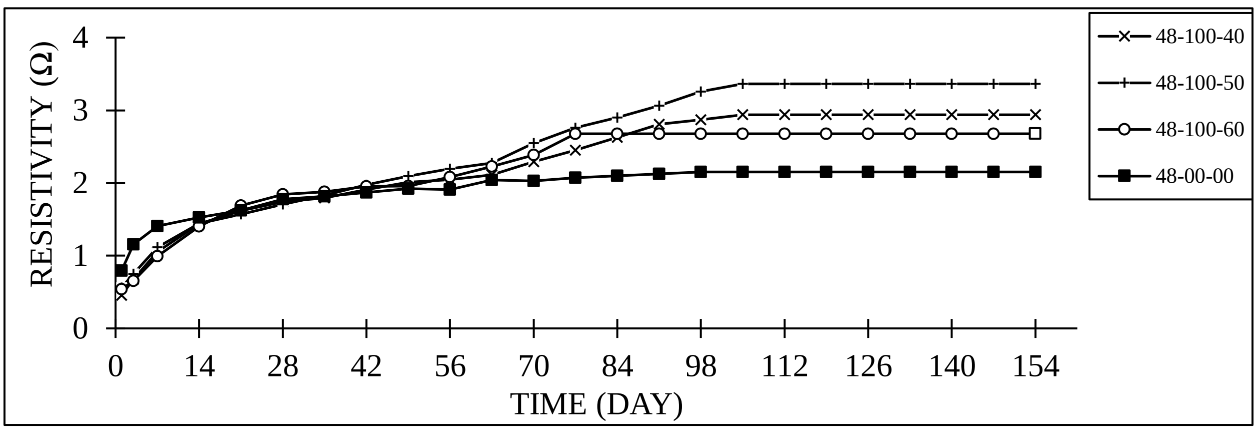

Figure 23: Bulk electrical resistivity for samples containing a combination of varying levels of FA and 100% RCA

4.7 Sorptivity

4.7.1 Sorptivity of samples tested on the finished surface

Figure 24 shows the results of the sorptivity test for concrete with varying levels of RCA and a constant FA (0%). Within the first 6 hours, the sample with 100% RCA showed the highest Sorptivity, with the next highest being the control sample. The samples with 25%, 50%, and 75% RCA have lower Sorptivity, and as such perform better, as compared to the control sample. The sample with the lowest sorptivity was the sample with 25% RCA. The results from day1-day8 of the test are similar to the results for the first 6 hours of the Sorptivity test. The sample with 100% RCA was the only one yielding higher Sorptivity than the control sample, and also showed the highest Sorptivity. The sample with 25% RCA showed the least Sorptivity, and therefore, had the best performance.

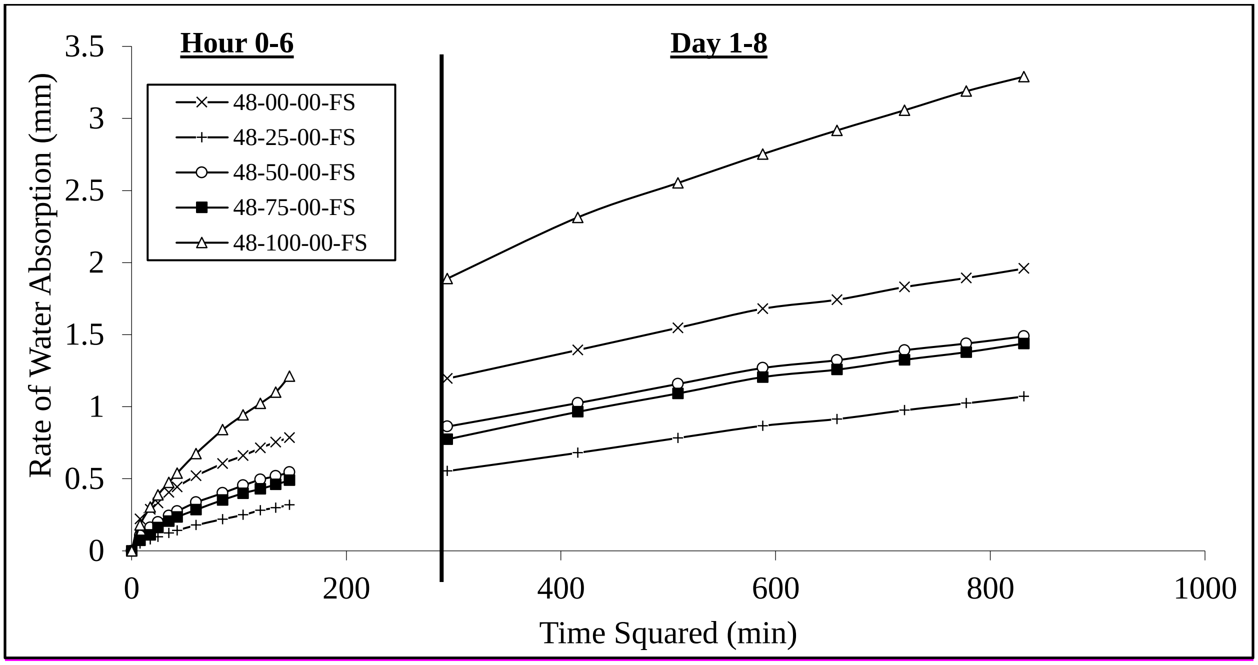

Figure 24: Sorptivity for samples containing varying levels of RCA (Finished Surface)

Figure 25 shows the results of the Sorptivity test for concrete with varying levels of FA and a constant RCA (0%). The sample with the highest sorptivity is the sample with 60% FA, whereas the sample with the lowest sorptivity has 40% FA. The sample with 40% FA is the only sample that indicates lower sorptivity compared to the control group, and subsequently has better performance, than the control sample. Results from day1-day8 were similar to the results from the first 6 hours of the test. The sample with 40% FA yielded the lowest Sorptivity, and is the only one lower than the control sample. The sample with 60% FA yielded the highest sorptivity. The results indicate that 40% FA is the point of best performance.

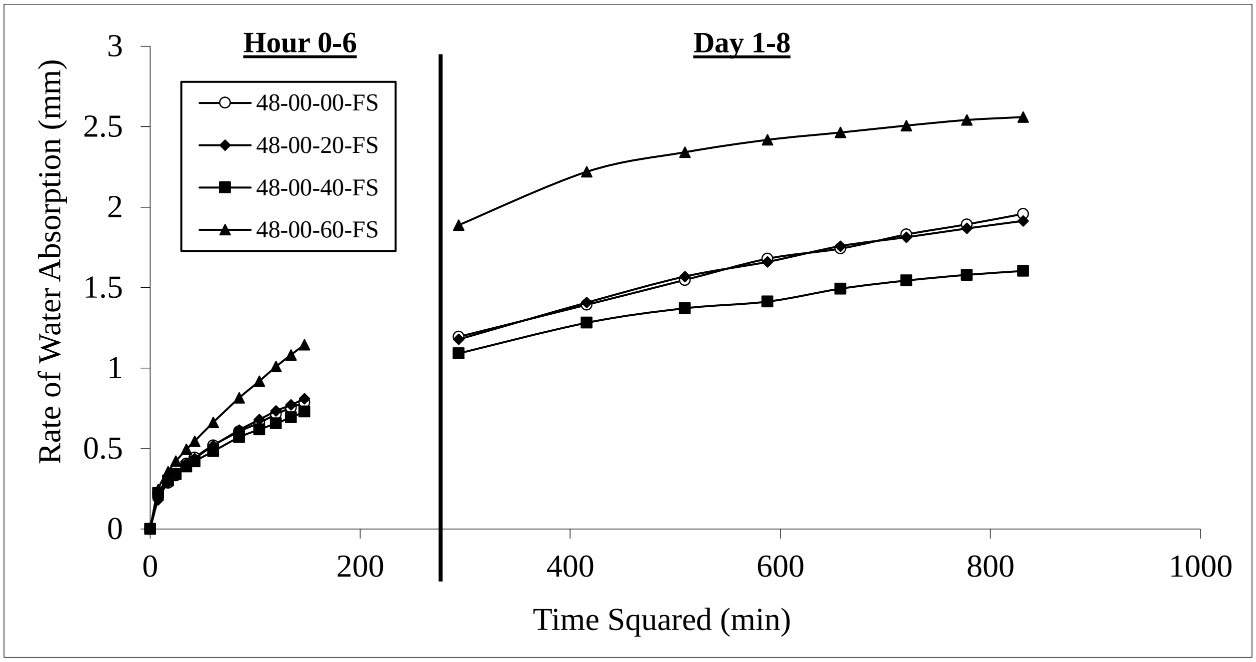

Figure 25: Sorptivity for samples containing varying levels of FA (Finished Surface)

Figure 26 shows the results of the first six hours of a sorptivity test for a concrete sample with varying levels of FA and a constant RCA (100%). The sample with lowest sorptivity and best performance is the control sample. The remaining samples decreased in order, with the highest sorptivity was founds in the sample with 40% FA, and then 50% FA being the next highest. This could be attributed to the fine particles in fly ash, and as such, the fine particles fill the pores.

The sample with 60% FA is the next lowest after the control sample. The results of day1-day8 of this test are again similar to the first 6 hours. Results showed that the control sample performed the best and had the least sorptivity. The combination of 60% FA and 100% RCA wielded the highest sorptivity, thus has the worst performance. These results are perhaps unsurprising when considering the results from the earlier test of varying RCA, where 100% RCA yielded the highest sorptivity.

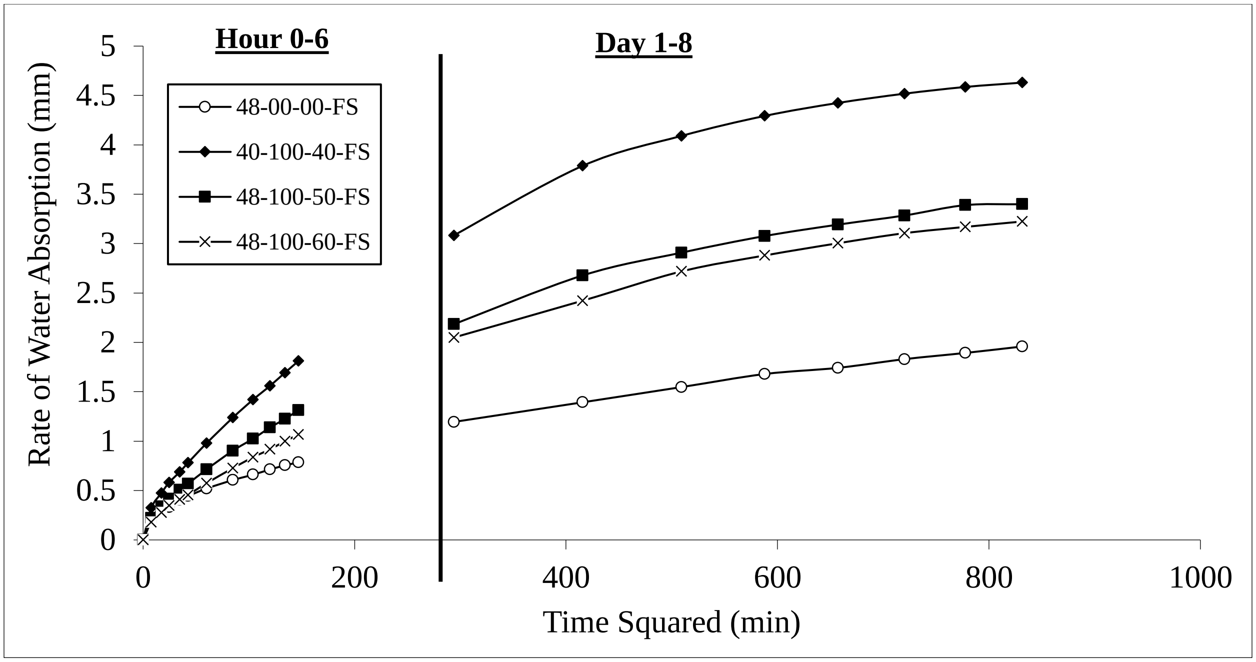

Figure 26: Sorptivity for samples containing a combination of varying levels of FA and 100% RCA (Finished Surface)

4.7.2 Sorptivity of samples tested on the cast surface

All of the previous data and graphs report on the results of Sorptivity testing on the finished surface of the concrete samples. The following data and graphs indicate the results of Sorptivity testing on the cast surface of the samples considering the surface condition of the sample plays significantly in the results. The results were generally similar to the results for tests on the finished surface. However, the results on the concrete with FA were surprisingly different, indicating that having no fly ash was the optimum level.

Figure 27 shows the results of the sorptivity test for a concrete sample with varying levels of RCA and a constant FA (0%) on the cast surface. Yet again, the sample with 100% RCA showed the highest sorptivity. This could be due to the heightened cement paste content in RCA mixtures; cement paste has more air voids which can lead to higher absorption of water. The control sample was the second highest, being much lower than the 100% RCA. Again, the 25% RCA sample was the lowest in Sorptivity, which is contrary to the hypothesis of the present study. The results from day1-day 8 are in agreeance with the results for the first 6 hours of the same test. The Sorptivity with 100% RCA had the highest Sorptivity. The sample with 25% RCA had the lowest sorptivity. The results from the sorptivity test on the casting surface are similar to the results from the sorptivity test on the finished surface.

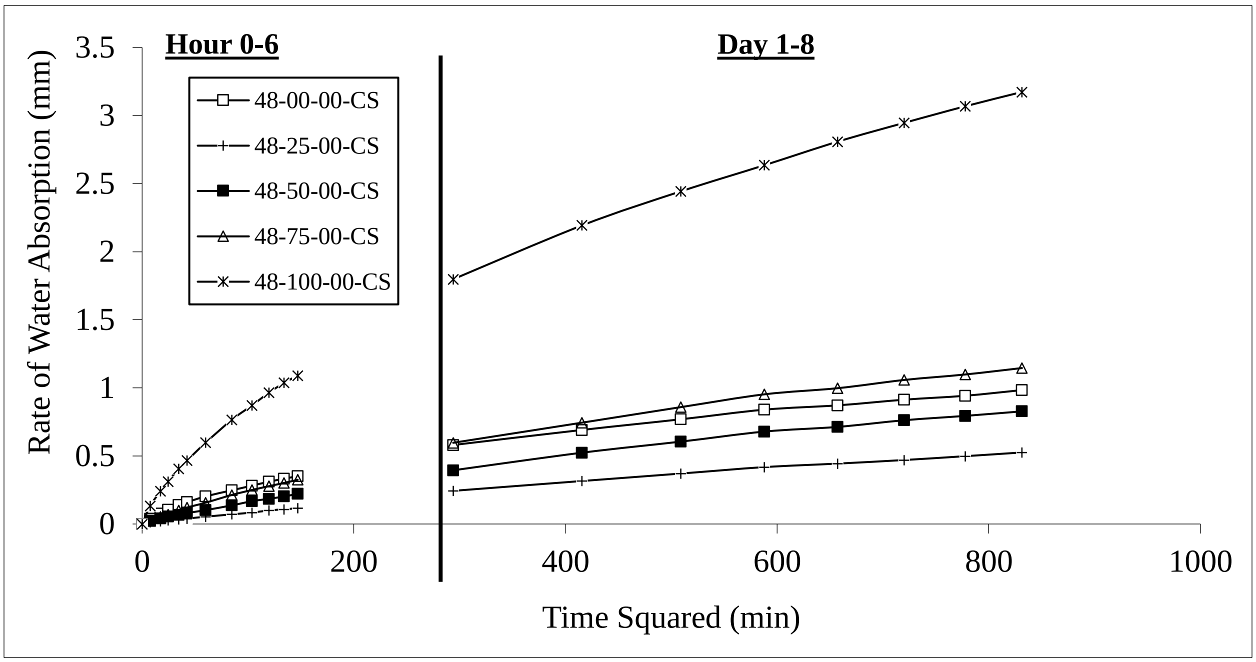

Figure 27: Sorptivity for samples containing varying levels of RCA (Cast Surface)

Figure 28 shows the results the sorptivity test for a concrete sample with varying levels of FA and a constant RCA (0%) on the cast surface. During the first six hours, the 60% FA sample yielded the highest sorptivity values. Contrary to results from the finished surface, the control sample wielded the lowest sorptivity. This same result continued throughout day1-day8; the control sample had the lowest sorptivity, while the 60% FA sample had the highest. The 40% FA sample was closest in sorptivity to the control sample. However, the control sample was still significantly lower in sorptivity. Therefore, the sample with best performance for the Sorptivity test on the casting surface was the control sample. The results from the sorptivity test on the casting surface are different from the results from the sorptivity test on the finished surface.

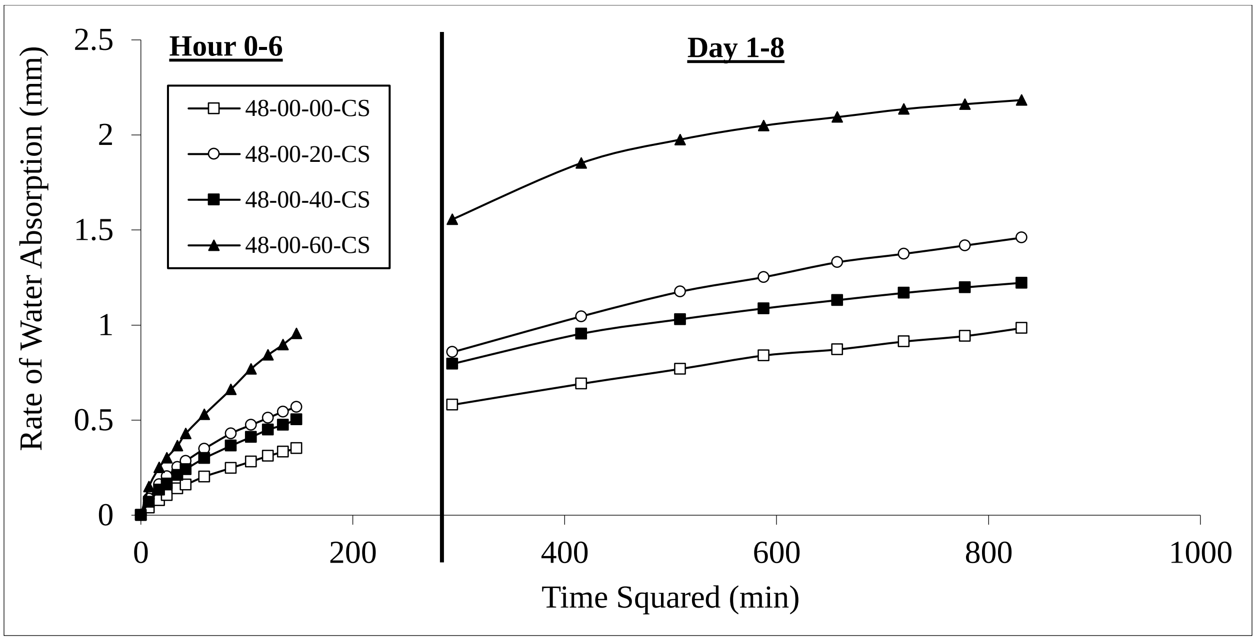

Figure 28: Sorptivity for samples containing varying levels of FA (Cast Surface)

Figure 29 shows the results of the sorptivity test for a concrete sample with varying levels of FA and a constant RCA (100%) on the cast surface. Results indicate that the control sample showed the lowest sorptivity, wielding the best results. Once again, the 40% FA sample had the highest Sorptivity, followed by the 50% sample, and then the 60% sample. The results during day1-day8 follow those of the first six hours, where the control group yielded the lowest Sorptivity. The 40% FA and 100% RCA mixture yielded the highest sorptivity. The results from the sorptivity test on the casting surface are similar to the results from the sorptivity test on the finished surface.

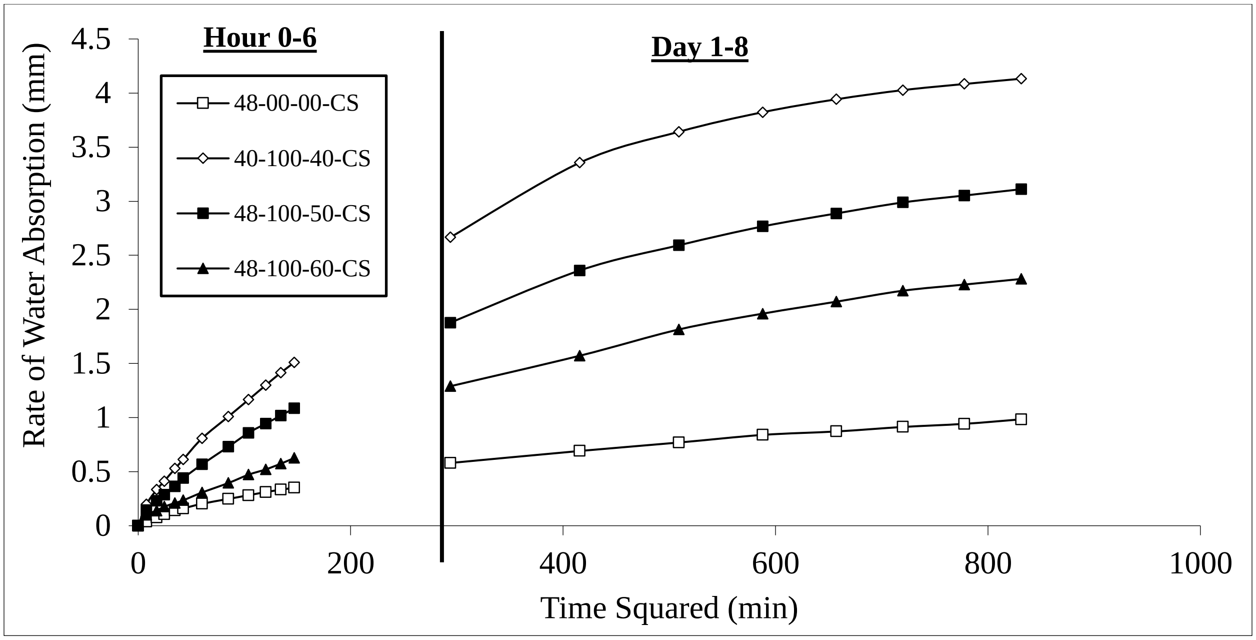

Figure 29: Sorptivity for samples containing a combination of varying levels of FA and 100% RCA (Cast Surface)

According to the results from the sorptivity tests on the finished surface, 40% FA and 25% RCA are the samples that produce the least sorptivity. However, no mixture with 40% FA and 25% RA were tested together. According to the results from the sorptivity tests on the cast surface, 0% FA and 25% RCA are the samples that produce the least sorptivity. The slope of each curve is taken as sorptivity coefficient. Table 6 has listed the sorptivity coefficient for each mix. As shown, adding 25% RCA will lead to the best performance in terms of the rate of water absorption.

Table 6: Sorptivity Coefficient for all mixtures

Sorptivity coefficient (mm/s^0.5)				
	Hour 0 to 6 (Cs)	Hour 0 to 6 (Fs)	Day 1 to 8 (Cs)	Day 1 to 8 (Fs)
48-00-00	0.0023	0.0044	0.0007	0.0014
48-25-00	0.0008	0.002	0.0005	0.001
48-50-00	0.0014	0.0033	0.0008	0.0012
48-75-00	0.0022	0.0031	0.001	0.0012
48-100-00	0.0071	0.0074	0.0025	0.0026
48-00-20	0.0035	0.0047	0.0011	0.0013
48-00-40	0.0032	0.0044	0.0008	0.0009
48-00-60	0.006	0.0068	0.0007	0.0011
48-100-40	0.0097	0.0111	0.0025	0.0027
48-100-50	0.0071	0.0081	0.0022	0.0022
48-100-60	0.0039	0.0066	0.0019	0.0022

One of the limitations that the sorptivity test has is that it only tests the surface of the sample, and cannot test the bulk of the sample. As such, researchers using the sorptivity test cannot know the results in the bulk of the sample.

In Phase II of the research, one new control mixture in addition to seven new mixtures were created. The purpose of this new phase was to perform and analyze the results of the freeze-thaw and salt scaling durability testing. In addition to these tests, mechanical properties of the mixtures were investigated with the ultrasonic pulse velocity, as well as the compression test and splitting tensile test. In order to meet the durability requirements, water-to-cement ratio changed to 0.44. For this phase, the mixtures were as follows: 25% RCA, 50% RCA, 75% RCA, 100% RCA, 20% FA + 100% RCA, 40% FA + 100%, 60% FA + 100% (all fly ash in class C) and the control sample with natural aggregate and no fly ash. Table 7 shows the fresh properties and the mechanical properties of all the mixtures.

Table 7: Fresh and mechanical properties of mixture with W/C=0.44

	Air Content (%)	Slump (in)	Unit Weight(Ib/ft^3)	Compression Strength (Mpa)	Tensile Strength (Mpa)

44-00-00	6.2	1.25	148.8	33.9	3.2
44-25-00	5.5	1.00	146.2	32.7	2.9
44-50-00	5.6	0.50	145.6	48.2	3.2
44-75-00	5.6	1.25	144.0	46.2	3.6
44-100-00	5.1	0.75	143.2	42.1	3.3
44-100-20	6.6	2.75	140.8	38.5	3.1
44-100-40	7.0	8.00	139.2	35.1	2.5
44-100-60	8.5	7.75	136.8	24.3	2.3

4.8 Ultrasonic pulse velocity

UPV results were listed in Table 8:

Table 8: Ultrasonic pulse velocity results

	UPV (m/s)
44-00-00	4958.9
44-25-00	4836.1
44-50-00	5036.8
44-75-00	4810.1
44-100-00	4735.9
44-100-20	4802.2
44-100-40	4670.3
44-100-60	4498.1

Based on British Standard Institution for the ultrasonic pulse velocity test, concrete quality has been classified into four categories in terms of velocity shown in Table 9 [82]:

Table 9: Four categories of concrete quality

UPV (m/s)	Concrete quality
Above 4500	Excellent
3500 to 4500	Good
3000 to 3500	Medium
Below 3000	Doubtful

The UPV results obtained from the present research study showed that all concrete mix designs showed successful performance in terms of concrete quality and they were all categorized as excellent except the mix containing 100% RCA and 60% FA which is in good category. Figure 31 indicates the relationship between UPV and 28 days compressive strength of the mixtures listed in Figure 12, 13, and 14. Each point is the average of three results. As shown, the coefficient of determination for the drawn curve relationship equals 0.424.

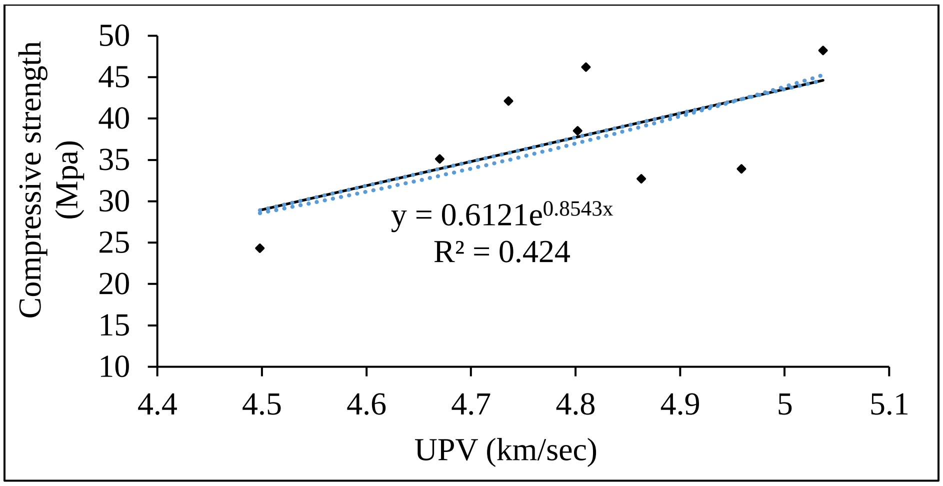

Figure 30: Correlation of UPV and 28-day compressive strength

Figure 31 shows the correlation between ultrasonic pulse velocity and unit weight of concrete. The coefficient determination for all eight-data point used is as 0.78. As shown below, UPV values increase when unit weight of concrete raises up. The present research study confirmed that as the unit weight increases, the density of concrete increases and this causes the wave to travel quicker throughout the specimen, while the presence of porosity leads to decrease in velocity values.

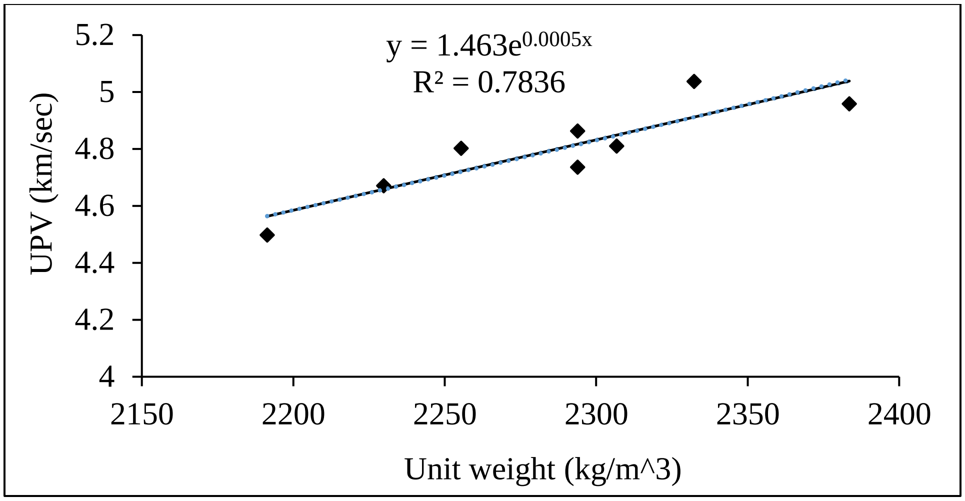

Figure 31*: Correlation of UPV and unit weight of mixtures*

4.9 Salt scaling

In accordance with BNQ NQ 2621-900 standard, having less than 500 grams of salt scaling residue in one square meter is considered as the passing limit for the test. Based on results, it is observed that all mixtures containing RCA, except the one containing 25% RCA, had a better salt scaling resistance than the reference mixture. Although mixtures containing 75% and 100% RCA passed the test satisfactorily, it seems a mixture containing 50% RCA has the most ideal results. Figure 32 represents the cumulative scaling loss of RCA mixes against the number of cycles.

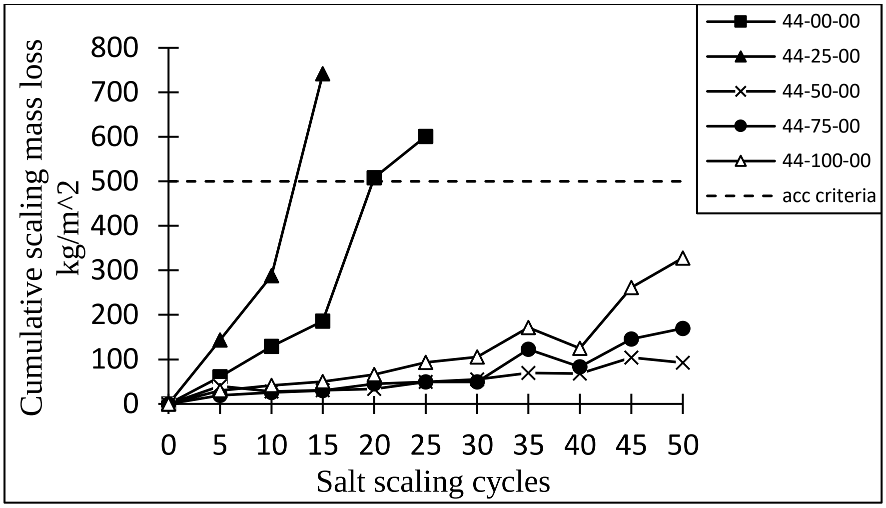

Figure 32: Cumulative scaling loss of samples containing varying levels of RCA

As previous researchers have shown, fly ash decreases the salt scaling resistance of concrete. The findings from the present research confirm those results. It can be observed from Figure 33 that adding 20% fly ash to 100% RCA concrete had a similar trend to the 100% RCA mix. However, after 40 cycles, it showed a sudden jump leading to test failure. Clearly adding high volumes of fly ash caused a drastic decline on de-icing-salt resistance. Based on findings, fly ash not only decreased the salt scaling resistance of natural aggregate concrete, but it leads to same results for RCA concrete as well.

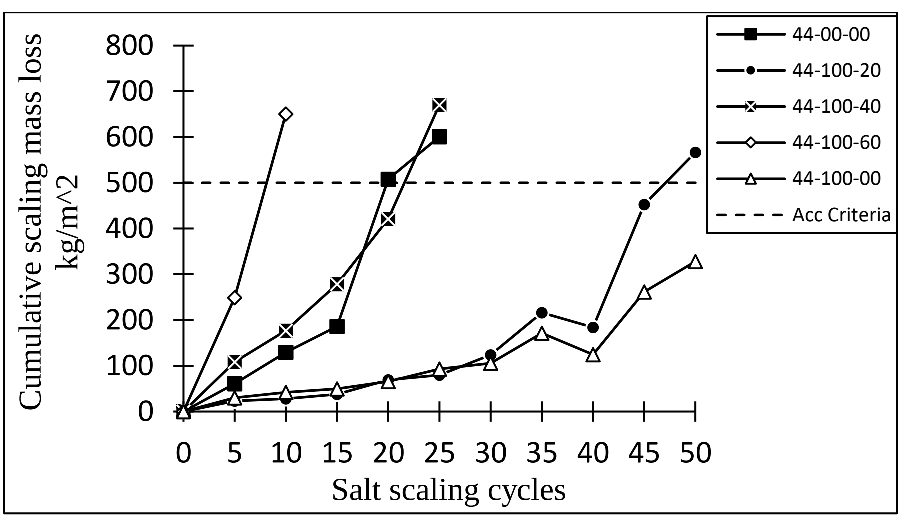

Figure 33: Cumulative scaling loss of samples containing varying levels of FA

Figures 34 to 41 represent the final condition of mixtures and the number of cycles they passed.

Figure 34: Control sample after 25 cycles

Figure 35: 50% RCA after 50 cycles

Figure 36: 25% RCA after 15 cycles

Figure 37: 75% RCA after 50 cycles

Figure 38: 100% RCA after 50 cycles

Figure 39: 40% FA + 100% RCA after 25 cycles

Figure 40: 20% FA + 100% RCA after 50 cycles

Figure 41: 60% FA + 100% RCA after 10 cycles

4.10 Freezing and thawing

Freezing and thawing starts as water enters the air void system through concrete. By freezing of water, its volume increases by 9%, which leads to a creation of 30,000 psi. Entrained air voids are known to act like a pressure release for the frozen water preventing its expansion.

Based on ACI recommendation for freezing and thawing resistance, appropriate amount of well-sized and evenly spaced air voids inside the concrete, high density and low permeability are significant requirements for freezing and thawing resistance of concrete. Adding fly ash can help in addressing a large portion of the ACI recommendations. In a fly ash reaction, the amount of CH can decrease, causing less concrete voids to form which are harmful for freezing and thawing. Fly ash due to its smaller particles, can fill the voids and form a denser and less absorptive concrete. Due its spherical shape, fly ash decreases the water demand for concrete mixture which means having more durability [83]. Freezing and thawing resistance of concrete is directly related to compressive strength, air percentage and permeability of the mixture. Relative dynamic modulus and mass loss of the specimens were measured considering the specified timeline of the test. Durability factor, compressive strength, air content and final dynamic modulus have been presented in Table 10.

Table 10: Freeze-thaw results for all mixtures

	Air Content (%)	28 Days compressive strength (MPa)	Dynamic Modulus (Hz)	Number of cycles	Durability factor (DF)
44-00-00	6.2	33.9	46.5	72	27.9
44-25-00	5.5	32.7	46.5	72	27.9
44-50-00	5.6	48.2	52	180	37.44
44-75-00	5.6	46.2	43	180	30.96
44-100-00	5.1	42.1	41.9	144	20.112
44-100-20	6.6	38.5	31.4	180	22.608
44-100-40	7	35.1	46.7	144	28.02
44-100-60	8.5	24.3	62	302	62

The results show that using RCA may not have an effect on the durability of concrete mixtures as none of mixture could pass the test successfully. Based on ASTM C 666, a mixture with a durability factor of 60 or more is considered to have the ability to show a good performance in the freezing and thawing test. According to ACI 318-08 [84], the required air content for mixture with maximum nominal aggregate size of 1 inch should be 4.5 and 5% for moderate and severe condition respectively. Moreover, ACI 318-08 suggests that the minimum of compressive strength to be 31 MPa. As shown in Table 6, all mixture met the minimum air content and compressive strength, but were not able to pass the test. However, surprisingly, the one containing 100% RCA and 60% of fly ash, while didn't meet ACI strength requirement, passed the test with a margin line DF value of 62. The drop trend of relative dynamic modulus for each mix design is compared in Figure 42 and Figure 43. Although adding RCA improved the freezing and thawing resistance compared to the control sample, it was not enough to pass the test. Adding 20% and 40% RCA did not have a significant durability performance, but it seems adding FA in values more than 50% can make a remarkable improvement. More research is needed to explore and confirm this finding.

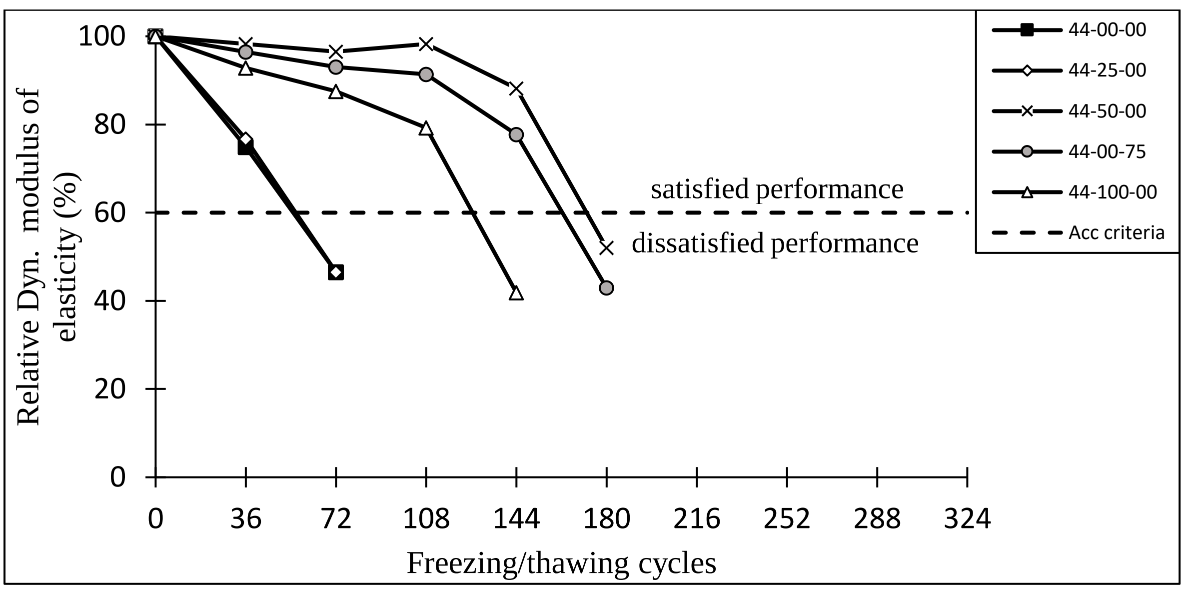

Figure 42: Freeze-thaw results for samples containing various levels of RCA

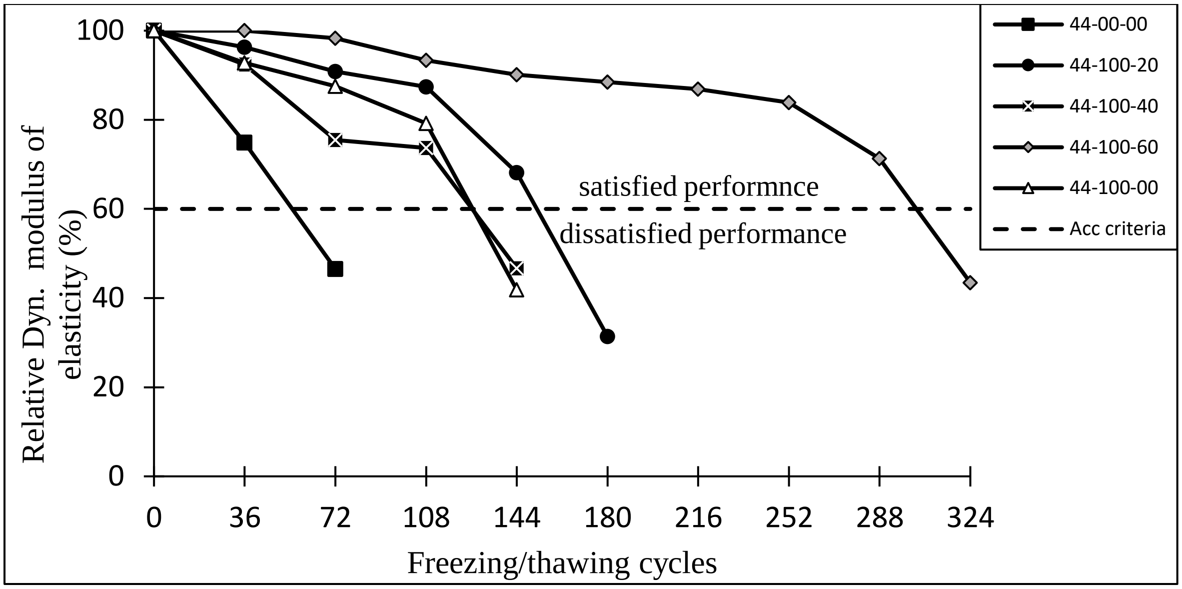

Figure 43: Freeze-thaw results for samples containing a combination of varying levels of FA and 100% RCA

The percentage of mass loss for each mixture has been shown in Figure 44. As shown, all mixture stood in positive values in the first 36 cycles, meaning that they gained weight. However, after 36 cycles, the following mixtures lost part of their weight due to higher portion of scaling to their weight gain: the control mix, the mix with 25% RCA, and the mix combining 100% RCA and 60% FA.

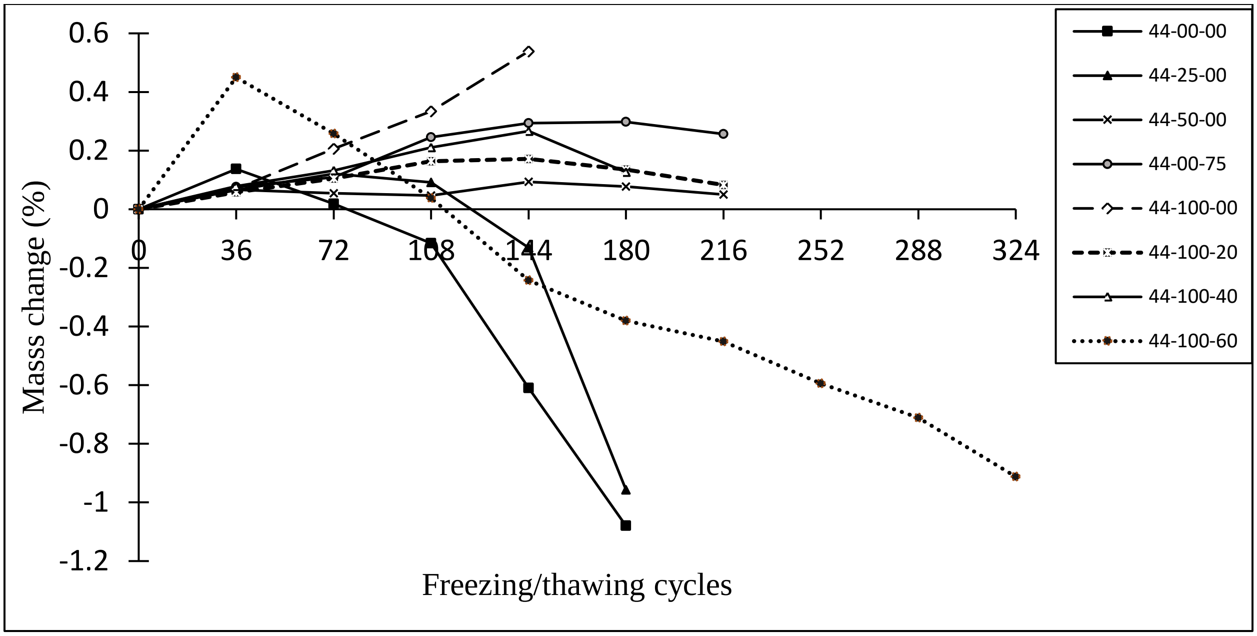

Figure 44: Mass loss for all sample mixtures

CHAPTER V

CONCLUSION AND RECOMMENDATION

Previous researchers thought that combining FA and RCA would decrease the mechanical properties of concrete. However, the findings in the present study contradict that idea. In fact, the present study found that combining Class-C FA and RCA could improve the mechanical properties of concrete. Moreover, when tested, samples combining FA and RCA show similar results for mechanical properties to the control sample. Therefore, for individual source of FA and RCA materials, their dosage compatibility or optimal mixture design.

FA and RCA replacement, even in high percentages, may yield moderate electrical resistivity performance in accordance with AASHTO TP-95. Although RCA replacement alone decreased the electrical resistivity of the mixtures in comparison to the control, the benefits of fly ash addition on ionic transport properties where noticeable. The resistivity values increased and surpassed that of the control mixture.

RCA replacement does not seem to improve the sorption transport mechanism of concrete material. In fact, for this study, it had a negative effect on sorptivity in comparison to the control specimen containing virgin aggregates alone. As for mixtures containing FA only, a decrease in the rate of water absorption was noticed. Conversely, the addition of FA to the mixtures containing 100% RCA did not have a positive effect; the results were still higher than the control.

For this study, RCA addition improved the scaling resistance of concrete. Mixtures containing high percent volumes of RCA passed the requirements of the standard test while the control sample did not. On the other hand, addition of high percent volume of FA and RCA decreased the scaling resistance of concrete where none of the mixtures met the acceptance specification. Therefore, in regions where concrete may be exposed to de-icing salt and frost, using the combination of FA and RCA may not be recommended. Further research is necessary to confirm results as these results are dependent on the materials evaluated in this study.

As for cyclic freeze-thaw performance, both addition of RCA and FA improved the mixtures performance in comparison to the control sample containing no recycled materials. However, the increase in performance was not sufficient as none of the mixtures met the standard's acceptance criteria. Here, further testing is recommended to optimize mixture proportioning and effective use of admixtures such as air entertainers to achieve desirable outcomes.

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VITA

Mohammad Zare Banadkoki

Candidate for the Degree of

Master of Science

Thesis: DURABILITY EVALUATION OF CONCRETE WITH HIGH-VOLUME RECYCLED MATERIALS

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December 2017.

Completed the requirements for the Bachelor of Science in Civil Engineering at Islamic Azad University, Karaj, Tehran in September 2012.

Experience:

Graduate Research Assistant in Civil Engineering Laboratory of Oklahoma State University: development of different mixture designs to meet durability requirements of concrete mixtures containing high percentages of recycled materials, 2015-2017

Voting member of ACI Subcommittee 228-0B, visual inspection, 2017-2018

Site engineer at Abdlahi Company, Tehran, Iran, 2013-2015

Professional Memberships:

Member of American Society of Non-Destructive Testing, 2016-present

Member of American Concrete Institute, 2015-present

Member of American Institute of Steel Construction, 2016-present

Member of American Society of Civil Engineering, 2015-present