INVESTIGATION OF THE QUALITY CONTROL OF WASTE PRODUCTS FOR CONCRETE

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2017

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, 2019

INVESTIGATION OF THE QUALITY CONTROL OF

WASTE PRODUCTS FOR CONCRETE

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ACKNOWLEDGEMENTS

I would like to acknowledge funding from the Illinois Department of Transportation and the Oklahoma Department of Transportation for supporting this research. A special thanks to Shinhyu Kang for previous research leading into this study as well as Jacob Peery for his groundwork in developing Pulp Cure. I would like to thank Dr. Tyler Ley for giving me a chance to work with him during my Masters, it has been an honor and a pleasure. Thank you to Dr. Bruce Russell and Dr. Julie Hartell for agreeing to serve on my committee and influencing my growth as an engineer through your class instruction. Justin Becker, Hope Hall, Bret Robertson, and Chad Staffileno: it was a pleasure to work with all of you on my research. Thank you to all of the undergraduate students at Bert Cooper Engineering Laboratory for all of your hard work and dedication in providing high-quality research.

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Date of Degree: MAY, 2019

Title of Study: INVESTIGATION OF THE QUALITY CONTROL OF WASTE PRODUCTS FOR CONCRETE

Major Field: CIVIL ENGINEERING

Abstract: This work uses testing for the quality of waste products in the production of concrete. This work will look at two different waste products. The first is Pulp Cure, a recently developed method for wet curing concrete. The other material is the usage of fly ash, a waste product from the coal power plant industry in higher volumes than is typically used in modern construction. A range of test methods were used on these materials. Some tests were novel and were developed and refined for this work and others were established ASTM methods. The test methods for Pulp Cure were developed and tested in the laboratory that could determine the quality of a Pulp Cure mixture through numerical data and visual observations. The performance of high volume fly ash, both class C and class F (ASTM C618), concrete was tested using ASTM methods for slump, strength, resistivity, and isothermal calorimetry. Comparisons were made to the bulk chemistry and particle size distribution of the fly ash in order to find correlations between oxide content and performance in order to promote the understanding of this material

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CHAPTER 1

INTRODUCTION TO RESEARCH PERFORMED

1.0 INTRODUCTION

This work uses testing for the quality of waste products in the production of concrete. This work will look at two different waste products. This thesis introduces two topics of research: quality control of a novel concrete curing agent called Pulp Cure, and the performance of fly ash in concrete at 20% and 40% replacement levels. Pulp Cure has been a recently developed method to improve the wet curing application process in order to promote cement hydration increasing strength and long term durability. Fly ash has been used as supplementary cementitious material (SCM) in concrete to cut cost, promote long term durability, and reduce the heat of hydration. Though these topics might seem to differ in scope, both projects focus on using quality control testing to govern the use of waste products in the production of concrete.

1.1 QUALITY CONTROL

Quality control is about knowing what the task requires or what the client desires and testing the product in order to determine if what you actually have meets these requirements. This is an important concept in the construction industry where poor quality can mean the loss of time, money, or in some cases, even life. Quality control is also about ensuring consistency when dealing with materials that are made of multiple components and especially when using waste products such as recycled paper or fly ash.

1.2 WASTE PRODUCTS

1.2.1 Fly Ash

Fly ash is a by-product of coal combustion, made up of particles that are collected through various methods before exiting the flu. It is therefore made up of several major oxides such as CaO, Al_20_3, $Si0_2$, Fe_2O_3, and some minor oxides. ASTM C618[1] uses a method that separates fly ash into two groups Class C or Class F based on their major oxide contents. Though there are many uses for fly ash such as soil stabilization, wastewater treatment, and supplementary cementitious material (SCM) for concrete, use as an SCM is steadily growing. Reports from AACA say fly ash used in concrete went from 11-million short tons used in 2010 to 14-million in 2019[2]. This is due to its economic and performance benefits. Despite this, there are some difficulties when it comes to consistency and performance predictability, which furthers the need for quality control testing.

1.2.2 Recycled Paper

Recycled paper is composed of paper products recycled from pre-consumer or post-consumer waste[3]. Utilization of this material as a waste product adds variability to the application. This can be revealed in the application of Pulp Cure through unknown chemicals or plastic waste that affect consistency. Without a consistent mixture, there may be issues that arise in concrete that is meant to be cured using Pulp Cure, which is a combination of water, recycled paper, and a viscosity modifier.

1.3 CURING

Curing is a beneficial step in the construction of many concrete projects. It achieves this by helping to promote the reaction or hydration of the cement paste and will help improve strength, reduce outside chemical penetration, and increase abrasion resistance. Figure 1-1**Error! Reference source not found.** illustrates the concept of curing cement grains, allowing it to hydrate more completely decreasing the porosity. There are three methods of curing: no cure, chemical cure, and a wet cure. Pulp Cure is a wet curing method that works by holding moisture close to the surface of the concrete, maintaining the moisture content throughout the curing process.

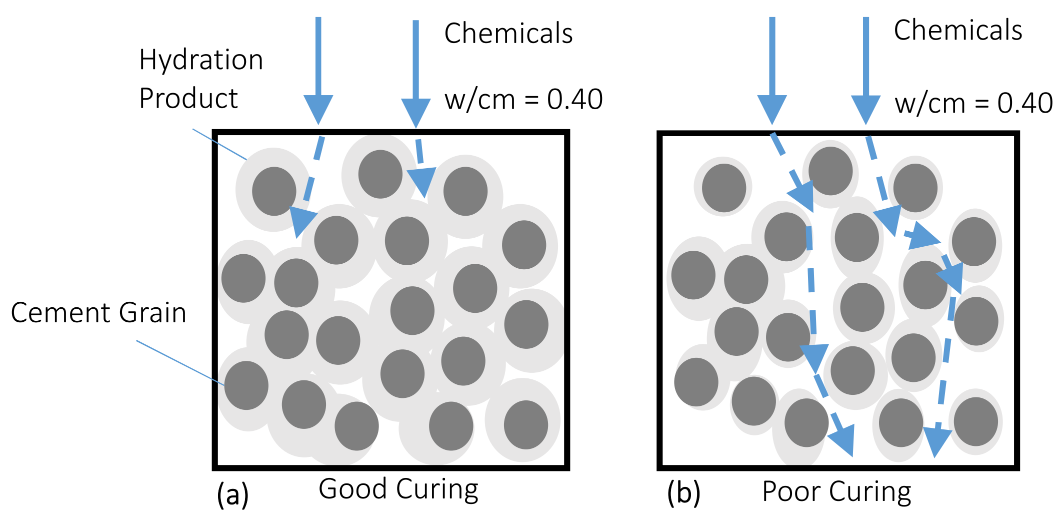

Figure 1-1: This graphic serves to illustrate the concept of curing. The figure (a) shows cement grains that have been properly cured, providing a dense pore structure and preventing penetration of outside chemicals. In figure (b), the cement is poorly cured, allowing for outside chemicals to penetrate

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1.4 OBJECTIVE

The object of this paper is to present the research findings in the development of test methods that describe the quality of Pulp Cure, and the performance of mixtures using fly ash as an SCM for replacement levels of 20% and 40%. This was done in order to provide the tools necessary for achieving consistent quality. It is the hope of the researcher that this paper will further propel the advancement of the body of knowledge in the realm of concrete performance.

CHAPTER 2

PULP CURE: IMPROVEMENTS IN QUALITY TESTING

2.0 INTRODUCTION

It is important for concrete to be kept moist as it is curing. This helps the reaction or hydration of the cement paste and will help improve strength, reduce outside chemical penetration, and increase abrasion resistance. Pulp Cure has been a recently developed method to improve the wet curing application process. Pulp Cure requires a lower amount of effort to apply the wet curing to the surface of the concrete. However, these benefits must be significant enough to convince people to change. Like any new technology, Pulp Cure has required time for adoption and improvements. Work was done to make improvements in mixing, delivery, and quality control. In addition, work has been done to evaluate the performance of the material and show that it has equivalent or better performance than wet burlap, the current method of wet curing used by contractors.

2.1 MATERIALS

The current design uses a 550-gallon tank filled with 300-gallons of water, 5 bales of recycled paper mulch that are 30 lbs. in weight and 6.7 lbs. of tackifier. The tackifier is used to make the mixture more cohesive so that the material does not segregate during the application and lose a significant amount of water. The tackifier is a viscosity modifying agent and acts as a "fluid glue" holding the paper particles in close proximity but allowing them to flow freely, maintaining their water content. Without tackifier to hold them together, the paper particles will settle together allowing free water to flow out of the mixture.

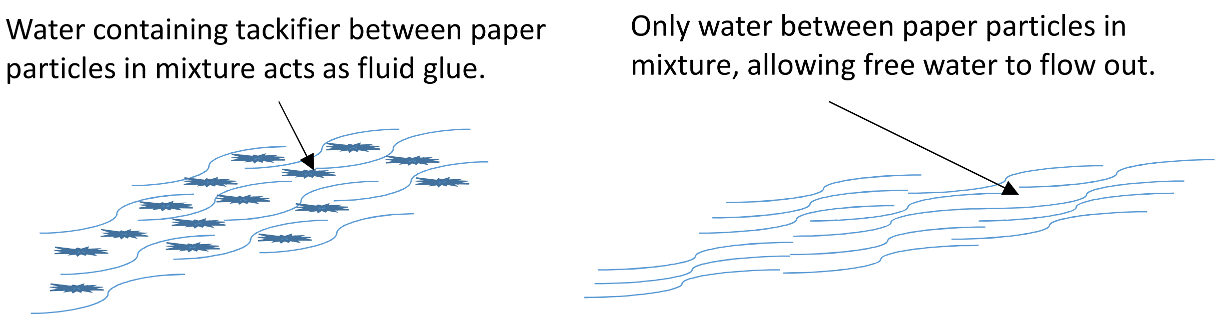

Figure 2-1: Graphic representation describing the influence of tackifier in the Pulp Cure matrix.

This has been batched using two separate pumps that are designed to draw water from the base of the tank and discharge it back into the tank creating a recirculation or vortex process. This process is repeated until the mixture appears to be uniform and free of large, dry paper debris. Though this has proven to be an efficient process, the system can become overloaded with paper which requires manual breaking up of the bales. When this occurs it takes more time and effort, delaying the application to the concrete. Blockages can form in the network if there are large pieces of dry paper that were not adequately mixed or pieces of plastic that are within the recycled newspaper.

This could be improved by modifying the circulators, increasing the pump size, or adding a mechanical agitator. These are all ideas for future modifications in the next phase of the project.

2.2 DELIVERY METHOD

Delivering Pulp Cure from the tank to the site has been completed by turning a valve that directs the return flow of one of the pumps to a tubing network. This network is connected to nozzles developed at Oklahoma State University specifically for this application. They are designed to have a spray width of 60˚ and to be mounted on a work bridge. The nozzle mounts are tilted upwards from the horizontal at approximately 30˚ which broadcasts the Pulp Cure over the concrete at a low angle of impact in order to preserve the surface (Figure 2-2).

The tank can hold 550-gallons, however, the effective volume that can be mixed is 400 gallons and 350 gallons can be pumped from the tank. This is due to the limits of the pump intake and outlet port. 50 gallons cannot be accessed by the pump intake. Filling the tank beyond the top of the pump outlet inside the tank will prevent necessary agitation of the mixture. For every 100 gallons of Pulp Cure, 320.8 ft^2 of the surface can be covered with ½” depth of coverage. This means that one 400 gallon tank of Pulp Cure can cover 1122.8 ft^2 with a ½” depth of coverage. For a bridge that is 30’ wide and 100’ long, approximately three batches will be needed.

The duration of mixing time can be reduced if a larger tank was used for the application as well as larger pumps for distributing the pulp to the nozzles.

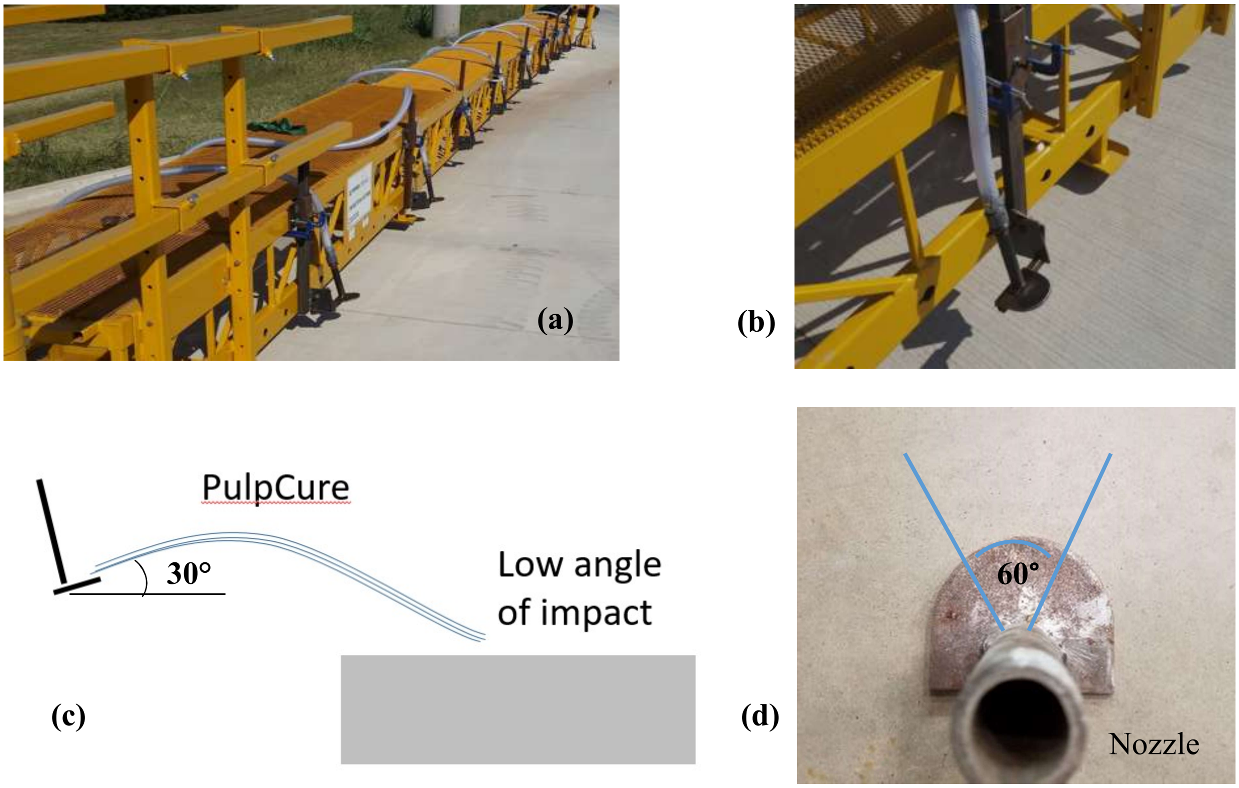

*Figure 2-2: **(a)** The nozzles and tubing are attached to work bridge. **(b)** Close up photo of the work bridge showing the nozzle mount. **(c)** The depiction of how the nozzle tilt angle affects the angle of impact. **(d)** The depiction of a nozzle spraying Pulp Cure at a spray width of 60°*

2.3 QUALITY CONTROL TESTS FOR PULP CURE

Based on the previous tests and in the field applications it is desirable to ensure the correct pulp to water ratio is used in the mixture. It is also important to be able to design mixtures to be applied on different slopes. For example, if Pulp Cure is used on a bridge with a superelevation it may have a higher slope than a bridge with just a 2% crown. As the slope increases, the ability of the material to hold the water decreases. Simple tests are needed to evaluate the Pulp Cure mixture for different applications. Two tests are being used to evaluate Pulp Cure. The first is called the

Runoff Test, and the other is the Drip Test. These will be discussed in more detail and data will be provided.

The time required to complete the Drip Test is five minutes, and only 1 minute for Runoff, therefore they can be completed in the lab or used to give quick feedback about Pulp Cure being produced in the field. Tests were executed using ten mixtures, these mixes are listed in Table 2-1. These mixtures were chosen because they allow us to calculate and physically see how the Pulp Cure will perform based on a controlled change of the variables. Initial testing focused primarily on mixtures with a range of tackifier from zero to double the typical amount. Upon establishing reasonable test methods, mixtures were then adjusted by the amount of paper and the amount of water. Lab testing involved using a smaller 5 gallon batch of Pulp Cure, discussed in the next section.

Table 2-1: Pulp Cure Test Mixture Designs

Mixtures Completed				
Mixture Designs	**Tackifier (lbs)**	**Paper (lbs)**	**Water (lbs)**	**Modification**
Mixture 1: 0% Tackifier	0	1.2	29.5	**Tackifier**
Mixture 2: 25% less Tackifier	0.0198	1.2	29.5	
Mixture 3: 50% less Tackifier	0.0397	1.2	29.5	
Mixture 4: Standard Tackifier	**0.0794**	**1.2**	**29.5**	
Mixture 5: 150% more Tackifier	0.1191	1.2	29.5	
Mixture 6: 200% more Tackifier	0.1587	1.2	29.5	
Mixture 7: Less 20% Paper	0.0794	0.96	29.5	**Paper**
Mixture 8: Plus 20% Paper	0.0794	1.44	29.5	
Mixture 9: Less 20% Water	0.0794	1.2	23.6	**Water**
Mixture 10: Plus 20% Water	0.0794	1.2	35.4	

2.3.1 Laboratory Mixing Procedure

Equipment needed to prepare lab testing mixtures is a drill with a 5” diameter mixing vane that is 24” long (Figure2-3c), 5-gallon plastic bucket, and scales. The process involves taring the empty five-gallon bucket in order to add the appropriate amount of water. Adding paper pulp to the water is done by taring the water first, or weighing the paper separately and combining (Figure2-3b). Before the addition of tackifier to the pulp and water, it is necessary to blend them together for one minute using the drill equipped with a paddle mixer. This time frame allows all of the paper clusters to break apart and become saturated in the mixture.

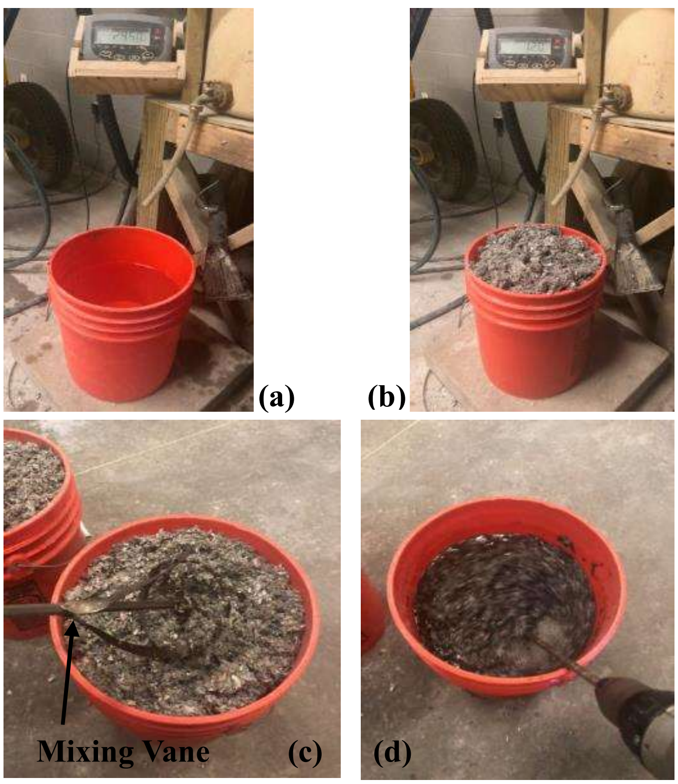

Figure2-3: ***(a)*** *Weighing water in a tared 5-gallon bucket.* ***(b)*** *Adding paper to the tared water bucket.* ***(c)*** *Inserting mixing vane into bucket in order to immerse paper.* ***(d)*** *The mixture is blended for 1 minute before adding tackifier.*

2.3.2 Runoff Test Methods:

This test is being developed because the water in Pulp Cure was observed to separate and run down the slope of a bridge deck, creating wide channels. In some cases, it was totally removed. Figure2-4 is a picture from a bridge deck that was cured using Pulp Cure. The mixture separated leaving the surface exposed to evaporation. This can be due to a higher water-to-pulp ratio. Ideally, the material would uniformly cover the surface. A test that could determine this for any randomly sampled mixture was needed.

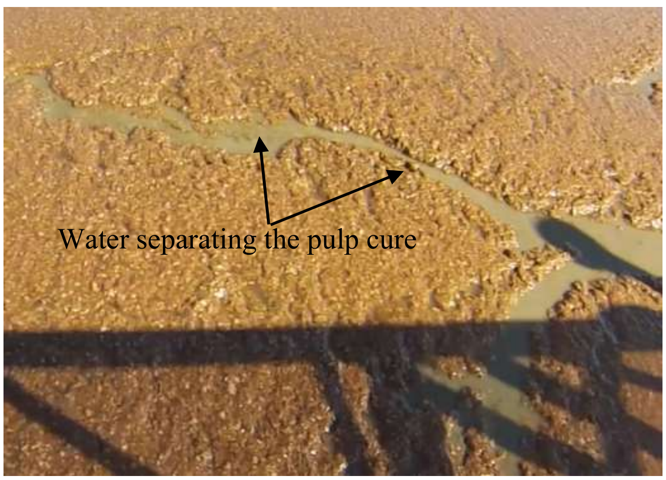

Figure2-4: Photo from previous bridge deck coating shows water separating from the material leaving open channels, which will expose the surface to evaporation.

The Runoff Test uses a 2'x2'x0.5" polyethylene sheet marked at 1-inch intervals and set at a slope to simulate a bridge deck. In order to simplify the analysis, the results are recorded using these marks to get a relative diameter called the "Spread", shown in Figure2-5. These marks are in place to set a standard to measure runoff. To improve repeatability, the Pulp Cure is placed in a funnel before testing. This funnel is centered on the 1-inch mark and filled with a 3"x6" cylinder of Pulp Cure. The cone is then lifted away using a 1-second lift, perpendicular to the board to allow the material to flow down.   These mixtures were inspected for their flow, uniformity, and thickness between 0.5” and 0.625”.

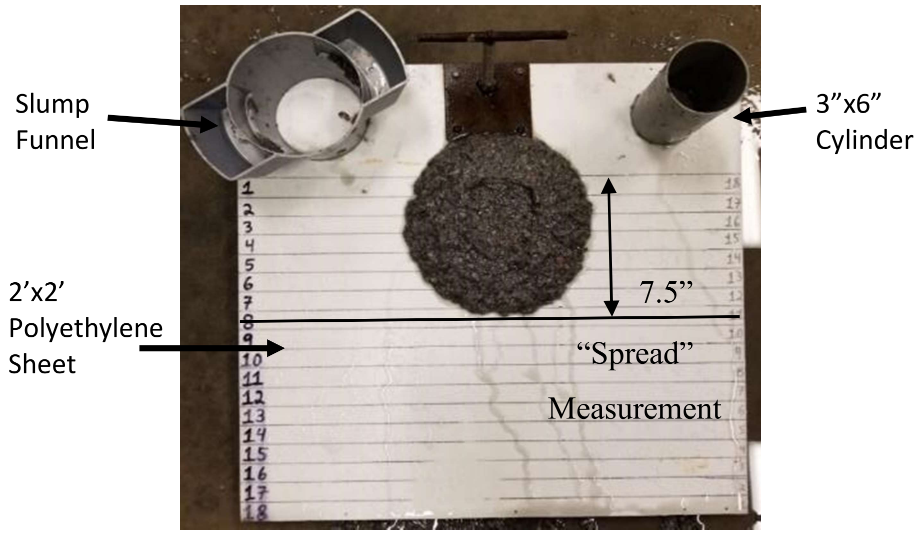

Figure2-5: Overview of Runoff Test setup, showing sheet with 1-inch marks, funnel, and 3x6 cylinder. The “Spread” is defined as the length the material flows down the sheet.

The sheet hinges on a plywood base. Figure2-6 shows how a constant slope of 12.5% or 7º, is achieved by raising the sheet 3” off the ground and setting the height with the threaded bolt. This was chosen because it is higher than a typical bridge deck and therefore would increase the likelihood of runoff giving a conservative estimate of performance. A 2’x2’x1.5” form filled with wet concrete held at the same slope of 12.5% was used in order to compare the performance of each surface. A batch of Pulp Cure with the recommended mixture proportions was tested on each surface. The Spread and material thickness were recorded. Figure2-7 shows that Pulp Cure had a Spread of 11.5” and the concrete with the polyethylene sheet and 7 inches with the wet concrete.

It was determined that the polyethylene sheet had lower surface friction compared to the fresh concrete and so this is useful to test the cohesion of the Pulp Cure.

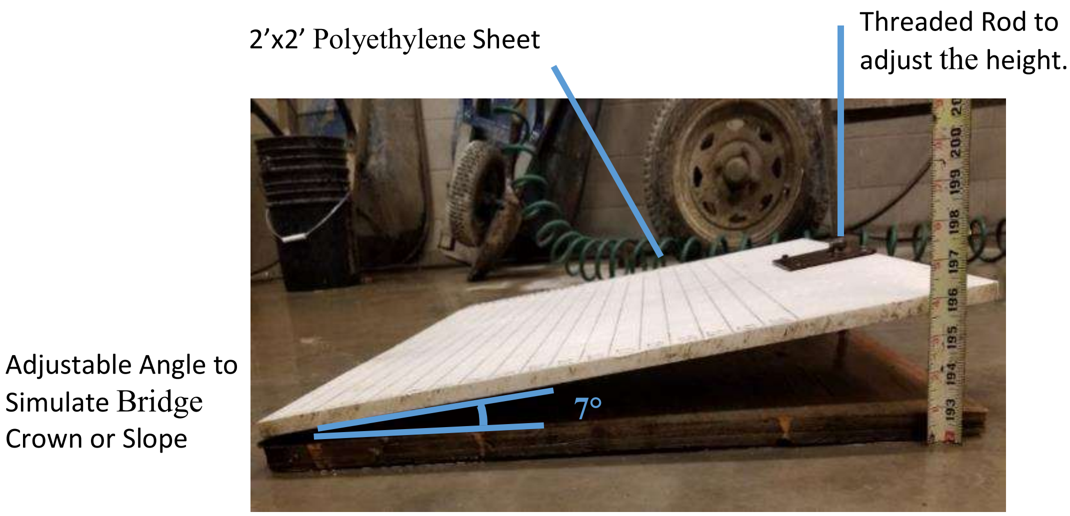

Figure2-6: Polyethylene sheet sloped at an angle of 7° to simulate a conservative bridge slope of 12.5%. This aids in determining the homogeneity of the mixture.

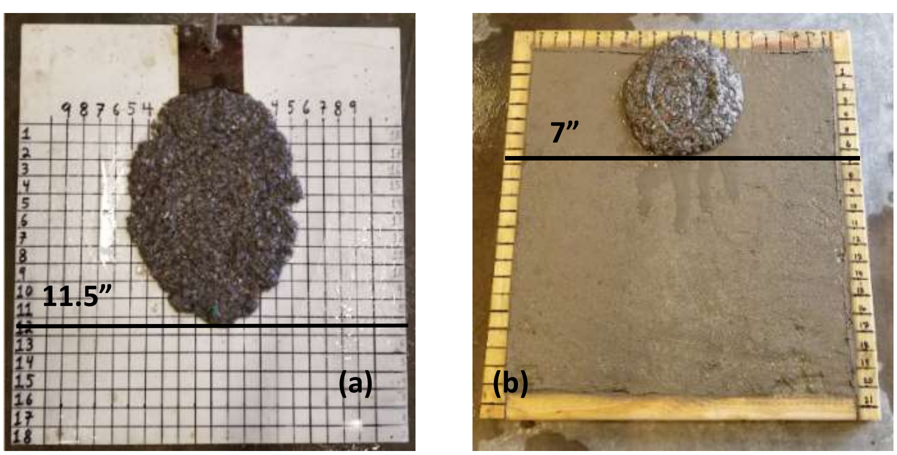

Figure2-7: Demonstration of how the polyethylene sheet has lower friction than fresh concrete. ***(a)*** *Photo showing an 11.5" Spread of a typical Pulp Cure mixture on the polyethylene sheet at 12.5% slope.* ***(b)*** *A 7" Spread of the same mixture on fresh concrete held at a 12.5% slope.*

2.3.3 Drip Test Methods:

This test involves preparing the mixtures described in Table 2-1. A 3"x6" cylinder is filled with Pulp Cure and poured into a 1-quart funnel, which has a No. 50 screen attached to the tip of the neck to prevent the paper from passing. The funnel rests on a beaker stand above a graduated cylinder (Figure2-8) placed on a scale to record the weight of fluid collected after 5 minutes. The volume of the fluid collected after 5 minutes is measured and used to compare mixtures.

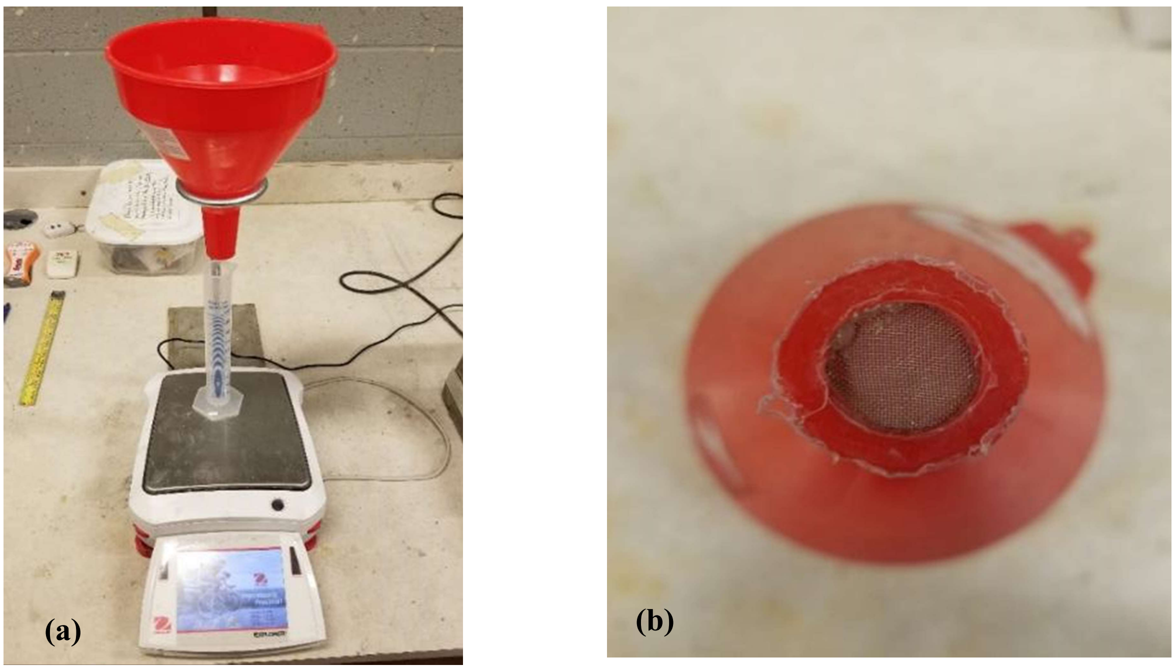

*Figure2-8: **(a)** Photograph showing the cone, stand, graduated cylinder, and scale. This setup allows for the collection of volume and weight data after 5 minutes of allowing a mixture to secrete liquid through the filtered funnel. **(b)** Photo of the #50 screen, which prevents the passing of solids.*

Figure2-9 demonstrates the results of three tests to confirm that when performed on three mixes of varying tackifier content. The three graduated cylinders contain fluid collected after 5 minutes, the volume is recorded. For the mixtures shown, there is a considerable difference between the volumes collected which demonstrates the potential effectiveness of the test.

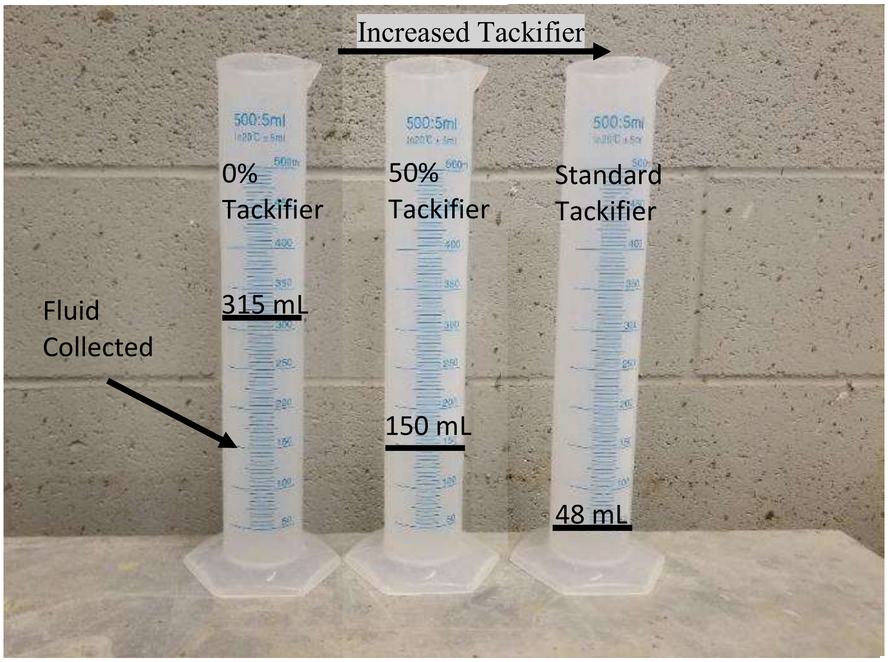

Figure2-9: Graduated cylinders representing the volumes of 315 mL for no tackifier, 150 mL for half the standard, and 48 mL for the standard drip collected after five minutes.

2.4 RESULTS AND DISCUSSION

2.4.1 Runoff Test Results:

To set a basis for comparison, results for the standard mixture, are shown in Figure2-10. Based on visual observations, the Pulp Cure has a uniform Spread of 11.5" (a), without any separation of paper particles due to the cohesive nature of the tackifier (b). This means that there is a good balance of tackifier, paper, and water in the mixture, which causes improved performance. This mixture also had a uniform thickness of 0.5".

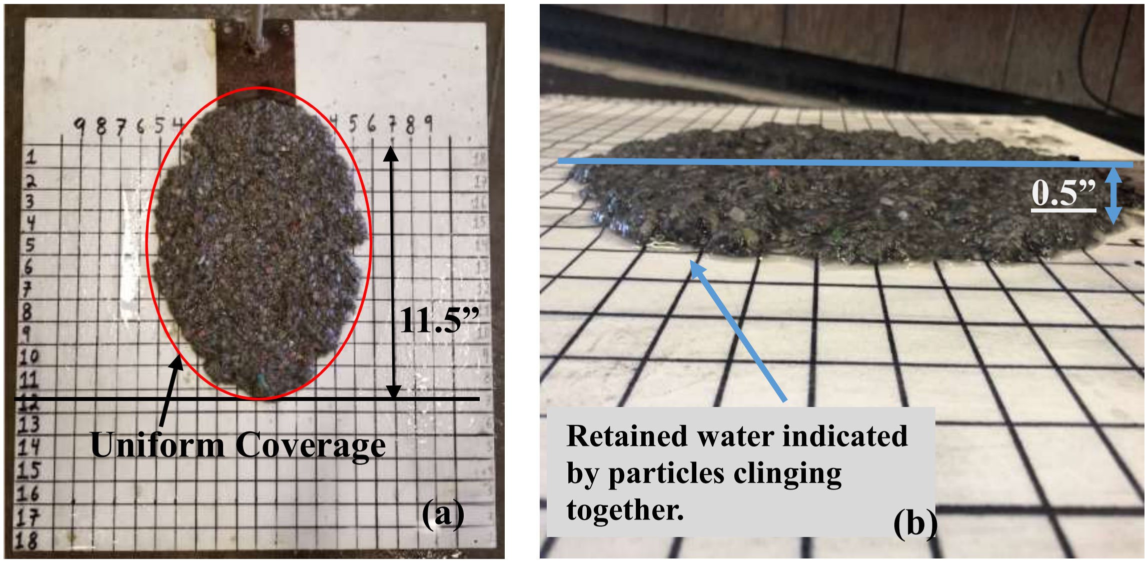

Figure2-10: ***(a)*** *Results of mixture 4 showing uniform Spread covering the surface evenly.* ***(b)*** *Picture showing the uniform thickness and particles clinging together due to the cohesion induced by tackifier.*

2.4.1.1 Modifying Tackifier in the Mixture

Figure 2-11 shows a mixture with no tackifier. Upon lifting the funnel, all of the water is allowed to freely flow off of the board leaving behind a clump or pile of non-uniform paper. This non-uniformity is caused by the paper and water act independently once released. In all cases, this led to a thick mat of uneven paper, which was measured to be 0.75 inches or greater, dispersed on the sheet. The problem with this mixture would lie in the application process. Problems would arise in using more material than desired and also not getting uniform coverage on the surface. Pumping only paper and water through the applicator could lead to clogged nozzles as well.

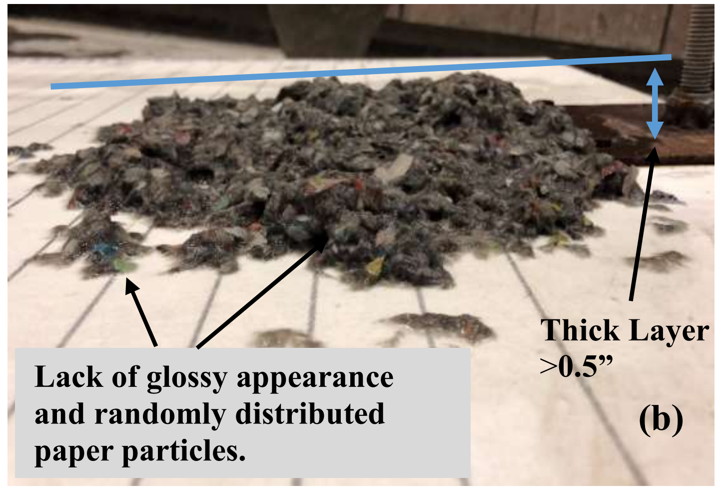

*Figure2-11: **(a)** Mixture 1 containing no tackifier, showing how water flows from the pulp leaving an irregular cover. This would be considered a non-uniform behavior. **(b)** The thickness of this mixture is greater than that of the standard mix. Paper particles can be seen scattered across the sheet in both (a) and (b).*

Figure2-12 shows the results of adding 25% of the typical tackifier, which is only 0.06% of the total volume. It can be seen that even a very low dose of tackifier begins to make the mixture more cohesive demonstrated by the semi-uniform behavior. However, the irregular perimeter means that it has not reached the ideal performance. The figure also shows the cohesion of the material beginning to improve, but the lack of glossy appearance means the water has left the mixture. The thickness of the pulp was measured to be > 0.5” which would be an inefficient use of the material but this mixture may be able to be used.

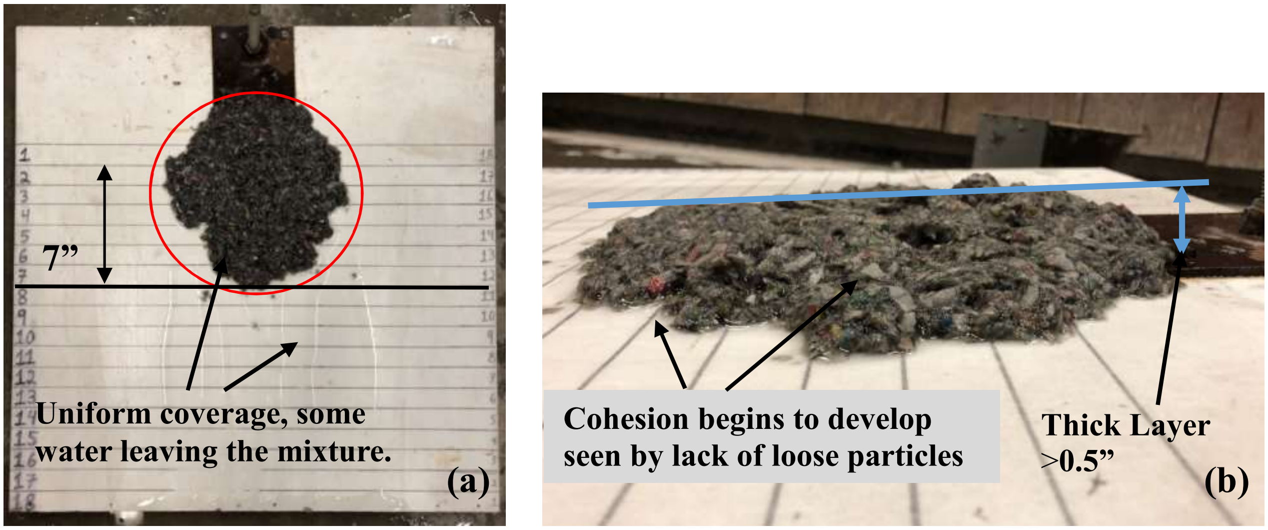

*Figure2-12: **(a)** Spread of mixture 2 with 25% of the standard tackifier, which demonstrates that the mixture has even coverage. **(b)** The photo shows the cohesion beginning to form. The thickness of the Pulp was measured to be greater than 0.5” which would be an inefficient use of the material.*

Fifty percent less than the standard tackifier had uniform coverage in most cases, also demonstrating the appropriate thickness of 0.5 inches (Figure2-13). Some tests showed that the mixture would begin to separate in the center of the Spread, which could lead to improper curing of concrete when applied. This is shown in Figure2-14. Pictures were not taken for every test, therefore, the percentage of tests that showed this behavior is not known. However, the slope test is able to identify this in the mixture design stage and so this could be corrected before being used in the field.

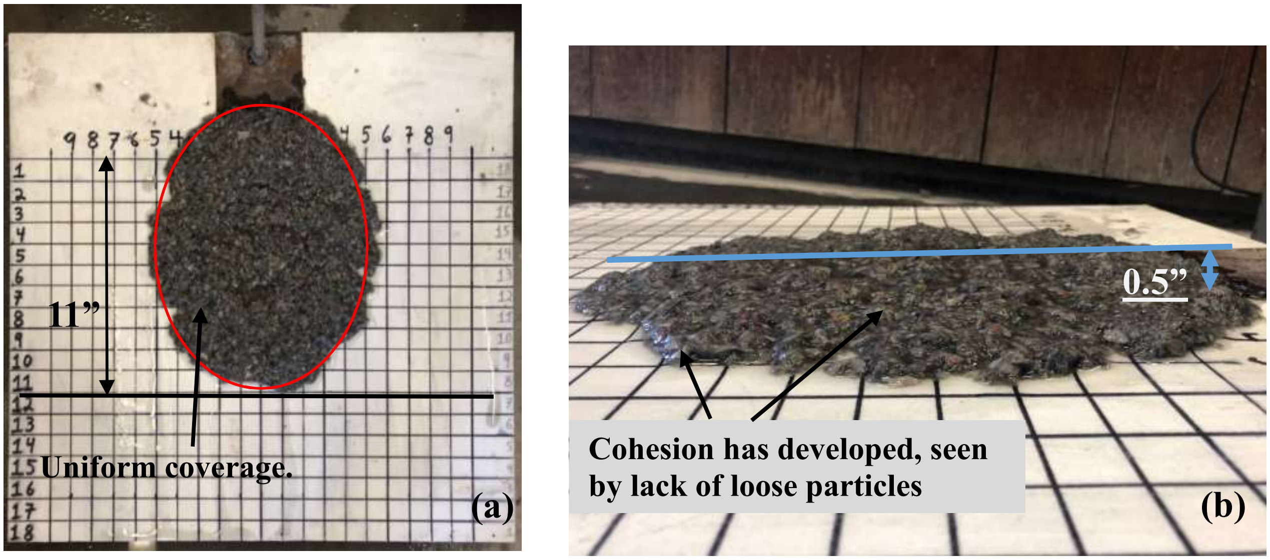

*Figure2-13: **(a) Table** showing the uniform coverage of a mixture with 50% less tackifier than the standard. **(b)** This mixture demonstrated a uniform thickness of 0.5 inches with cohesive behavior indicated by the lack of loose particles.*

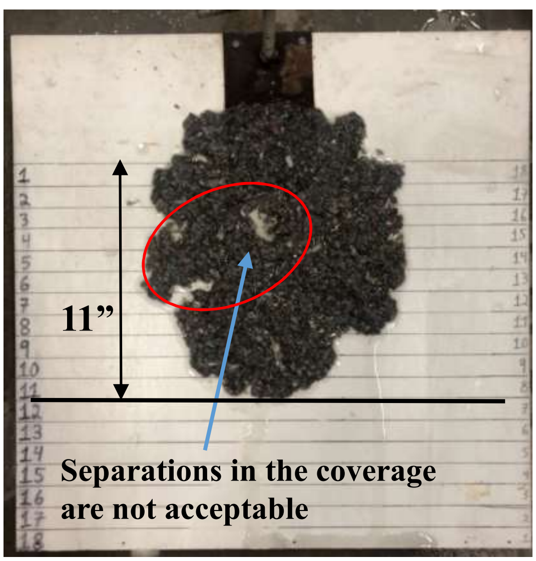

Figure2-14: The figure shows separations in the Spread, revealing the white sheet beneath. This would not be acceptable performance. Addition of tackifier would solve this issue.

Fifty percent more than the standard tackifier had uniform coverage in most cases, also demonstrating the appropriate thickness of 0.5 inches (Figure2-15b). This means that a range of tackifier can be acceptable for these materials and mixtures. Figure2-15 shows a case where the

Pulp Cure did not have the cohesiveness desired and separation occurred in the center of the Spread. Pictures were not taken for every test so the percentage of tests that showed this behavior is not known. A solution for mixtures such as this consists of the addition of water and/or paper in order to dilute the Pulp Cure. A quick test after each modification would indicate if a uniform Spread, moderate cohesive behavior, and a thickness of 0.5" has been achieved.

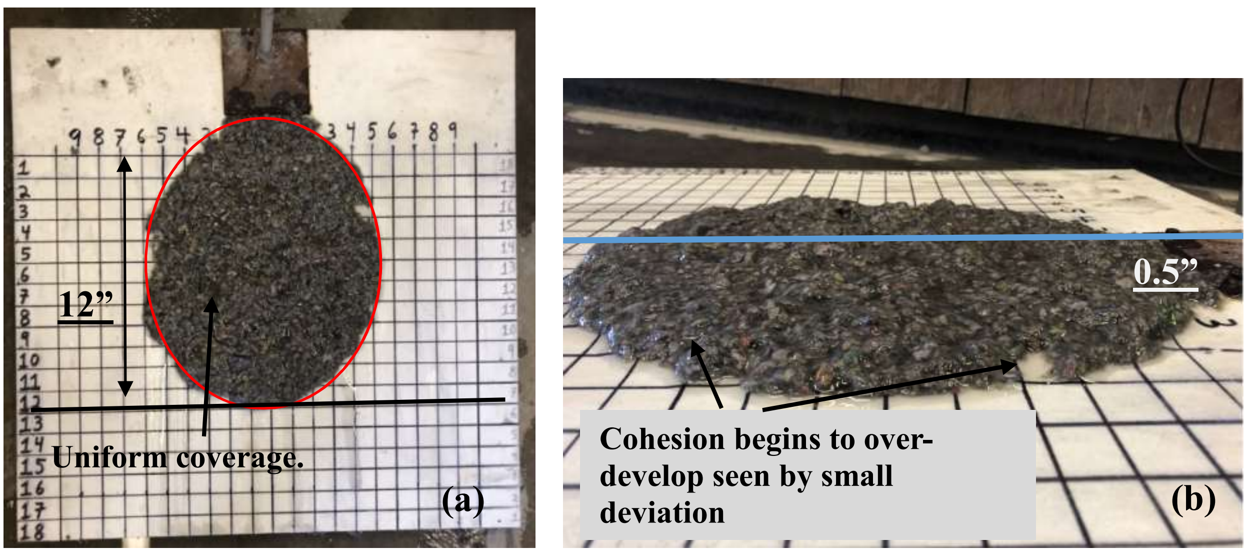

*Figure2-15: **(a)** A Spread of 12 inches is achieved with uniform coverage. **(b)** The cohesiveness is beginning to over-develop, indicated by no loose particles and a small deviation beginning to form due to mixture pulling together.*

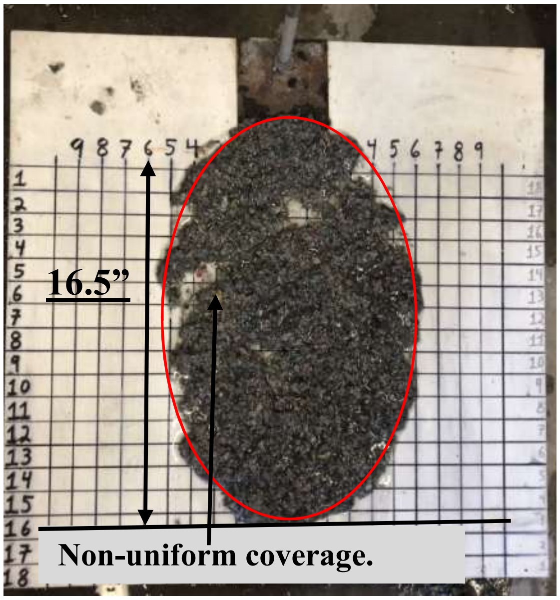

Figure2-16: The figure shows separations in the Spread, revealing the white sheet beneath. This would not be acceptable performance. A solution for mixtures such as this consists of the addition of water and/or paper in order to dilute the Pulp Cure.

Figure2-17 shows the results from mixture 6 containing double the amount of tackifier required. The sample has a Spread > 13". This is larger than previous mixtures and it causes the mixture to gather on the downhill end of the board, bulking up in that region and leading to an uneven distribution as shown in Figure2-17b. High water retention due to the excess tackifier has increased the cohesion of the material so much that it is not leaving a uniform thickness on the surface of the board. Figure2-18 represents cases where the material separated into individual masses that flowed separately, resulting in a portion of the sheet left uncovered. This is caused by too much tackifier being used in the Pulp Cure. A reduced amount of tackifier or an increase in the water in the mixture may solve this issue. One valuable thing about this test is that these changes could be rapidly made and then this could be used to modify the mixture and it could be retested.

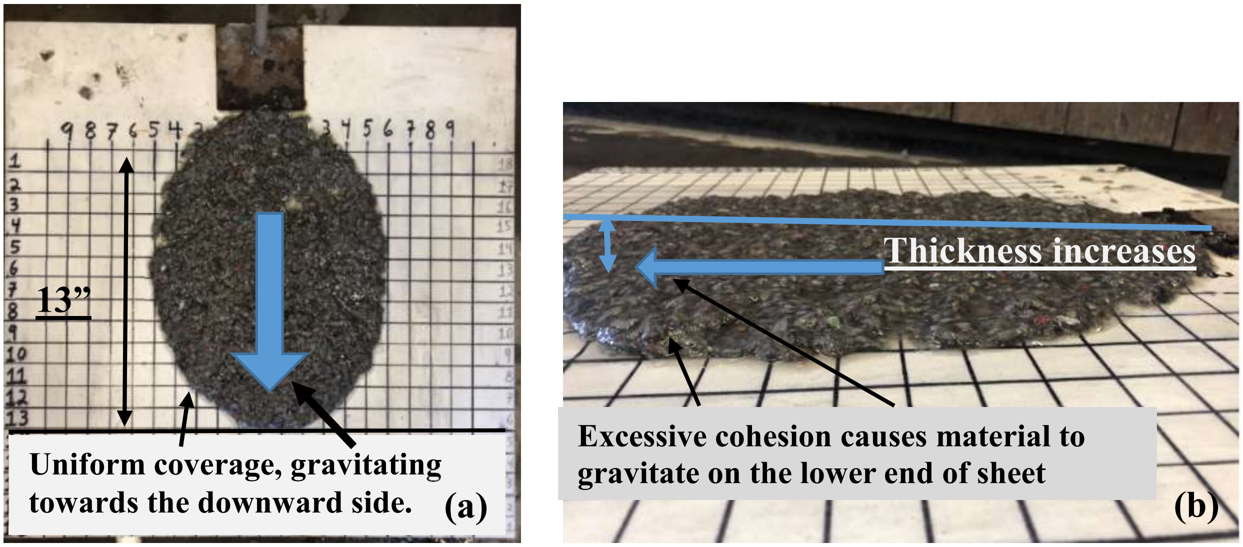

*Figure2-17: **(a)** Table showing the uniform coverage of Pulp Cure with a Spread of 13 inches. This indicates the flow is increasing. **(b)** The picture shows the thickness increasing towards the lower end of the slope.*

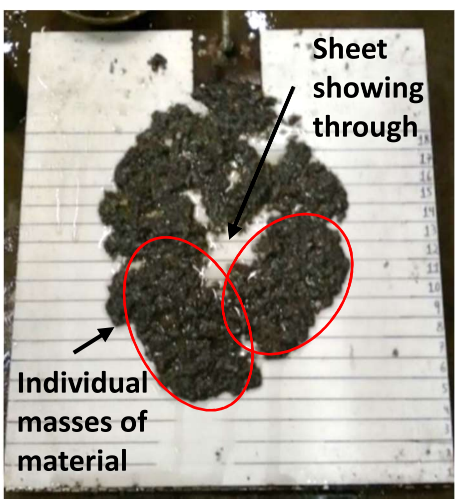

Figure2-18: The figure represents cases where the Pulp Cure separated into individual masses, resulting in non-uniform coverage, seen by the sheet being revealed in the center.

2.4.1.2 Modifying Paper in the Mixture

Modifying the paper content showed similar results to cases with the mixes that varied in no tackifier to double the standard, however, the behavior was slightly different. Figure2-19 shows the results of a mixture with 20% less paper than the standard. It demonstrated a Spread of 13 inches with non-uniform coverage. This can be seen in (a) where the sheet is seen through the center of the Spread. The distribution of the material also demonstrated a Spread wider than the previous mixes (a), making the coverage thinner (b) than the recommended 0.5 inches. The mixture retains water appropriately but lacks necessary paper to allow the cohesive forces to hold it together. This performance would not be acceptable. The addition of paper would be required in order to achieve the desired performance.

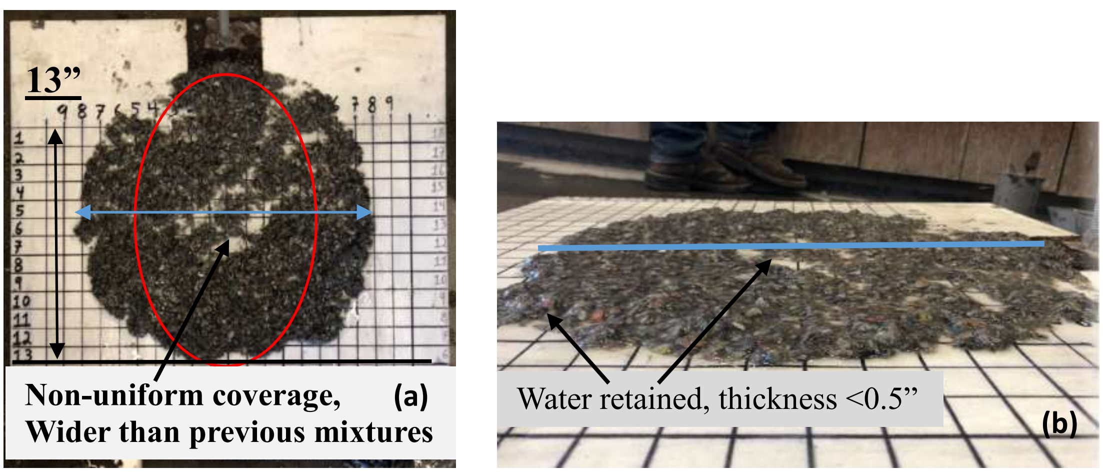

*Figure2-19: **(a)** Figure showing non-uniform coverage and a wider diameter, indicated by the blue arrow, than previous mixtures. **(b)** The figure shows a thin coverage with retained water. The lack of paper prevented the cohesion of the material to act uniformly.*

Mixtures having 20% more paper do provide even coverage (Figure2-20a). However, the Spread of 8 inches indicates that the material does not have an adequate amount of flow. This mixture would be an inefficient use of the material and could be difficult to mix in the applicator. Figure2-20b shows that the thickness is greater than the desired 0.5 inches. Desired water is retained, however, the excess paper allows the material to hold tightly together due to cohesive forces. Adding water to a mixture with this behavior and testing until desired performance is achieved would be required.

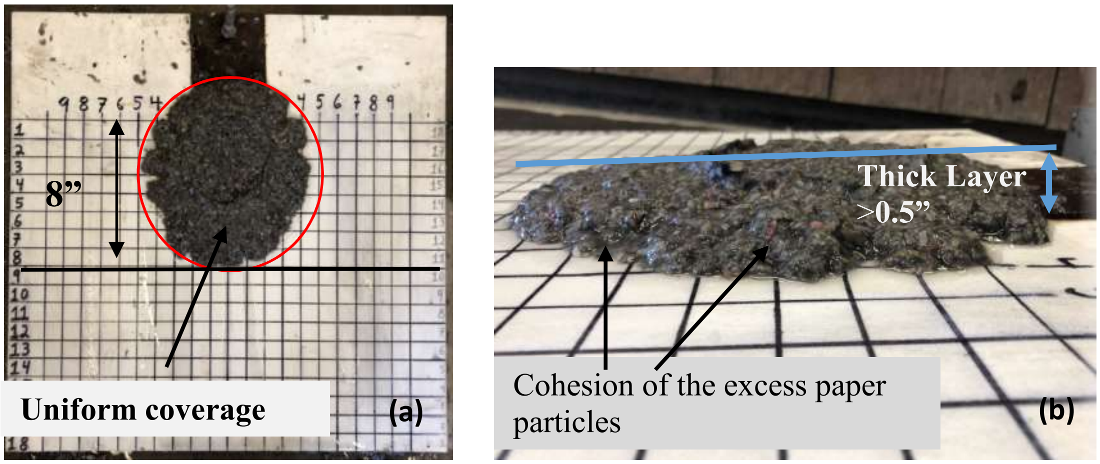

*Figure2-20: **(a)** The figure shows uniform coverage for a mixture with 20% more paper having a Spread of 8 inches. This indicates the reduced flow of the mixture. **(b)** A photo showing that though the material indicates retained water, its thickness is greater than the desired 0.5” due to the excess paper held tightly due to cohesion*

2.4.1.3 Modifying Water in the Mixture

Mixtures having 20% less water do provide even coverage (Figure2-21a). However, the Spread of 8 inches indicates that the material does not have an adequate amount of flow. This mixture would be an inefficient use of the material and could be difficult to mix in the applicator. Figure2-21b shows that the thickness is greater than the desired 0.5 inches. Adding water to a mixture with this behavior and testing until desired performance is achieved would be required.

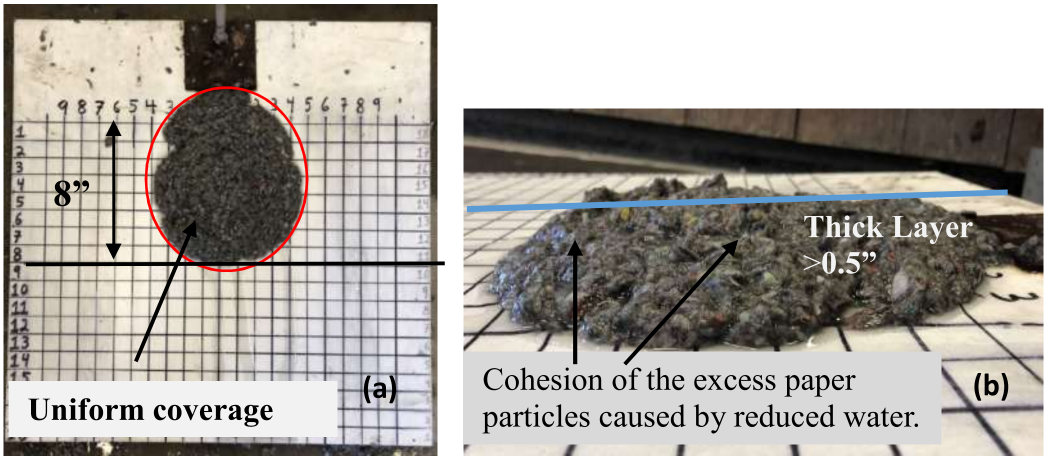

*Figure2-21: **(a)** The figure shows uniform coverage for a mixture with 20% less water having a Spread of 8 inches. This indicates the reduced flow of the mixture. **(b)** A photo showing that though the material retained water, its thickness is greater than the desired 0.5" due to cohesion of paper particles. Without the proper water, the material will not have the desired flow.*

Increasing the water content by 20% showed similar results to cases with reduced paper. Figure2-22 shows the results of a mixture with 20% more water than the standard. It demonstrated a Spread of 13 inches with non-uniform coverage. This can be seen in (a) where the sheet is seen through the center of the Spread. The distribution of the material also demonstrated a Spread wider than the previous mixes (red circle in (a)), making the coverage thinner (b) than the recommended 0.5 inches. Though it did seem to have retained water, this performance would not be acceptable. Addition of paper would be required in order to achieve the desired performance.

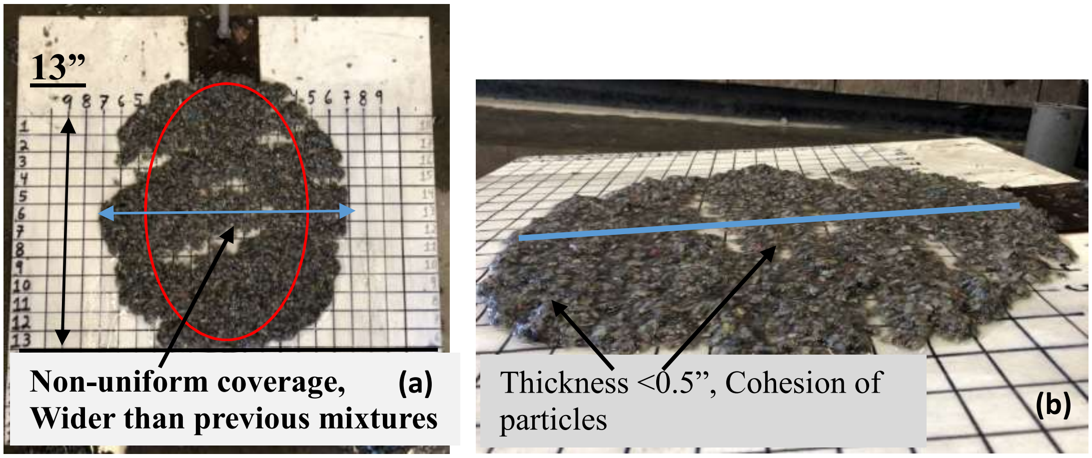

*Figure2-22: **(a) Table** showing non-uniform coverage and a wider diameter, indicated by the blue arrow, than previous mixtures. **(b)** The figure shows a thin coverage while maintaining the desired retained water. The cohesiveness of the tackifier is not enough to hold the diluted paper particles together*

The following Table 2-2**Error! Reference source not found.** presents statistics of the means, number of trials, and statistical significance using a calculated p-value to determine mixtures that have similar distributions based on the population. Statistical analysis using the Wilcoxon Signed-Rank Test, in R-Studio[4], was used to compare each mixture for a total of 45 comparisons. This method was chosen for its ability to analyze non-normally distributed data. It was found that all mixes were significantly different ($p<0.05$) except those listed in Table 2-2 tells us that for mixtures containing any more or any less than 50% of the standard tackifier, the Runoff Test will be able to determine the performance of Pulp Cure. This can be determined from the mean Spread values. Mixtures with no statistically significant difference ($p>0.05$) were found for mixtures +/- 50% tackifier from the ideal mixture. This says that the runoff test was not able to tell these mixtures apart. However, the visual observations as shown in Figs. 2-13 to 2-16 seem to be needed in order to verify a mixtures performance.

One challenge with the Runoff test is that different combinations of materials may provide the same flow. This is shown in Table 2-3. For example, the mixtures with 200% tackifier and a 20% reduction in paper both showed an increased flow over the standard mixture. However, both of these mixtures had similar values but the Runoff test finds them statistically similar. This means that either change could occur and the Runoff test would not be able to determine what caused the change. This means the visual observations of the test would be more important for these mixtures. Another example is shown with a mixture with a 25% reduction in tackifier and 20% less water.

Table 2-2: Mean Runoff Values for Each Mixture and Statistical Significance

Runoff Statistics			
Mixture Designs	***No. of Tests***	***Mean (in)***	***p-Value***
Mixture 1: *0% Tackifier*	*45*	*6.4*	$p<0.05$
Mixture 2: *25% less Tackifier*	*42*	*8.8*	$p<0.05$
Mixture 3: *50% less Tackifier*	*94*	***11.5***	***p>0.05, No Statistical Difference***
Mixture 4: Standard Tackifier	***39***	***11.9***	
Mixture 5: *150% more Tackifier*	*40*	***11.3***	
Mixture 6: *200% more Tackifier*	*42*	*14.9*	$p<0.05$
Mixture 7: *Less 20% Paper*	*36*	*15.4*	$p<0.05$
Mixture 8: *Plus 20% Paper*	*51*	*7.4*	$p<0.05$
Mixture 9: *Less 20% Water*	*37*	*8.2*	$p<0.05$
Mixture 10: *Plus 20% Water*	*27*	*13.7*	$p<0.05$

Table 2-2**Error! Reference source not found.** tells us that for mixtures containing any more or any less than 50% of the standard tackifier, the Runoff Test will be able to determine the performance of Pulp Cure. This can be determined from the mean Spread values. Mixtures with no statistically significant difference ($p>0.05$) were found for mixtures +/- 50% tackifier from the ideal mixture. This says that the runoff test was not able to tell these mixtures apart. However, the visual observations as shown in Figs. 2-13 to 2-16 seem to be needed in order to verify a mixtures performance.

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Table 2-3: Mean Runoff Values of Significant Mixtures

	Runoff Statistics		
Mixture Designs	***No. of Tests***	***Mean (in)***	***p-Value***
Mixture 6: *200% more Tackifier*	*42*	*14.9*	*p=0.4366*
Mixture 7: *Less 20% Paper*	*36*	*15.4*	
Mixture 2: *25% less Tackifier*	*42*	*8.8*	*p=0.8464*
Mixture 9: *Less 20% Water*	*37*	*8.2*	

Means for mixtures containing double the standard amount of tackifier had a significantly similar mean to mixtures with 20% less paper. Mixtures with 25% of the standard tackifier had significantly similar means to mixtures with 20% less paper. This tells us that for these mixtures, Spread value alone is not enough to determine the performance. However, the Runoff Test will be very effective when used in combination with Spread measurement and visual observation.

2.4.1.4 Practical Significance

The Runoff Test proves to work well in determining if the Pulp Cure will cover the surface uniformly with at least 0.5" of material thickness and have the ability to retain moisture. This concluded that mixtures within 50% of the standard tackifier amount can meet these requirements, but should be confirmed using the Runoff Test and visual observation. Mixtures with a Spread less than 9 inches that demonstrate cohesion from the tackifier and uniform coverage, may be suitable for curing. However, they would be an inefficient use of the material and would be difficult to thoroughly mix in the applicator. This can be solved by adding water and re-evaluating until the desired performance is achieved.

Mixtures that have a Spread > 13 inches with non-uniform coverage need to be adjusted by adding paper and re-testing until the desired performance is achieved. Testing showed that mixtures with more than 150% of the standard tackifier exhibit high water retention, which will cause the material to flow off of a surface with a slope higher than 12.5% and for slopes less than 12.5% it may segregate leaving the surface exposed. Water and paper will need to be added then the material re-evaluated until the desired performance is achieved.

2.4.2 Drip Test:

The statistics for mixtures 1-10, including number of tests and mean volumes, are presented in Table 2-4. Statistical analysis using the Wilcoxon Signed-Rank Test, in R Studio[4], was used to compare each mixture for a total of 45 comparisons. This method was chosen for its ability to analyze non-normally distributed data. It was found that all mixes were significantly different ($p<0.05$) except those listed in Table 2-5.

Table 2-4: Drip Test Statistics

Drip Test Statistics			
Mixture Designs	***No. of Tests***	***Mean (mL)***	***p-Value***
Mixture 1: *0% Tackifier*	*34*	*393*	*p<0.05*
Mixture 2: *25% less Tackifier*	*42*	*177*	*p<0.05*
Mixture 3: *50% less Tackifier*	*52*	*103*	*p<0.05*
Mixture 4: Standard	***84***	***64.4***	*p<0.05*
Mixture 5: *150% more Tackifier*	*38*	*53.1*	*p<0.05*
Mixture 6: *200% more Tackifier*	*67*	*29.8*	*p<0.05*
Mixture 7: *Less 20% Paper*	*36*	*63.9*	*p<0.05*
Mixture 8: *Plus 20% Paper*	*59*	*72.5*	*p<0.05*
Mixture 9: *Less 20% Water*	*37*	*46.1*	*p<0.05*
Mixture 10: *Plus 20% Water*	*31*	*74.6*	*p<0.05*

It can be seen in the table that for the mixture with zero tackifier, the mean volume collected is 393 mL and decreases to 29.8 mL when the tackifier amount reaches double the standard amount. The data in the table suggests that, based on the means, the volume collected after 5 minutes can determine approximate tackifier content. Means for mixtures varying in paper or water content by 20% can also be verified using the Drip Test. When cross comparing the means for all mixtures it was found that there were significant ($p>0.05$) values for the mixtures listed in Table 2-5.

Table 2-5: Statistically Significant Drip Test Mixtures

Drip Test Statistics			
Mixture Designs	***No. of Tests***	***Mean (mL)***	***p-Value***
Mixture 4: Standard	***84***	***64.4***	*p=0.6395*
***Mixture 7:** Less 20% Paper*	*36*	*63.9*	
***Mixture 5:** 150% more Tackifier*	*38*	*53.1*	*p=0.1319*
***Mixture 9:** Less 20% Water*	*37*	*46.1*	
***Mixture 8:** Plus 20% Paper*	*59*	*72.5*	*p=0.8451*
***Mixture 10:** Plus 20% Water*	*31*	*74.6*	

Mixture 7 with 20% less paper than the standard has almost the exact same mean volume collected as the standard at 63.9 and 64.4 mL respectively. The significance is confirmed with the Wilcoxon Method given a p-value greater than 0.05. Mixture 9 with 20% less water than the standard is shown to be significantly similar ($p<0.05$) to mixtures containing 150% of the standard tackifier. Mixtures 8 and 10 with 20% more paper and water than the standard performed significantly similar ($p<0.05$) with means of 72.5 and 74.6 respectively.

2.4.2.1 Practical Significance

The Drip Test performed well in determining mixtures with varying tackifier content. It is also worthy to note that the volumes are contradictory to intuition. Data in Table 2-3 suggests that in the Drip Test the mixture with excess water drips a similar volume as the mixture with excess paper. However, it was seen in the Runoff Test that mixtures with less paper performed similarly to mixtures with excess water. It is difficult to differentiate mixtures that vary in paper or water by 20% using the Drip Test because it does not directly indicate how the mixture will behave when it is applied. This is important because the Runoff Test showed that these mixtures vary greatly in physical behavior by the way they Spread and if they present uniform coverage. Further testing at higher replacement levels of paper and water would be beneficial in confirming this.

2.5 CONCLUSION

In conclusion, significant progress has been made developing Pulp Cure as a new curing method for concrete. Development of a batching and delivery system made possible field applications that led to the need for quality testing. The Runoff Test is proving to be a powerful aid in performing these quality tests quickly and with relative certainty. This test is unique because it allows both qualitative and quantitative data to be gathered and used together to determine the quality of the Pulp Cure mixture. The testing found that there is a range of mixture designs that showed successful performance. This can help save cost or modify the desired performance for different applications.

The Drip Test proved to work well when mixtures varied in tackifier content. However, it was difficult to distinguish mixtures varying in tackifier content to those of paper or water. This could be verified testing mixtures with higher replacement levels of water and paper in order to see if the volume collected would give a greater significance of the means.

Overall, the Runoff Test proves to be the best suited for any mixture such as Pulp Cure when quality testing is required in the field. This is because it is a simple, practical, and cheap method. The Runoff Test utilizes the natural physical behavior of the material, allowing it to reveal how it will perform. This, in turn, allows the user to determine what is appropriate for the application and what might be altered to achieve the desired performance.

2.6 FUTURE WORKS

Going forward, testing will be needed at higher levels of varying paper and water. This will help to confirm which variable has the greatest impact on physical behavior when the Pulp Cure is applied. Determining with certainty what ingredient is missing and which ingredient will fix the issue is extremely valuable. It is also proving helpful to have both horizontal and vertical grid lines in order to measure both the length and width of Spread when using the Runoff Test. This will add tools to be able to determine the area the Spread covers or what percent of the sheet is revealed if there is non-uniform Spread.

In order for Pulp Cure to really be time and cost efficient in the field, modifications are needed in the batching system. By designing a larger batching and delivery system, the time needed to cover a bridge deck will greatly be reduced. This is due to the reduced number of times workers will need to mix new batches. Multiple mixtures also increase the variability from mixture to mixture, which will, in turn, add additional time needed to test for quality. All of this cannot be viable without quality control that is used in designing and verifying that Pulp Cure can be regularly produced. Further development of these testing procedures at higher variations in paper and water content is going to produce such quality control.

CHAPTER 3

INVESTIGATING PERFORMANCE AND QUALITY CONTROL OF CONCRETE WITH INCREASED FLY ASH REPLACEMENT

3.0 INTRODUCTION

Fly ash is a by-product of coal combustion, made up of particles that are collected through various methods before exiting the flu. It is therefore made up of several major oxides such as CaO, Al_20_3, $Si0_2$, Fe_2O_3, and some minor oxides. ASTM C618[1] uses a method that separates fly ash into two groups Class C or Class F based on their major oxide contents. Though there are many uses for fly ash such as soil stabilization, wastewater treatment, and supplementary cementitious material (SCM) for concrete, use as an SCM is steadily growing. Reports from AACA say fly ash used in concrete went from 11-million short tons used in 2010 to 14-million in 2019[2]. This is due to its economic and performance benefits. Despite this, there are some difficulties when it comes to consistency and performance predictability. This chapter aims to gather the performance data for a variety of different fly ash at both 20% and 40%. A general evaluation will be made to compare the performances between these materials in concrete mixtures at different volumes to see if the mixtures are feasible to be used and if there is a bulk property that can be used to evaluate the performance in concrete. The goal of this chapter is gathering this information for much more detailed investigations by other research in the future.

3.1 EXPERIMENTAL METHODS

3.1.1 Laboratory Materials

All of the laboratory concrete mixtures in this research used a Type I cement that met the requirements of ASTM C150[5]. Both the oxide analysis and Bogue calculations for the cement used is shown in Table 3-1. All 19 fly ash were produced in the United States from sources in various states including Texas, Oklahoma, and Illinois. Of these, 12 of the fly ash were classified as Class C and 7 were classified as Class F by ASTM C618[1]. Oxide analysis and particle size distribution were completed by Shinhyu Kang using an automated scanning electron microscope (ASEM)[6]. The chemical compositions for each fly ash are presented in Table 3-2**Error! Reference source not found.**. The aggregates used were locally available crushed limestone and natural sand used in commercial concrete. The crushed limestone had a maximum nominal aggregate size of 19 mm (3/4"). Both the crushed limestone and the sand met ASTM C33 specifications[7].

Fly Ash listed in Table 3-2**Error! Reference source not found.** is labeled using an existing system for fly ash frequently tested within our research facility. The letters represent the class of fly ash followed by an identifying number "C#" or "F#" exceptions being IC and IF, which were obtained for research by the Illinois Department of Transportation and thereby denoted with the letter "I" in order to differentiate them.

Table 3-1: Type I cement Oxide Analysis and Bogue Calculations

Oxide (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	P_2O_5	SO_3	K_2O	TiO_2	SrO	C_3S	C_2S	C_3A	C_4AF
Cement	62.1	21.1	4.7	2.6	0.2	2.4	-	3.2	0.3	-	-	56.7	17.8	8.2	7.8

Table 3-2: Fly Ash Oxide Analysis

Oxide (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	P_2O_5	SO_3	K_2O	TiO_2	SrO
Class C Fly Ash											
C1	23.2	36.2	21.7	5.3	3.6	5.4	1.9	0.7	1.0	0.8	0.2
C2	26.9	35.8	19.2	5.6	3.0	5.5	1.2	1.0	0.9	0.7	0.2
C3	32.5	25.3	19.3	5.2	3.4	7.8	1.9	2.6	0.6	1.1	0.3
C4	22.4	36.7	22.8	4.5	3.4	4.3	1.1	1.2	1.0	1.3	1.2
C5	26.1	31.3	22.5	5.4	4.3	6.0	2.1	0.6	0.8	0.8	0.2
C6	21.5	27.7	22.9	4.2	12.6	4.5	0.7	2.5	0.8	1.3	1.3
C7	24.7	35.3	20.6	4.7	4.3	4.9	0.8	0.7	1.2	1.6	1.0
C11	27.1	31.0	20.8	6.4	3.5	7.1	0.8	1.6	0.7	0.8	0.2
IC1	28.2	31.8	22.9	5.7	2.3	5.5	0.5	1.1	1.0	0.8	0.3
IC2	30.5	25.2	21.2	6.2	4.0	7.8	2.2	1.0	0.6	1.2	0.2
IC3	30.3	29.7	21.0	5.9	2.2	5.4	1.6	1.9	0.6	1.0	0.5
IC4	31.8	29.9	17.7	4.7	2.6	9.3	1.1	1.2	0.8	0.8	0.2
Class F Fly Ash											
F1	12.5	48.8	23.8	7.4	0.9	3.0	0.1	0.5	2.1	0.8	0.3
F2	17.1	50.4	20.9	3.9	1.0	3.7	0.1	0.5	1.4	0.7	0.3
F3	9.3	48.8	26.6	6.6	1.7	2.0	0.1	0.3	1.9	1.5	1.1
F4	14.6	45.3	27.4	4.0	1.5	3.6	0.4	0.7	0.6	1.1	0.8
F5	2.1	53.2	25.4	11.2	1.0	0.2	0.0	0.9	4.4	0.7	1.0
F6	2.5	51.9	25.7	12.3	1.6	0.3	0.1	0.7	4.1	0.7	0.2
IF1	3.7	58.3	21.9	6.9	2.2	1.4	0.4	0.6	4.3	0.2	0.2

Table 3-3 displays the fly ash and OPC ranked in order by their calcium oxide content. This table calculates the ratio of calcium oxide to silica plus aluminum content in order to use as a comparison versus various hardened properties, which will be discussed in the results section of this paper.

Table 3-3: Fly Ash Ranked in order of their Calcium Oxide Contents. Displaying the ratio of calcium oxide to silica plus alumina.

Cementitious Material	CaO	SiO_2	Al_2O_3	$CaO/(SiO_2+Al_2O_3)$
OPC	62.1	21.1	4.7	2.41
C3	32.5	25.3	19.3	0.73
IC4	31.8	29.9	17.7	0.67
IC2	30.5	25.2	21.2	0.66
IC3	30.3	29.7	21.0	0.60
C11	27.1	31.0	20.8	0.52
IC1	28.2	31.8	22.9	0.52
C2	26.9	35.8	19.2	0.49
C5	26.1	31.3	22.5	0.49
C7	24.7	35.3	20.6	0.44
C6	21.5	27.7	22.9	0.43
C1	23.2	36.2	21.7	0.40
C4	22.4	36.7	22.8	0.38
F2	17.1	50.4	20.9	0.24
F4	14.6	45.3	27.4	0.20
F1	12.5	48.8	23.8	0.17
F3	9.3	48.8	26.6	0.12
IF1	3.7	58.3	21.9	0.05
F6	2.5	51.9	25.7	0.03
F5	2.1	53.2	25.4	0.03

3.1.2 Mixture Design

A conventional concrete with 100% cement was compared to 20% fly ash and 40% fly ash replacement with the nineteen different sources provided in Table 3-1 and Table 3-2. These mixture designs used for the mixtures in Table 3-4. No air-entraining or water reducing admixtures were used in the testing.

Table 3-4: Mixture Designs

Mixture	w/b	Cement (lbs)	Fly Ash (lbs)	Water (lbs)	Paste (%)	Coarse (lbs)	Fine (lbs)
OPC	0.45	625	0	281	28.8	1903	1243
20% Fly Ash	0.45	500	125	281	28.9	1900	1240
40% Fly Ash	0.45	375	250	281	29.0	1892	1228

Isothermal calorimetry testing was performed according to ASTM 1702[8] for all 40% mixtures and ten fly ash at 20% replacement using mixtures described in Table 3-5.

Table 3-5 : Isothermal Calorimetry Paste Design

Mixture	w/b	Cement (lbs (10^{-3}))	Fly Ash (lbs (10^{-3}))	Water (lbs (10^{-3}))	Paste (%)
OPC	0.45	4.409	0	1.984	100
20% Fly Ash	0.45	3.527	0.8818	1.984	100
40% Fly Ash	0.45	2.645	1.764	1.984	100

3.1.3 Concrete Mixing Procedure

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 23°C for at least 24 hours before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately one half 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 concrete was mixed for three minutes.

3.1.4 Testing Procedure

Fresh concrete was then transferred from the mixer to a wheelbarrow where it was tested for air using an ASTM C231[9] Type B air meter. The slump and unit weight were also collected according to ASTM C143 and C138[10, 11], respectively.

The concrete was then used to make 24 samples of 4"x8" cylinders, prepared according to ASTM C192[12]. These cylinders were then placed in a controlled environment chamber at 70 ˚F and 100% RH until the day of testing. Compressive strength (ASTM C39[13]) and resistivity (AASHTO T 358) testing was completed at 3, 7, 14, 28, 56, 90, and 180 days. The samples were left in their cylinder molds until they were tested. This was done to prevent leaching from the surface of the cylinder by the spray in the fog room. A control mixture was tested for strength and resistivity to set a basis for comparison. Kang completed preliminary testing of all fly ash listed in Table 3-2 with 20% replacement, except fly ash listed IC or IF[6, 14].

3.2 RESULTS & DISCUSSION

3.2.1 Overview

Table 3-6 presents a summary of data collected for each set of mixtures. These are presented as the maximum and minimum values recorded for the fresh properties and hardened properties. Extensive tables for the entire data set are included in the appendix. Two OPC mixtures were tested, one from Kang's research[6] and one for the research discussed here. They were compared and found that the strengths varied by a coefficient of variation less than 8% up to 90 days and 13% at 180 days. The data listed for OPC is an average of the two mixtures.

Slumps showed an increase for all mixtures that included fly ash when compared to the OPC mixture, which had a 1-inch slump. This is due to the small spherical fly ash particles acting as ball-bearings within the paste matrix, reducing friction between particles in the mixture. There were three fly ash that did not follow this behavior. This is discussed in the next section.

Table 3-6: Summary of Testing Results

Test	***OPC***	***20% Fly Ash Replacement***	***40% Fly Ash Replacement***
Slump (in)	1	1.5-6.5	2.5-7
Air (%)	1.7	0.8-1.5	0.8-1.4
Unit Weight (lb/ft^3)	149.8	148.3-154.7	149.2-152.8
28-Day	5450-6480	5130-7800	4040-7590

Compressive Strength (psi)			
28-Day Resistivity (kOhm-cm)	8.35-13.0	9.58-19.0	8.98-27.3
Isothermal Calorimetry (J/g)	172	*113-153	138-341

*Only Ten of the 19 fly ash were tested for Isothermal Calorimetry.

3.2.2 Slump test

Slump tests were performed for each mixture following the ASTM C143[10] testing method. While the slump test is not a workability test, it has great merit in providing consistency of fresh concrete to fall under its own weight. Therefore, this can provide an understanding of the change in consistency. Figure3-1 displays the slumps for all fly ash, comparing the 20% to 40% mixtures.

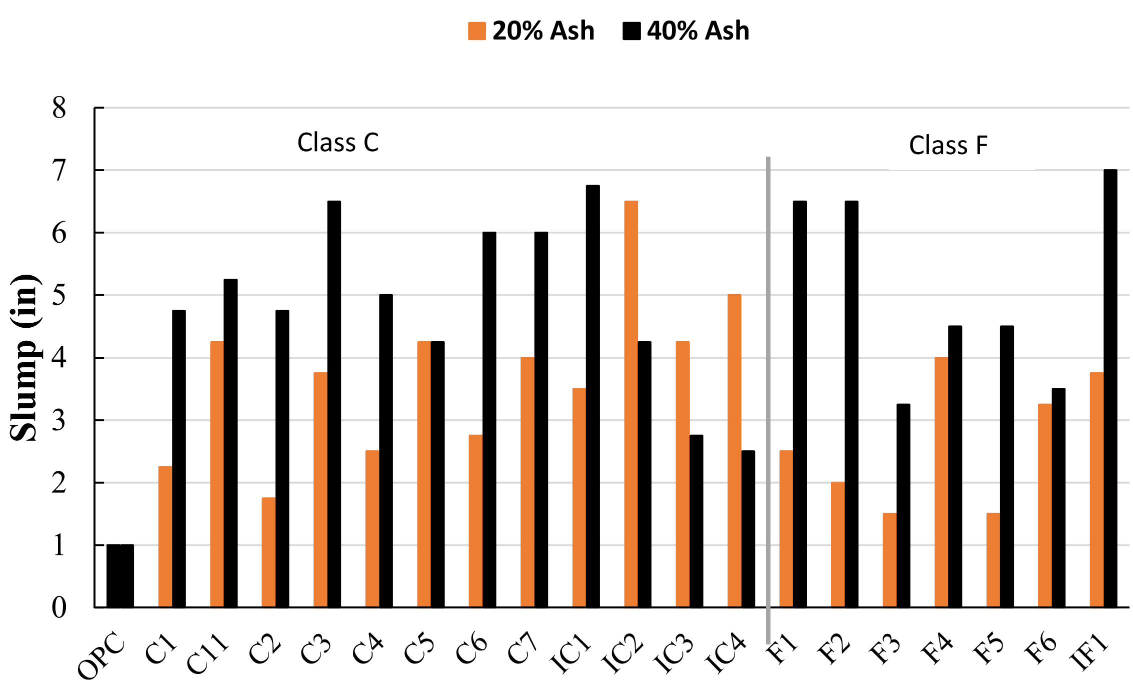

Figure3-1: Table showing the comparison of slumps measured for each fly ash mixture at 20% and 40% replacement levels. This demonstrates the variation of workability that is achieved based on the type of fly ash.

Results varied for each mixture, in most cases the 40% mixtures had a higher slump than the mixtures at 20% replacement by an average of 1.2 inches. Of the class C mixtures, C6 and IC1 showed the greatest increase in the slump at 3.25 inches. Of the class F mixtures, F2 fly ash showed the greatest increase in slump with 2 inches at 20% compared to a slump of 6.5 inches at 40% replacement. However, this is not always the case. IC2, IC3, and IC4 showed higher slumps at the 20% replacement level by 2.25, 1.5, and 2.5 inches, respectively, while F6 and F4 showed little effect on the slumps for the 40% mixture. C5 had no change in slumps between 20% and 40% replacement levels.

3.2.2.1 Discussion of Varying Slumps of IC2, IC3, and IC4

The reason for the slumps of IC2, IC3, and IC4 being higher at 20% than 40% replacement were thought to be directly related to particle size distribution (PSD). However, when looking closely at the PSD, these three fly ash did not show a distribution profile that was significantly different from the other fly ash. Figure3-2 shows a cumulative distribution. In the plot, the D50 or diameter of 50% of the distribution is highlighted and used to discuss the results.

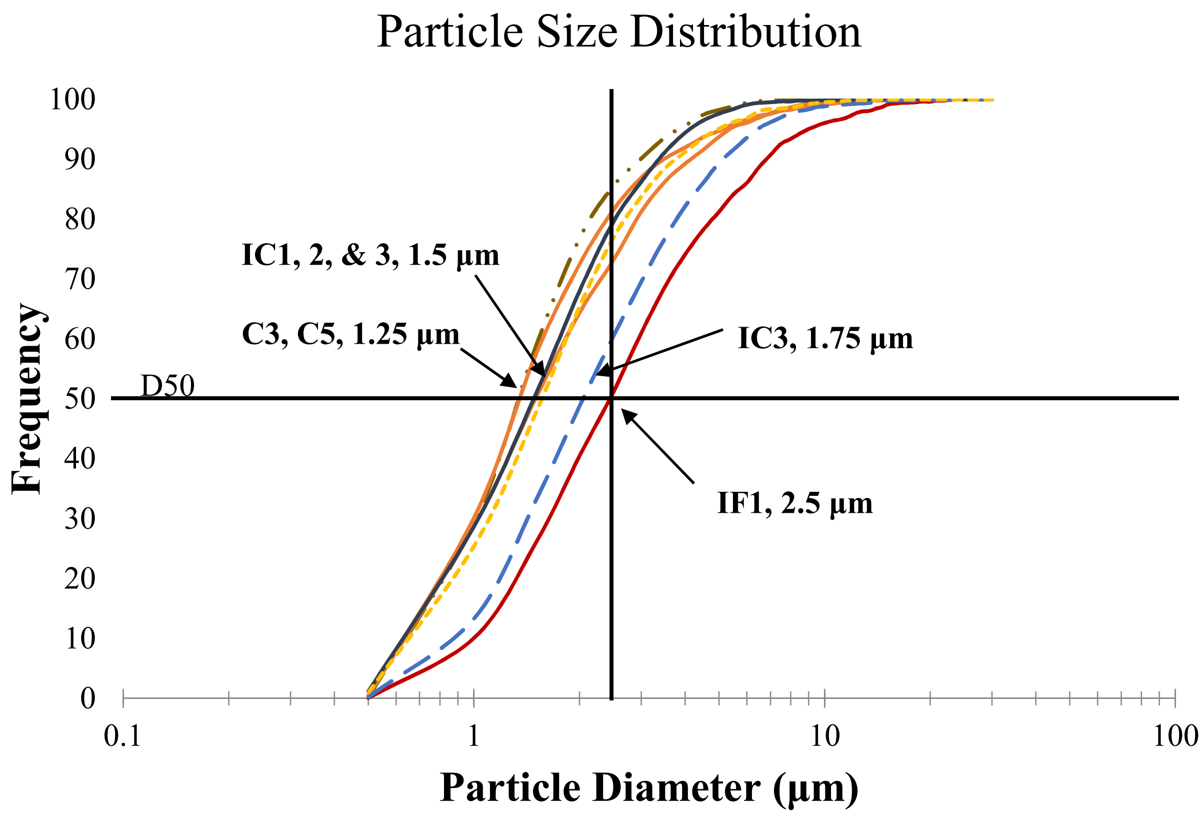

Figure3-2: The figure shows that fly ash C5 and C3 have D50 particles that are 1.25 microns and IF1 has a D50 of 2.5 microns. IC2, IC3, and IC4 have particle size distributions that fall between the range for all fly ash, yet their slumps were higher at 20% than 40%.

3.2.2.2 Discussion of the varying slumps of C3, C5, and IF1

Upon closer inspection of Figure3-2, C5 and C3 have 50% of their particles that are less than 1.25 microns and IF1 has particles that are 2.5 microns and less. It could be concluded that, if particle size distribution has a significant contribution to the set of fly ash tested herein, there would be a significant difference between the slumps of C5 or C3, and IF1. This is due to their particles setting the minimum and maximum range at D50 for the fly ash tested. It would also be reasonable to assume that C5 and C3 would have very similar slump behavior in that they appear to have a very similar PSD. In Figure3-1, shown previously, C5 showed no change in a slump for both 20% and 40% mixtures, whereas C3 had slumps of 3.75 and 6.5 inches. This disproves the hypothesis that the similar PSD for C5 and C3 would also contribute to a similar slump. IF1 had similar slump values at 3.75 and 7 inches, compared to C3, which had a smaller particle size. This is evidence to disprove the hypothesis mentioned previously that for IF1 to have a factor of 2 times the PSD of C3, there would be slump values with a greater difference than what is shown.

Further investigation consisted of determining if there was a direct correlation between slump and the mean particle size. The following Figure 3-3 shows slump measurement versus the mean particle size for each fly ash at 20% and 40% replacement. The R^2 values indicate that there is no correlation. An R^2 value of one would indicate strong correlation, while an R^2 value of zero indicates zero correlation. The 40% mixtures show an R^2 of zero and the 20% a value of 0.2. This could be an area for future research through testing slumps with repeated mixtures.

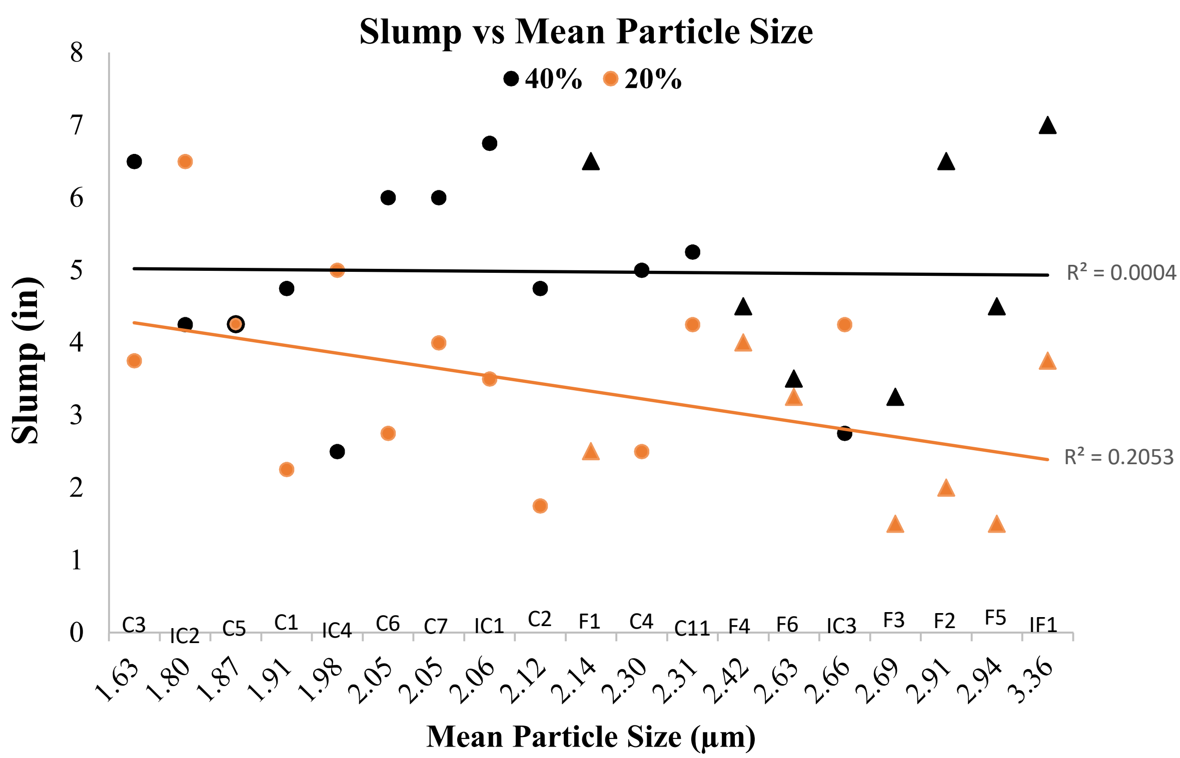

Figure 3-3: Comparing slump versus mean particle size showed no correlation for mixtures with 20% or 40% fly ash. Note: Round data points represent Class C fly ash, and triangles represent Class F.

3.2.3 Compressive Strength Testing of 3-day and 90-day Samples

Figure3-4 shows all 20% fly ash mixtures as a percent of OPC at 3 and 90 days, OPC being 100% denoted by the solid black horizontal line. Standard deviations are indicated by lines above and below each data point, except for cases with deviations less than 1%. Class C and F fly ash are divided by the vertical grey line. Class C fly ash reached the strength of the control at 3 days, the minimum being C4 and IC1 at 91% and C5 reaching the greatest at 135%. Class F fly ash did not reach the strength of OPC at 3 days, which is typical of the pozzolanic behavior of F fly ash. However, they did reach within 20% of OPC, IF1 reaching 83% and F2 reaching 95%.

All mixtures met or exceeded the strength of OPC at 90 days by as much as 135%. The maximum for Class C, C5 reached 135% at 90 days, F1, F2, and F3 fly ash reached a maximum of 121% of OPC at 90-days. A table of the compressive strengths will be listed in the appendix.

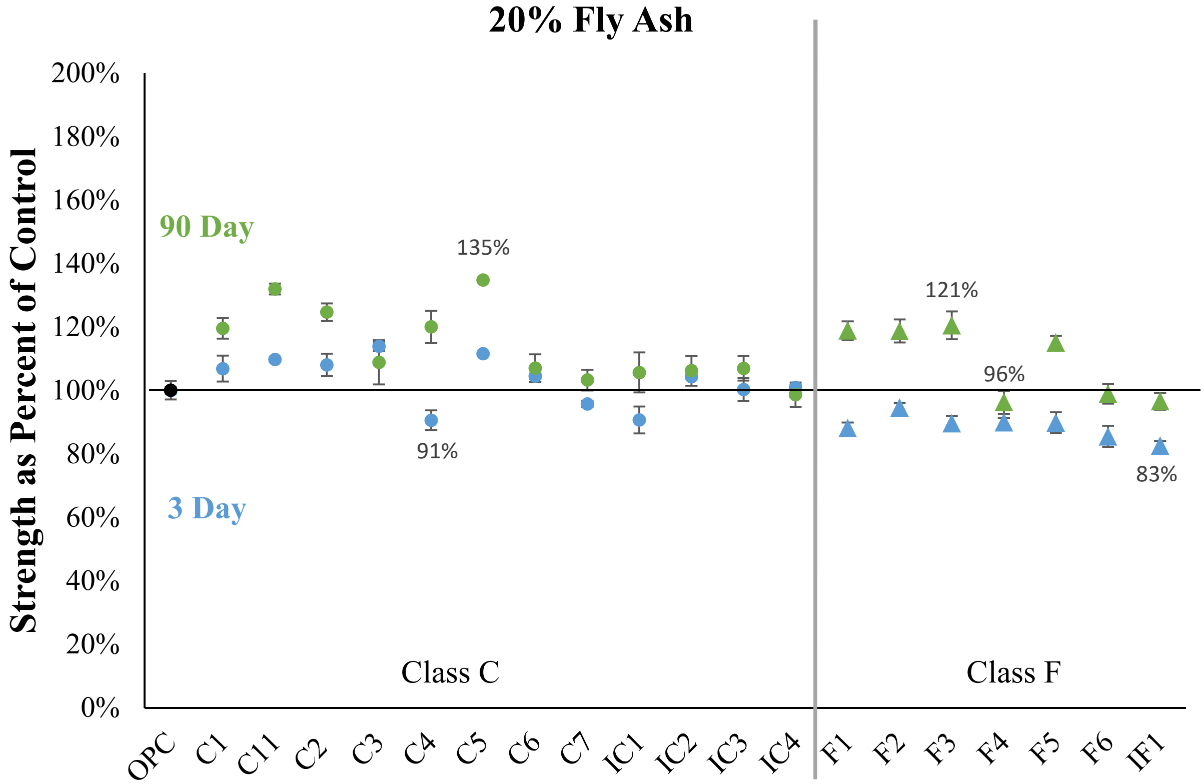

Figure3-4: 20% fly ash mixtures compressive strength presented as a percent of the control. All mixtures at the 20% replacement level met or exceeded the 90-day strength of the control.

Figure 3-5 shows all 40% fly ash mixtures as a percent of OPC at 3 and 90 days, OPC being 100% denoted by the solid black horizontal line. One standard deviation is shown by the lines above and below each data point, except for cases with deviations less than 1%. Class F fly ash did not show as much reactivity as compared to Class C at three days with 40% replacement. This is most likely contributed to the pozzolanic effect of Class F fly ash, which requires more time due to the delayed reactions and is magnified by the amount of replacement. IF1 only reached 51% of OPC at three days, the maximum being F2 at 80% of OPC. C6 had the lowest overall strength for Class C at three days with 59%, the rest of Class C fly ash were within 35% of OPC.

Fly ash F4 reached the greatest strength for the F fly ash with 120% of OPC at 90-days, the minimum was IF1 at 87%. Class C fly ash all met or exceeded OPC at 90-days, except for C6 which reached 89%. The highest was C4 at 126%, though C3 was right behind at 125%.

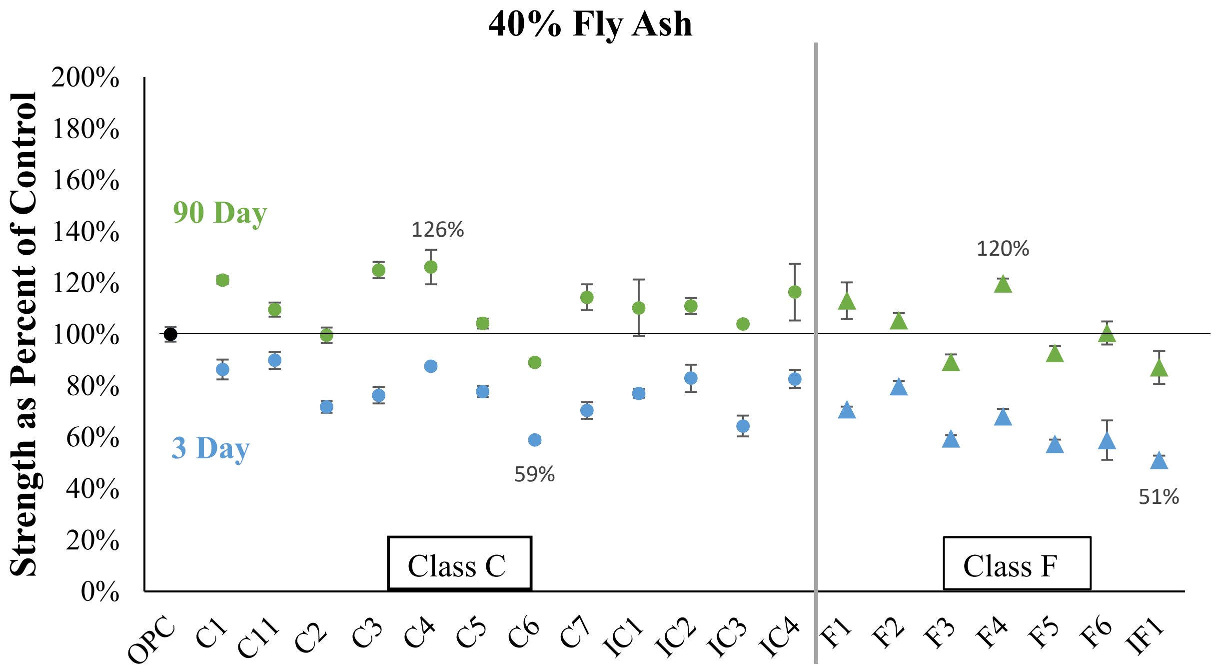

Figure3-5: 40% fly ash mixtures compressive strength presented as a percent of the control. All Class C mixtures at the 40% replacement level met or exceeded the 90-day strength of the OPC, except for C6 at 89%. Class F mixtures ranged between 87% and 120% of OPC

Data in Figure3-4 and 3-4 indicate that mixtures with 20% and 40% fly ash replacement may not reach the strength of OPC at three days. *However,* they do meet and often *exceed* the strength of OPC at 90 days. Reasons for some fly ash performing better than others, such as the 20% C4 (135% 90-day) versus 20% IC4 (99% 90-day) or 40% replacement with F4 (120% 90-day) versus IF1 (87% 90-day), could be due to their individual particle size distribution and chemical content. The particle size distribution in Figure3-6 indicates that though C4 and F4 share a similar size distribution, which could indicate their similar strength gain, IC4 and IF1 have different distributions. In fact, if it were the case, IC4 would share a similar strength gain to C4 and F4 due to the very similar PSD. This means that the particle surface could possibly be a better indicator of their reactivity as well as chemical content.

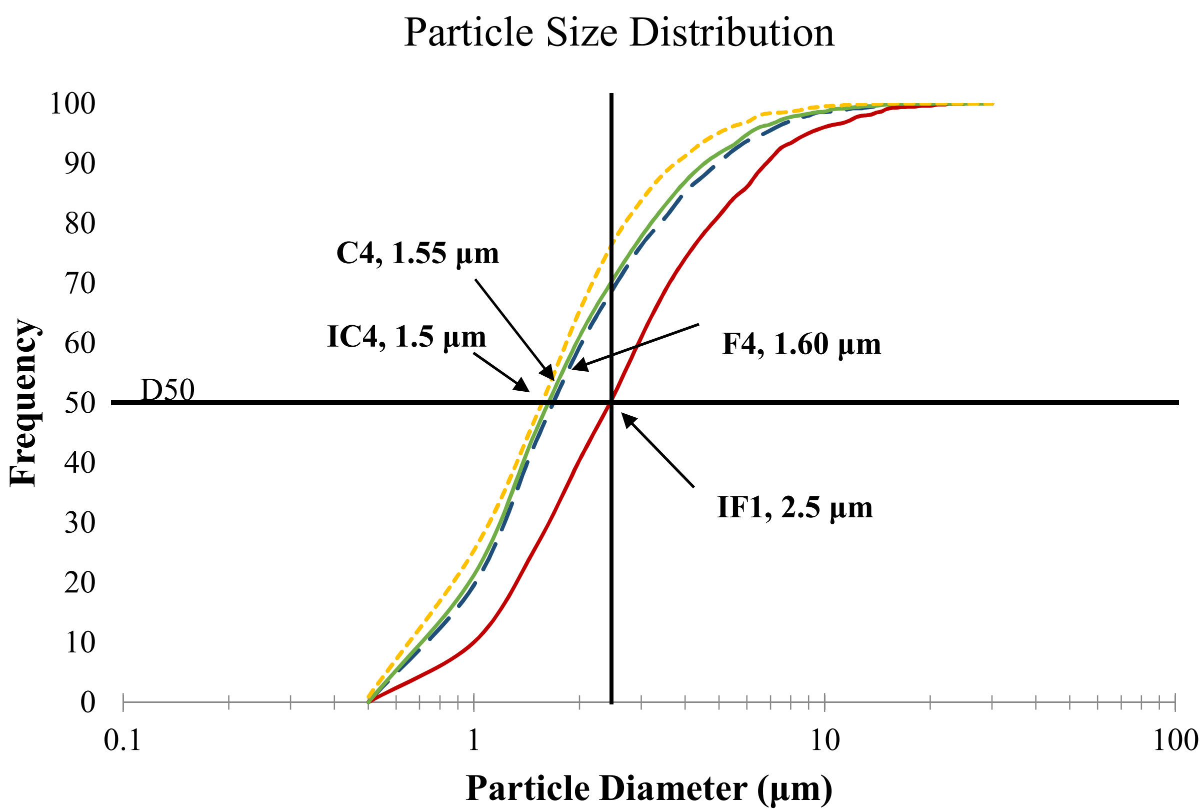

Figure3-6: Table showing the PSD of IF1, F4, C4, and IC4, which demonstrates that C4 and F4 have very similar PSD. IC4 and IF1 do not, yet each set of fly ash display similar strength with respect to OPC. This indicates that PSD is not enough to determine its strength.

Figure3-7 illustrates the relationship between the chemical content and early age strength of the 20% and 40% fly ash mixtures. The chemical content is represented as a ratio of calcium oxide to the sum of silicon and aluminum oxides for the fly ash and OPC in the mixture. This has proven to be a useful technique to evaluate fly ash behavior[15]. This method is used based on the order of hydration reactions that take place. Hydraulic reaction forming calcium hydroxide occurs before activating pozzolanic reactions of aluminum and silicon oxide, which can begin to occur up to 28-days after initial hydration[15]. The three-day strengths do seem to show a slight trend of lower strengths in fly ash with lower calcium oxide, seen in the trend lines. R-squared values are not very close to 1 and so the trend is weak. This indicates that early age strengths are not directly determined through a ratio of the major oxides, but this concept does show some potential for predicting performance.

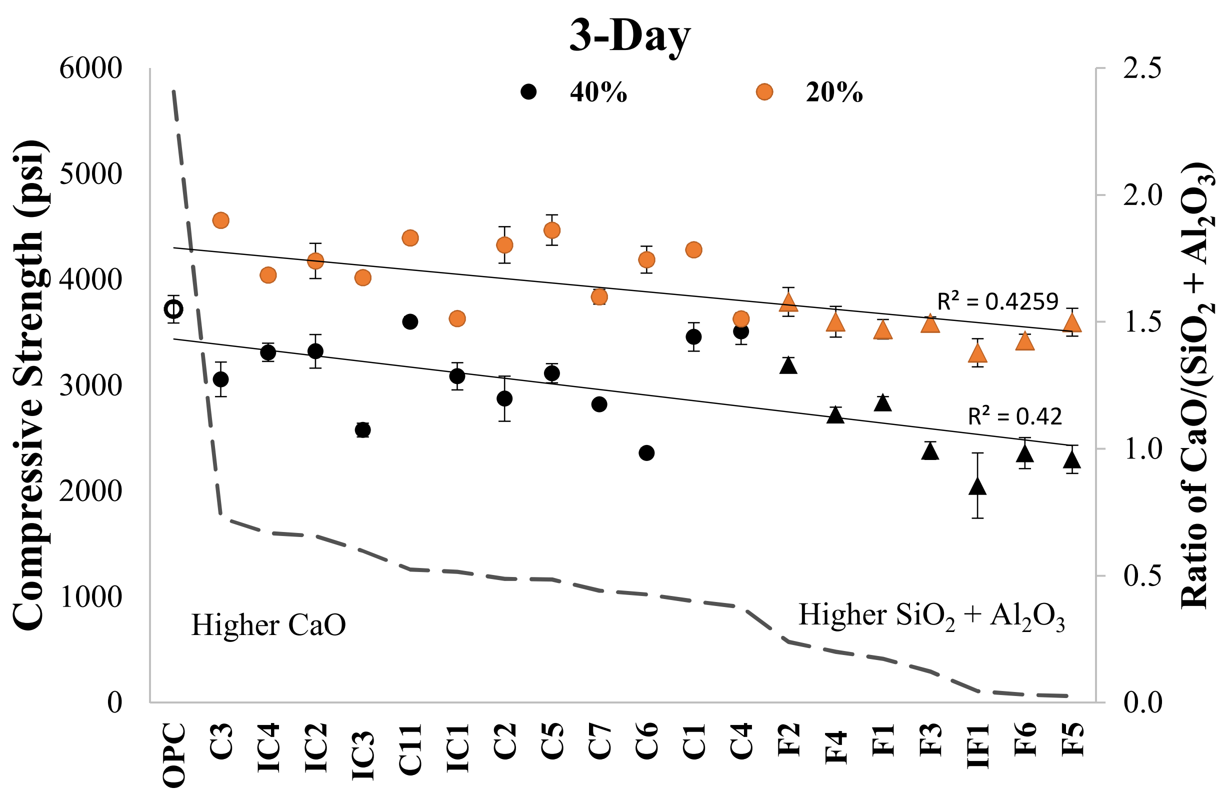

Figure3-7: This graph displays the three-day compressive strength of 20% and 40% fly ash on the left y-axis, the fly ash is listed on the x-axis. On the right y-axis is a measurement of the ratio of calcium oxide to the sum of silicon and aluminum oxides. Note: the r-squared values indicate a poor correlation between the strengths and oxide ratio.

Figure3-8 illustrates the relationship between the chemical content and 90-day strength of the 20% and 40% fly ash mixtures. This is the same method used in the previous figure but was investigated to determine if mixtures with higher aluminum and silicon oxides would show an increase in strength at 90-days. R-squared values are given for the trend lines and are very low (< 0.08). This indicates that the 90-day strengths are not directly determined through a ratio of the major oxides.

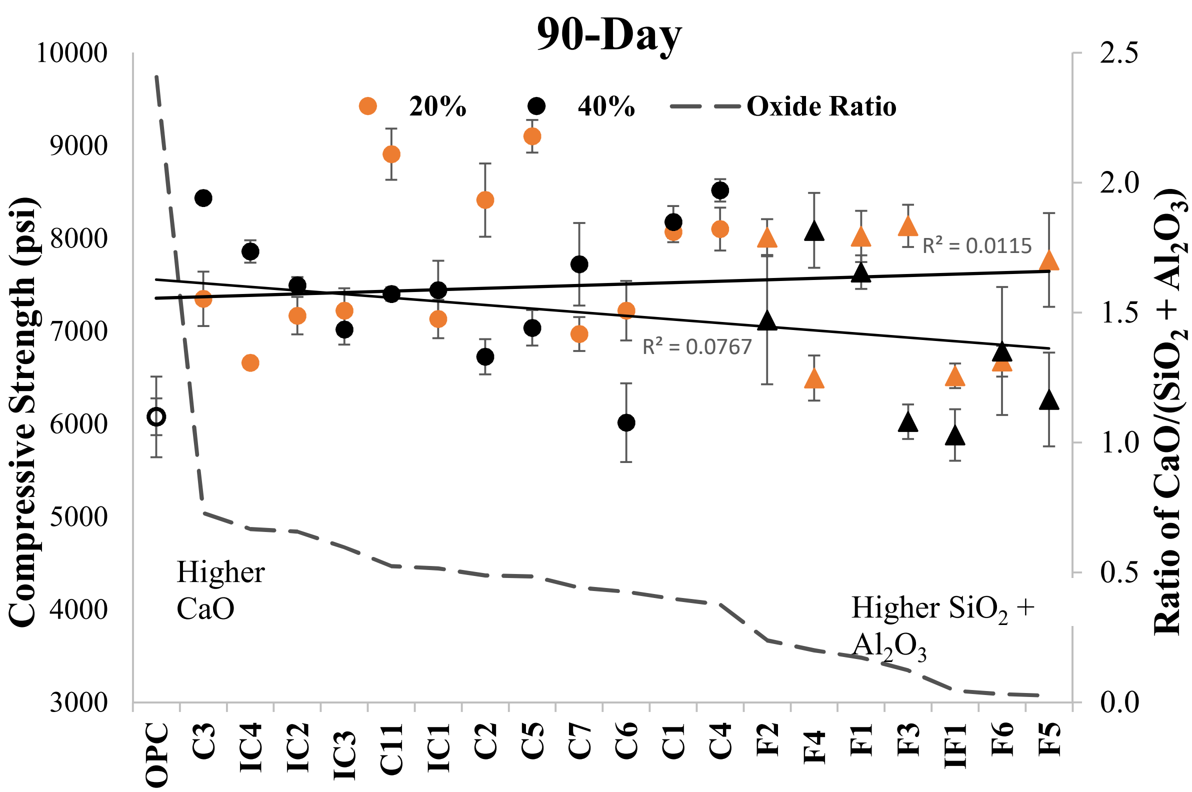

Figure3-8: This graph displays the 90-day compressive strength of 20% and 40% fly ash on the left y-axis, the fly ash is listed on the x-axis. On the right y-axis is a measurement of the ratio of calcium oxide to the sum of silicon and aluminum oxides. Note: the r-squared values indicate a poor correlation between the strengths and oxide ratio.

This reinforced the idea that the performance of fly ash is dependent on more than PSD *or* bulk chemical content alone, and must be dependent on a combination of these two factors or perhaps a different parameter. This is an area of future research being performed by Kang[6].

3.2.4 Resistivity Testing of 3-day and 90-day Samples

Figure3-9 shows all 20% fly ash mixtures as a percent of OPC at 3 and 90 days, OPC being 100% denoted by the solid black horizontal line. Standard deviations are indicated by lines above and below each data point, except for cases with deviations less than 1%. Class C fly ash resistivity reached 72% to 90% of OPC at three-day testing, C3 having the maximum. Class F fly ash had a similar range of 71% to 101% and F4 having the maximum.

The 90-day resistivity revealed that all fly ash exceeded the resistivity of OPC. C7 had the maximum at 256% higher resistivity than OPC. Even the lowest, IC4, reached 128% of OPC. F3 reached 301% greater resistivity than OPC while F3 reached 156%.

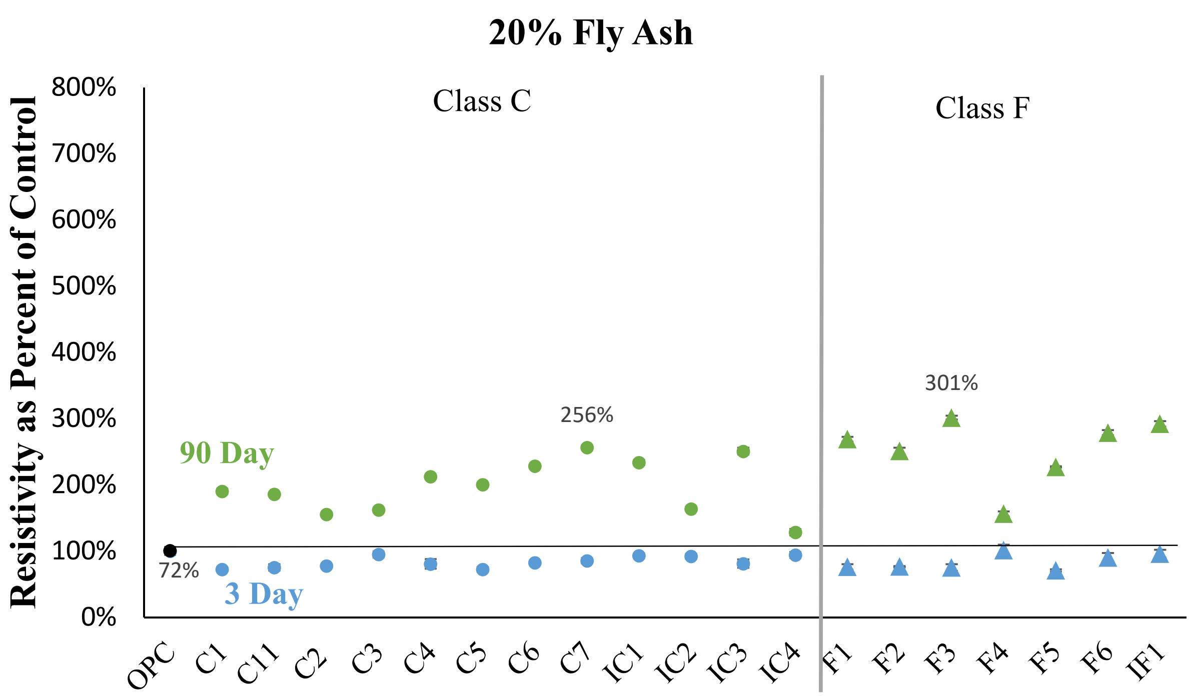

Figure3-9: 20% Fly Ash mixtures shown as a percent of OPC at 3 and 90-day testing. This shows that the majority of fly ash will exceed the resistivity of OPC at 90-days, but there is select fly ash that does not reach the resistivity of OPC at early ages.

Figure3-10 shows all 40% fly ash mixtures as a percent of OPC at 3 and 90 days, OPC being 100% denoted by the solid black horizontal line. Standard deviations are indicated by lines above and below each data point, except for cases with deviations less than 1%. All fly ash, both Class C and F, reached between 59% to 82% resistivity values of OPC at three-day testing, F1 having the maximum. IC1 had the maximum class C resistivity for three days at 81%.

Class C fly ash exceeded resistivity at 90-day testing by as much as 462% (C6), with IC4 having the minimum at 168% of OPC. Class F fly ash had higher values overall with F3 reaching the maximum at 669% of OPC. The minimum, F6, still had 341% higher resistivity than OPC.

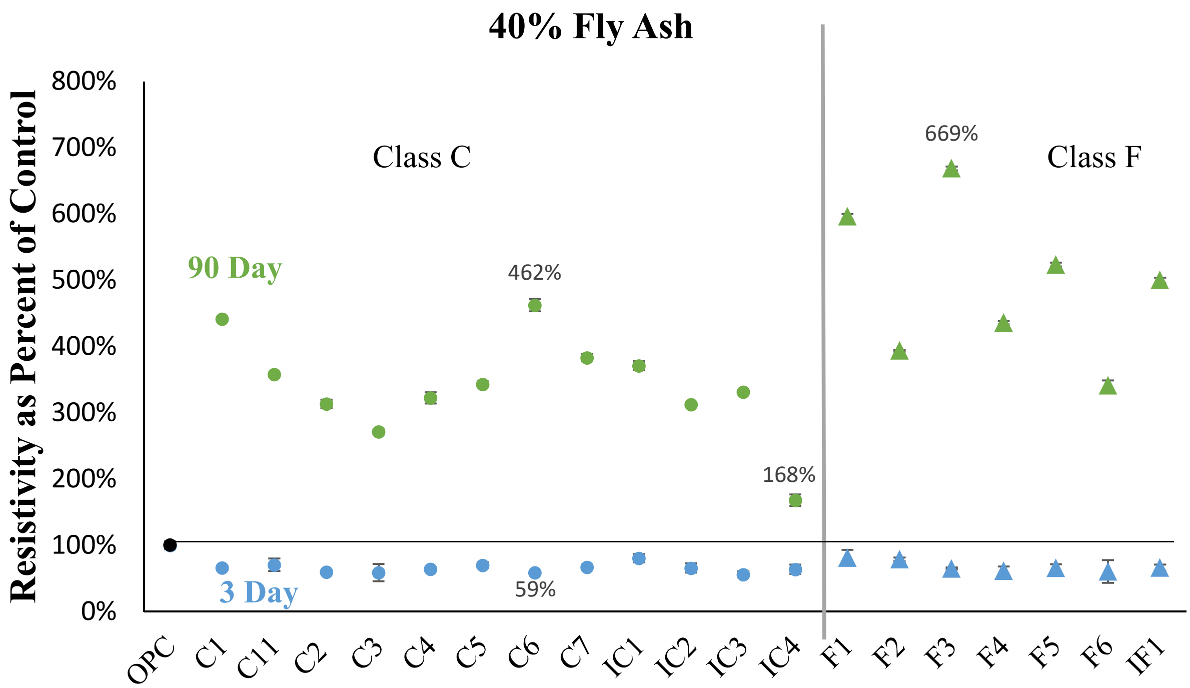

Figure3-10: 40% Fly ash mixtures shown as a percent of the control at 3 and 90-day testing. This shows that the majority of fly ash will exceed the resistivity of OPC at 90-days by as much as 669%.

The figures above indicate that resistivity values for mixtures containing 20% fly ash may vary depending on the fly ash source, but can add a significant improvement to concrete. Mixtures containing 40% fly ash all exceeded OPC at 90 days. When inspecting Figure3-4 for compressive strength at 20% replacement, all fly ash met or exceeded the strength of OPC. This is very valuable information which indicates that fly ash exceeding both resistivity and strength of OPC will improve the performance of the concrete. Determining what particle properties contribute the most to the performance of fly ash has been discussed in the previous section. An attempt to investigate the oxide ratio and compare to the resistivity of 20% and 40% fly ash was made and showed a much stronger correlation at 90-days than for strength. Figure3-11 shows the 20% and 40% resistivity values for three-day testing. There doesn't seem to be any trend between bulk oxide content and the resistivity at 3-days. This may be caused because there is an expected delay in the reaction of the pozzolans within the fly ash. Over time these reactions are expected to occur and this will reduce the connectivity of the pore structure which would increase the resistivity of concrete.

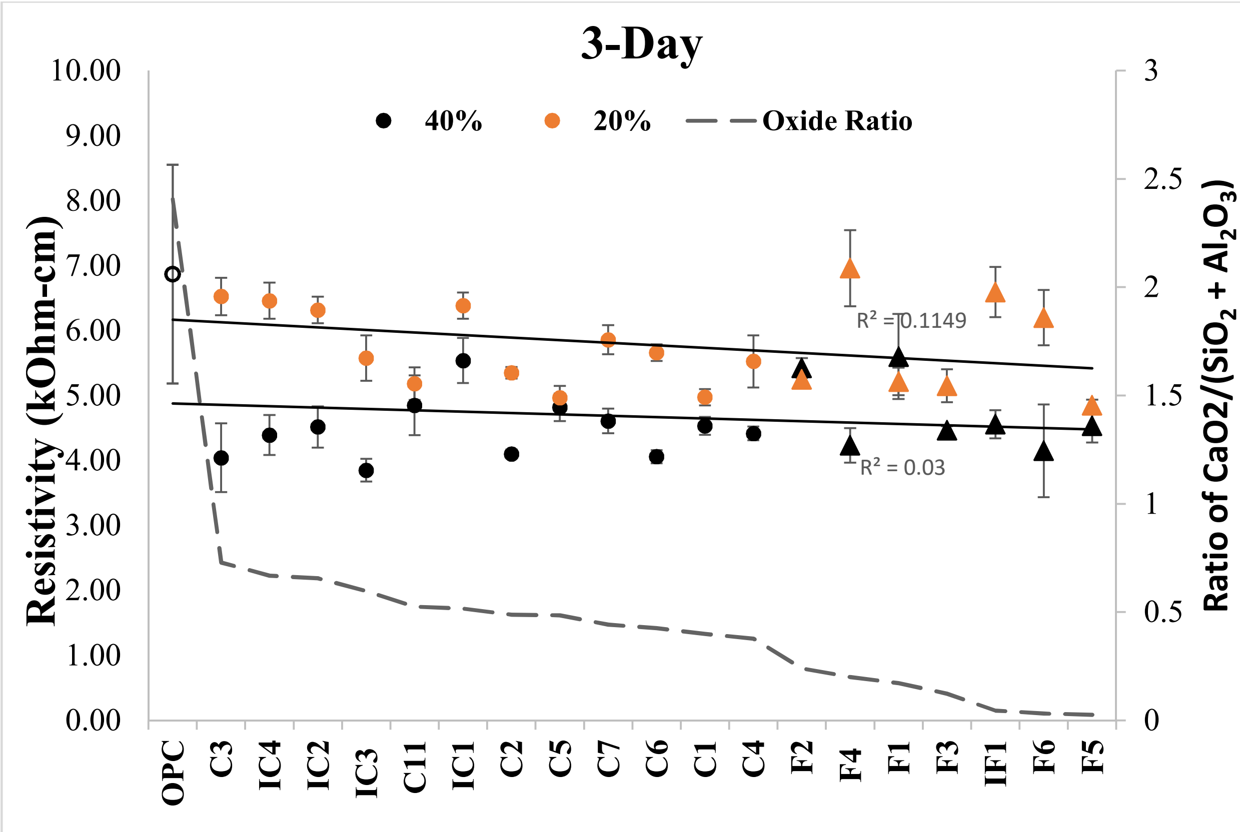

Figure3-11: This graph displays the three-day resistivity of 20% and 40% fly ash on the left y-axis, the ash are listed on the x-axis. On the right y-axis is a measurement of the ratio of calcium oxide to the sum of silicon and aluminum oxides. Note: the r-squared values indicate minimal correlation between the resistivity and oxide ratio.

Figure3-12 shows the 20% and 40% resistivity values for 90-day testing. Trend lines indicate a correlation at 40% replacement levels for lower calcium content having higher resistivity. However, there is significant variation in the results. For example for the samples with 40% replacement with the lowest $CaO/(SiO_2 + Al_2O_3)$ the resistivity values vary by more than a factor of two despite having very similar chemical composition. While this could be caused by different degrees of pore structure refinement, it could also be caused by changes in pore solution chemistry from the dissolution of the fly ash[14]. Kang is doing additional research to investigate this.

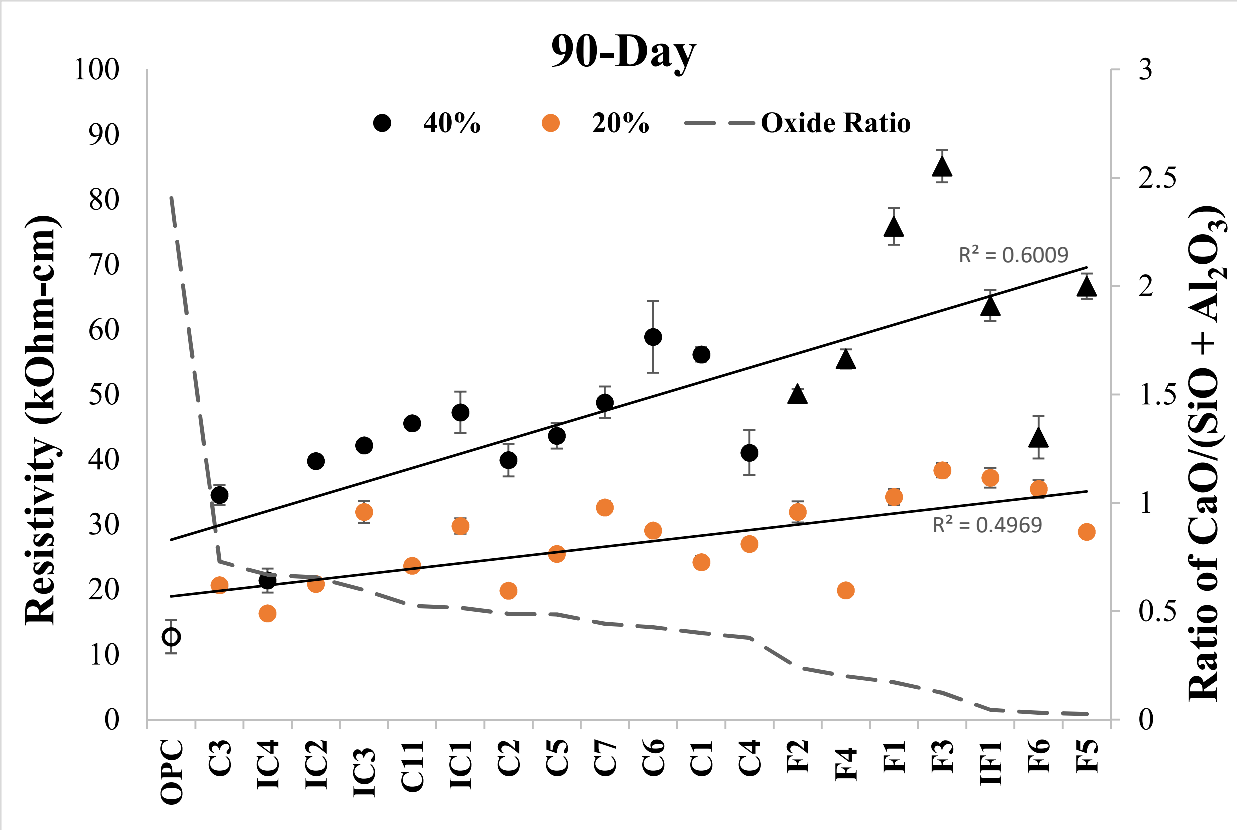

Figure3-12: This graph displays the 90-day resistivity of 20% and 40% fly ash on the left y-axis, the fly ash is listed on the x-axis. On the right y-axis is a measurement of the ratio of calcium oxide to the sum of silicon and aluminum oxides. Note: the r-squared values indicate a correlation between the resistivity and oxide ratio.

3.2.5 Isothermal Calorimetry

Figure3-13 is a chart displaying the range of heat transferred (Joules/gram) during the first 48 hours of hydration for the fly ash tested, shown as a percent of OPC. Testing showed that various replacement levels and fly ash produced varying amounts of heat during the hydration process. All fly ash tested at 20% replacement, did not demonstrate the amount of heat transferred by OPC during hydration. Only ten of the 20% replacement mixtures were tested because it was deemed more valuable to determine the magnified effects of 40% replacement compared to OPC. Most mixtures displayed higher heat transfer when replaced at 40% levels when compared to their 20%

counterparts. While most only came within 20% of the heat transferred by OPC. Though only four of the class C fly ash and two of the class F ash exceeded OPC at 40% replacement. The lowest recorded value and highest recorded value for all fly ash was for C3 at 20% and 40%, respectively. The exact cause is not known as to why this occurred, though it could be speculated that it occurred due to the high calcium content (Figure3-14) and fine particle size (Figure3-6). This is discussed below.

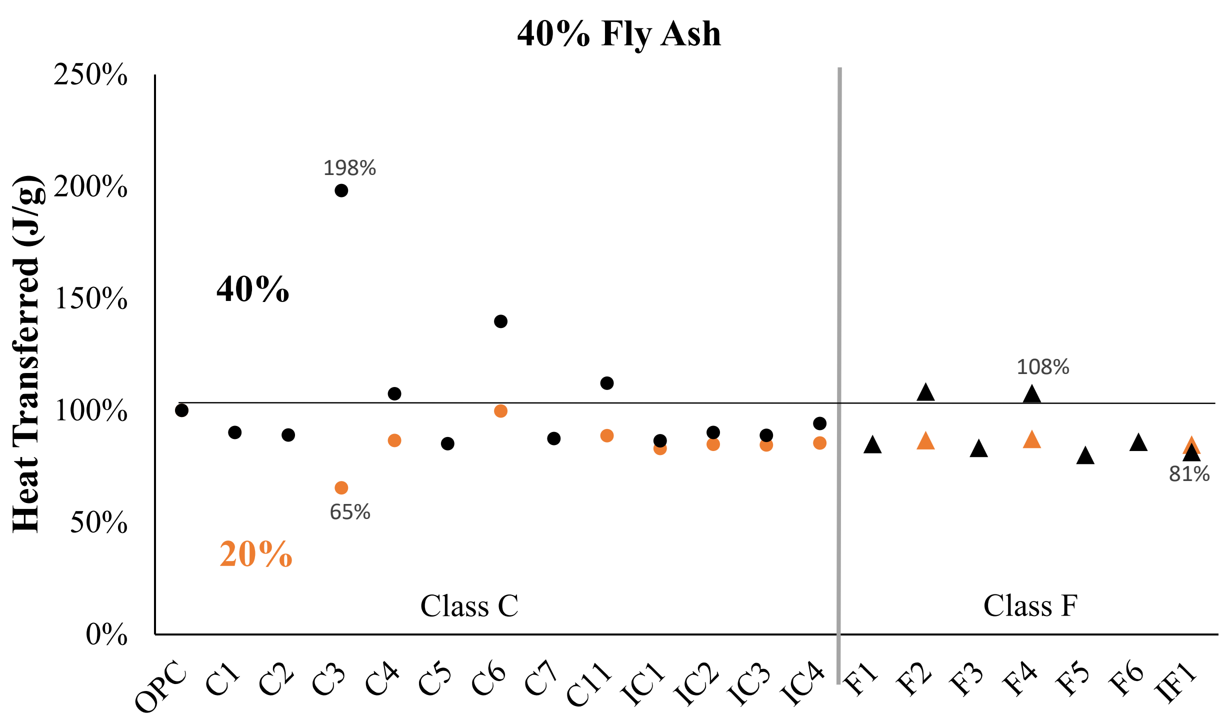

Figure3-13: The graph displays the range of heat released for isothermal calorimetry tests of the nineteen ash, shown as a percent of the control. Select fly ash produced more heat at 40% than at 20%. C3 transferred over twice the amount of heat when replaced with 40%.

The oxide ratio of $CaO/(SiO_2 + Al_2O_3)$ was also used to observe the effect of calcium oxide content on the amount of heat transferred. There does seem to be a slight trend at the 40% replacement level for higher calcium fly ash to have a higher amount of heat transferred. C3 shows the highest amount of heat transferred while containing the second most amount of calcium oxide compared to OPC. It could be possible that the fine particles (< 1.25μm, Figure3-2) provide more surface area and therefore nucleation sites for hydrolysis to occur. Future testing could include measurements of the fly ash at 20% replacement level and further investigation of C3.

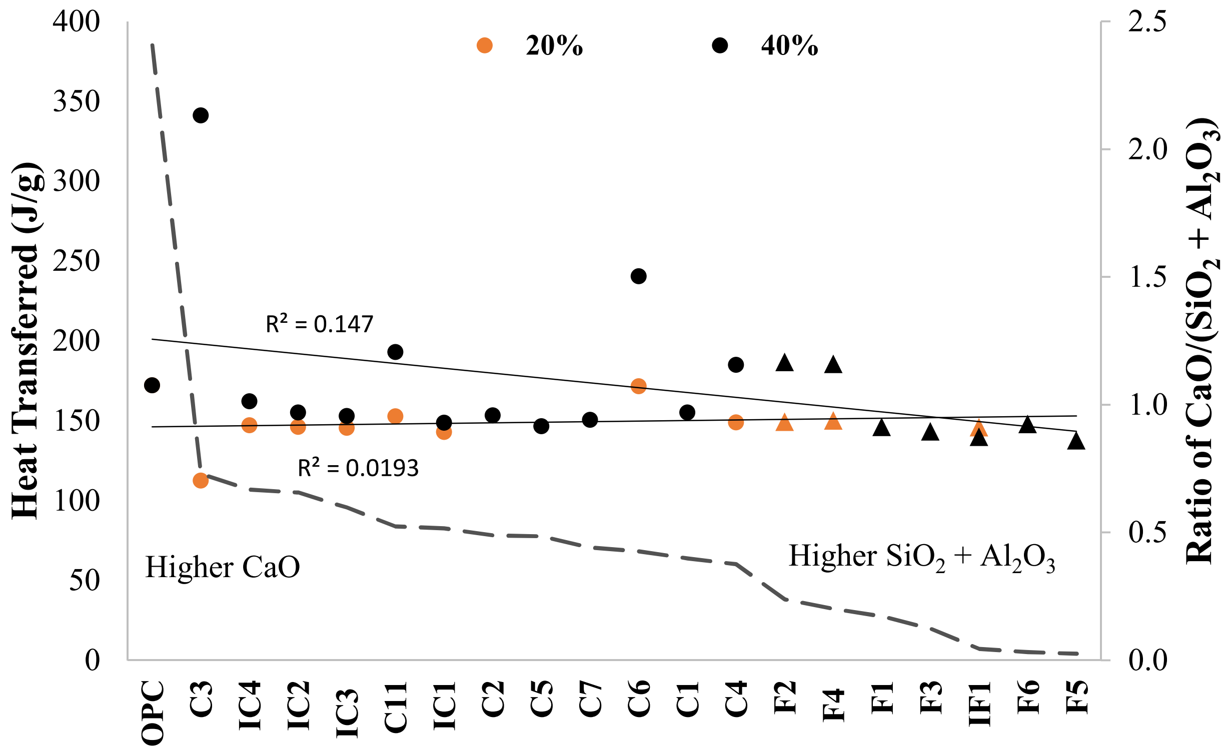

Figure3-14: The graph illustrates the correlation between the oxide ratio of calcium to silica plus aluminum and the heat transfer. There is not a strong correlation at the 20% replacement levels indicated by the r-squared value of 0.01. At the 40% replacement level, there is a slight correlation between the heat transferred showing that the lower calcium fly ash tend to have a lower heat.

3.3 CONCLUSION

This work shows that 20% and 40% replacement provided concrete mixtures that could be used for acceptable workability, strength, and resistivity. Increasing the amount of fly ash also improved the workability of the mixtures in most cases which is beneficial for placing concrete in the field.

While the 3-day strengths of these mixtures were shown to be lower than OPC, the 90-day strengths exceeded those for OPC in almost every case. Strength was met or exceeded for mixtures at the 20% replacement level compared to OPC. When increased to 40% replacement, the mixtures achieved 95% to 126% strength when compared to OPC. Particle size distribution did not seem to directly correlate to strength gain. The ratio of calcium oxide to silica plus aluminum did indicate some correlation to the three-day strengths given that the lower calcium fly ash had lower strengths. When observing the strengths at 90-day testing versus the oxide ratio, there did not seem to be a strong correlation between strength and calcium content.

Resistivity measurements showed that mixtures at both the 20% and 40% replacement levels nearly met the resistivity of OPC at three-day testing. However, nearly all fly ash exceeded the resistivity of OPC by as much as 300% for the 20% replacement and over 600% for the 40% replacement. The lowest measurements for 20% fly ash replacement were able to exceed the OPC mixtures by at least 30%. Testing of IC4 at 90-days with a 40% replacement showed it had the lowest resistivity of all the fly ash, but exceeded OPC by 68%. When investigating the correlation of the oxide ratio to three-day resistivity testing, there did not seem to be a strong correlation at the 20% or 40% replacement level. Yet 90-day testing showed a significant correlation for fly ash with lower calcium content to have higher resistivity at the 40% replacement level. While this could be caused by a refinement in the pore structure of the fly ash with lower amounts of calcium, it is also possible that the change in chemical composition of the fly ash also changes the pore solution chemistry and so this would, in turn, impact the resistivity. Kang is doing additional research to investigate this[6, 14].

Isothermal calorimetry demonstrated that the majority of fly ash tested did not exceed the amount of heat transferred by OPC at 20% or 40% replacement levels. Most only came within 20% of OPC in terms of heat transferred. There were four Class C fly ash and two Class F that exceeded the heat transfer of OPC. These results did not directly correlate to the oxide ratio and an exact answer could be sought through future testing currently underway.

Conclusions as to what determines the performance of mixtures discussed herein with regards to the chemical content or particle size distribution could not be conclusively determined and is beyond the scope of this paper. However, work is being done at Oklahoma State University to predict performance based on clusters of chemical particles within the fly ash.

CHAPTER 4

CONCLUSION

4.0 PULP CURE CONCLUSIONS

Significant progress has been made developing Pulp Cure as a new curing method for concrete. Development of a batching and delivery system made possible field applications that led to the need for quality testing. The Runoff Test is proving to be a powerful aid in performing these quality tests quickly and with relative certainty. This test is unique because it allows both qualitative and quantitative data to be gathered and used together to determine the quality of the Pulp Cure mixture. The testing found that there is a range of mixture designs that showed successful performance. This can help save cost or modify the desired performance for different applications.

The Drip Test proved to work well when mixtures varied in tackifier content. However, it was difficult to distinguish mixtures varying in tackifier content to those of paper or water. This could be verified testing mixtures with higher replacement levels of water and paper in order to see if the volume collected would give a greater significance of the means.

Overall, the Runoff Test proves to be the best suited for any mixture such as Pulp Cure when quality testing is required in the field. This is because it is a simple, practical, and cheap method. The Runoff Test utilizes the natural physical behavior of the material, allowing it to reveal how it will perform. This, in turn, allows the user to determine what is appropriate for the application and what might be altered to achieve the desired performance.

4.1 FLY ASH PERFORMANCE

This work shows that 20% and 40% replacement provided concrete mixtures that could be optimized for their workability, strength, and durability. Increasing the amount of fly ash also improved the consistency of the mixtures in most cases which is beneficial for placing concrete in the field. Select fly ash showed to reduce slumps when going from a 20% to 40% replacement level, however additional testing is needed to verify these findings.

While the 3-day strengths of these mixtures were shown to possibly be lower than OPC, the 90-day strengths exceeded those for OPC in almost every case. Strength was met or exceeded for mixtures at the 20% replacement level compared to OPC. When increased to 40% replacement, the mixtures achieved 95% to 126% strength when compared to OPC. Particle size distribution did not seem to directly correlate to strength gain. The ratio of calcium oxide to silica plus aluminum did indicate some correlation to the three-day strengths given that the lower calcium fly ash had lower strengths. When observing the strengths at 90-day testing versus the oxide ratio, there did not seem to be a strong correlation between strength and calcium content.

Resistivity measurements showed that mixtures at both the 20% and 40% replacement levels nearly met the resistivity of OPC at three-day testing. However, nearly all fly ash exceeded the resistivity of OPC by as much as 300% for the 20% replacement and over 600% for the 40%

replacement. The lowest measurements for 20% replacement were able to exceed OPC by at least 30%. Testing of IC4 at 90-days with a 40% replacement showed it had the lowest resistivity of all the fly ash, but exceeded OPC by 68%. When investigating the correlation of the oxide ratio to three-day resistivity testing, there did not seem to be a strong correlation at the 20% or 40% replacement level. Yet 90-day testing showed a significant correlation for fly ash with lower calcium content to have higher resistivity at the 40% replacement level. While this could be caused by a refinement in the pore structure of the fly ash with lower amounts of calcium, it is also possible that the change in chemical composition of the fly ash also changes the pore solution chemistry and so this would, in turn, impact the resistivity. Kang is doing additional research to investigate this[6, 14].

Isothermal calorimetry demonstrated that the majority of fly ash tested did not exceed the amount of heat transferred by OPC at 20% or 40% replacement levels. Most only came within 20% of OPC in terms of heat transferred. There were four class C ash and two class F that exceeded the heat transfer of OPC. These results did not directly correlate to the oxide ratio and an exact answer could be sought through future testing currently underway.

Conclusions as to what determines the performance of mixtures discussed herein with regards to the chemical content or particle size distribution could not be conclusively determined and is should be investigated with more detailed analysis techniques. This work is being done at Oklahoma State University to predict performance based on clusters of particles with unique chemical constituents within the fly ash.

In conclusion, this research has explored the importance of quality control whether it be for a novel curing product such as Pulp Cure or a concrete mixture with a specific application where consistency and durability are key. It is the hope of the author that this paper will further propel the advancement of the body of knowledge in the realm of concrete performance.

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APPENDICES

A1 CONCRETE MIXTURES RESULTS

A1.1 Fresh Properties

Table A1-1: 20% Fly Ash Mixtures

20% Fly Ash	Slump (inches)	Unit Weight (pcf)	Air (%)
OPC	1.25	149.82	1.65
C1	2.25	154.72	1.3
C11	4.25	150.88	1.2
C2	1.75	154.4	1.4
C3	3.75	151.68	1.1
C4	2.5	148.32	1.2
C5	4.25	150.32	1.3
C6	2.75	154.64	1.5
C7	4	151.36	1.2
F1	2.5	153.92	1.3
F2	2	153.2	1.4
F3	1.5	153.12	1.5
F4	4	150.72	1
F5	1.5	150.96	1.2
F6	3.25	151.12	1.3
IC1	3.5	151.76	1.1
IC2	6.5	152.32	0.9
IC3	4.25	150.96	1.2
IC4	5	152.64	0.8
IF1	3.75	150.48	1.5

Table A1-2: 40% Fly Ash Mixtures

40% Fly Ash	Slump (inches)	Unit Weight (pcf)	Air (%)
OPC	1.25	149.82	1.7
C1	4.75	151.52	1.2
C11	5.25	151.52	1.2
C2	4.75	150.24	1.3
C3	6.50	151.52	0.9
C4	5.00	150.88	1.0
C5	4.25	150.96	1.2
C6	6.00	150.72	1.2
C7	6.00	151.28	0.7
F1	6.50	151.52	0.8
F2	6.50	151.68	0.8
F3	3.25	149.2	1.0
F4	4.50	149.52	1.4
F5	4.50	150.48	1.1
F6	3.50	150.48	1.2
IC1	6.75	151.92	0.8
IC2	4.25	152.8	1.1
IC3	2.75	149.84	1.2
IC4	2.50	149.76	1.4
IF1	7.00	150.56	1.0

A1.2 Compressive Strengths

Table A1-3: 20% Compressive Strengths

Curing Time (days)	OP C	C1 20%	C11 20%	C2 20%	C3 20%	C4 20%	C5 20%	C6 20%	C7 20%	IC1 20%	IC2 20%	IC3 20%	IC4 20%	F1 20%	F2 20%	F3 20%	F4 20%	F5 20%	F6 20%	IF1 20%
3	4076	4123	4417	4127	4635	3465	4474	4143	3824	3781	4193	4197	4041	3610	3869	3621	3596	3713	3233	3310
3	4085	4510	4420	4408	4506	3651	4444	4202	3793	3727	4159	3838	4093	3441	3768	3464	3674	3410	3527	3378
3	3856	4210	4349	4447	4542	3774	4485	4219	3891	3390	4178	4017	3992	3540	3730	3683	3534	3668	3516	3237
Ave.	4006	4281	4395	4327	4561	3630	4468	4188	3836	3633	4177	4017	4042	3530	3789	3589	3601	3597	3425	3308
STD	106	166	33	143	54	127	17	33	41	173	14	147	41	69	59	92	57	133	136	58
7	4798	5155	5714	5488	4725	4831	5760	5135	4794	4557	4725	4459	5011	4352	4613	4672	4623	4384	4376	4274
7	4985	5169	5708	5396	4864	4882	5673	5322	4672	4578	5240	5741	4708	4580	4585	4694	4427	4624	4247	3975
7	4886	5579	5736	5440	5521	4844	5461	5276	4555	4490	4800	4535	4895	4146	4585	4542	4588	4510	4138	4250
Ave.	4890	5301	5719	5441	5037	4852	5631	5244	4674	4542	4922	4912	4871	4359	4594	4636	4546	4506	4254	4166
STD	76	197	12	38	347	22	126	80	98	38	227	587	125	177	13	67	85	98	97	136
14	5402	6239	6388	5923	5774	5986	6489	5683	5523	5345	5590	5736	5277	5295	5205	5312	5080	5044	5074	4838
14	5234	6363	6707	6242	5250	5840	6599	6094	5296	5401	5761	5522	5258	5055	5426	5508	5304	5119	4874	4580
14	5573	6179	6539	5992	5637	5679	6669	5800	5714	5364	5969	5445	5250	5195	5317	5223	5189	5009	4485	4688
Ave.	5403	6260	6545	6052	5554	5835	6586	5859	5511	5370	5773	5568	5262	5182	5316	5348	5191	5057	4811	4702
STD	138	77	130	137	222	125	74	173	171	23	155	123	11	98	90	119	91	46	245	106
28	5968	7265	7807	6864	6069	6524	7454	6506	6070	5666	7201	6368	5972	6138	6278	6267	5934	5650	5134	5400
28	5986	7285	7477	7110	5943	6547	7335	6492	6091	5623	6310	5962	5953	5840	6446	6257	5355	5850	5339	5252
28	5917	7294	7245	6942	5903	6474	7476	6500	6297	5796	6270	5873	5818	5767	6203	6186	5932	5921	5185	5384
Ave.	5957	7281	7510	6972	5972	6515	7422	6499	6153	5695	6594	6068	5914	5915	6309	6237	5740	5807	5219	5345
STD	29	12	231	103	71	30	62	6	102	74	430	215	69	160	102	36	272	115	87	66
56	6411	7894	8362	8259	6483	7283	8154	6842	6710	6802	6645	6956	6460	7170	7230	7871	6221	7470	6088	6008
56	6342	8599	8761	8163	7255	7269	8600	7060	6317	6492	7127	7196	6733	7026	7052	7635	6383	7202	6228	5335
56	6125	8247	8540	7565	6966	7507	8332	6974	6783	6964	7028	6865	6220	7085	7458	7312	6128	7209	6200	5331
Ave.	6293	8247	8554	7996	6901	7353	8362	6959	6603	6753	6933	7006	6471	7094	7247	7606	6244	7294	6172	5558
STD	122	288	163	307	318	109	183	90	205	196	208	140	210	59	166	229	105	125	60	318
90	6871	8324	8923	8385	7794	8383	9111	6844	6777	7532	7419	6960	6994	7958	7779	7963	6820	7953	6905	6599
90	6707	8046	8766	8640	6760	8264	9049	7321	7256	7269	7325	7159	6530	8270	7938	8525	6340	7691	6433	6288
90	6673	7834	9032	8214	7489	7653	9140	7498	6875	6594	6757	7543	6448	7836	8323	7918	6327	7655	6692	6672
Ave.	6750	8068	8907	8413	7348	8100	9100	7221	6969	7132	7167	7221	6657	8021	8013	8135	6496	7766	6677	6520
STD	86	201	109	175	434	320	38	276	207	395	292	242	240	183	228	276	229	133	193	167
180	6656	9073	9308	9094	7526	8551	9551	8187	7319	7443	8919	7564	6928	8464	8326	8317	6997	8474	7249	7124
180	7447	9486	9367	8981	7852	8086	10066	8282	7149	7707	8148	7248	6968	8781	8810	8881	7335	8646	7609	7116
180	6936	9053	9413	9071	7376	8724	9631	8091	7582	7475	8765	8899	7194	8743	8833	8637	7478	8331	7283	6955
Ave.	7013	9204	9363	9049	7585	8454	9749	8187	7350	7542	8611	7904	7030	8663	8656	8612	7270	8484	7380	7065

STD	327	200	43	49	199	269	226	78	178	118	333	716	117	141	234	231	202	129	162	78

Table A1-4: 40% Compressive Strengths

Curing Time (days)	OPC	C1	C11	C2	C3	C4	C5	C6	C7	IC1	IC2	IC3	IC4	F1	F2	F3	F4	F5	F6	IF1
3	4076	3455	3778	2756	3162	3510	3235	2389	2638	3037	3611	2457	3518	2790	3309	2344	2893	2310	2093	2072
3	4085	3653	3452	2975	2874	3458	3036	2401	2924	3051	3103	2467	3214	2840	3114	2460	2601	2376	2192	2120
3	3856	3266	3576	2894	3135	3564	3074	2296	2900	3051	3252	2810	3202	2887	3163	2346	2684	2216	2792	1962
Ave.	4006	3458	3602	2875	3057	3511	3115	2362	2821	3046	3322	2578	3311	2839	3195	2383	2726	2301	2359	2051
STD	106	158	134	90	130	43	86	47	130	7	213	164	146	40	83	54	123	66	309	66
7	4798	4895	4634	4209	4912	5197	4576	2865	4283	3721	4722	3620	4240	3196	3844	2998	3513	3184	2884	2892
7	4985	4992	4542	4186	4625	4836	4372	3099	4256	3842	4658	3624	4708	3307	3591	3071	3584	3400	2328	2860
7	4886	5030	4648	3710	4560	4955	4245	2936	4385	-	4730	3813	4681	-	3887	3049	3628	3343	2650	2892
Ave.	4890	4972	4608	4035	4699	4996	4398	2967	4308	3782	4703	3686	4543	3252	3774	3039	3575	3309	2621	2881
STD	76	57	47	230	153	150	136	98	56	61	32	90	215	56	131	31	47	91	228	15
14	5402	6271	5728	4990	6011	6609	4974	3412	5339	4475	4700	4805	5171	4270	4606	3946	4067	3446	3690	3273
14	5234	6966	5294	5013	6312	6470	5139	3763	5267	4910	5865	4938	6080	4299	4476	3780	4310	3850	3431	3391
14	5573	-	5636	-	5784	6070	5057	3977	5435	4700	5640	4957	5198	4494	4281	3645	4552	3617	-	-
Ave.	5403	6619	5553	5002	6036	6383	5057	3717	5347	4695	5402	4900	5483	4354	4454	3790	4310	3638	3561	3332
STD	138	348	187	12	216	228	67	233	69	178	505	68	422	99	134	123	198	166	130	59
28	5968	7591	5993	5345	6386	7351	6239	4755	6531	5479	6821	6305	6340	5244	5503	4697	5621	4590	4252	4518
28	5986	7031	6396	5587	7344	7010	5938	5121	6509	6222	6689	6236	5727	5781	5195	5401	5374	4806	4788	4603
28	5917	7101	6325	5561	7294	7082	6600	4470	6401	5231	6428	6597	6934	5906	5862	5070	5614	4548	4044	4486
Ave.	5957	7241	6238	5498	7008	7148	6259	4782	6480	5644	6646	6379	6334	5644	5520	5056	5536	4648	4361	4536
STD	29	249	176	108	440	147	271	266	57	421	163	156	493	287	273	288	115	113	313	49
56	6411	7820	7203	6357	7897	7822	7103	5533	6827	6270	6884	6914	6559	6860	6031	5867	6300	5339	5253	6095
56	6342	8609	7153	6330	7908	8094	6980	5659	7667	6359	7649	6793	6418	6687	6245	5582	5850	5268	5606	5255
56	6125	8057	7120	6324	8034	8601	7016	5709	7506	6040	6835	6830	6572	6837	5998	5440	6351	5588	5297	
Ave.	6293	8162	7159	6337	7946	8172	7033	5634	7333	6223	7123	6846	6516	6795	6091	5630	6167	5398	5385	5675

STD		122	331	34	14	62	323	52	74	364	134	373	51	70	77	109	178	225	137	157	420
	90	6871	8125	7165	6819	8418	8161	6867	5934	7275	6954	7751	6969	8418	7161	7066	5816	8249	6444	6804	6448
	90	6707	8301	7457	6895	8202	9111	7144	5998	7976	8418	7297	7021	8271	8231	6920	6258	7963	6300	7117	5643
	90	6673	8100	7577	6458	8687	8276	7098	6110	7914	6954	7434	7064	6889	7517	7369	6000	8044	6049	6438	5550
Ave.		6750	8175	7400	6724	8436	8516	7036	6014	7722	7442	7494	7018	7859	7636	7118	6025	8085	6264	6786	5880
STD		86	89	173	191	198	423	121	73	317	690	190	39	689	445	187	181	120	163	277	403
	180	6656	9272	8084	7633	9460	8450	7387	7037	8834	7706	7530	7614	8447	8054	7250	6341	8400	6465	7539	6178
	180	7447	8414	7987	7518	9797	8875	7521	6687	8170	7545	7982	8098	8239	7832	7938	6187	7882	5818	6854	6441
	180	6936	8939	7904	7268	9705	8735	7709	6526	7990	7237	8145	7310	8074	7274	7721	6242	8019	6927	6993	6432
Ave.		7013	8875	7992	7473	9654	8687	7539	6750	8331	7496	7886	7674	8253	7720	7636	6257	8100	6403	7129	6350
STD		327	353	74	152	142	177	132	213	363	195	260	324	153	328	287	64	219	455	296	122

A1.3 Resistivity Values

Table A1-5: 20% Resistivity Values

Curing Time (days)	Point	OPC	C1	C2	C3	C4	C5	C6	C7	C11	IC1	IC2	IC3	IC4	F1	F2	F3	F4	F5	F6	IF1
3	1	5.00	5.40	5.60	5.20	6.30	5.00	6.20	5.10	5.40	7.10	5.70	5.20	7.00	5.40	5.10	5.90	5.30	5.00	5.10	5.50
	2	5.00	5.00	5.10	5.20	6.10	5.00	5.80	5.30	5.00	6.90	5.70	5.10	6.30	5.20	5.00	5.20	5.20	4.90	5.00	6.60
	3	5.20	5.20	5.60	4.90	5.80	5.40	5.40	4.80	5.30	6.30	5.30	5.40	6.80	5.40	5.40	5.10	5.60	4.90	4.90	6.40
	4	6.40	4.80	4.80	5.30	5.60	5.30	5.80	4.80	5.80	6.10	5.40	5.60	7.00	5.50	5.50	5.50	5.20	4.80	4.70	6.80
	5	5.60	4.80	5.20	4.80	5.00	4.50	5.40	5.10	5.10	6.00	6.40	5.30	6.20	4.80	5.10	5.00	5.10	4.60	4.90	6.00
	6	5.30	5.10	5.20	5.70	5.20	4.60	6.50	5.20	5.40	7.50	5.50	5.10	6.40	4.80	5.20	5.40	5.60	4.90	5.10	6.10
	7	5.10	4.90	5.50	5.80	5.10	5.30	5.20	4.90	5.10	5.60	5.80	5.70	6.40	5.20	5.20	5.20	5.00	4.70	5.10	6.60
	8	5.20	4.60	5.40	4.70	5.30	5.00	5.40	5.20	5.50	6.30	5.80	5.60	6.00	5.10	5.30	4.80	4.80	5.40	4.60	6.20
	9	5.00	4.60	5.40	5.50	5.70	5.00	5.80	5.30	5.10	5.80	5.40	6.20	6.30	5.70	5.30	4.90	5.30	5.00	5.30	5.80
	10	5.50	5.80	5.30	5.30	5.00	4.50	5.60	4.90	4.90	6.80	5.70	6.30	6.30	4.50	5.50	4.80	5.40	4.80	5.00	6.50
	11	5.30	4.60	5.40	5.10	5.50	4.90	5.50	5.10	4.80	6.10	5.50	5.70	6.20	5.40	5.20	4.90	5.20	4.50	5.30	6.80
	12	5.40	4.90	5.70	5.60	5.70	5.10	5.30	5.10	4.80	6.10	5.90	5.70	6.60	5.60	5.20	5.10	4.80	4.70	5.20	6.50
	Aver.	5.33	4.98	5.35	5.26	5.53	4.97	5.66	5.07	5.18	6.38	5.68	5.58	6.46	5.22	5.25	5.15	5.21	4.85	5.02	6.32
	STDEV	0.39	0.36	0.25	0.35	0.42	0.30	0.38	0.18	0.30	0.57	0.30	0.39	0.32	0.36	0.16	0.32	0.26	0.23	0.22	0.40
7	1	7.00	6.80	7.10	6.50	6.70	6.70	8.70	6.60	7.30	7.30	7.00	7.60	8.40	7.70	6.30	5.80	6.20	6.10	6.30	7.60
	2	7.20	6.40	6.20	7.10	6.50	6.00	8.30	7.00	6.60	6.80	6.60	7.50	7.00	7.00	6.40	5.60	6.60	6.10	5.60	7.00
	3	6.60	6.50	6.60	6.80	6.50	6.70	8.10	6.30	6.60	7.60	7.90	8.30	7.30	7.10	6.10	5.90	6.40	5.80	6.90	7.40
	4	7.00	6.40	6.80	7.00	6.00	6.60	8.10	5.90	7.20	7.00	7.70	7.30	7.60	7.40	6.60	5.50	6.40	6.10	6.80	7.40
	5	6.40	6.70	7.00	6.40	6.40	6.40	8.00	5.80	6.70	7.50	7.70	7.60	7.80	6.80	6.50	7.20	6.00	5.90	6.80	7.40
	6	6.80	6.50	6.70	6.30	6.60	5.70	7.40	6.10	6.40	7.60	7.20	8.60	7.70	6.70	7.10	6.70	6.10	5.60	6.30	7.10
	7	6.90	7.00	6.10	6.70	6.50	5.80	7.50	6.60	6.80	7.50	7.30	7.90	7.80	6.80	6.30	6.30	6.30	5.70	6.70	7.20
	8	6.10	6.40	7.00	5.80	6.80	6.50	7.90	6.40	6.80	6.90	7.20	7.60	7.30	6.60	7.00	6.20	6.20	5.90	7.40	7.30
	9	6.30	5.70	6.20	5.90	6.10	6.10	8.50	6.10	6.60	9.10	7.30	-	8.70	6.20	6.90	7.00	6.80	6.20	7.00	6.80
	10	6.60	6.30	6.70	6.10	7.30	6.40	8.80	6.00	6.10	6.30	6.80	-	7.80	6.70	7.00	6.40	7.00	5.70	6.00	7.30
	11	5.80	6.70	6.30	6.10	7.40	6.10	8.90	6.90	6.70	8.10	6.90	-	8.40	6.50	6.10	6.80	6.30	6.30	6.40	7.80

	12	6.20	6.80	6.10	6.50	7.40	6.30	7.30	6.20	7.60	7.30	7.00	-	8.70	6.40	6.00	6.50	6.50	6.10	6.70	7.30
	Aver.	6.58	6.52	6.57	6.43	6.68	6.28	8.13	6.33	6.78	7.42	7.22	7.80	7.88	6.83	6.53	6.33	6.40	5.96	6.58	7.30
	STDEV	0.42	0.33	0.37	0.42	0.47	0.34	0.54	0.38	0.41	0.71	0.39	0.44	0.56	0.42	0.39	0.55	0.29	0.22	0.48	0.26
14	1	7.50	9.10	9.20	7.10	9.80	7.70	13.50	8.90	8.70	11.40	9.70	12.50	7.40	9.50	8.60	8.30	7.60	8.10	6.80	8.70
	2	8.80	8.60	7.40	7.00	9.90	7.00	12.20	8.40	8.90	10.60	8.20	9.80	8.50	9.20	8.60	8.70	7.70	8.70	7.30	9.70
	3	7.40	8.40	7.60	7.50	10.00	7.10	12.30	8.00	6.90	10.60	8.80	10.30	8.40	9.20	9.40	8.20	7.40	8.10	6.90	9.50
	4	8.50	8.50	7.80	6.90	9.90	7.30	12.30	8.60	8.20	10.20	9.00	11.00	8.30	10.70	8.40	7.90	8.50	7.90	6.70	8.70
	5	7.70	9.70	8.20	8.10	10.50	7.00	12.70	8.10	9.00	10.90	9.80	10.50	8.70	8.10	8.50	7.50	8.70	8.40	7.40	8.60
	6	8.00	8.70	7.80	7.50	10.60	7.20	11.80	8.20	7.00	10.40	8.40	10.30	8.90	8.80	8.20	8.00	8.60	8.30	7.90	8.70
	7	7.60	9.40	8.10	7.60	9.80	7.50	13.20	7.20	7.50	10.70	8.20	10.10	8.80	7.80	9.20	8.60	8.10	7.70	7.00	8.80
	8	7.00	8.90	7.70	7.80	9.60	7.00	13.80	7.30	7.30	10.90	8.80	10.50	8.80	7.10	8.20	8.30	8.70	7.20	7.10	8.30
	9	7.60	9.20	8.20	7.30	10.30	7.40	11.20	8.70	7.70	10.40	9.70	10.40	9.90	8.50	8.20	8.80	7.40	8.20	7.40	8.50
	10	7.90	9.20	8.30	7.20	8.50	7.30	13.50	8.00	8.00	10.60	9.60	10.20	8.50	9.40	7.90	8.10	7.20	8.60	7.60	8.80
	11	8.20	8.60	8.10	7.50	9.70	7.40	13.40	8.40	8.20	11.60	9.60	9.70	8.40	9.80	8.20	9.00	7.30	7.40	6.40	8.00
	12	7.80	9.20	7.40	7.40	10.20	6.80	13.80	8.10	8.30	11.80	9.50	9.60	8.80	8.80	8.20	8.30	8.40	7.70	6.30	8.20
	Aver.	7.83	8.96	7.98	7.41	9.90	7.23	12.81	8.16	7.98	10.84	9.11	10.41	8.62	8.91	8.47	8.31	7.97	8.03	7.07	8.71
	STDEV	0.49	0.40	0.49	0.34	0.54	0.26	0.85	0.51	0.71	0.51	0.62	0.76	0.57	0.96	0.44	0.42	0.59	0.46	0.48	0.49
28	1	7.40	11.80	12.40	10.10	14.80	10.30	18.80	10.60	11.90	13.90	13.50	15.30	10.60	14.20	12.20	14.20	12.60	9.90	11.10	12.90
	2	9.00	13.20	11.00	9.50	13.90	11.20	17.80	11.00	12.70	14.90	13.40	15.10	10.60	12.90	12.70	15.30	11.50	10.40	10.60	12.30
	3	8.70	13.80	10.40	9.40	13.10	11.30	19.20	11.40	10.70	15.00	12.80	15.30	9.90	13.00	14.50	14.30	11.40	10.60	9.40	12.70
	4	8.30	15.60	11.10	9.00	14.30	10.50	19.40	11.10	12.40	15.10	13.00	15.00	10.40	11.90	13.10	13.50	10.80	9.20	11.40	13.40
	5	10.30	11.90	11.60	9.20	14.30	11.80	19.90	11.40	11.80	11.90	12.80	17.40	11.00	12.60	13.10	13.80	11.00	10.60	10.60	13.40
	6	9.10	13.20	9.60	9.40	15.60	11.40	17.00	10.60	12.80	11.80	13.10	17.00	11.70	13.70	12.90	15.10	11.50	11.80	10.40	14.40
	7	8.50	13.20	10.20	8.90	15.30	10.50	17.40	11.10	12.70	13.30	13.50	16.50	11.00	13.40	12.70	13.50	11.30	10.50	10.30	14.70
	8	9.80	12.00	11.40	8.80	14.90	11.30	19.20	10.70	11.90	13.80	14.00	17.80	11.20	13.10	12.90	13.70	10.30	11.00	10.30	15.40
	9	8.00	13.50	10.00	10.20	14.70	11.00	18.30	10.90	10.80	14.50	13.90	17.40	10.80	12.60	13.10	13.50	11.30	10.90	11.20	14.10
	10	9.70	12.70	10.60	9.90	14.40	10.80	19.90	10.70	12.30	16.90	13.30	17.00	9.20	13.40	12.80	14.80	11.40	11.60	12.00	12.90
	11	8.50	13.90	10.70	9.90	13.70	11.80	19.30	11.00	11.40	15.60	13.50	15.60	10.60	13.20	12.60	15.30	12.00	10.30	11.40	13.10
	12	7.80	12.20	10.10	9.50	13.60	10.40	18.50	11.60	10.60	15.20	14.00	16.00	10.60	14.40	12.50	13.90	11.60	11.40	11.40	13.90
	Aver.	8.76	13.08	10.76	9.48	14.38	11.03	18.73	11.01	11.83	14.33	13.40	16.28	10.63	13.20	12.93	14.24	11.39	10.68	10.84	13.60

	STDEV	0.86	1.08	0.79	0.46	0.73	0.53	0.94	0.33	0.80	1.48	0.42	1.02	0.63	0.70	0.56	0.71	0.57	0.73	0.70	0.92
56	1	9.70	19.50	15.10	12.30	21.30	18.90	25.40	15.10	16.00	25.50	17.50	24.20	12.90	25.40	25.10	27.60	19.60	19.30	22.50	27.10
	2	9.40	18.60	15.70	11.90	20.90	18.30	25.70	14.70	17.60	24.40	17.20	24.80	12.30	24.80	24.10	27.70	18.70	18.60	23.30	25.10
	3	9.50	20.80	16.40	10.40	21.10	18.30	27.10	14.80	17.40	25.00	16.40	25.70	12.10	24.40	25.50	28.50	19.40	18.50	21.40	24.00
	4	9.40	19.80	16.30	11.90	23.60	18.80	27.70	13.60	16.30	26.00	16.80	26.40	13.80	26.00	24.90	26.50	18.30	19.60	21.50	23.60
	5	10.60	19.60	15.20	11.50	20.50	18.60	24.50	12.90	17.80	23.30	18.20	24.60	12.20	25.60	22.40	29.10	19.70	20.50	23.60	27.20
	6	9.50	20.80	15.30	11.20	21.90	19.80	24.20	14.00	18.60	24.40	17.80	24.70	12.10	22.70	24.30	26.50	20.60	21.40	24.70	29.70
	7	10.60	19.40	15.30	12.20	21.50	18.70	23.80	15.40	16.40	24.00	17.20	26.40	12.10	21.90	20.70	29.00	18.50	21.70	25.70	30.00
	8	9.70	19.90	13.80	12.30	20.00	19.90	25.10	15.20	17.60	23.90	18.10	24.40	11.70	20.60	21.50	30.80	19.50	20.40	26.70	29.10
	9	10.10	-	15.70	11.30	21.30	19.20	23.00	14.90	17.20	26.60	15.10	25.50	13.40	22.40	21.70	26.50	18.00	21.00	25.10	-
	10	8.70	-	15.60	11.10	22.20	17.90	26.10	15.10	16.70	26.90	15.90	24.90	13.70	22.30	20.40	25.40	19.60	20.80	26.60	-
	11	9.40	-	15.10	11.40	22.00	18.80	23.90	15.30	18.90	27.00	17.60	21.70	13.10	22.90	21.90	26.30	18.50	22.40	24.70	-
	12	8.50	-	14.50	11.40	22.60	18.80	24.80	15.00	17.20	27.00	17.00	24.40	13.50	23.90	21.40	27.40	19.90	19.50	25.10	-
	Aver.	9.59	19.80	15.33	11.58	21.58	18.83	25.11	14.67	17.31	25.33	17.07	24.81	12.74	23.58	22.83	27.61	19.19	20.31	24.24	26.98
	STDEV	0.63	0.73	0.71	0.57	0.97	0.58	1.38	0.77	0.88	1.35	0.91	1.23	0.74	1.69	1.83	1.52	0.78	1.23	1.80	2.53
90	1	10.20	24.20	19.40	15.20	27.80	23.40	28.60	20.70	23.60	29.40	20.60	29.70	15.20	36.20	31.40	37.50	26.30	28.20	32.10	37.80
	2	10.50	23.00	19.60	14.70	26.50	23.10	29.80	20.20	22.00	32.20	20.90	29.80	14.90	29.80	29.10	38.80	28.80	28.90	32.40	36.00
	3	10.60	24.20	20.90	15.10	29.10	25.20	29.50	21.00	24.90	28.10	23.30	31.00	17.30	31.90	32.90	39.20	27.80	29.70	31.80	42.20
	4	8.60	21.10	19.60	14.60	28.30	27.20	29.40	20.00	25.40	30.00	22.90	31.90	16.00	34.90	33.70	35.00	27.90	30.10	32.50	37.50
	5	10.10	23.80	19.20	14.60	27.20	26.40	28.20	22.00	24.00	27.10	23.40	35.20	16.00	32.50	31.10	41.30	25.60	25.60	32.80	38.00
	6	11.70	24.90	21.20	13.60	23.80	27.40	28.60	20.60	24.50	28.90	22.90	33.30	16.40	36.40	29.70	38.00	26.50	30.10	30.50	35.80
	7	10.60	24.60	19.70	15.20	26.70	24.20	28.80	20.30	23.40	30.30	24.70	33.50	16.40	33.60	31.60	39.90	26.30	29.80	31.10	37.50
	8	9.40	25.30	19.60	13.40	27.80	24.70	32.20	23.90	23.20	27.80	23.10	33.20	15.10	33.10	29.20	39.30	27.70	28.80	30.80	39.60
	9	11.20	23.50	19.70	14.00	25.10	25.70	24.70	20.40	23.50	29.40	20.20	29.40	16.60	38.30	33.30	35.90	26.70	28.70	31.10	36.30
	10	10.60	25.20	20.50	15.00	29.80	27.10	26.70	19.30	23.10	33.80	20.20	30.40	17.10	32.40	30.10	37.20	25.90	29.40	32.40	36.80
	11	10.40	24.80	19.10	13.80	26.90	24.10	33.20	19.60	22.60	30.40	21.30	34.40	17.60	34.90	34.60	39.80	26.40	28.80	30.20	34.00
	12	11.50	25.80	19.20	13.10	25.30	27.40	29.00	20.00	23.90	29.80	20.10	31.50	17.60	36.80	36.60	38.30	25.90	28.60	34.10	34.80
	Aver.	10.45	24.20	19.81	14.36	27.03	25.49	29.06	20.67	23.68	29.77	21.97	31.94	16.35	34.23	31.94	38.35	26.82	28.89	31.82	37.19
	STDEV	0.85	1.26	0.69	0.75	1.71	1.60	2.21	1.23	0.95	1.85	1.58	1.96	0.95	2.44	2.33	1.77	0.99	1.21	1.12	2.18
180	1	10.20	29.80	25.90	18.60	36.20	33.10	31.80	28.60	31.80	46.90	33.70	44.60	17.00	45.50	45.20	56.80	38.70	49.90	53.70	63.10

	2	9.70	31.90	26.40	19.20	40.20	35.40	32.40	31.70	33.40	50.20	31.20	46.30	20.60	45.60	48.60	53.50	41.60	45.40	54.20	65.40
	3	10.20	33.60	26.00	16.90	38.30	32.70	34.10	27.30	32.70	45.80	31.60	44.60	18.80	47.60	43.40	55.20	44.60	40.40	52.50	73.00
	4	9.50	30.60	24.50	18.80	35.20	32.50	35.80	27.80	36.00	48.60	29.30	47.40	19.20	45.50	42.60	56.40	37.00	45.20	50.60	61.70
	5	11.40	33.40	25.40	17.80	35.70	34.40	31.10	27.40	35.00	50.50	25.30	45.10	21.80	47.00	40.90	54.60	40.70	48.80	54.60	62.30
	6	11.20	32.40	29.40	18.00	31.10	34.10	31.10	25.70	37.60	56.40	25.20	43.80	17.80	49.50	44.90	54.80	43.70	48.70	55.90	63.80
	7	10.90	33.50	27.50	18.80	36.10	37.10	29.40	24.60	35.50	50.90	27.60	45.20	17.60	47.20	47.10	50.00	43.10	47.10	55.20	56.10
	8	10.70	32.60	27.00	17.10	39.20	33.20	30.90	24.90	35.20	52.00	27.20	46.60	18.60	48.30	42.20	53.90	43.20	47.70	56.00	64.10
	9	11.30	30.40	28.40	17.80	37.60	35.20	31.30	28.50	31.70	48.30	-	-	19.50	50.50	40.90	57.20	41.80	47.20	49.00	66.30
	10	12.20	31.10	27.90	17.60	37.30	35.40	28.90	26.40	31.30	49.20	-	-	18.50	48.20	46.30	50.50	44.70	46.40	58.60	61.70
	11	12.40	28.60	27.10	18.40	38.80	36.40	31.40	27.00	34.10	47.80	-	-	17.90	47.20	46.00	57.70	43.70	45.80	53.50	64.20
	12	10.90	30.40	26.70	19.20	35.50	36.90	34.00	26.20	33.70	48.80	-	-	19.90	51.10	41.60	57.60	41.30	45.90	57.70	63.10
	Aver.	10.88	31.53	26.85	18.18	36.77	34.70	31.85	27.18	34.00	49.62	28.89	45.45	18.93	47.77	44.14	54.85	42.01	46.54	54.29	63.73
	STDEV	0.90	1.62	1.35	0.77	2.40	1.62	1.97	1.91	1.94	2.75	3.09	1.21	1.37	1.87	2.57	2.57	2.35	2.43	2.74	3.87

Table A-6: 40% Resistivity Values

Curing Time (days)	Point	OPC	C1	C2	C3	C4	C5	C6	C7	C11	IC1	IC2	IC3	IC4	F1	F2	F3	F4	F5	F6	IF1
	1	8.70	4.30	4.00	3.40	4.45	4.70	4.10	4.10	4.60	5.10	4.10	3.40	4.10	4.80	5.90	4.90	4.30	4.30	3.40	4.70
	2	8.10	4.30	4.40	3.60	4.30	5.30	4.00	4.80	3.90	5.20	4.10	3.60	3.60	5.20	4.80	4.50	4.30	4.90	3.70	4.90
	3	8.50	4.90	4.10	3.50	4.50	5.50	3.80	4.60	4.30	5.10	4.10	4.10	4.40	4.50	5.20	4.20	4.20	4.90	3.90	4.50
	4	8.60	4.10	4.00	3.40	-	4.60	4.10	4.40	4.50	5.10	4.30	3.80	4.10	5.10	5.10	4.30	4.30	5.20	3.90	4.30
3	5	9.20	4.50	4.00	4.40	-	5.40	4.00	4.50	5.10	5.80	4.60	4.00	4.50	5.70	5.60	4.20	3.90	4.30	3.60	4.10
	6	7.70	4.30	4.10	4.50	-	4.60	4.20	4.60	5.30	6.10	4.60	4.10	4.60	5.70	5.10	4.70	3.70	4.50	3.90	4.60
	7	8.50	4.80	4.30	4.70	-	4.50	4.00	4.20	5.30	5.80	4.70	4.30	4.60	5.40	5.50	4.60	3.90	4.30	3.80	4.20
	8	8.60	4.50	4.20	4.50	-	4.80	4.50	4.80	5.00	5.60	5.00	3.80	4.90	6.00	5.90	4.60	4.30	4.30	3.70	4.40
	9	8.10	4.70	4.10	3.90	-	4.60	3.80	4.90	5.50	5.10	4.50	3.60	4.80	6.20	5.70	4.60	4.40	4.30	4.70	4.60

	10	8.10	4.60	4.10	4.20	-	4.50	3.90	4.70	4.80	5.50	4.50	4.00	4.00	6.30	5.40	4.40	4.50	4.60	4.90	5.00
	11	8.10	4.90	4.00	4.20	-	4.70	4.10	4.80	4.90	5.70	4.80	3.90	4.20	6.10	5.30	4.10	4.60	4.20	5.00	4.90
	12	8.60	4.50	3.90	4.20	-	4.60	4.20	4.90	5.00	5.20	4.90	3.60	4.90	6.20	5.60	4.50	4.40	4.60	5.30	4.50
	Ave.	8.40	4.53	4.10	4.04	4.42	4.82	4.06	4.61	4.85	5.44	4.52	3.85	4.39	5.60	5.43	4.47	4.23	4.53	4.15	4.56
	STD.	0.40	0.26	0.14	0.47	0.10	0.36	0.19	0.26	0.46	0.35	0.31	0.26	0.40	0.60	0.34	0.23	0.27	0.32	0.64	0.28
7	1	9.40	8.00	5.50	6.00	6.80	5.90	5.20	6.10	7.50	7.00	7.90	6.20	5.80	7.40	6.80	6.10	5.80	7.60	5.20	5.90
	2	10.70	7.90	6.10	6.60	6.80	6.20	4.70	6.20	7.90	7.00	7.30	7.00	6.20	7.30	7.20	5.30	6.60	7.20	5.00	5.80
	3	9.70	6.60	6.20	6.70	7.30	6.90	5.20	6.10	8.00	6.90	8.50	6.10	5.90	8.10	7.10	5.90	6.40	7.00	5.30	6.50
	4	10.00	7.50	6.20	6.50	6.80	6.30	5.10	6.30	8.00	7.10	7.80	6.10	5.90	8.20	6.87	5.90	6.90	7.30	5.10	6.20
	5	9.70	6.40	6.20	5.80	7.10	6.30	5.40	6.60	8.40	7.00	7.80	6.20	5.80	6.80	6.50	6.80	5.40	6.80	4.80	5.50
	6	10.10	6.30	6.30	5.80	7.20	6.20	5.30	6.00	8.00	7.10	7.20	6.10	5.50	6.00	6.80	6.10	5.90	7.40	5.00	6.00
	7	10.80	6.80	6.60	5.90	7.60	6.00	5.80	6.50	8.90	6.90	7.40	6.20	5.70	6.00	7.20	6.30	5.50	7.90	4.70	5.40
	8	10.20	7.00	6.10	5.50	7.30	6.40	5.30	6.20	8.30	8.00	8.00	6.50	5.50	6.60	7.30	6.50	5.70	7.20	4.90	5.40
	9	9.50	7.00	6.50	6.10	6.70	6.70	5.00	6.00	7.80	7.50	8.20	6.20	5.70	-	7.00	6.60	5.90	7.50	4.53	6.90
	10	10.40	6.40	6.20	6.10	6.50	6.60	5.20	6.00	7.80	7.40	6.70	6.10	5.60	-	7.20	6.20	5.90	8.00	-	5.80
	11	10.70	6.70	6.00	6.00	6.50	6.40	4.90	6.00	7.20	7.60	7.80	6.10	5.90	-	6.80	6.60	5.30	7.20	-	6.40
	12	10.90	6.50	5.10	6.60	6.80	6.90	5.10	6.00	8.10	7.30	7.70	5.60	5.50	-	7.60	6.10	5.60	7.50	-	5.80
	Ave.	10.18	6.93	6.08	6.13	6.95	6.40	5.18	6.17	7.99	7.23	7.69	6.20	5.75	7.05	7.03	6.20	5.91	7.38	4.95	5.97
	STD.	0.53	0.58	0.41	0.38	0.35	0.32	0.27	0.21	0.43	0.34	0.48	0.32	0.21	0.85	0.29	0.40	0.49	0.35	0.25	0.46
14	1	12.00	15.70	10.00	10.10	10.70	11.80	9.00	10.40	12.10	12.70	13.00	11.50	7.80	11.20	9.50	10.90	10.90	9.50	7.50	8.80
	2	11.30	14.50	10.00	9.70	11.70	11.00	8.70	11.90	11.30	12.80	11.50	12.50	8.40	11.70	10.10	11.00	10.70	9.70	7.40	9.10
	3	11.90	14.60	10.70	9.60	12.10	10.40	8.50	10.60	11.90	12.00	12.00	11.80	7.20	11.50	9.30	11.30	10.10	9.20	7.10	8.60
	4	11.70	14.50	10.70	10.20	12.30	10.70	9.00	10.80	12.00	11.70	12.10	10.20	8.80	11.60	10.30	10.60	10.40	9.20	7.20	10.10
	5	10.00	14.70	10.60	10.40	12.10	11.30	8.00	11.60	13.70	11.20	12.90	10.70	8.20	11.00	9.40	10.80	8.50	10.00	7.00	7.70
	6	11.40	13.60	-	10.10	12.20	10.70	9.00	11.00	13.70	11.60	11.50	11.70	8.00	9.80	9.50	10.90	8.10	9.20	8.00	7.60
	7	12.20	14.70	-	11.10	11.70	11.30	8.10	11.60	14.30	12.20	12.80	10.80	7.20	10.10	9.80	9.10	8.50	10.10	7.80	8.20
	8	11.80	14.30	-	11.00	11.80	10.60	7.70	10.60	14.10	12.00	12.70	9.90	8.80	10.50	10.00	11.00	8.60	10.10	7.70	8.40
	9	11.20	15.50	-	8.90	11.40	10.60	7.80	10.60	12.80	11.50	14.00	11.60	-	11.40	9.20	11.10	10.00	10.30	7.00	8.70
	10	12.10	14.10	-	10.90	12.90	11.60	7.90	10.40	12.80	10.80	12.90	11.20	-	10.90	10.00	10.90	9.60	9.80	7.30	9.20
	11	13.40	14.50	-	9.50	12.60	10.40	8.20	10.20	12.50	10.90	12.50	10.70	-	11.60	10.30	9.90	9.60	9.20	7.10	8.70
	12	12.40	13.60	-	9.50	10.80	9.60	7.90	10.70	12.20	11.20	12.50	9.80	-	11.60	10.00	10.60	10.10	9.80	6.70	10.20

	Ave.	11.78	14.53	10.40	10.08	11.86	10.83	8.32	10.87	12.78	11.72	12.53	11.03	8.05	11.08	9.78	10.68	9.59	9.68	7.32	8.78
	STD.	0.81	0.63	0.37	0.68	0.66	0.61	0.50	0.55	0.96	0.65	0.70	0.83	0.63	0.64	0.39	0.61	0.95	0.41	0.38	0.80
28	1	10.70	21.30	14.10	16.40	17.70	19.30	17.80	20.20	22.50	20.30	21.70	19.90	10.70	22.70	19.50	27.20	17.20	16.90	12.40	19.10
	2	10.90	21.50	14.50	16.70	18.30	19.50	19.30	22.40	22.00	21.10	21.70	19.10	10.80	23.70	19.60	27.30	16.90	17.90	12.10	19.40
	3	10.90	22.10	13.80	16.40	17.20	19.70	18.30	19.30	22.50	20.90	21.80	19.10	11.20	23.20	19.20	26.60	16.40	20.10	12.20	21.30
	4	11.20	21.60	15.10	14.90	17.80	20.90	16.20	19.30	24.30	20.70	21.60	18.40	10.60	20.30	18.80	28.10	17.80	17.30	12.80	19.30
	5	10.80	23.30	14.30	18.60	18.40	19.60	16.40	18.80	23.40	19.80	21.80	19.80	13.30	22.80	19.10	23.00	17.10	19.30	12.50	16.20
	6	11.10	23.30	15.30	18.20	20.00	18.30	15.00	20.30	23.30	19.90	21.30	19.90	11.60	24.20	19.50	23.10	17.80	21.00	12.60	18.90
	7	11.30	19.00	15.30	17.00	18.60	18.60	16.10	19.10	21.00	20.20	20.90	19.60	12.00	24.30	18.20	23.20	16.80	18.80	13.70	20.20
	8	11.30	22.30	13.60	18.40	18.60	20.70	16.80	18.30	21.50	19.20	23.40	20.50	12.70	22.40	19.30	23.80	15.40	17.20	13.10	20.70
	9	12.10	22.60	14.00	-	17.10	19.40	18.50	20.10	19.00	21.80	20.20	19.50	-	22.90	18.10	26.50	-	18.20	12.30	20.90
	10	13.40	24.00	13.20	-	20.00	19.60	18.40	20.30	21.80	21.30	20.20	18.80	-	22.00	19.30	26.50	-	18.30	12.60	17.90
	11	14.10	24.60	13.50	-	20.40	18.80	18.50	19.00	20.30	18.90	18.90	16.70	-	22.20	18.60	28.30	-	17.00	11.90	19.20
	12	12.30	21.80	14.00	-	16.90	21.00	17.40	19.70	19.70	19.80	19.70	17.30	-	21.10	20.30	25.60	-	17.30	13.30	19.20
	Ave.	11.68	22.28	14.23	17.08	18.42	19.62	17.39	19.73	21.78	20.33	21.10	19.05	11.61	22.65	19.13	25.77	16.93	18.28	12.63	19.36
	STD.	1.09	1.46	0.70	1.26	1.18	0.87	1.29	1.06	1.58	0.87	1.20	1.12	0.99	1.18	0.62	1.98	0.78	1.31	0.52	1.38
56	1	14.90	43.50	27.30	29.30	27.60	34.30	43.80	29.70	34.40	35.50	29.10	35.60	18.23	47.30	35.50	54.30	36.50	41.50	26.60	37.40
	2	14.00	46.10	27.70	28.00	26.70	34.10	44.00	27.70	40.20	38.10	32.30	31.20	18.15	45.30	36.00	51.70	39.00	45.30	24.40	37.60
	3	14.20	39.50	27.20	26.70	26.10	31.40	35.60	33.40	36.00	37.60	30.80	32.00	14.30	42.10	37.50	51.60	34.20	40.50	26.60	39.50
	4	13.80	42.10	27.80	27.10	25.60	34.80	45.80	32.50	35.30	35.80	27.20	32.00	18.60	39.00	33.00	50.60	31.90	42.20	25.10	36.00
	5	13.90	40.00	24.90	19.50	31.30	31.60	43.10	33.30	31.10	36.80	29.40	36.00	15.90	41.20	32.60	51.80	32.00	37.50	31.10	40.50
	6	14.70	44.00	28.10	23.30	29.80	30.90	38.30	35.10	33.60	38.90	34.80	35.10	16.70	40.30	35.20	54.80	33.10	37.00	29.80	37.40
	7	14.40	42.00	26.80	21.60	29.40	35.40	36.80	31.50	33.40	33.60	30.70	33.60	18.50	42.50	34.80	50.70	31.00	37.60	27.90	42.10
	8	13.60	44.00	25.00	22.90	30.40	32.70	37.90	31.80	34.50	33.50	29.40	32.40	17.60	42.40	35.80	49.10	30.60	36.50	28.90	41.90
	9	12.60	42.20	27.60	24.70	30.30	27.80	38.70	32.20	32.80	34.70	30.40	31.70	17.20	47.70	36.00	55.80	-	43.20	27.10	40.50
	10	13.20	41.00	26.50	21.80	35.00	30.20	37.10	35.70	34.80	35.30	30.20	32.90	16.00	46.70	37.70	53.10	-	40.20	28.50	36.20
	11	12.40	44.60	28.50	27.00	29.30	29.70	35.50	30.90	31.30	35.70	31.20	34.20	13.90	45.30	36.60	51.80	-	40.60	24.10	40.10
	12	13.20	44.10	27.30	29.10	27.80	31.20	35.50	32.00	31.30	35.60	31.90	32.93	16.89	46.90	36.60	55.40	-	42.10	26.30	39.20
	Ave.	13.74	42.76	27.06	25.08	29.11	32.01	39.34	32.15	34.06	35.93	30.62	33.30	16.83	43.89	35.61	52.56	33.54	40.35	27.20	39.03
	STD.	0.78	1.97	1.12	3.23	2.60	2.30	3.77	2.18	2.52	1.67	1.90	1.60	1.56	2.99	1.57	2.11	2.91	2.73	2.14	2.09
90	1	14.80	61.20	37.50	33.40	39.50	46.10	59.20	48.50	46.20	54.70	40.10	40.90	19.90	45.00	54.20	84.90	51.80	49.90	47.60	55.50

	2	14.20	56.00	37.90	28.70	47.10	45.30	64.90	48.20	46.70	53.10	38.40	39.20	21.50	68.80	54.10	81.70	52.70	65.20	47.50	71.70
	3	14.20	47.90	38.10	36.40	43.90	42.30	54.20	45.00	46.60	54.60	41.50	45.80	19.30	75.90	50.60	79.80	59.20	60.80	44.70	64.30
	4	13.60	54.50	38.30	32.70	44.80	41.20	57.10	43.30	43.40	51.10	42.00	39.30	18.80	77.40	43.60	82.80	58.70	54.40	46.80	65.30
	5	16.00	63.80	37.70	35.60	46.40	44.30	49.80	50.80	47.40	51.70	39.90	48.30	18.90	80.00	45.80	88.60	55.60	79.40	43.20	59.30
	6	15.80	56.30	38.80	36.40	45.30	47.80	55.80	48.50	46.60	47.30	40.60	39.30	22.90	71.20	51.80	93.10	51.20	68.90	37.30	64.70
	7	15.40	49.70	39.00	33.40	38.40	45.00	55.80	46.80	46.30	47.80	37.90	40.10	19.20	73.50	51.50	73.20	58.40	68.70	34.20	62.80
	8	15.70	58.30	40.50	35.00	38.80	45.30	52.10	50.00	44.30	49.50	37.70	43.40	22.20	72.20	48.20	93.30	50.60	75.90	45.80	57.40
	9	15.00	53.40	44.30	36.00	38.20	41.20	66.50	46.00	48.20	46.00	39.80	43.80	27.30	73.20	50.80	85.90	55.70	63.10	44.40	69.20
	10	15.60	49.60	41.20	37.30	39.10	43.30	67.80	51.60	46.60	43.60	38.50	43.40	21.50	85.20	55.10	82.40	59.40	61.40	43.20	65.80
	11	15.20	54.80	43.20	33.90	33.70	40.90	60.80	52.00	43.40	45.20	39.70	43.10	21.80	73.50	46.90	89.30	52.40	63.80	44.80	65.10
	12	14.60	58.60	42.20	35.70	37.60	41.30	62.40	54.80	41.30	39.40	41.10	39.40	23.20	84.70	49.10	86.50	60.10	60.20	41.60	62.80
	Ave.	15.01	55.34	39.89	34.54	41.07	43.67	58.87	48.79	45.58	48.67	39.77	42.17	21.38	73.38	50.14	85.13	55.48	64.31	43.43	63.66
	STD.	0.75	4.78	2.34	2.33	4.24	2.30	5.74	3.26	2.02	4.67	1.41	2.96	2.44	10.30	3.55	5.70	3.60	8.25	4.06	4.60
180	1	16.10	103.00	76.80	55.40	51.80	66.70	96.60	100.50	76.00	85.10	55.00	82.40	37.00	131.20	96.20	117.70	94.10	132.40	81.90	106.40
	2	15.70	92.10	76.70	53.80	62.00	77.20	100.30	84.20	75.50	79.40	61.10	80.50	39.10	128.00	95.60	114.10	86.10	132.70	107.40	100.30
	3	15.90	115.80	69.80	55.10	55.10	76.20	100.20	95.50	66.70	74.60	54.70	88.00	35.10	136.40	92.00	104.30	84.00	100.40	112.00	91.80
	4	15.00	117.60	76.70	49.70	66.70	65.80	97.10	110.80	84.50	84.00	60.60	89.40	39.40	125.20	102.10	109.40	100.50	91.10	94.60	116.20
	5	15.10	101.10	70.10	55.60	70.20	66.20	89.10	80.10	73.20	76.60	55.70	74.00	37.60	115.00	92.50	106.30	83.40	118.80	118.80	94.00
	6	16.40	95.40	78.30	58.80	75.20	78.30	88.50	73.50	75.10	79.80	59.20	72.60	35.20	132.20	102.30	106.30	91.20	117.30	104.10	89.20
	7	16.10	96.80	75.60	58.70	67.80	70.30	89.90	78.60	69.40	75.50	66.10	70.30	37.80	107.00	102.20	102.20	82.20	138.60	114.60	98.00
	8	15.40	96.50	80.20	57.40	64.40	85.20	84.40	74.60	68.70	85.50	55.50	75.50	36.30	123.90	101.30	91.90	80.20	148.10	116.00	95.50
	9	17.60	87.50	67.20	53.70	61.50	68.10	95.10	84.60	63.70	75.40	60.00	81.40	37.60	124.80	100.20	98.30	96.30	132.20	111.10	105.50
	10	18.20	108.00	76.40	48.60	64.20	70.20	96.10	91.00	80.50	80.40	54.10	74.90	38.70	115.70	98.10	108.40	95.10	116.80	95.20	103.30
	11	18.50	95.10	73.50	49.30	65.30	64.30	96.70	89.50	85.80	79.10	53.20	88.60	39.20	116.40	97.60	102.40	83.60	108.40	89.20	102.60
	12	18.50	108.50	71.40	50.30	63.10	71.60	91.60	69.70	71.30	78.50	56.70	84.30	35.60	118.50	100.10	107.50	85.70	126.10	88.40	109.10
	Ave.	16.54	101.45	74.39	53.87	63.94	71.68	93.80	86.05	74.20	79.49	57.66	80.16	37.38	122.86	98.35	105.73	88.53	121.91	102.78	100.99
	STD.	1.31	9.38	3.95	3.64	6.23	6.31	5.01	12.06	6.84	3.75	3.78	6.63	1.56	8.54	3.66	6.81	6.60	16.42	12.43	7.78

VITA

Zane Arthur Lloyd

Candidate for the Degree of

Master of Science

Thesis: INVESTIGATION OF THE QUALITY CONTROL OF WASTE PRODUCTS FOR CONCRETE

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, 2019.

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Professional Memberships: ASCE, ACI