FIELD INVESTIGATION OF PUMPING AIR ENTRAINED CONCRETE AND VALIDATION OF THE SAM TEST ON LIGHTWEIGHT AGGREGATE CONCRETE MIXTURES

By

CHAD JORDAN STAFFILENO

Bachelor of Science in Civil Engineering

Oklahoma State University

Stillwater, Oklahoma

2018

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, 2020

FIELD INVESTIGATION OF PUMPING AIR ENTRAINED CONCRETE AND VALIDATION OF THE SAM TEST ON LIGHTWEIGHT AGGREGATE CONCRETE MIXTURES

Thesis Approved:

Dr. Tyler Ley

Thesis Adviser

Dr. Bruce Russell

Dr. Norb Delatte

ACKNOWLEDGEMENTS

The authors would like to thank Jim Wilde and Justin LaRoche of the Vermont Department of Transportation for providing testing data and samples. Also, the authors would like to thank the companies who helped us obtain this data

Name: CHAD STAFFILENO

Date of Degree: MAY 2020

Title of Study: FIELD INVESTIGATION OF PUMPING AIR ENTRAINED CONCRETE AND THE VALIDATION OF THE SAM TEST ON LIGHTWEIGHT CONCRETE MIXTURES

Major Field: CIVIL ENGINEERING

Abstract:

The use of a pump to transport concrete is one of the most common and widely accepted methods to distribute and place concrete. An air-entraining admixture can be added to fresh concrete to prevent freeze-thaw durability issues from occurring. Unfortunately, the air volume and bubble quality of air-entrained concrete is problematic when pumped. In some situations, concrete can lose up to half of its air volume after being pumped in comparison to the concrete discharged out of the mixing truck. This work focuses on investigating the air volume and SAM Number with pumped concrete mixtures and on non-pumped mixtures with fine LWA's. The key findings show that after pumping the fresh properties of air entrained concrete yield decreased air contents and increased SAM Numbers however, when compared to the hardened properties, the samples show that air volume recovered and the spacing factor of the bubbles were not impacted. In addition, air entrained concrete with fine LWA shows a small impact on air content and SAM Number when certain LWA' s prewetted prior to mixing. However, not all aggregates were applicable to the SAM Test. A test method is presented to determine if a LWA is applicable.

Keywords: air entrained concrete; concrete; pumping concrete; SAM; Super Air Meter, Lightweight Aggregate; LWA; internal curing; curing

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION OF AIR ENTRAINED CONCRETE TESTING AFTER PUMPING & CONCRETE WITH LIGHTWEIGHT AGGREGATE MIXTURES

1.0 Air Entrained Concrete

An air-entraining admixture (AEA) can be added to fresh concrete to prevent freeze-thaw durability issues from occurring. This AEA is intended to create small well distributed air filled voids at the time of mixing. These air filled voids are then cast into the concrete to provide more space for moisture to expand and thus reduces the damage caused a freeze-thaw cycle. The air void quality of concrete relies on the size and spacing of the air bubbles in a concrete mixture. A mixture is said to have good air void quality when the bubbles are small and well dispersed throughout[1]. These parameters provide better performance in freeze-thaw environments. The spacing factor from ASTM C457 and the durability factor from ASTM C666 have commonly been used to describe to the air void quality[2, 3]. However, both of the previous tests utilize a hardened concrete sample. A new test developed by researchers at Oklahoma State University, is used to predict the air void quality in fresh concrete. The Super Air Meter (SAM), a pressure test, not only outputs the air volume in the concrete but also a SAM Number. This SAM Number has been correlated to the spacing factor and freeze-thaw resistance in hardened concrete[1, 4]

1.1 Sampling Air Entrained Concrete

When pumping is required to place concrete, testing is often completed at the point of placement. The specifier assumes that this is a representative of the air content in the hardened concrete[5]. A typical sample size of air entrained concrete is 1 ft^3 and testing should be completed within 5 minutes of obtaining the representative sample[6]

1.2 Measuring Air Entrained Concrete

A typical value desired for concrete is 6% air by volume of the concrete to be considered freeze thaw durable[7]. Sampling air entrained concrete is typically done using ASTM C231 Type B[2]. This is a pressure test that uses the pressure change between two chambers to determine air content. This is typically used with denser aggregates and requires a correction factor. However, when lightweight aggregates are in the mixture design ASTM C173 the Volumetric meter (Roll-A-Meter) is used, it should be noted that this method can also be used with concrete that does not contain lightweight aggregates. This a volumetric test method and involves using alcohol and foam level reading to test for air volume of any aggregate dense or light weight. However, it would advantageous for the industry if the SAM Test (AASHTO TP 118) could be used in both cases since it gives more insight into the size and spacing of the bubbles [4]. The SAM test provides the air volume and a SAM Number. The SAM Number can be correlated with the spacing factor (ASTM C457) and the durability factor (ASTM C666). The SAM test takes approximately test 10 minutes on fresh concrete and the spacing factor and durability factor can take weeks or months.

1.3 Pumping Air Entrained Concrete

The use of a concrete pump is one of the most common and widely accepted methods to distribute and place concrete. However, this can lead to quality control concerns in relation to the air volume in the concrete. Concrete can lose up to half of the original air volume through the pump. In other situations, the air content measured will increase after pumping[5, 8, 9]. This has caused concerns where the concrete is exposed to freezing and thawing cycles. Due to these quality control concerns, specifications typically require concrete to be tested at the point of placement after the pump.

1.3.1 Pumping Mechanisms that Impact Air Void Distribution

The air volume in a mixture can reduce by up to half of the original air content during pumping process. However, it has also been shown to increase in air content. Either way, it is important to understand the mechanisms that impact the air void quality while pumping [5, 9]. The three main mechanisms typically discussed are vacuum, impact, and pressure. The literature suggests that these variables likely play a key role in the bubble size, distribution, and volume in a concrete mixture [5].

1.3.1.1 Vacuum Mechanism

The vacuum mechanism relates to pumping concrete downward in a section of pipe. When the weight of the mixture overcomes the resistance of frictional force, the concrete will slide down the pipe. During this scenario it is possible that a vacuum will develop on the concrete which can potentially produce a loss of air content when the mixture is discharged from the pump [10, 11]. This would cause the bubbles to become large enough to burst or be at a higher risk of bursting [10, 11].

1.3.1.2 Impact Mechanism

When concrete overcomes the frictional resistance in the pipe network and free falls to a 90 degree bend, when concrete free falls from excessive heights while being placed, or when concrete is poured into the hopper of the pump, air content can be “knocked out” of the mixture[8, 11, 12]. Research has suggested that the impact of “rapidly moving concrete” can reduce air content[11]

1.3.1.3 Pressure Mechanism

Typical concrete pumps can apple pressure ranging from 300 psi to 500 psi[10, 13]. Research has shown that when the concrete is under pressure it will be affected by Henry’s Law with shows that the amount of dissolved gas is directly related to the pressure applied to the gas out of solution[10, 13]. This then means that the air entrained bubbles inside of the concrete, while under high pressures, can dissolve into the paste solution[10, 11, 13]. Furthermore, the Young-Laplace equation would suggest that the smaller bubbles, which have a higher internal pressure, would be more likely to dissolve into the paste[10, 11]. However, once the pressure is released, a reversal process will begin to happen and the air dissolved into solution will begin to return to the gaseous state in concrete mixture. It has been suggested that the air will return to the larger bubbles instead of creating new air voids[9, 10, 12, 13]. This would increase the spacing factor and would negatively impact the freeze-thaw durability of the concrete. By way of contrast, new research has suggested that when the air bubble return to the concrete there was not a significant coarsening of the air void system[13].

1.3.2 Previous Work of Pumping Air Entrained Concrete

New research from Oklahoma State University has shown that testing concrete out of the ready-mix truck before pumping gives a more accurate description of the air void quality in the hardened concrete[13]. Chapter II of this research is an extension of this previous research from Oklahoma State University including an extensive field investigation of the fresh air content and SAM Number of concrete tested before and after pumping. Also included is hardened air void analysis and a comparison between the fresh properties and hardened properties. This investigation aims to focus on the impact, negative or positive, that pumping has on air entrained concrete.

1.4 Air Entrained Light Weight Aggregates Concrete

Another quality control concern involves the use of light weight aggregate (LWA) and air volume in concrete. The typical usage of LWA is to reduce the dead load of a concrete element. However, in recent years the practice of internal curing has been used due to the benefits of longer curing duration, reduced plastic shrinkage cracking, increased strength, and improved durability [14-17]. This is done by fine LWA's retaining additional water in the aggregate pores that can then be used later on in the curing process.

1.4.1 Measuring Air in LWA Concrete

There are challenges measuring the air content when LWA are used in an air entrained concrete mixture. ASTM C231 Type B is a popular pressure method used to evaluate the air content in concrete, however, this method is not applicable to mixes containing LWA according to the standard. Instead ASTM C173 the "Roll-A-Meter" is the recommended test to provide the air content in light weight mixtures[18]. Still, this test requires a significant amount of effort and can easily have operator error in ensuring the mixture is adequately mixed. In addition, this test relies on the judgement of the operator to determine the appropriate amount of alcohol used and foam levels[18].

1.4.2 Mechanism of Air Measurements with LWA Concrete

Typical LWA’s used for internal curing are expanded clays, shales, and slates. These aggregates have a higher absorption due to the higher porosity and lower density[14]. In order to reduce the absorption impact on the mixing water of the concrete it is suggested that the aggregate be prewetted prior to mixing [14]. LWA’s batched with a large amount of water absorbed in the pores may be used for internal curing (IC). It has been suggested that ASTM C231, a pressure air volume test, will cause varying results due to the porosity of the LWA’s. However, it has been suggested that a pressure method can work when the aggregates are prewetted for IC[17].

1.4.3 Measuring LWA with the SAM

Chapter III of this research focuses on the applicability of the Super Air Meter (SAM) AASHTO TP 118 on mixtures containing light weight aggregates [4] The SAM is based on the Type B pressure meter but not only measures air volume, it also yields the SAM Number which can be correlated to the spacing factor of the air bubbles inside of the concrete mixture[1, 4]. This research concluded that pre wetted aggregates can be used with the SAM test at certain recommended levels of replacement.

1.5 Overview of research

This work investigates two major issues with air measurements in concrete, which is quality of air entrained concrete being pumped and measuring air entrained lightweight aggregate concrete. Both of these topics have unique challenges and this work can be found in the following chapter of this thesis:

- **Chapter II: Pumping Air Entrained Concrete**
    - Comparing air entrained concrete before and after pumping with fresh and hardened samples.
- **Chapter III: Air Entrained Light Weight Aggregates Concrete**
    - Examining the use of the Super Air Meter with mixtures containing prewetted lightweight aggregates for internal curing.

CHAPTER II

PUMPING AIR ENTRAINED CONCRETE

2.0 Introduction

Freeze-thaw durability issues in concrete will lead to early degradation, excessive costs, and the need to repair the damaged area [1, 19]. This is due to moisture penetrating the pores of the concrete and this moisture freezing and thawing multiple times creating stresses which crack and deteriorate the concrete. To prevent such damage an air-entraining admixture can be added to fresh concrete. This admixture creates small well-distributed air-filled voids during mixing. These voids are cast into the hardened concrete to provide more space for moisture to expand and thus reduces the damage caused by the freeze-thaw cycles. It is widely recognized that having small well-distributed air bubbles creates a good air void quality[1]. On the other hand, large bubbles with inconsistent spacing provide poor freeze-thaw performance despite having similar volume[1, 19] Additionally, the air volume and bubble quality of air-entrained concrete is problematic when pumped. The use of a pump to transport concrete is one of the most common and widely accepted methods to distribute and place concrete. In some situations, concrete can lose up to half of its air volume after being pumped in comparison to the concrete discharged out of a mixing truck [5, 8, 9].

However, in other situations, the air volume measured will increase after pumping [8]. Testing is often required after the pump because the specifier assumes that this is representative of the air content in the hardened concrete [5, 10, 12, 20]. Since the impact on the air content from pumping is unpredictable then this creates arguments between contractors and suppliers on how to produce consistent air entrained concrete. Also, testing concrete after the pump can lead to safety and quality control concerns as it may be done in an area with congested reinforcing and busy construction crews.

Recent research shows new insights into the effects of pumping on air-entrained concrete. The study compares fresh samples using the sequential pressure method (AASHTO TP118)[4] and hardened samples using ASTM C457[3], as well as freeze-thaw durability with ASTM C666[2]from the same mixtures before and after pumping. The sequential pressure method is an emerging test that has been shown to measure the air void spacing in fresh concrete with a term called the SAM Number. The SAM Number is correlated to both the spacing factor and performance in rapid freeze thaw testing ASTM C666 [2, 21].

By investigating 16 laboratory and 18 field mixtures the work shows that by comparing mixtures before and after pumping there is a decrease in fresh air volume and an increase in the air void spacing according to the SAM Number. However, the researchers continued to measure the air volume and SAM Number over time for the concrete that was pumped. This concrete showed small increases in air volume and significant improvements in bubble spacing over 30 min. This suggests that the small air entrained bubbles are returning to the concrete. This work concluded that the pressures from pumping are causing the small entrained air voids to be dissolved and this is why the air volume and SAM Number change after pumping. However, after releasing the pressure on the concrete these voids seem to return to the fresh concrete. This returning of a dissolved gas can be seen in a carbonated beverage when the pressure is removed by opening the cap.

This recovery of the small air entrained voids was confirmed with the hardened air void analysis. The spacing factor found in samples before and after pumping were within the accepted variation of ASTM C457 [3] Furthermore, samples that lost air and increased in SAM Number showed satisfactory performance in ASTM C666 testing despite fresh air contents as low as 2% being measured in the fresh concrete [2]. This indicates that changes observed in the air void system after pumping were not found in the hardened concrete[13].

While these are important findings, there was a limited number of materials and equipment investigated. This work aims to extend this study by repeating much of these measurements at 20 field projects with 62 different concrete mixtures with 18 concrete pumps. The samples were taken before the concrete entered the pump and after the concrete was discharged from the pump hose. This method of sampling and testing allowed for the total air volume and the air void distribution effects of the concrete to be compared before pumping the concrete, after pumping the concrete, and also in a hardened state. These results are then used to provide guidance about air void sampling practices in the field.

2.1 Experimental Methods

2.1.1 Materials & Mixture Designs

All the concrete mixtures were prepared at the concrete batch plants and transported using a revolving drum truck mixer. Concrete from 20 different batch plants was investigated. Each concrete batch plant had different sources of aggregate, ASTM C150 Type I-II cement, either Class C or F fly ash ASTM C618, ASTM C260 air entraining admixtures, and a combination of different water reducers and retarders meeting ASTM C494. The mixture designs were specific to the project at each site. The common factor among all these mixtures was the workability requirement of being pumped and so the slump was between 5 in. and 10 in. The mixtures were provided for bridge decks, sidewalks, walls, and drilled shafts. Additional information about mixture designs can be found in Appendix A.1.

2.1.2 Concrete Pumps

There were 18 different models of truck-mounted concrete pumps used on-site to complete this research. Each pump varied in size with boom lengths between 100 and 200 feet with discharge pipe diameters from 4 to 6 inches. Below is a picture of a concrete pump similar to those used. A full list of the concrete pumps used can be found in Appendix A.2. All the pumps used were dual-piston systems with an s-valve to provide an almost continuous flow of concrete [22]. The trucks used a boom, with interconnected metal pipes attached to achieve different configurations. The last pipe section is composed of a durable flexible rubber hose. This hose is used to allow the workers to direct the flow of the concrete.

2.1.2.1 Boom Configuration of Concrete Pumps

As part of this work, the pipe network boom configuration of the pump was recorded just before the sample was gathered. The boom configurations described the shape of the boom arm with pipe configuration and can be separated into three categories, flat, arch, and A-frame. Images of the three configurations can be seen below in Figure 2-2. The flat configuration of the boom describes when the arm becomes close to being fully extended and almost parallel to the ground as shown in Figure 2-2(a). An arch configuration of the boom is visually shaped like an arch as shown in Figure 2-2(b). The A-frame configuration boom as shown in Figure 2-2(c), has the general shape of a capital “A” with fairly steep upward and downward slope in-between one or possibly two bends at the joints. For this research, there were eight flat configurations, nineteen arch configurations, and twenty-three A-frame configurations measured. For twelve of the samples the configuration was not recorded and they are reported as unknown.

(a) **(b)** **(c)**

Figure 2-1 - Show (a) flat, (b) arch, and (c) A-frame pipe configuration.

2.1.3 Sampling and Testing Procedures

2.1.3.1 Sampling Concrete

All concrete was sampled as per ASTM C172. Samples were taken from each truck; one sample before the pump and one sample after the pump as shown in Figure 2-3. The sample size was approximately two cubic feet for each test. This was obtained by filling a two separate six cubic foot wheel barrows filled one third of the way. The samples taken before the pump were obtained directly from the chute of the concrete trucks. The samples taken after the pump were obtained from the rubber outlet hose of the pump boom. The samples at the boom were taken approximately 45 seconds after obtaining the sample at the concrete truck to ensure that the samples were from the same portion of the concrete truck. The “after pump” concrete was tested immediately after receiving the sample without operator agitation. Then the “before pump” samples were tested about 15 minutes from the time the sample was collected. Wet burlap was placed over the “before pump” samples while the “after pump” tests were performed.

(a) **(b)**

Figure 2-2 shows the sample location (a) before the pump and (b) after the pump.

2.1.3.2 Testing of the Concrete Samples

Two different samples from each truck were measured during the field testing phase. Samples obtained at the concrete truck will be labeled “before pump” and samples obtained at the rubber discharge will be labeled “after pump”. The goal of gathering the before pump and after pump samples is to evaluate the change in the total air volume and the air void distribution effects with the SAM Number and hardened air void analysis due to pumping. These factors provide insights into the freeze-thaw performance of the concrete mixtures. For each sample, one Slump (ASTM C143) [23], three Unit Weight (ASTM C138) [24], and three SAM (AASHTO TP 118)[4] tests were gathered to evaluate the consistency, workability, and air void volume and quality of the fresh concrete. Moreover, one concrete sample was made before and after the pump for a hardened air void analysis (ASTM C457) [3]. The ambient temperature at the time of testing and sampling ranged from 70 to 100 °F.

2.1.3.3 Hardened Air Sample Measuring

Hardened concrete samples were collected in 4” x 4” prisms and cut into approximately 3/4 in. thick slabs and the surface was washed with a lacquer and acetone mixture to harden the surface. Then a polishing process took place ascending in grit until a satisfactory surface was obtained. The surface was then blackened using a permanent marker and the air voids were filled with white barium sulfate powder. The air voids in the aggregate were blackened using a stereomicroscope. The sample was then evaluated using ASTM C457 method C. This method yielded results of air volume, specific surface, spacing factor, void frequency, average chord length, and paste to air ratio [3, 25].

2.1.3.4 Data Analysis

To compare the samples before and after pumping, a line of agreement is shown. This line represents where a point would fall if there was no difference between a sample before and after pumping. A “significant change” for this work is considered a change by more than two standard deviations. This ensures that a sample is outside of the 95% confidence interval and can be considered as statistcally different. For the spacing factor in ASTM C457 the standard deviation is not listed but there is a coefficient of variation given. This work uses twice the coefficient of variation from samples prepared and measured in different laboratories.

Table 2-1 – Shows the confidence intervals for each test.

Concrete Parameter	95% Confidence Boundary (2SD’s)	Referenced Standard
Fresh Air Content (%)	0.7	ASTM C231
SAM Number	0.098	AASHTO TP 118
Hardened Air Content (%)	1.42	ASTM C457
Spacing Factor (%)	40.2*	ASTM C457

*Spacing Factor uses coefficent of variation based on ASTM C457

2.2 Results

The concrete mixtures tested were designed for the local project specifications. The slumps ranged from 5 to 10 inches and the air volume of these mixtures ranged from 2 to 10%.

2.2.1 Air Content of Fresh Concrete

A plot of air content before pumping vs. after pumping is shown in Figure 2-5. Out of 62 mixtures 24% show a decrease in air volume greater than two standard deviations. After pumping, the air volume decreased by approximately 20% of the value that was added to the pump. This means that if a concrete mixture has a 5% air content before it went into the pump then it would have 4% air volume when measured after the pump.

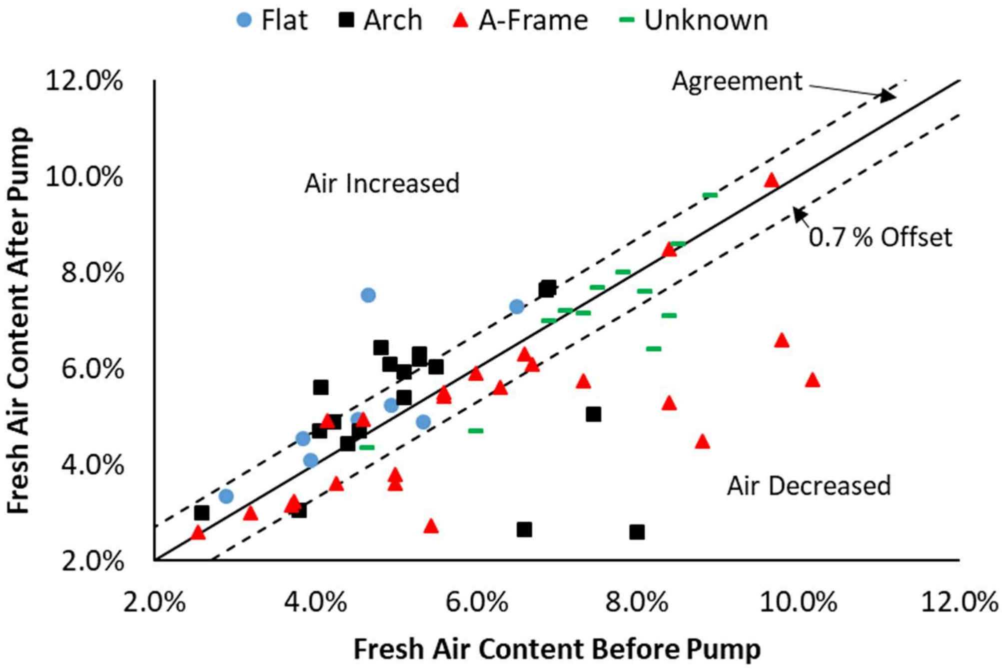

Figure 2-3 - The fresh air content from ASTM C 231 before pumping and after pumping.

The flat, arch, and A-frame configurations had 0%, 21%, and 35% of samples decrease more than two standard deviations. This means that roughly one out of three trucks lost a significant amount of air after pumping with the A-frame configuration and one out of five trucks lost a significant amount of air after pumping with the arch configuration. While no air loss in the flat configuration for these tests, previous testing has shown that air can be lost in this configuration [13].

2.2.2 SAM Number

The SAM Number before pumping compared to after pumping is shown in Figure 2.5. After pumping, 29% of the SAM Numbers increase by more than two standard deviations. This correlates with previous laboratory testing[13].

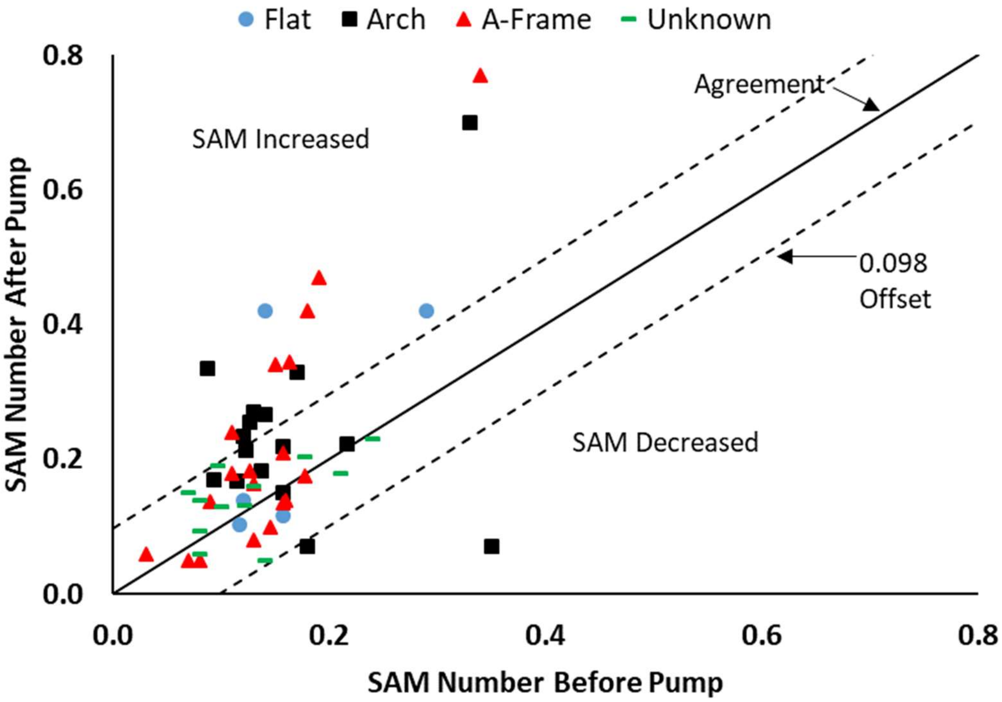

Figure 2-4 - Compares the SAM Number before pumping and after pumping.

The arch configuration has the most significant impact of the SAM Number. In all of the known configurations, at least 30 percent of the samples increase in SAM Number by a statistically significant amount. An increase in SAM Number represents a coarser air void system where the bubbles are bigger and not well distributed. It has been proposed that the increase in the SAM Number is caused by the small air bubbles dissolving into the solution from the pumping pressures[13].

2.2.3 Hardened Air Void Analysis

Figure 2-7 shows the hardened air content of samples before and after the pump. The hardened air analysis shows that, after pumping, 11% of samples lose air content greater than two standard deviations compared to 24% in the fresh air content measurements. This suggests that the fresh air content after pumping may not be representative of the hardened concrete. It should also be noted that 29% of the samples gained a statistically significant amount of air volume after pumping. This could happen if air is introduced to the concrete while pumping either through non uniform filling in the hopper or poor gaskets in the pipe line. This is an area of future research.

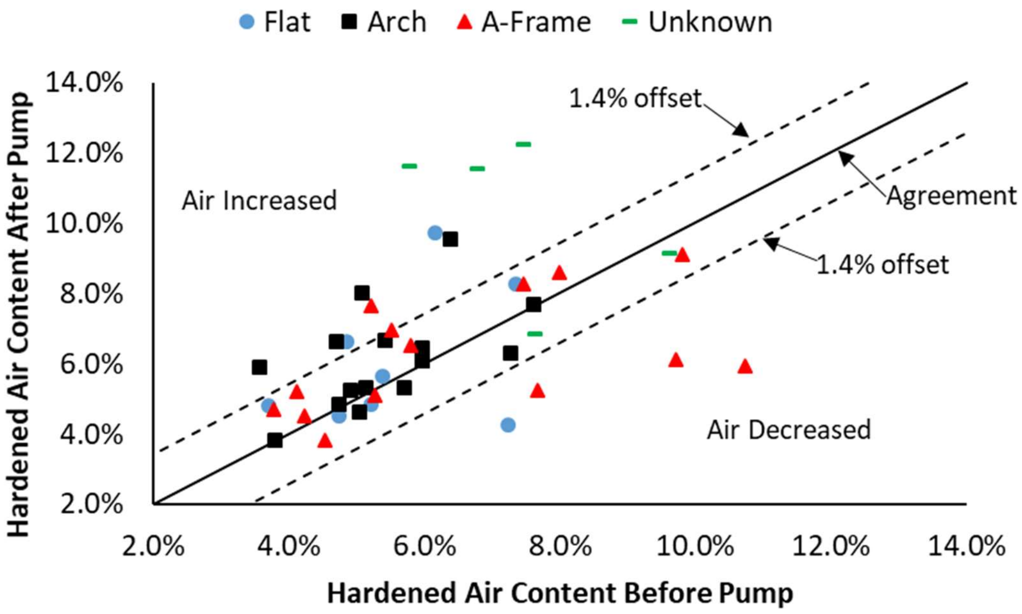

Figure 2-5 - Shows a plot of air content before and after pumping of hardened concrete samples.

In order to learn more about the change in the air content from pumping, the hardened and fresh air measurements are normalized in Figure 2-8 and measurements from a previous study are also included. These values are normalized by dividing the hardened air volume by the fresh air volume and multiplying by 100 for samples before and after pumping. A number greater than 100% means that the hardened air content is greater than the fresh air content. Included in the graph are error bars reflecting one standard deviation. The graph shows the hardened air volume was on average 14% greater than the fresh air volume before pumping. However, after pumping the hardened air is 28% greater than the fresh air content. This shows that the air volume measurements taken before the pump are more representative of the air volumes in the hardened concrete than measurements taken after the pump. Since the fresh air content is shown to be lower in the fresh concrete after pumping but higher in the hardened concrete this suggests that air volume seems to be recovering after pumping. For example, if the air volume of concrete after pumping is 5.0% the hardened air content would be expected to be 6.4%. This change is almost four times the standard deviation found in a fresh air volume test. This same trend was found in the previous research[13]; which shows that hardened air contents after pumping are 11% higher than before pumping. This data has been included in Figure 2-8 for comparison.

The differences in these studies could be because pumping in the field uses pressures that are potentially 10x higher than those measured in the previous research [12, 13]. If these high pressures are applied to the concrete then, Henry's Law, which relates increasing pressure directly to dissolved gas in the paste, suggests that more air volume is dissolved into the paste[12]. Once the concrete experiences depressurization, the air then recovers back into the paste of the concrete. Even so, this recovery is dependent on time and temperature. Since concrete sets more rapidly in warmer temperatures this could reduce the amount of air volume that returns to the concrete. This said it should be noted that ambient temperatures for this testing ranged from 70 to 100 °F.

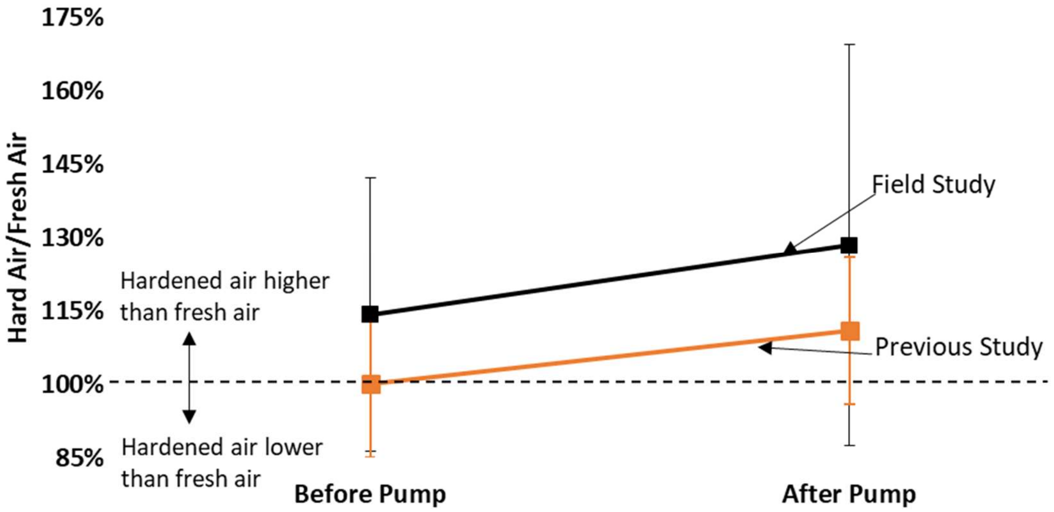

Figure 2-6 - Illustrates the change in hardened and fresh concrete based on air content before and after pumping[13].

Figure 2-9 shows the spacing factor of the sample before and after pumping. These results are important because it gives insight into air void quality of the hardened concrete. Despite seeing loss of air volume in 24% and an increase in the SAM Number of 29% of the mixtures, 0% of the hardened air void measurements show spacing factors that significantly increase after pumping. These findings match previous publications where a small fraction of the samples show an increase in the spacing factor after pumping [13]. In this work, the samples in an A-frame configuration showed the largest increase in a spacing factor but none of them were statistically significant changes. These few increases in the spacing factor may be caused by the larger drop height or the vacuum of the concrete in this configuration[8, 10-12]. This is an area of future study.

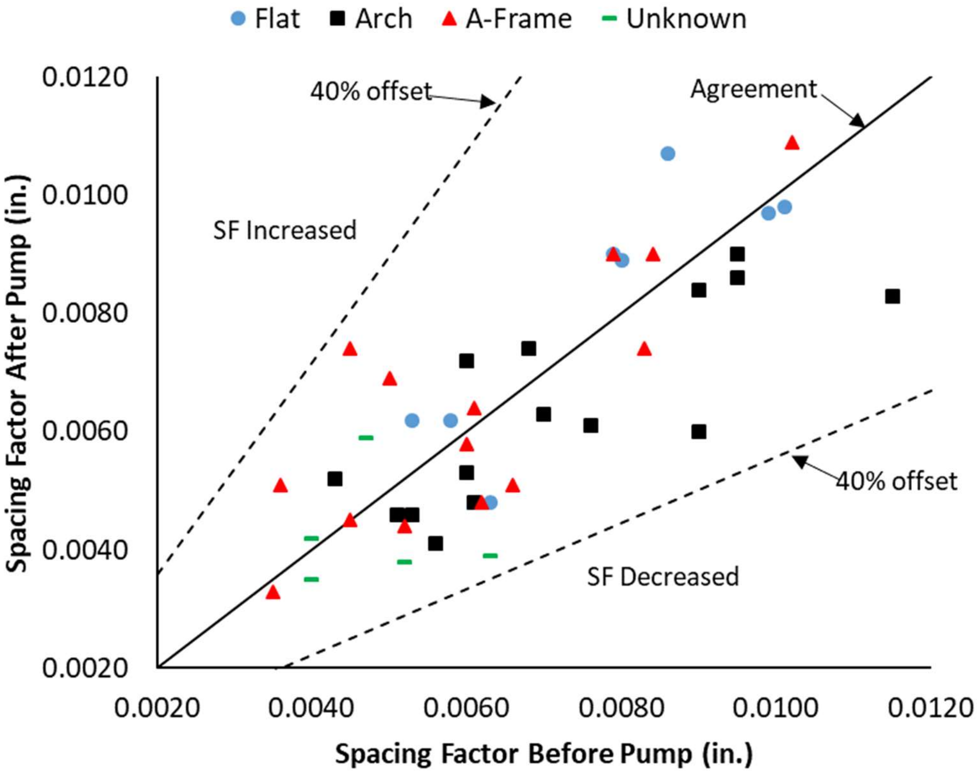

Figure 2-7 - Compares spacing factor before and after pumping.

2.2.4 Variability of Air Test Measurements

Table 2-2 summarizes the statistically significant changes of individual measurements based on the boom configuration. This shows that the fresh measurements have twice as many observations of significant change in the measurement of the air volume and the SAM Number as compared to the hardened air content and spacing factor. This table also highlights that the air lost during pumping seems to return to the concrete except for 10% of the observations. However, the spacing factor did not significantly change for these mixtures. This again highlights the differences in the fresh and hardened air void systems measured after pumping.

Table 2-2 Variability of Measurements After Pumping

		Flat	Arch	A-frame	Unknown	Total
Fresh Concrete After Pumping	Decrease in Air Vol > two SD	0%	21%	35%	25%	24%
	Increase in SAM Number > two SD	40%	44%	32%	0%	29%
Hardened Concrete After Pumping	Decrease in Air Vol > two SD	13%	0%	21%	0%	10%
	Increase in Spacing Factor > two COV	0%	0%	0%	0%	0%

2.2.5 Sampling and Testing for Air Volume and Distribution of Fresh Concrete

While the air content of fresh concrete being pumped can either increase, decrease, or show negligible change, the hardened concrete after being pumped provided significant insights. This work shows that concrete that is sampled before being pumped provides a more representative air volume and distribution values than concrete tested after being pumped. This work regularly measured an air recovery of 30% from the fresh to the hardened concrete and little change in the spacing factor of the concrete when comparing concrete before and after pumping. This matches previous research but provides a larger number of observations and a wider variety of equipment and materials [13]. *These results suggest that the air volume and SAM Number tested immediately after pumping are not an accurate representation of the air volume and spacing factor in the hardened concrete.*

2.2.6 Practical Significance

This work confirms findings from previous work by sampling 62 different concrete mixtures from 20 different field projects. The field data suggests that the measurement of the air volume and SAM Number after pumping is not representative of the hardened concrete. Therefore, rejecting fresh concrete based on testing the air void system after it is pumped is not a recommended practice. Alternatively, measuring air content and SAM Number before it is pumped can lead to a more accurate estimate of the air void quality. These findings may require a change in the sampling location of concrete in the field but this will increase the safety of the workers, reduce construction logistics, and provide more representative measurements of the in place concrete. It should be stated that this work is not recommending that all inspection at the point of placement be removed. Limiting the drop height of the concrete has been shown in several previous studies to also be important to produce a quality air void system in the concrete and this must be monitored[8, 11, 12].

2.4 Conclusion

This research investigated concrete before and after pumping with fresh and hardened testing. This work shows that pumping concrete can impact the fresh air measurements of both the fresh air volume and SAM Number. However, in the hardened concrete the amount of change in the concrete was significantly less and thus fresh measurements taken after pumping are not recommended for acceptance of the concrete.

Based on 62 field measurements the following conclusions have been made:

- When comparing the air content and SAM Number before and after pumping there is a statistically significant decrease in the fresh air volume for 24% of the samples and an increase in the SAM Number for 29% of the samples.
- In the hardened concrete, the samples before and after pumping show that only 10% of the samples show a statistically significant decrease in air volume. This is significantly lower than the fresh air measurements and shows there is a difference between the hardened and fresh measurements.

- In the hardened concrete, the air volume was on average 28% greater than the fresh sample air content after pumping. This shows the air can recover after pumping as suggested by other research[13].
- There was no impact to the spacing factor for the flat, arch, and A-frame configurations after pumping.

These finding show that in the fresh concrete it is common to observe a decrease in air content and an increase in the SAM Number in pumped concrete. However, the hardened air void analysis from the mixtures before and after the pump do not show significant changes. These findings indicate that measuring SAM Number and air volume before it is pumped can lead to a more accurate representation of the air void system in the hardened concrete.

CHAPTER III

AIR ENTRAINED LIGHTWEIGHT AGGREGATE CONCRETE

3.0 Introduction

Traditionally, lightweight aggregate (LWA) has been primarily used to reduce the dead load of a concrete element. In recent years, the practice of internal curing (IC) is growing in popularity especially in bridge decks due to the positive benefits of longer curing duration, reduced plastic shrinkage cracking, increased strength, and improved durability [14-16]. This is achieved by LWA retaining additional water internally within the concrete and then releasing this water within the aggregate pores to continue the hydration process and reduce the loss of moisture in the concrete. This process is called internal curing [26].

However, there are challenges measuring the air volume of lightweight aggregates in air entrained concrete. It is common to use a Type B air meter to measure the air volume as per ASTM C231; however, this test method is not applicable when there is LWA in concrete [27]. This is due to the voids within the aggregates causing an impact on the measurement. Instead, the ASTM C173 Volumetric Meter, also known as the “Roll-A-Meter”, has been recommended to be used in measuring the air content of LWA concrete [18].

This test requires significant operator effort and the validity of the results depend on the mixing action and energy of the operator. Therefore, if one test could be used on all aggregates this would be advantageous to the concrete industry.

The Super Air Meter (SAM) AASHTO TP 118, measures air based on the same mechanism of the Type B pressure test, and has an advantage over the Type B meter and Roll-A-Meter by not only measuring air volume but also giving information about the air bubble distribution with a parameter called the SAM Number. The SAM Number of fresh concrete can correlate to a spacing factor in ASTM C457 and performance in Bulk Freeze-Thaw ASTM C666 [1-3].

The goal of this research is to examine the use of the SAM with mixtures containing saturated fine LWA used for IC. This uses four different LWA with the geologies of either clay, shale, or slate. Fine LWA are investigated at different replacement rates of natural sand. While most LWAs are prewetted before mixing, some testing was done on non-saturated LWA for comparison.

3.1 Experimental Methods

3.1.1 Laboratory Materials

The fine lightweight aggregate has a geology of either a shale, slate, or clay and met the requirements of ASTMC330 [28]. The specific gravity and absorption of the fine LWA were determined in accordance with ASTM C1761. The normal weight aggregates were locally available crushed limestone and natural sand that is typically used in commercial concrete. The coarse aggregate was an ASTM C33 #57 crushed limestone and a natural sand met the requirements of ASTM C33 [29]. Some of the mixtures contained a blend of natural sand and lightweight sand. The aggregate source and properties information are in Table 3-1.

Table 3-1 - LWA Properties

Aggregate Name	Geology	Specific Gravity	Absorption (%)	Recommended LWA Replacement (%)*
Fine Aggregate	Natural Sand	2.61	0.55	-
Slate A	Slate	1.74	8.47	31%
Slate B	Slate	1.66	13.06	23%
Shale A	Shale	1.61	19.00	16%
Shale B	Shale	1.74	11.70	27%
Clay	Clay	0.95	28.87	12%

*recommended replacement levels as per ACI (308-213)R13

All of the laboratory mixtures used a Type I Portland cement that met the requirements under ASTM C150. The mixtures used a commercial wood rosin air-entraining admixture (AEA). The AEA dosage was constant throughout the testing to investigate how the fine LWA affected the air content and air void distribution of the concrete. The target air content for each mixture was between 4 to 5%. The aggregate correction factor was determined using AASHTO TP118 and is reported in Table 3-2. The target SAM Number range for each mixture was between 0.15 to 0.20. The mixture designs are shown in Table 4-2. The mixtures used LWA at a 10% to 50% replacement of a portion of the natural sand in the mixture . The recommended replacement level of LWA for internal curing as per ACI 308 for a mixture with 0.45 w/cm is reported in Table 3-1[30]. Mixtures contained LWA in a saturated surface dry condition and four mixtures were made using aggregates that were not prewetted.

Table 3-2 LWA Mixture Designs & Respective Aggregate Correction Factor

Mixture	Cement (lbs/yd^3)	Paste Volume	Coarse (lbs/yd^3)	Fine I (lbs/yd^3)	Fine LWA (lbs/yd^3)	Water (lbs/yd^3)	Aggregate Correction Factor (%)
Control Mixture	611	27.8%	1850	1279	0	275	-
10% Slate A	611	27.8%	1850	1028	79.5	275	0.2
30% Slate A	611	27.8%	1850	895	255	275	0.4
35% Slate A	611	27.8%	1850	831	297	275	0.4
35% Slate A	611	27.8%	1850	831	297	275	0.4
50% Slate A	611	27.8%	1850	524.5	398.8	275	0.4
10% Clay A	611	27.8%	1850	1151	71	275	0.2
15% Clay A	611	27.8%	1850	1087	107	275	0.2
20% Clay A	611	27.8%	1850	1023	142	275	0.3
30% Clay A	611	27.8%	1850	895	214	275	0.3
10% Shale B	611	27.8%	1850	1151	81	275	0.2
20% Shale B	611	27.8%	1850	1023	162	275	0.2
30% Shale B	611	27.8%	1850	895	295	275	0.2
15% Slate B	611	27.8%	1850	1087	127	275	0.2
20% Slate B	611	27.8%	1850	1023	162	275	0.3
30% Slate B	611	27.8%	1850	895	243	275	0.4
10% Shale A	611	27.8%	1850	1151	79	275	0.2
15% Shale A	611	27.8%	1850	1087	118	275	0.2
20% Shale A	611	27.8%	1850	1023	157	275	0.2
30% Shale A	611	27.8%	1850	895	236	275	0.2
10% Shale A Not Prewetted	611	27.8%	1850	1151	79	275	-
30% Shale A Not Prewetted	611	27.8%	1850	895	236	275	-
30% Slate B Not Prewetted	611	27.8%	1850	895	243	275	-

3.1.2 Mixture Preparation

Normal weight aggregates from stockpiles were brought into a 73 °F lab 24 hours prior to mixing. The Aggregates were placed in a mixer and spun and a representative sample was taken for a moisture correction. The LWA was stored inside for 60 hours prior to mixing. The LWA was submerged in water for a 48-hour period. Immediately following the ponding, the LWA was laid on a suspended towel to allow air flow around the sample for 12 hours. This drying process was used to ensure the LWA reached a prewetted saturated surface dry (SSD) condition. For comparison four mixes were performed without prewetted aggregates. These LWA's were moisture corrected in the current condition in which they were stored.

Next, the LWA was mixed and a representative sample was taken for a moisture correction. Then, the aggregates were batched according to the mixture design. All the aggregates (normal and lightweight) were loaded into the mixer along with two-thirds of the mixing water and allowed to spin for three minutes to allow the aggregates to reach a saturated surface dry (SSD).

After the aggregates were evenly mixed, the cement was added to the mixer along with the remaining one-third of the water and blended together in the mixer for another three minutes. After this, the resulting mixture was allowed to rest for two minutes while the sides of the mixer were scrapped. Next, the mixer was started and the AEA was added and allowed to mix for an additional three minutes to produce an air entrained concrete.

3.1.3 Modified Sequential Pressure Method with LWA

A modified version of AASHTO TP 118 was used to find the SAM Number. The test was modified to accommodate for the time required for the pressure to stabilize using fine lightweight aggregates. Typically, the lever is held for 10 seconds to allow the top and bottom chamber to equalize, for the LWA mixtures the lever was held down until equilibrium was achieved. Due to the porosity of the LWA, the time it took to reach equilibrium ranged between 30 seconds to 170 seconds. The rest of the test was run following AASHTO TP 118.

3.2 Results & Discussion

3.2.1 Air Volume & SAM Number

The air volume of the fresh concrete LWA mixtures are compared to a mixture without LWA in Figure 3-1. The LWA replacement percentage of natural sand is on the x-axis and air volume percentage is on the y-axis. The testing of each LWA source is plotted with an error bar to show the test variability. The legend lists the name of the LWA used and the absorption percentage.

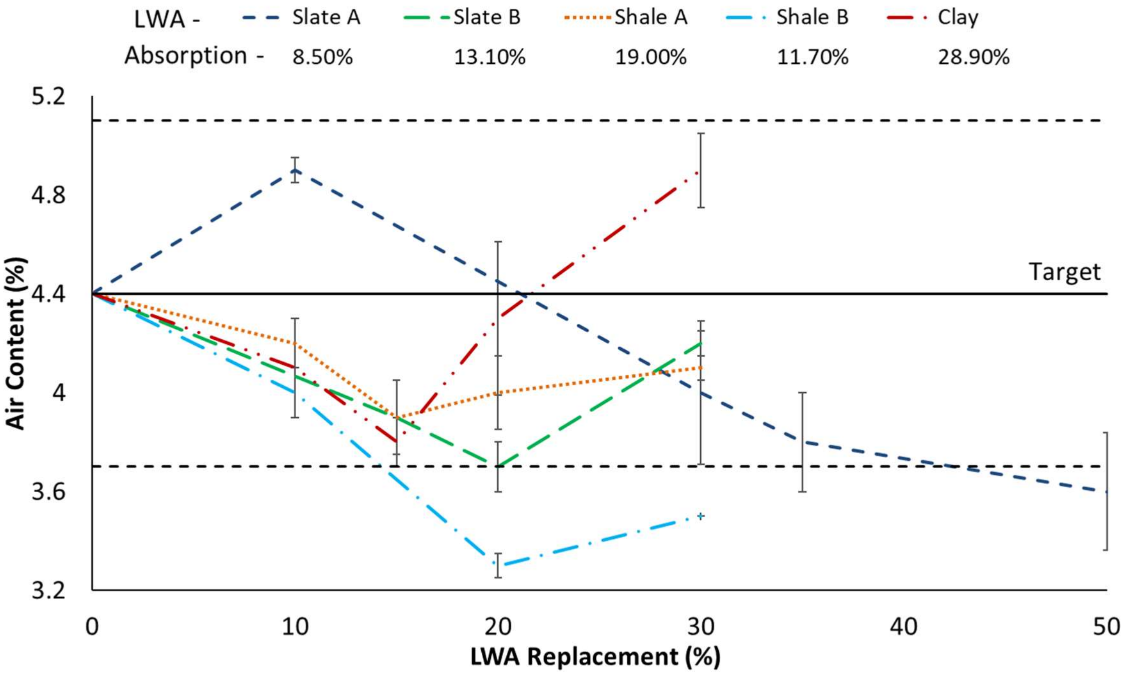

Figure 3-1 - Plots LWA replacement vs. air content.

Typically, as the amount of LWA in a mixture increases the air volume is shown to decrease. However, when the LWA replacement level is above 15% to 20% the measured air volume tends to increase. An increase in air content can be seen in mixtures containing Shale A, Shale B, Slate B, and Clay when the LWA replacement level is over

20%. This increase in the air content could be due to the air void structure of the aggregate. LWA has a porous structure and thus inherently could contain air, that at certain levels, will impact the measurement of the air volume. Still, compared to the mixture with normal weight aggregates, the LWA mixtures typically show lower air contents for the replacement level investigated. The absorption content of each material varied greatly and there does not seem to be a correlation between air content and absorption.

Figure 3-2 presents the results of the SAM Number from the modified test method. The target SAM Number for each mixture was 0.15 with a standard deviation of 0.049. However, when analyzing the SAM results a significant change is two standard deviations or a 95% confidence interval. Thus, the dashed lines represent an offset boundary of 0.098. Figure 3-2 shows the LWA replacement percentage on the x-axis and SAM Number on the y-axis.

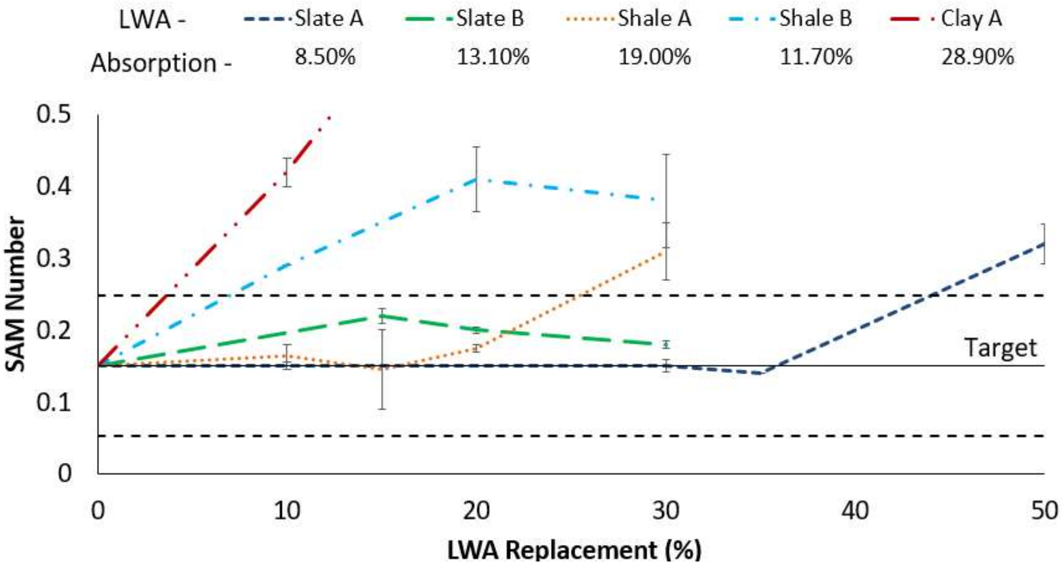

Figure 3-2 - Shows the modified test SAM Number with SSD aggregates.

In Figure 3-2, two of the LWA significantly increase the SAM Number at only 10% replacement of normal sand and all other show satisfactory results through 20% LWA replacement. In addition, one LWA showed no change in SAM Number up to 35%. This shows that certain LWA do not cause a significant impact of the SAM Number when at SSD before mixing.

When looking at the absorption of the aggregate, it is apparent that the absorption does not impact the SAM Number. For instance, Clay has the highest absorption and the SAM Number was significantly increased during all tests performed. Yet, Shale A which had the second-highest absorption showed less impact of the SAM Number through a 20% replacement level.

3.2.2 Moisture Content of LWA and Air Volume and SAM

One concern with using LWA is that the material may be lower than SSD. Four mixtures on two different types of fine LWA were performed when the aggregates were in a non-prewetted state. The results for the air content and SAM Number are presented in Figures 3-3 and 3-4 below. The discrete points on the graph represent mixtures with non-prewetted LWA.

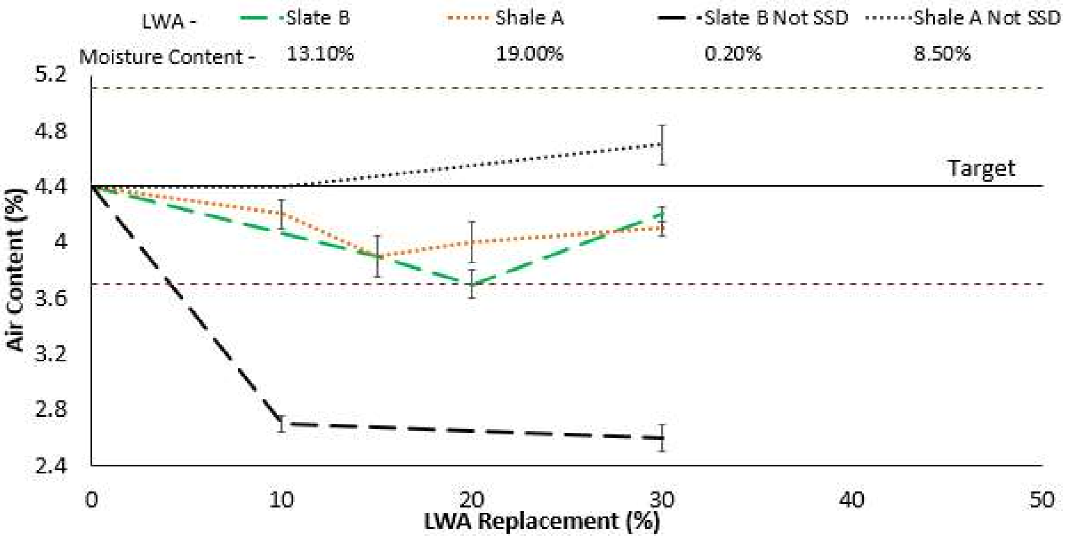

Figure 3-3 - Compares Shale A & Slate B air content vs. LWA replacement including aggregates that were not pre-wetted before mixing.

The moisture content of the non prewetted LWA from the manufacturer of Shale A is around 8.5% while the SSD moisture content is around 19%, which means Shale A is 120% away from meeting SSD. The figure shows the air content is not significantly affected despite the increased porosity of the aggregate. Slate B is 6450% more dry than its SSD condition. The moisture content before mixing is 0.2% and the SSD moisture content is approximately 13% . The air content of Slate B shows a decrease by 35% when the aggregate has a moisture content of 0.2%. This shows that the moisture content of the LWA can be important in measuring the air content of the mixture.

Figure 3-4 shows the SAM Number results for the unsaturated LWA. The LWA replacement mixtures with the non prewetted aggregates showed an overall increase in the SAM Number. It appears that the SAM Number is more dependent on the moisture condition of the LWA prior to mixing. This data suggests that the as the moisture content in the LWA decreases the SAM Number increases.

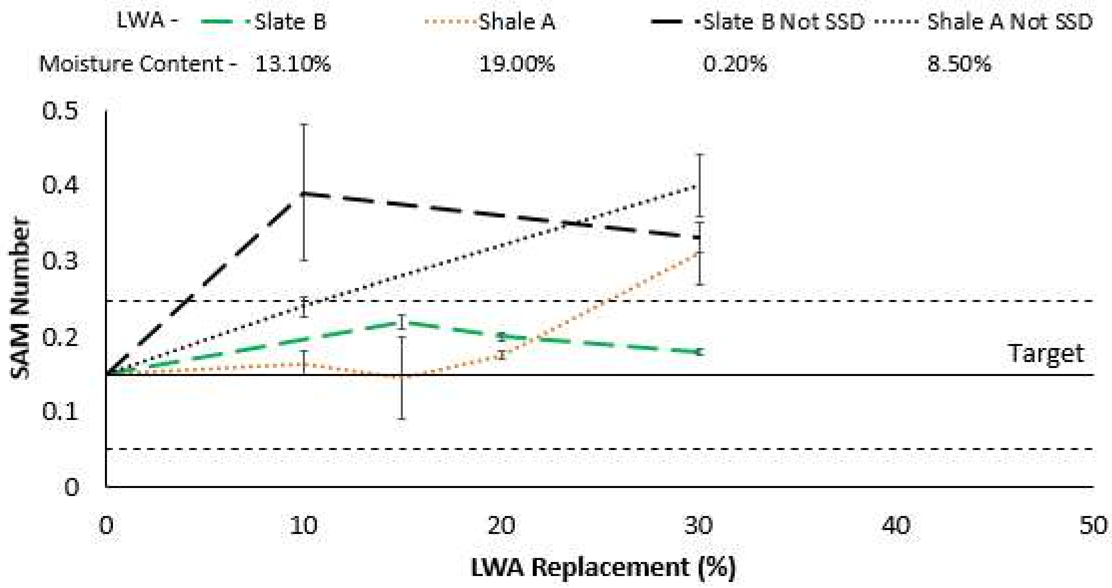

Figure 3-4 - Compares Shale A & Slate B SAM Number vs. LWA replacement including aggregates that were not pre-wetted before mixing.

Overall, the results show that when the LWA is in a prewetted SSD condition four out of the five aggregates did not show a significant change in air the content and none of the aggregates showed significant changes when the replacement level was < 20%. In addition, the SAM Numbers were not impacted in three out of five aggregates (Slate A, Slate B, and Shale A). Table 3-2 gives the replacement level of the LWA where significant changes occur in air volume and SAM Number.

The recommended replacement levels from ACI 308 for internal curing listed in table 3-1 is lower than the values listed in Table 3-3 for 4 of the 5 LWAs for air volume and 3 of the 5 LWAs for SAM Number. This shows that there is potential to use saturated LWA in concrete mixtures and not use the roll-a-meter to measure the concrete.

Table 3-3 - Replacement Levels for each Fine LWA before causing a change of two standard deviations.

Aggregate Source	LWA % with Significant Impact on Air Content	LWA % with significant impact on SAM Number	ACI 308 [30] Recommended LWA Replacement (%)	Can the Air Volume and SAM Number be determined for internal curing?
Slate A	35%	35%	31%	Yes
Slate B	30%	30%	23%	Yes
Shale A	30%	20%	16%	Yes
Shale B	10%	0%	29%	No
Clay	30%	0%	12%	No

*These are not recommendations and aggregates are based off of SSD conditions.

Numbers are compared to the results to a mixture with 100% natural sand. Clay A, which showed the highest volatility in SAM Number also had the highest absorption of all the aggregates. Other than this there does not appear to be a correlation between absorption, air content, and SAM Number. However, the moisture content of the aggregate at the time of mixing has shown to have an impact. The void structure of the LWA could potentially have the greatest impact on the SAM Number and air content. This is potentially why two different shales from different locations yield vastly different results during the SAM test. More testing is needed to investigate the impact of the void structure of the LWA on the results.

3.2.3 Practical application

Based on the data presented the air volume and the SAM Number from the modified AASHTO TP118 can be used for certain saturated LWA within certain replacement levels. Since these tests do not work for all saturated LWA then it is recommended that a testing procedure be used to evaluate mixtures that contain LWAs.

This work can serve as an outline for the mixture evaluation procedure. For example, the first step is to create a concrete mixture with a normal weight sand and enough air entraining admixture to create an acceptable air volume and SAM Number. Next, a new mixture where the LWA replaces the normal weight sand and with the same dosage of air entraining admixture. The air volume and SAM Number can be recorded from the second mixture can be compared to the first to determine the difference. Either a target difference could be set for the air volume and SAM Number or an offset for the mixture may be established. This is called the LWA mixture correction factor. This correction factor can be used for the air volume or the SAM Number in the field to adjust the measured values. It is recommended that these corrections only be used if they are within a reasonable range. For example this work used two standard deviations from the test method but more research may be needed to find an acceptable limit.

3.3. CONCLUSION

This research tested five different fine LWA for their impact on the air volume and SAM Number in a concrete mixture used for internal curing. These aggregates had high absorptions and lower specific gravities than typical natural sand but were primarily tested in a saturated condition. The geology types of fine LWA tested were shales, slates, and a clay. A modified version of the SAM test was developed to evaluate these materials. Below list the findings of this research.

- The Air Content and SAM Number of the LWA can be measured in most LWA when they are used in a prewetted condition, however the allowable replacement level will depend on the LWA. Three out of the five LWA's exceed the replacement percentage recommended by ACI 308 with satisfactory SAM Results [30].

- Mixtures with LWA that were prewetted prior to mixing showed lower changes in Air volume and SAM Number than those that were not saturated.
- The absorption of the aggregate does not correlate with the LWA performance in the air volume or SAM Number measurements.
- The air volume is able to be accurately determined when using four out of five aggregates up to a 30% replacement level, when in a pre-wetted SSD Condition. Three out of five aggregates show satisfactory results in the SAM test up to 20% replacement level with two achieving a 30% replacement level.

A proposed mixture correction factor for LWA is suggested in this paper as a way to more accurately use these materials in concrete. This would be a useful tool to allow different testing methods to be used in the field with internally cured concrete mixtures. More work is needed to understand the pore structure of different aggregates and how this impacts the performance in these tests.

CHAPTER IV

CONCLUSION

4.0 Overview

4.1 Conclusions from Chapter II.

This research investigated concrete before and after pumping with fresh and hardened testing. This work shows that pumping concrete can impact the fresh air measurements of both the fresh air volume and SAM Number. However, in the hardened concrete the amount of change in the concrete was significantly less and recommendations are made that fresh measurements taken after pumping are not recommended for acceptance of the concrete.

Based on 62 field measurements the following conclusions have been made:

- When comparing the air content and SAM Number before and after pumping there is a statistically significant decrease in the fresh air volume for 24% of the samples and an increase in the SAM Number for 29% of the samples.

- In the hardened concrete, the samples before and after pumping show that only 10% of the samples showed a statistically significant decrease in air volume and 0% showed a statistically significant increase in the spacing factor. This is significantly lower than the fresh air measurements and shows there is a difference between these measurements.
- In the hardened concrete, the air volume was on average 28% greater than the fresh sample air content after pumping. This shows the air can recover after pumping as suggested by other research[13].
- There was no impact to the spacing factor for the flat, arch, and A-frame configurations after pumping.

These finding show that in the fresh concrete it is common to observe a decrease in air content and an increase in the SAM Number in pumped concrete. However, the hardened air void analysis from the mixtures before and after the pump do not show significant changes. These findings indicate that measuring SAM Number and air volume before it is pumped can lead to a more accurate representation of the air void system in the hardened concrete. Additionally, the results suggest that pumping with an A-frame configuration creates a more lasting impact on the air content. Yet, spacing factors after pumping with all configurations are satisfactory.

4.2 Conclusions From Chapter III.

This research tested five different fine LWA for their impact on the air volume and SAM Number in a concrete mixture used for internal curing. These aggregates had high absorptions and lower specific gravities than typical natural sand but were primarily tested in a saturated condition. The geology types of fine LWA tested were shales, slates, and a clay. A modified version of the SAM test was developed to evaluate these materials. Below list the findings of this research.

- The Air Content and SAM Number of the LWA can be measured in most LWA when they are used in a prewetted condition, however the allowable replacement level will depend on the LWA. Three out of the five LWA's exceed the replacement percentage recommended by ACI 308 with satisfactory SAM Results [30].
- Mixtures with LWA that were prewetted prior to mixing yielded more accurate results than those with a small amount of moisture present. The test results show that if the LWA has a low moisture content prior to mixing, then the air volume may decrease and the SAM Number may increase.
- The absorption of the aggregate does not correlate with the LWA performance in the air volume or SAM Number measurements.
- The air volume is able to be accurately determined four out of five aggregates up to a 30% replacement level, when in a pre-wetted SSD Condition. Three out of five aggregates show satisfactory results in the SAM test up to 20% replacement level with two achieving a 30% replacement level.

A proposed mixture correction factor for LWA is suggested in this paper as a way to more accurately use these materials in concrete. This would be a useful tool to allow different testing methods to be used in the field with internally cured concrete mixtures.

REFERENCES

1. Ley, M.T., et al., *Determining the air-void distribution in fresh concrete with the Sequential Air Method.* Construction and Building Materials, 2017. **150**: p. 723-737.
2. *ASTM C666/C666M-15*, in *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. 2015.
3. *ASTM International C457/C457M-16*, in *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. 2016.
4. TP118, *Charactorization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method*. AASHTO.
5. N.R.M.CA, *Loss of Air Content in Pumped Concrete.* CIP21, 1992,2005.
6. *ASTM C172/172M-17*, in *Standard Practice for Sampling Freshly Mixed Concrete*. 2017.
7. N.R.M.C.A, *Air Entrainment and Concrete.* 1976.
8. Hover, K.C. and R.J. Phares, *Impact of concrete placing method on air content, air-void system parameters, and freeze-thaw durability.* Transportation research record, 1996. **1532**(1): p. 1-8.
9. Janssen, D., K. MacDonald, and A. Gardiner. *Effects of pumping parameters on the stability of entrained air voids*. in *CONSEC'01: Third International Conference on Concrete Under Severe Conditions*. 2001.
10. Elkey, W., D. Janssen, and K. Hover, *CONCRETE PUMPING EFFECTS ON ENTRAINED AIR-VOIDS. FINAL REPORT*. 1994.
11. James Yingling, G.M.M. and D.G. Richard, *Loss of Air Content in Pumped Concrete.* Concrete International, 1992. **14**(10).
12. Janssen, D., *EFFECT OF PUMPING ON ENTRAINED AIR VOIDS: ROLE OF PRESSURE.* Concrete Under Severe Conditions: Environmental and Loading, 1995. **1**: p. 233.
13. Becker, J., *Investigation of Concrete Pumping Effects on Air-Entrained Concrete*. 2018, Oklahoma State University.
14. Holm, T.A. and J.P. Ries, *Chapter 46: Lightweight Concrete and Aggregates*, J.F. Lamond and J.H. Pielert, Editors. 2006, ASTM International: West Conshohocken, PA. p. 548-560.
15. Castro, J., et al., *Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures.* Cement and Concrete Composites, 2011. **33**(10): p. 1001-1008.
16. Steven Kosmatka, M.W., *Design and Control of Concrete Mixtures*, in *The guide to applications, methods, and materials*. 2011, Portland Cement Association: Skokie, Illinois. p. 395 - 396.

17. Wesley Jones, M.H., Jason Weiss, *Internal Curing of High Performance Concrete Using Lightweight Aggregates and Other Techniques*. 2014, Colorado Department of Transportation.
18. *ASTM International C173/C173M-16*, in *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*. 2016.
19. Pigeon M, P.R., *Durability of concrete in cold climates.* CRC Press, 1995.
20. Cooke, T.H., *Concrete pumping and spraying: a practical guide*. 1990: Thomas Telford.
21. Mariusz Dabrowski, M.G., Kinga Dziedzic, Aneta Antolik, *Validation of sequential pressure method for evaluation of the content of microvoids in airi entrained concrete.* Construction and Building Materials, 2019.
22. Fisher, T.S., *How a Concrete Pump Works.* Concrete Construction, 1994: p. 629.
23. *ASTM C143/C143M-15a*, in *Standard Test Method for Slump of Hydraulic-Cement Concrete*. 2015.
24. *ASTM C138/C138M-17a*, in *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. 2017.
25. Welchel, D., *Determining the Size and Spacing of Air Bubbles in Fresh Concrete.* . 2014.
26. Bentz, D.P., P. Lura, and J.W. Roberts, *Mixture proportioning for internal curing.* Concrete international, 2005. **27**(2): p. 35-40.
27. *ASTM International. C231/C231M-17a*, in *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. 2017.
28. *ASTM International C330/C330M-17a*, in *Standard Specification for Lightweight Aggregates for Structural Concrete*. 2017.
29. *ASTM International. C33/C33M-18*, in *Standard Specification for Concrete Aggregates*. 2018.
30. ACI Commitees 308, *ACI(308-213)R-13 Report on Internally Cured Concrete Using Prewetted Absorptive Aggregates.* 2013

APPENDICES

A.1 MIXTURE DESIGNS USED FOR FIELD PUMPING

Table A.1.1 - Shows a summary of the mixture designs used from the field.

Location	Test Number	Truck Number	Pump Configuration	Boom Length [Feet]	Mix Design						
					Coarse (lb/yd^3)	Fine (lb/yd^3)	Cement (lb/yd^3)	Fly-Ash (lb/yd^3)	Water (lb/yd^3)	Air Entrainer (oz/yd^3)	Water Reducer (oz/yd^3)
Sapulpa 1	1-A	Truck 1 after	Arch	171	1834	1268	453	113	222	3	8
Sapulpa 1	1-B	Truck 1 before	Arch	171	1834	1268	453	113	222	3	8
Sapulpa 1	2-A	Truck 2 After	Arch	171	1830	1280	450	112	215	3	8
Sapulpa 1	2-B	Truck 2 Before	Arch	171	1830	1280	450	112	215	3	8
Sapulpa 1	3-A	Truck 3 After	Arch	171	1836	1294	452	111	216	3	8
Sapulpa 1	3-B	Truck 3 Before	Arch	171	1836	1294	452	111	216	3	8
Purcell	4A	Truck 1 After	Arch	N/A	1840	1194	485	122	243	7	61
Purcell	4B	Truck 1 Before	Arch	N/A	1840	1194	485	122	243	7	61
Purcell	5A	Truck 2 After	Arch	N/A	1841	1201	485	119	243	7	61
Purcell	5B	Truck 2 Before	Arch	N/A	1841	1201	485	119	243	7	61
Carnegie	6A	Truck 2 After	Aframe	154	1804	1348	519	92	195	5	37
Carnegie	6B	Truck 2 Before	Aframe	154	1804	1348	519	92	195	5	37
Carnegie	7A	Truck 3 After	Aframe	154	1808	1346	519	92	195	5	37
Carnegie	7B	Truck 3 Before	Aframe	154	1808	1346	519	92	195	5	37
Carnegie	8A	Truck 4 After	Arch	154	1806	1346	519	93	195	5	37
Carnegie	8B	Truck 4 Before	Arch	154	1806	1346	519	93	195	5	37
Pawnee		Truck 1 Before	N/A	-	-	-	-	-	-	-	
Pawnee		Truck 1 After	N/A	-	-	-	-	-	-	-	
KC day 1	9A	Truck 1 After	Arch	128	1739	1381	431	100	178	2	32
KC day 1	9B	Truck 1 Before	Arch	128	1739	1381	431	100	178	2	32
KC day 1	10A	Truck 2 After	Flat	128	1744	1393	429	102	169	2	32
KC day 1	10B	Truck 2 Before	Flat	128	1744	1393	429	102	169	2	32
KC Day 2	11A	Truck 1 After	arch	N/A	1589	1377	361	94	183	4	27
KC Day 2	11B	Truck 1 Before	arch	N/A	1589	1377	361	94	183	4	27
KC Day 3	12A	Truck 1 After	Flat	N/A	1655	1358	479	120	207	6	18
KC Day 3	12B	Truck 1 Before	Flat	N/A	1655	1358	479	120	207	6	18
KC Day 4	13A	Truck 1 After	Aframe	128	1647	1445	380	101	196	6	29
KC Day 4	13B	Truck Before	Aframe	128	1647	1445	380	101	196	6	29
Ardmore D1	14A	Truck 1 After	Arch	128	1858	1196	488	121	169	6	28
Ardmore D1	14B	Truck 1 Before	Arch	128	1858	1196	488	121	169	6	28
Ardmore D2	15A	Truck 1 After	Aframe	125	1852	1198	488	124	160	7	27
Ardmore D2	15B	Truck 2 Before	Aframe	125	1852	1198	488	124	160	7	27
Ardmore D2	16A	Truck 2 After	Aframe	125	1862	1200	487	123	152	7	27
Ardmore D2	16B	Truck 2 Before	Aframe	125	1862	1200	487	123	152	7	27
Guthrie	17A	Truck 1 After	Aframe	154	1822	1220	610	-	179	2	50
Guthrie	17B	Truck 1 before	Aframe	154	1822	1220	610	-	179	2	50
Guthrie	18A	Truck 2 After	Aframe	154	1806	1228	607	-	209	2	50
Guthrie	18B	Truck 2 Before	Aframe	154	1806	1228	607	-	209	2	50
Guthrie	19A	Truck 3 After	Arch	154	1798	1210	607	-	184	2	50
Guthrie	19B	Truck 3 Before	Arch	154	1798	1210	607	-	184	2	50
Sapulpa 2	20A	Truck 1 after	N/A	N/A	1842	1330	553	-	228	N/A	N/A
Sapulpa 2	20B	Truck 1 before	N/A	N/A	1842	1330	553	-	228	N/A	N/A
Sapulpa 2	21A	Truck 2 after	N/A	N/A	1844	1342	555	-	219	N/A	N/A
Sapulpa 2	21B	Truck 2 before	N/A	N/A	1844	1342	555	-	219	N/A	N/A
Luther	22A	Truck 1 after	Arch	154	3077	1238	486	607	250	4	49
Luther	22B	Truck 1 before	Arch	154	3077	1238	486	607	250	4	49

Location	**Test Number**	**Truck Number**	**Pump Configuration**	**Boom Length [Feet]**	**Mix Design**						
					Coarse (lb/yd^3)	**Fine (lb/yd^3)**	**Cement (lb/yd^3)**	**Fly-Ash (lb/yd^3)**	**Water (lb/yd^3)**	**Air Entrainer (oz/yd^3)**	**Water Reducer (oz/yd^3)**
Perry			N/A	-	-	-	-	-	-	-	49
Perry			N/A	-	-	-	-	-	-	-	49
Vermont	23A	VTRANS 1-A	N/A	207	1659	1398	525	101	224	21	45
Vermont	23B	VTRANS 1-C	N/A	207	1659	1398	525	101	224	21	45
Vermont	24A	VTRANS 2-A	N/A	207	1634	1397	523	101	229	21	45
Vermont	24B	VTRANS 2-C	N/A	207	1634	1397	523	101	229	21	45
Vermont	25A	VTRANS 3-A	N/A	207	1653	1388	524	101	241	21	45
Vermont	25B	VTRANS 3-C	N/A	207	1653	1388	524	101	241	21	45
Vermont	26A	VTRANS 4-A	N/A	105	1653	1390	526	100	240	21	45
Vermont	26B	VTRANS 4-C	N/A	105	1653	1390	526	100	240	21	45
Vermont	27A	VTRANS 5-A	Aframe	125	1714	1351	486	158	251	4	19
Vermont	27B	VTRANS 5-C	Aframe	125	1714	1351	486	158	251	4	19
Vermont	28A	VTRANS 6-A	Aframe	125	1727	1342	486	158	248	5	20
Vermont	28B	VTRANS 6-C	Aframe	125	1727	1342	486	158	248	5	20
Vermont	29A	VTRANS 7-A	Aframe	125	1668	1328	449	38	268	2	20
Vermont	29B	VTRANS 7-C	Aframe	125	1668	1328	449	38	268	2	20
Vermont	30A	VTRANS 8-A	Aframe	125	1648	1326	449	38	261	2	20
Vermont	30B	VTRANS 8-C	Aframe	125	1648	1326	449	38	261	2	20
Vermont	31A	VTRANS 9-A	Aframe	125	1663	1332	449	38	262	2	15
Vermont	31B	VTRANS 9-C	Aframe	125	1663	1332	449	38	262	2	15
Vermont	32A	VTRANS 10-A	Aframe	98	1650	1354	450	35	250	3	49
Vermont	32B	VTRANS 10-C	Aframe	98	1650	1354	450	35	250	3	49
Vermont	33A	VTRANS 11-A	N/A	98	1650	1364	445	35	251	4	39
Vermont	33B	VTRANS 11-C	N/A	98	1650	1364	445	35	251	4	39
Vermont	34A	VTRANS 12-A	Aframe	98	1647	1355	445	35	259	3	29
Vermont	34B	VTRANS 12-C	Aframe	98	1647	1355	445	35	259	3	29
Vermont	35A	VTRANS 13-A	N/A	98	1648	1347	450	35	234	3	19
Vermont	35B	VTRANS 13-C	N/A	98	1648	1347	450	35	234	3	19
Vermont	36A	VTRANS 14-A	N/A	98	1655	1371	448	35	237	3	19
Vermont	36B	VTRANS 14-C	N/A	98	1655	1371	448	35	237	3	19
Vermont	37A	VTRANS 15-A	N/A	125	1648	1326	448	38	263	3	15
Vermont	37B	VTRANS 15-C	N/A	125	1648	1326	448	38	263	3	15
Vermont	38A	VTRANS 16-A	Arch	125	1656	1330	448	38	266	2	15
Vermont	38B	VTRANS 16-C	Arch	125	1656	1330	448	38	266	2	15
Vermont	39A	VTRANS 17-A	Arch	125	1661	1326	450	38	278	2	15
Vermont	39B	VTRANS 17-C	Arch	125	1661	1326	450	38	278	2	15
Stillwater	OSUA	OSU FIELD	Flat	112	1234	1501	489	122	275	-	-
Stillwater	OSUB	OSU FIELD	Arch	112	1234	1501	489	122	275	-	-
Stillwater	OSUC	OSU FIELD	Aframe	112	1234	1501	489	122	275	-	-

A.2 ADDITIONAL INFORMATION ON THE CONCRETE PUMPS USED

Table A.2.1 - Shows additional information on pump manufacturers and boom configuration and length from samples tested.

Test Number	Truck Number	Pump Type	Pump Configuration	Pump Boom Length [Feet]
1-A	Truck 1 after	2018 Concord 52m	Arch	171
1-B	Truck 1 before	2018 Concord 52m	Arch	171
2-A	Truck 2 After	2018 Concord 52m	Arch	171
2-B	Truck 2 Before	2018 Concord 52m	Arch	171
3-A	Truck 3 After	2018 Concord 52m	Arch	171
3-B	Truck 3 Before	2018 Concord 52m	Arch	171
4A	Truck 1 After	N/A	Arch	N/A
4B	Truck 1 Before	N/A	Arch	N/A
5A	Truck 2 After	N/A	Arch	N/A
5B	Truck 2 Before	N/A	Arch	N/A
6A	Truck 2 After	2004 Schwing 47m	Aframe	154
6B	Truck 2 Before	2004 Schwing 47m	Aframe	154
7A	Truck 3 After	2004 Schwing 47m	Aframe	154
7B	Truck 3 Before	2004 Schwing 47m	Aframe	154
8A	Truck 4 After	2004 Schwing 47m	Arch	154
8B	Truck 4 Before	2004 Schwing 47m	Arch	154
9A	Truck 1 After	Schwing 39m	Arch	128
9B	Truck 1 Before	Schwing 39m	Arch	128
10A	Truck 2 After	Schwing 39m	Flat	128
10B	Truck 2 Before	Schwing 39m	Flat	128
11A	Truck 1 After	N/A	arch	N/A
11B	Truck 1 Before	N/A	arch	N/A
12A	Truck 1 After	2019 kw t880 achingly	Flat	N/A
12B	Truck 1 Before	2019 kw t880 achingly	Flat	N/A
13A	Truck 1 After	Schwing 39m	Aframe	128
13B	Truck Before	Schwing 39m	Aframe	128
14A	Truck 1 After	Schwing 39m	Arch	128
14B	Truck 1 Before	Schwing 39m	Arch	128
15A	Truck 1 After	Putzmeister 38m	Aframe	125
15B	Truck 2 Before	Putzmeister 38m	Aframe	125
16A	Truck 2 After	Putzmeister 38m	Aframe	125
16B	Truck 2 Before	Putzmeister 38m	Aframe	125
17A	Truck 1 After	Schwing 47m	Aframe	154
17B	Truck 1 before	Schwing 47m	Aframe	154
18A	Truck 2 After	Schwing 47m	Aframe	154
18B	Truck 2 Before	Schwing 47m	Aframe	154
19A	Truck 3 After	Schwing 47m	Arch	154
19B	Truck 3 Before	Schwing 47m	Arch	154
20A	Truck 1 after	CPP-52XZ5-180	N/A	N/A
20B	Truck 1 before	CPP-52XZ5-180	N/A	N/A
21A	Truck 2 after	CPP-52XZ5-180	N/A	N/A
21B	Truck 2 before	CPP-52XZ5-180	N/A	N/A
22A	Truck 1 after	04 Schwing 47 m	Arch	154
22B	Truck 1 before	04 Schwing 47 m	Arch	154

23A	VTRANS 1-A	Putzmeister 63Z	N/A	207
23B	VTRANS 1-C	Putzmeister 63Z	N/A	207
24A	VTRANS 2-A	Putzmeister 63Z	N/A	207
24B	VTRANS 2-C	Putzmeister 63Z	N/A	207
25A	VTRANS 3-A	Putzmeister 63Z	N/A	207
25B	VTRANS 3-C	Putzmeister 63Z	N/A	207
26A	VTRANS 4-A	Shwing S32X	N/A	105
26B	VTRANS 4-C	Shwing S32X	N/A	105
27A	VTRANS 5-A	Putzmeister 38Z	Aframe	125
27B	VTRANS 5-C	Putzmeister 38Z	Aframe	125
28A	VTRANS 6-A	Putzmeister 38Z	Aframe	125
28B	VTRANS 6-C	Putzmeister 38Z	Aframe	125
29A	VTRANS 7-A	Putzmeister BSF38Z.16H	Aframe	125
29B	VTRANS 7-C	Putzmeister BSF38Z.16H	Aframe	125
30A	VTRANS 8-A	Putzmeister BSF38Z.16H	Aframe	125
30B	VTRANS 8-C	Putzmeister BSF38Z.16H	Aframe	125
31A	VTRANS 9-A	Putzmeister BSF38Z.16H	Aframe	125
31B	VTRANS 9-C	Putzmeister BSF38Z.16H	Aframe	125
32A	VTRANS 10-A	Schwing 30X	Aframe	98
32B	VTRANS 10-C	Schwing 30X	Aframe	98
33A	VTRANS 11-A	Schwing 30X	N/A	98
33B	VTRANS 11-C	Schwing 30X	N/A	98
34A	VTRANS 12-A	Schwing 30X	Aframe	98
34B	VTRANS 12-C	Schwing 30X	Aframe	98
35A	VTRANS 13-A	Schwing 30X	N/A	98
35B	VTRANS 13-C	Schwing 30X	N/A	98
36A	VTRANS 14-A	Schwing 30X	N/A	98
36B	VTRANS 14-C	Schwing 30X	N/A	98
37A	VTRANS 15-A	Putzmeister BSF38Z.16H	N/A	125
37B	VTRANS 15-C	Putzmeister BSF38Z.16H	N/A	125
38A	VTRANS 16-A	Putzmeister BSF38Z.16H	Arch	125
38B	VTRANS 16-C	Putzmeister BSF38Z.16H	Arch	125
39A	VTRANS 17-A	Putzmeister BSF38Z.16H	Arch	125
39B	VTRANS 17-C	Putzmeister BSF38Z.16H	Arch	125
OSUA	OSU FIELD	Pumpstar AZ-34.6	Flat	112
OSUB	OSU FIELD	Pumpstar AZ-34.6	Arch	112
OSUC	OSU FIELD	Pumpstar AZ-34.6	Aframe	112

A.3 HARDENED AND FRESH PROPERTIES FROM FIELD TESTING

Table A.3.1 - Shows the fresh and hardened properties of Slump, Unit Weight, Air Content, SAM Number, and Spacing Factor before and after pumping.

Test	Boom Configuration	SLUMP (Inches)		UNIT WEIGHT (lb/ft^3)		AIR CONTENT (%)		SAM NUMBER		Hardened Air Content (%)		Spacing Factor (Inches)	
	-	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
1A-B	Arch	5.00	7.00	140.9	147.0	6.6%	2.7%	0.16	0.22	7.6	7.7	0.0051	0.0046
2A-B	Arch	3.50	4.00	144.6	143.5	5.3%	6.2%	0.13	0.25	5.4	6.7	0.0090	0.0060
3A-B	Arch	3.00	7.50	145.8	143.5	4.9%	6.1%	0.16	0.15	5.1	8.0	0.0053	0.0046
6A-B	Aframe	6.25	6.50	145.3	145.1	5.6%	5.4%	0.15	0.10	5.5	6.9	0.0062	0.0048
7A-B	Aframe	5.00	4.00	146.7	148.6	5.0%	3.8%	0.16	0.14	5.3	5.1	0.0061	0.0064
8A-B	Arch	4.00	6.75	143.6	145.5	7.5%	5.1%	0.12	0.24	10.3	-	0.0039	-
4A-B	Arch	2.75	4.00	147.0	143.9	4.1%	5.6%	0.22	0.22	5.1	5.3	0.0060	0.0053
5A-B	Arch	2.75	6.00	144.4	142.5	4.8%	6.5%	0.12	0.17	4.7	6.6	0.0070	0.0063
58A-B	n/a	3.50	7.00	141.1	140.4	7.8%	8.0%	0.08	0.09	14.3	-	-	-
59A-B	n/a	4.75	4.00	142.5	143.1	7.3%	7.2%	0.10	0.19	18.0	-	-	-
60A-B	Aframe	7.50	10.00	137.8	134.0	9.7%	9.9%	0.09	0.14	14.2	-	0.0029	-
61A-B	Aframe	8.25	8.25	140.9	142.3	7.3%	5.7%	0.13	0.16	9.8	9.1	0.0035	0.0033
62A-B	Aframe	6.50	8.25	137.7	145.7	8.8%	4.5%	0.11	0.18	14.8	5.1	0.0030	0.0065
9A-B	Arch	5.50	8.00	145.3	144.2	4.2%	4.9%	0.14	0.18	5.7	5.3	0.0068	0.0074
10A-B	Flat	3.25	8.00	145.7	145.4	4.5%	4.9%	0.16	0.12	7.2	4.3	0.0053	0.0062
11A-B	Arch	1.75	6.00	145.4	143.4	5.1%	5.9%	0.14	0.27	3.8	3.8	0.0115	0.0083
12A-B	Flat	3.25	5.25	137.0	131.4	4.7%	7.5%	0.12	0.10	7.4	8.3	0.0063	0.0048
13A-B	Aframe	8.00	8.25	138.3	143.3	10.2%	5.8%	0.13	0.18	10.7	6.0	0.00	0.0051
14A-B	Arch	7.25	7.50	144.1	144.3	5.1%	5.4%	0.12	0.21	6.0	6.4	0.0061	0.0048
15A-B	Aframe	7.00	7.50	146.3	146.9	4.3%	3.6%	0.18	0.18	7.7	5.2	0.0050	0.0069
16A-B	Aframe	8.00	7.50	146.8	148.1	3.7%	3.3%	0.16	0.13	8.5	-	0.0045	-
17A-B	Aframe	5.50	7.75	143.9	143.2	6.0%	5.9%	0.16	0.21	-	8.2	-	0.0051
18A-B	Aframe	9.25	9.00	143.8	148.4	5.4%	2.7%	0.16	0.34	5.8	6.5	0.0060	0.0058
19A-B	Arch	4.00	7.75	142.8	141.8	6.9%	7.6%	0.09	0.17	7.3	6.3	0.0043	0.0052
20A-B	n/a	7.00	7.25	143.9	146.9	6.0%	4.7%	0.18	0.20	-	8.0	-	0.0040
21A-B	n/a	6.50	6.50	147.8	148.2	4.6%	4.4%	0.12	0.13	7.6	4.9	0.0045	0.0066
22A-B	Arch	8.25	10.00	140.1	147.2	8.0%	2.6%	0.09	0.34	7.0	-	0.0047	-
23A-B	n/a	6.50	4.75	138.8	142.2	8.1%	7.6%	0.14	0.05	5.4	-	0.0070	-
24A-B	n/a	5.00	4.00	142.4	144.3	8.4%	7.1%	0.08	0.06	5.8	11.6	0.0063	0.0039
25A-B	n/a	5.25	3.00	143.6	145.2	8.2%	6.4%	0.21	0.18	6.8	11.5	0.0052	0.0038
26A-B	n/a	7.00	7.00	143.4	143.4	7.1%	7.2%	0.24	0.23	4.4	-	0.0078	-
27A-B	Aframe	6.50	5.75	140.3	145.0	9.8%	6.6%	0.07	0.05	8.3	-	0.0051	-
28A-B	Aframe	5.75	3.75	143.6	147.8	8.4%	5.3%	0.08	0.05	9.0	-	0.0044	-
29A-B	Aframe	8.00	8.25	148.4	148.6	6.7%	6.1%	n err	0.39	9.7	6.1	0.0045	0.0074
30A-B	Aframe	6.00	6.00	149.0	150.5	5.6%	5.5%	0.11	0.24	5.2	7.6	0.0066	0.0051

Test	Boom Configuration	SLUMP (Inches)		UNIT WEIGHT (lb/ft^3)		AIR CONTENT (%)		SAM NUMBER		Hardened Air Content (%)		Spacing Factor (Inches)	
	-	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
31A-B	Aframe	6.00	7.00	148.8	148.4	6.3%	5.6%	0.19	0.47	8.0	8.6	0.0045	0.0045
32A-B	Aframe	7.25	7.75	146.2	146.7	6.6%	6.3%	0.13	0.08	7.5	8.3	0.0052	0.0044
33A-B	n/a	8.75	8.00	141.7	144.8	8.5%	8.6%	0.07	0.15	9.6	9.1	0.0040	0.0042
34A-B	Aframe	8.50	8.50	141.4	142.1	8.4%	8.5%	0.03	0.06	8.5	-	0.0045	-
35A-B	n/a	7.25	6.25	144.7	143.6	7.5%	7.7%	0.08	0.14	7.5	12.2	0.0040	0.0035
36A-B	n/a	7.25	7.00	141.7	142.9	8.9%	9.6%	0.10	0.13	12.0	15.1	0.0030	0.0026
37A-B	n/a	8.00	8.00	147.8	147.9	6.9%	7.0%	0.13	0.16	7.6	6.9	0.0047	0.0059
38A-B	ARCH	8.25	8.25	144.5	146.7	6.9%	7.7%	0.18	0.07	6.4	9.5	0.0056	0.0041
39A-B	ARCH	7.25	7.75	150.0	148.4	5.3%	6.3%	0.35	0.07	4.9	5.2	0.0076	0.0061
40A-B	Flat	-	-	-	-	6.5%	7.3%	0.12	0.14	6.2	9.7	0.0058	0.0062
41A-B	Flat	-	-	-	-	5.4%	4.9%	0.14	0.42	4.9	6.6	0.0099	0.0097
42A-B	Flat	-	-	-	-	4.0%	4.1%	0.29	0.42	3.7	4.8	0.0101	0.0098
43A-B	Flat	-	-	-	-	3.9%	4.6%	0.37	---	4.7	4.5	0.0079	0.009
44A-B	Flat	-	-	-	-	2.9%	3.4%	0.39	-	5.2	4.8	0.008	0.0089
45A-B	Flat	-	-	-	-	5.0%	5.3%	0.30	-	5.4	5.6	0.0086	0.0107
46A-B	Arch	-	-	-	-	5.5%	6.0%	0.13	0.27	6.0	6.1	0.006	0.0072
47A-B	Arch	-	-	-	-	4.6%	4.7%	0.17	0.33	3.6	5.9	0.009	0.0084
48A-B	Arch	-	-	-	-	3.8%	3.1%	0.33	0.70	0.0	3.8	-	0.0104
49A-B	Arch	-	-	-	-	4.4%	4.5%	0.34	-	4.7	4.8	0.0095	0.0086
50A-B	Arch	-	-	-	-	2.6%	3.0%	0.43	-	5.0	4.6	0.0095	0.009
51A-B	Arch	-	-	-	-	4.1%	4.7%	0.42	-	0.0	-	-	-
52A-B	Aframe	-	-	-	-	4.6%	5.0%	0.15	0.34	3.8	4.7	0.0083	0.0074
53A-B	Aframe	-	-	-	-	4.2%	4.9%	0.18	0.42	4.1	5.2	0.0084	0.009
54A-B	Aframe	-	-	-	-	3.2%	3.0%	0.34	0.77	4.2	4.5	0.0102	0.0109
55A-B	Aframe	-	-	-	-	5.0%	3.6%	0.24	-	4.5	3.8	0.0079	0.009
56A-B	Aframe	-	-	-	-	2.6%	2.6%	0.40	-	-	4.4	-	0.0086
57A-B	Aframe	-	-	-	-	3.7%	3.2%	0.24		-	3.8	-	0.0109

A.4 FRESH PROPERTIES FROM LWA MIXTURES

Table A.4.1 - Shows the fresh Unit Weight, Air Content, and SAM Number with mixtures performed with lightweight aggregates.

Sample	Fresh Properties				
	Unit Weight	Air Content (%)	Air Content STDV	Equalized SAM number	Equalized SAM number STDV
Control Mixture	147.20	4.4%	0.00	0.16	0.16
10% Slate A	145.40	4.9%	0.000	0.15	0.005
30% Slate A	144.12	4.0%	0.003	0.15	0.009
35% Slate A	144.48	3.8%	0.002	0.14	0
35% Slate A	143.28	4.4%	0.001	0.24	0
50% Slate A	142.98	3.6%	0.002	0.32	0.027
30% Clay A	140.19	4.6%	0.0015	1.07	0.035
20% Clay A	141.93	4.2%	0.0031	0.95	0.005
15% Clay A	144.41	3.8%	0.001	0.59	0.03
10% Clay A	145.27	4.1%	0	0.42	0.02
30% Shale B	145.88	3.5%	0	0.38	0.065
10% Shale B	147.00	4.0%	0.001	0.29	3.55E-15
20% Shale B	147.56	3.3%	0.0005	0.41	0.045
15% Slate B	146.36	3.9%	0.0015	0.23	0.01
20% Slate B	145.92	3.7%	0.001	0.20	0.005
30% Slate B		4.3%	0.0005	0.18	0.005
10% Shale A	147.72	4.2%	0.001	0.16	0.015
15% Shale A	147.76	3.8%	0	0.15	0.055
20% Shale A	146.88	4.0%	0.0015	0.18	0.005
30% Shale A	146.16	4.1%	0.0005	0.31	0.04
10% Shale A Not Prewetted	147.72	4.2%	0.000%	0.24	0.014
30% Shale A Not Prewetted	144.36	4.5%	0.141%	0.40	0.042
10% Slate B Not Prewetted	149.76	2.9%	0.058%	0.39	0.093
30% Slate B Not Prewetted	147.17	2.8%	0.100%	0.33	0.020

VITA

Chad Staffileno

Candidate for the Degree of

Master of Science

Thesis: FIELD INVESTIGATION OF PUMPING AIR ENTRAINED CONCRETE AND THE VALIDATION OF THE SAM TEST ON LIGHTWEIGHT CONCRETE MIXTURES

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering Oklahoma State University, Stillwater, Oklahoma in May 2020

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May 2018