INVESTIGATION OF CONCRETE PUMPING EFFECTS ON AIR-ENTRAINED CONCRETE

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INVESTIGATION OF CONCRETE PUMPING EFFECTS

ON AIR-ENTRAINED CONCRETE

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Abstract: This work investigates how pumping affects the air void system in the fresh and hardened concrete. This work pumped a similar mixture design with varying air contents in laboratory and field environments to investigate the air void system before and after pumping. The Super Air Meter (AASHTO TP118) was used to give the air volume and SAM Number of the fresh concrete. The hardened concrete was evaluated using hardened air void analysis (ASTM C457) and freeze-thaw durability testing (ASTM C666). For the mixtures investigated, concrete pumping did not cause a significant change to the hardened air void system. The research conducted suggests the fresh air content and SAM Number measured after pumping on the fresh concrete is not representative of the hardened concrete. Because of this, it is suggested to sample fresh concrete prior to pumping to determine the quality of the air void system. The work also gives a framework for future testing.

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CHAPTER I

INTRODUCTION TO PUMPING AIR-ENTRAINED CONCRETE

1.0 INTRODUCTION

Pumping is the preferred concrete placement method for many jobsite applications due to the increased efficiency, versatility, and economic benefits. However, the pumping of air-entrained concrete frequently results in quality control issues due to the loss of air content during pumping [1]. This has caused concern in environments where the concrete will experience repeated freezing and thawing cycles. Due to this, it is common practice for specifiers to require air content testing at the discharge of the concrete pump, after it has been manipulated by all steps on the construction process [1]. This work concludes that this is not a good practice because the air measurements after pumping are not representative of what will be found within the hardened concrete. While this is a controversial finding, there is significant data presented to support this change in practice.

The most common used indicator for freeze-thaw resistance in concrete is the total air volume. In most cases, the total air volume is specified and the air volume is determined using a Type B pressure meter. However, previous research has shown the quality of the air void system has greater significance in predicting the freeze-thaw performance of a concrete mixture [2, 3]. The quality of the air void system depends on the size and spacing of the air bubbles. The research conducted investigates how pumping affects the total air volume and air void system in the fresh and hardened concrete.

1.1 AIR-VOID DISTRIBUTION IN FRESH CONCRETE

The quality of the air-void system depends on the size and spacing of air bubbles within a concrete mixture. Smaller, well-dispersed bubbles provide finer air-void systems that perform better in freezing and thawing environments [2-4]. Two common indicators of the air void quality in the hardened concrete are the Spacing Factor per ASTM C457 and the Durability Factor per ASTM C666. In previous research, the air-void size and spacing in the fresh concrete was studied using the Super Air Meter (SAM). Research has shown the SAM Number of the fresh concrete correlates to the spacing factor and freeze-thaw resistance in the hardened concrete [3]. This work focuses on providing insight into the changes in the quality of the air void system due to pumping.

1.2 MECHANISMS

Typical air losses reported during pumping range from one-half to three percent, with less frequent larger losses and increases also reported [1, 5, 6]. These variations depend on numerous factors that make it hard to predict the air content after pumping. The general mechanisms thought to change the air content during pumping are the vacuum, impact, and pressure dissolution mechanisms [6-9] . The literature discusses these mechanisms and all likely play a role in the change of air volume during pumping. In practice, contractors try to minimize circumstances that contribute to these mechanisms [1].

1.2.1 Vacuum Mechanism

When pumping concrete in downward sections of pipe, the weight of the concrete may overcome the frictional resistance, allowing the concrete to slide down the pipe. As the concrete slides down the pipe, it is possible to develop a vacuum behind the concrete. This may cause the bubbles to rapidly expand and burst [6, 7]. The phenomena can be explained per Boyle's Law, which states the pressure of the gas is inversely proportional to volume. In addition, the vacuum can form a pressure gradient that may allow bubbles to more easily escape the concrete mixture [6]. This may be a contributing cause of air loss in vertical or downhill boom configurations.

1.2.2 Impact Mechanism

The air bubbles may be 'knocked out' of the mixture after falling and hitting a surface. In concrete pumping, this could happen when concrete impacts 90° elbows in the pipeline or when falling excessive heights at discharge [6-8]. Yingling et. al. performed research showing impact put on rapidly moving concrete can cause significant air loss. Little research has been performed regarding the size of air voids that are 'knocked out', but some within the concrete industry have suggested that the larger voids will most likely be lost due to buoyancy effects [6].

1.2.3 Pressure Dissolution Mechanism

As the concrete is subjected to increased pressure, some of the bubbles may dissolve into the aqueous solution of the paste. Typical concrete pumping pressures can range up to 300-500 psi [6, 9]. At these high pressures, some of the air bubbles may have the tendency to dissolve based on Henry's Law [6, 9-11]. In addition, based on the Young-Laplace equation, it is expected the smaller bubbles will likely dissolve first because of higher internal pressures [6, 9-12].

When the concrete is depressurized, it can cause a reversal of the dissolution process. This can cause the air to return to the system. It has been suggested that upon leaving solution, the dissolved air will reform upon exiting bubbles, as it is easier to form on existing bubbles than create new bubbles. This mechanism would cause the air void system to form a distribution of larger bubbles and be detrimental to freeze-thaw durability, as it would result in the removal of many of smaller bubbles from the mixture [5, 6, 9, 11]. However, there are no direct observations of this process in pumped concrete.

The laboratory pumping minimized all factors contributing to the vacuum and impact mechanisms, thus isolating the pressure-dissolution mechanism. The following chapters discuss the impact the pressure-dissolution mechanism has on the air void quality of the concrete.

1.3 OBJECTIVE

The main goal of this research was to advance the knowledge of pumping air-entrained concrete. The work provides insight on how pumping affects the quality of the air-void system in concrete. The work used a similar mixture design in the laboratory and field to evaluate the air void system before and after pumping. The work performed tests on the fresh and hardened concrete. Chapter 2 focuses on the direct impact pumping has on air-void system parameters critical to freeze-thaw durability. Chapter 3 investigates the processes associated with the pressure-dissolution mechanism and the return of the air void system after pumping. This work provided several useful observations.

CHAPTER II

EFFECTS OF PUMPING CONCRETE BASED ON THE AIR VOID PARAMETERS IN FRESH AND HARDENED CONCRETE

2.0 INTRODUCTION

The pumping of air-entrained concrete frequently results in quality control issues and even rejection of the load due to the loss of air content [1]. Elevated slabs exposed to the weather, such as concrete bridge decks, are highly susceptible to this sort of damage due to rapid freezing and thawing. This problem is addressed by entraining air bubbles into the concrete mixture. The proper air void distribution in concrete provides an air void system that allows space for the water to freeze and expand without damaging the concrete [3, 13].

In many cases, concrete pumps are used to construct bridge decks. It has been recognized that pumping concrete has the potential to reduce the air volume due to increases in pressures [6, 9, 11, 14]. Regardless, many of these bridges remain standing after excessive freezing and thawing cycles. This suggests there is more to be learned about how pumping affects the air void quality of concrete. This chapter uses different methods to investigate how the air void quality and freeze-thaw durability of concrete changes due to pumping. This work investigates concrete mixtures with various air contents before and after pumping.

2.1 EXPERIMENTAL METHODS

2.1.1 Materials

All of the concrete and grout mixtures described in this work were prepared using a Type I cement that meets requirements of ASTM C150 and a fly ash that meets the requirements of ASTM 618 Class C. Table 2-1 shows the oxide analysis for cement and fly ash used for the laboratory mixtures. All of the concrete mixtures had a water-to-cementitious material ratio (w/cm) of 0.45, 611 lbs/yd^3 of total binder with 20% Class C fly ash replacement by weight. The fine aggregate came from a single natural sand source and the coarse and intermediate aggregates came from a single dolomitic limestone available in Oklahoma approved for concrete production. The laboratory and field mixtures used the same aggregates.

The mixtures used a wood rosin based air-entraining admixture (AEA) to stabilize air during mixing. Some mixtures used a food grade citric acid at 0.25% weight of the cementitious material, a midrange water reducer (WR) meeting ASTM C494 at a dosage of 7 oz/cwt, or a polycarboxylate (PC) superplasticizer meeting ASTM C1017 at a dosage of 2.5 oz/cwt. These dosages were chosen to provide approximately the same slump before pumping for all mixtures. The citric acid is a primary ingredient to several commercial set retarders and acted as a water reducer. The field mixtures used a wood rosin AEA and a mid-range WR at 7 oz/cwt.

Table 2-1 – Type I cement oxide analysis

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	C_3S	C_2S	C_3A	C_4AF
Cement	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	-	-	56.7	17.8	8.2	7.8
Fly Ash	38.7	18.8	5.8	23.1	5.6	1.2	1.8	0.6	1.5	0.4	-	-	-	-

2.1.1.2 Mixture Design

Aggregate proportions were adjusted on each mixture to maintain an approximately constant aggregate gradation. Figure 2-1 shows the total aggregate gradations for all mixtures along with the Tarantula Curve limits. Previous research shows the Tarantula Curve successfully guides the aggregate gradation to improve pumpability of concrete [14]. The sum of the fine and coarse sand was approximately 38% and 27% respectively. The coarse sand is the sum of the material contained on the #8, #16, and #30 sieve. The fine sand is the sum of the #30, #50, #100, and #200 sieve. This falls within the recommended range for flowable concrete [15]. Table 2-2 displays a summary of the mixture proportions. The paste content of each mixture was 28.9%; the air content was not included in determining the paste content.

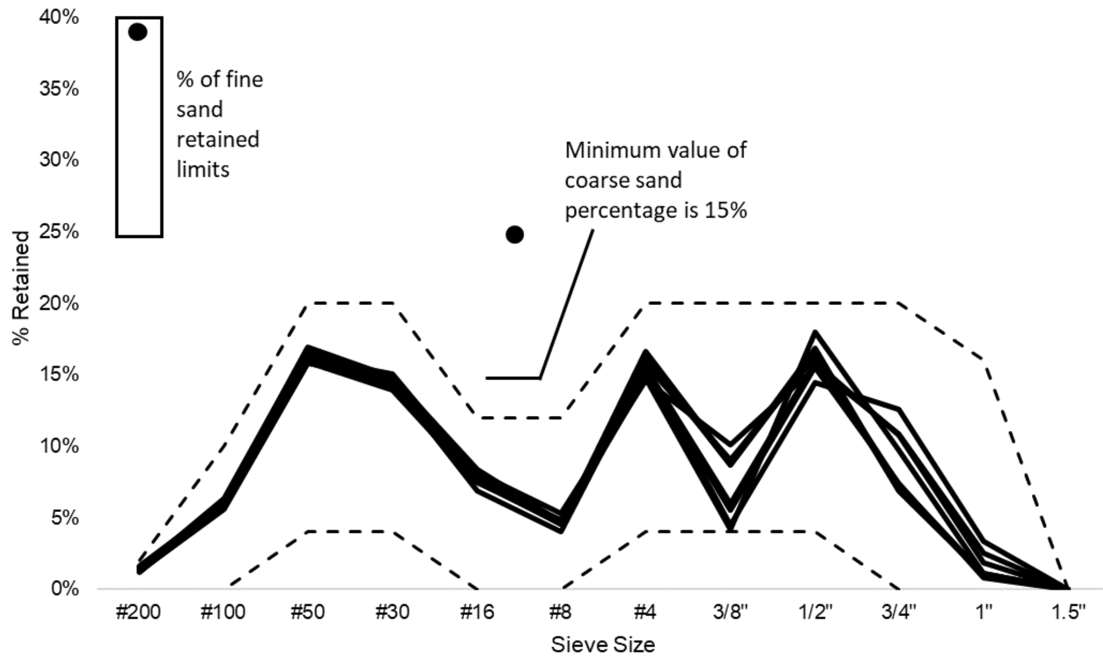

Figure 2-1 –Gradation used in the testing shown against the Tarantula Curve.

Table 2-2 – Concrete Mixture Summary

Cement (lbs/cy)	**Fly Ash (lbs/cy)**	**Water (lbs/cy)**	**Coarse (SSD lbs/cy)**	**Int. (SSD lbs/cy)**	**Fine (SSD lbs/cy)**	**Paste Content**
489	122	275	1263.8	426.2	1471.0	28.9%

2.1.1.3 Grout Mixtures

The pump and pipe network were primed with grout prior to each laboratory pumping session. Priming consists of lining the walls of the pump and pipe network with a thin lubricating layer of mortar [14]. The grout mixture was prepared using a Type I cement that meets the requirement of ASTM C150 with a w/cm of 0.40, 1006 lbs/yd^3 of cement, and 2514 lbs/ yd^3 of sand from the same natural sand source used in the concrete mixtures.

2.1.1.4 Mixing Procedure

For the laboratory mixtures, aggregates were brought from outside stockpiles into a temperature-controlled room at 72°F for at least 24 hours before mixing. The aggregates spun in a mixing drum for at least three minutes. A representative sample for moisture content testing was used to apply a moisture correction to the mixture. At the time of mixing, all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water mixed for three minutes. The resulting mixture rested for two minutes while scraping the sides of the mixing drum. After the rest period, the admixtures were added and mixing continued for three minutes. Information on charging the pump and pipe network, and how the concrete was gathered was included in Section A.3 of the Appendix.

For the field testing, concrete was delivered in five cubic yard increments. Field mixing followed ASTM C94 and moisture corrections used probes within the aggregates. All of the concrete tested in the field was truck-mixed.

2.1.2 Equipment

2.1.2.1 Concrete Pumps

The Putzmeister TK 50 concrete pump used for the laboratory testing is shown in Figure 2-2. This pump provides an almost continuous concrete flow by two alternating pistons. One piston draws concrete from the hopper as it retracts, and the second piston pushes concrete out as it extends. An S-valve alternating delivery system shifts from one delivery cylinder to the other. This delivers concrete from the pump. The pump is equipped with a remixer that continually agitates the concrete in the hopper. The pump settings used in this work were 1500 RPM, and the piston volume was 0.57 ft^3 as determined by previous work [14]. Additional information on the Putzmeister TK 50 pump and the values used are included in Section A.2 in the Appendix.

Figure 2-2 – The Putzmeister TK 50 Concrete Pump used for all laboratory testing.

A PumpStar AZ34.5-PS220 truck-mounted concrete pump was used for the field research. The pump is shown in Figure 2-3. This pump has two 9.0 in. inside diameter (I.D) delivery cylinders with an approximate length of 6.5 ft. An S-valve delivery system switches between the delivery cylinders. After the S-valve, the pipe diameter reduced to 5.0 in. I.D. Following this was approximately 110 ft. of 5.0 in. I.D. double-wall steel pipe. At the end of the boom was a reducer and approximately 10 ft. of 4.0 in. I.D. rubber hose for easier placement.

Figure 2-3 – Pumpstar AZ-34.5 / PS-220 Truck Mounted Concrete Pump used in the field-testing.

2.1.2.2 Pressure Sensors

Measurement of the concrete pressure near the edge of the pipe was completed for laboratory and field testing with a novel pressure sensor setup developed by previous work[14]. Figure 2-4 shows a typical pressure sensor. Each pressure sensor consisted of a GE 5000 pressure sensor in conjunction with a buffer chamber filled with hydraulic fluid. The GE 5000 pressure sensor is capable of measuring pressures between 14.5 psi to 500 psi with +/-0.5psi accuracy. The buffer chamber was required to separate the sensor from the concrete. The buffer chamber consists of a hydraulic fluid-filled chamber with a flexible rubber membrane on one end and the other end connected to the GE 5000 pressure sensor. As pressures increase on the rubber membrane, the pressures transfer to the fluid in the chamber and to the GE 5000 sensor. The walls of the buffer chamber perpendicular to the rubber membrane were threaded.

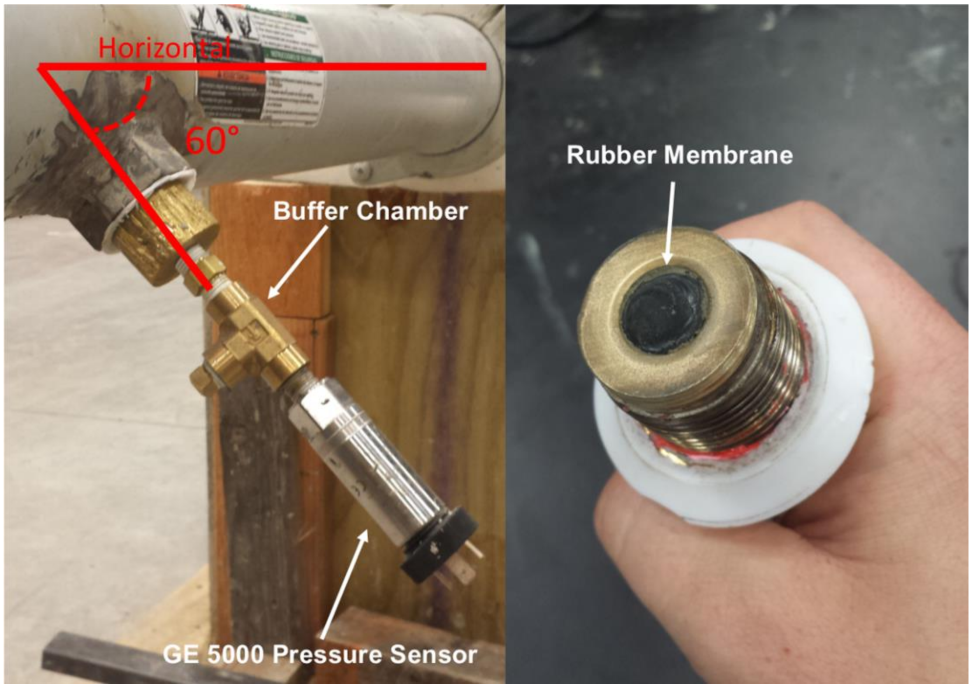

Figure 2-4 - Overview of the pressure sensors.

To connect the sensor to the pipe, a 1.125 in. diameter hole was drilled and a nut was welded to the outside of the pipe as shown in Figure 2-4. The buffer chamber threads into the nut until the rubber membrane is adjacent to the walls of the pipe. The pressure sensors were rotated approximately 60° from the horizontal to keep aggregate, paste, and water from collecting on top of the flexible rubber membrane. Figure 2-4 shows the assembled pressure sensor. The pressure sensor recorded data every 0.02 seconds.

Calibration of the sensor assembly used a water-filled pipe. A hand pump increased the pressure in the pipe from 0 to 110 psi in systematic steps. By plotting the voltage and water pressure, a calibration curve was created. Typical results from the sensor calibration are in Figure 2-5. A linear model fit the data with an average R^2-value of 0.99. Table A.4-1 in Section A.4 of the Appendix shows the calibration and goodness of fit values.

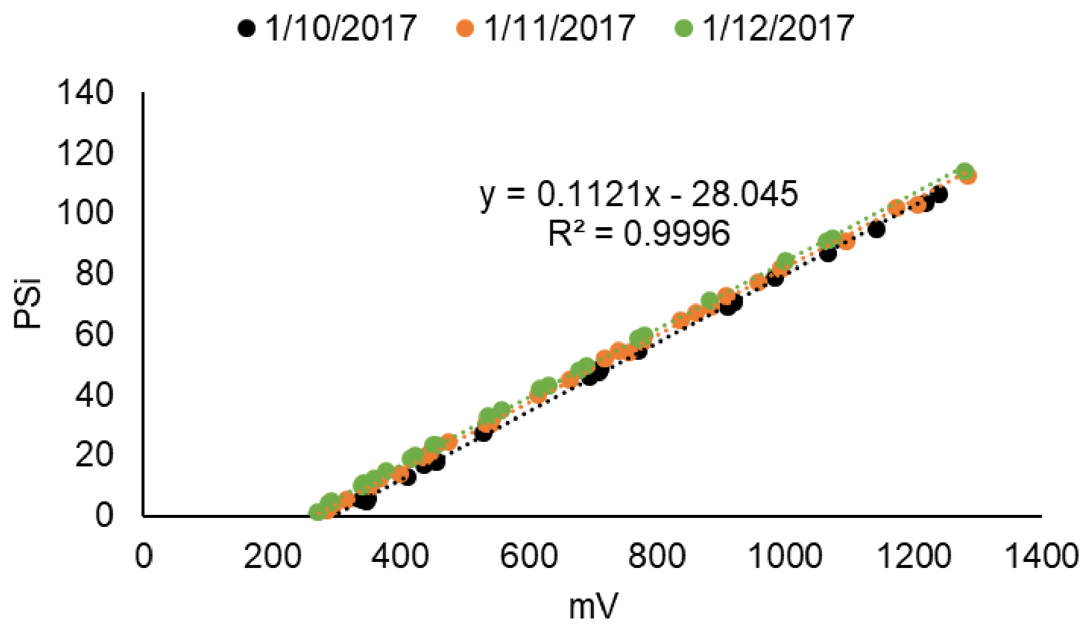

Figure 2-5 – The voltage and pressure correlation for a typical calibration curve.

All measurements used the linear model to determine the pressure at the surface of the pipe. During calibration of the sensor, the y-intercept would shift 0 to 20 psi between measurements, but the slope of the calibration line remained constant. This may be caused by the wear and relaxation of the rubber membrane on the pressure sensor. To account for this, the pressure sensor measured the empty pipe network to determine the 0 psi or atmospheric pressure value before each experiment.

Details about the response from pumping are included in the Appendix in Section A.5. This work used the peak pressure to characterize each mixture. The peak pressure is the maximum pressure recorded from each piston stroke. Details about the program used to analyze the results is included in Section A.5 of the Appendix. The maximum pressure measured in the laboratory mixtures was between 50 and 120 psi. The maximum pressures for the field mixtures was between 150 and 200 psi.

2.1.2.3 Pipe Configurations

The laboratory testing used a standard pipe network. Figure 2-6 shows an overview of the pipe network. The pipe network used 4.0 in. I.D. single wall steel pipe. Rubber gaskets and couplings secured the sections of pipe together. The pipe network consists of a 3.3 ft. long single wall steel pipe reducer that reduces the 5.0 in. I.D. output of the pump to 4.0 in. After the reducer, there is 52.5ft. of 4.0 in. I.D. steel pipe with three 1.5ft radius 90° bends. At the end of the steel pipe network a 9.8 ft. 4.0 in. I.D. flexible rubber hose returns the concrete to the hopper of the pump creating a continuous flow. The total volume of the pipe network is approximately 6.0 ft^3. Along the pipe network, four sensors measured the pressures at the walls of the pipe during pumping. The locations of the four sensors are in Figure 2-6. Section 2.1.2.2 explains the pressure sensors.

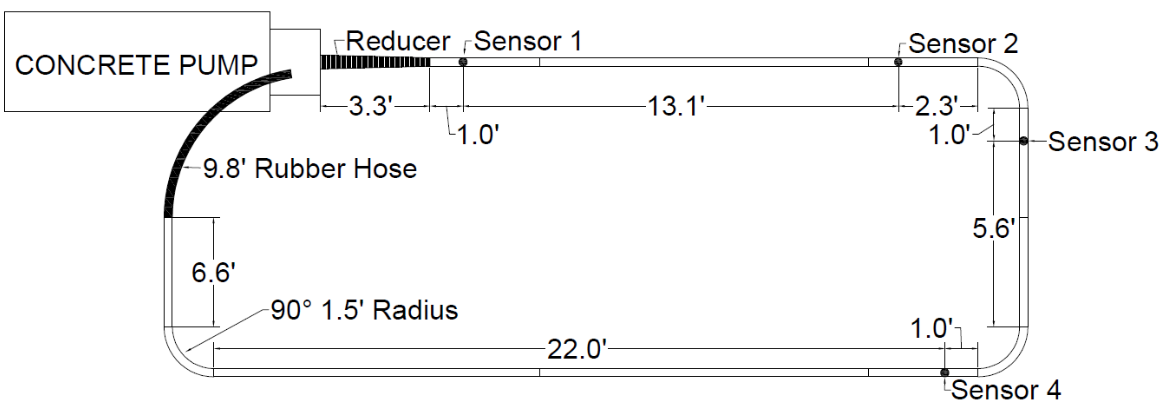

Figure 2-6 – Plan View of the pipe network.

The field testing used three different configurations. These configurations are known as flat, arch, and A-frame and are shown in Figure 2-7. In the flat configuration, the pipe was placed horizontally to discharge approximately 100 ft. from the pump. In the arch configuration, the boom followed a curve with the maximum height at approximately 40 ft. above the ground and the point of discharge at approximately 60 ft. from the pump. The final configuration is the A-frame. In the A-frame orientation, the boom was in a sharp upward and downward configuration with the maximum height of approximately 50 ft. above the ground and the outlet of the pump approximately 30 ft. from the pump. The first pressure sensor was at the discharge of the piston. The second sensor was before the peak of the arch and A-frame and the third sensor was after the peak.

Figure 2-7 – The flat, arch, and A-Frame orientations of the concrete pump.

2.1.3 Evaluation of Air Entrained Concrete

In evaluating the properties of air-entrained concrete after pumping, there is a concern with how the total air volume, air void quality, and freeze-thaw resistance of the concrete changes due to pumping. The following tests were run on the concrete before and after adding to the pump: Slump (ASTM C143), Unit Weight (ASTM C138), Super Air Meter (AASHTO TP 118), Freeze-Thaw Resistance (ASTM C666), and Hardened Air Void Analysis (ASTM C457). For this work, ASTM C666 Durability Factors less than 70% after 300 freeze-thaw cycles are considered failing and is consistent with previous work [3].

In the laboratory testing the concrete was tested before pumping, after one cycle through the pipe network, and then every 15 minutes of recirculating the concrete through the pump and pipe network. For each 15 minutes of pumping, the concrete circulated approximately 40 times through the pipe network. This is the same as traveling approximately 2400 ft. of 4.0 in. diameter line and passing through the reducer forty times. The concrete tested after one cycle through the pump is most representative of typical construction applications. The concrete tested after several cycles through the pump provides insight to how excessive pumping affects the properties of the concrete. The pumping session was stopped when the slump was less than 3.0 in. to avoid blockages in the line.

In the field, the same tests were run before and after the pump in each boom configuration. The concrete was tested simultaneously before and after the pump to ensure measurements are as comparable as possible.

For a few laboratory mixtures, the concrete was tested before pumping, immediately after pumping, and then every 20 to 30 minutes without agitation to determine how the slump, unit weight, air volume, and SAM Number changed over time. A sample was also collected for hardened air void analysis. This testing procedure was performed three times using citric acid and twice using a PC. This was done to show how the air void system recovered over time.

2.2 RESULTS AND DISCUSSION

2.2.1 Air Volume and Super Air Meter Results

The raw data is included in Section A.1 of the Appendix. Figure 2-8 shows a plot of the air content before and after one cycle through the pump for the laboratory and field mixtures. The plot shows a line of equality. If a mixture had the same air content before and after pumping then it would be on this line. All of the laboratory mixtures with citric acid and WR showed a decrease in air content after pumping. The PC samples and field samples did not show a significant change in air content. Of the 18 field mixtures, five samples showed a change in air volume greater than ± 0.5%.

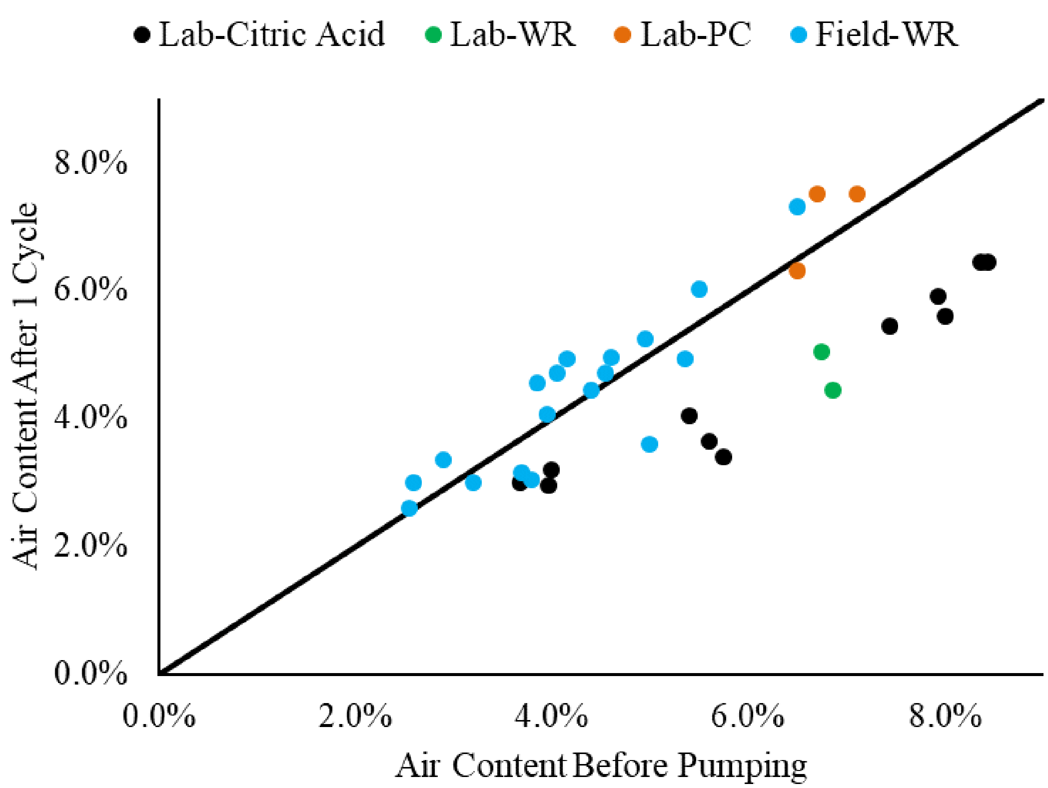

Figure 2-8 – Plot of Air content before pumping vs. Air content after 1 cycle

Figure 2-9 shows the normalized air content versus the number of cycles through the pump. The normalized air content is the ratio of the air before pumping to the air measured after pumping multiplied by 100. All lab mixtures containing a citric acid and WR showed the most significant decrease in air content between the measurements right after mixing and the measurements after one pumping cycle. After the first pumping cycle, the air content of the citric acid and WR mixtures either decreased at a slower rate or remained approximately constant with additional cycles through the pump. On average, the citric acid and WR lost approximately 25% of the initial air content after one cycle through the pump with a standard deviation of 4.5% and 7.1% respectively. In contrast, the PC mixture and field mixtures did not show a significant change in air volume after one pumping cycle. These results indicate that most of the air lost during pumping occurs during the first cycle for the citric acid and WR mixtures. In addition, the relative proportion of air lost for all citric acid and WR samples was comparable.

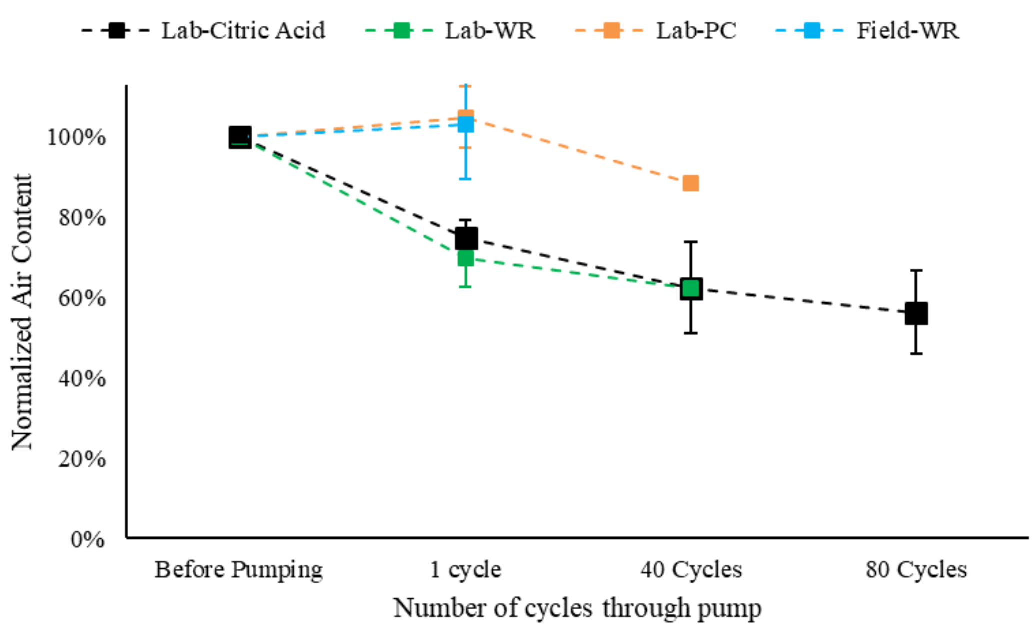

Figure 2-9 – Plot of Normalized air content vs. Number of cycles through the pump.

Figure 2-10 shows the SAM Number before pumping compared to the SAM Number after one cycle through the pump and pipe network. In all citric acid, WR, and field mixtures, the SAM Number increased by at least 50% for 87% of the mixtures after one cycle through the pump. In the PC samples, the SAM Number slightly decreased after one pumping cycle. Figure 2-11 plots the Normalized SAM Number vs. number of cycles through the pump for laboratory and field samples. The Normalized SAM Number is the SAM Number after pumping divided by the SAM Number before pumping multiplied by 100. Also shown on the graph is error bars from one standard deviation. A positive number indicates an increase in SAM Number and a negative number indicates a decrease in SAM Number. After one pumping cycle, the SAM Number for the citric acid, WR, and Field samples increased. PC samples showed a slight decrease in SAM Number after one pumping cycle. With multiple cycles, the SAM Number remained approximately constant or increased for all samples.

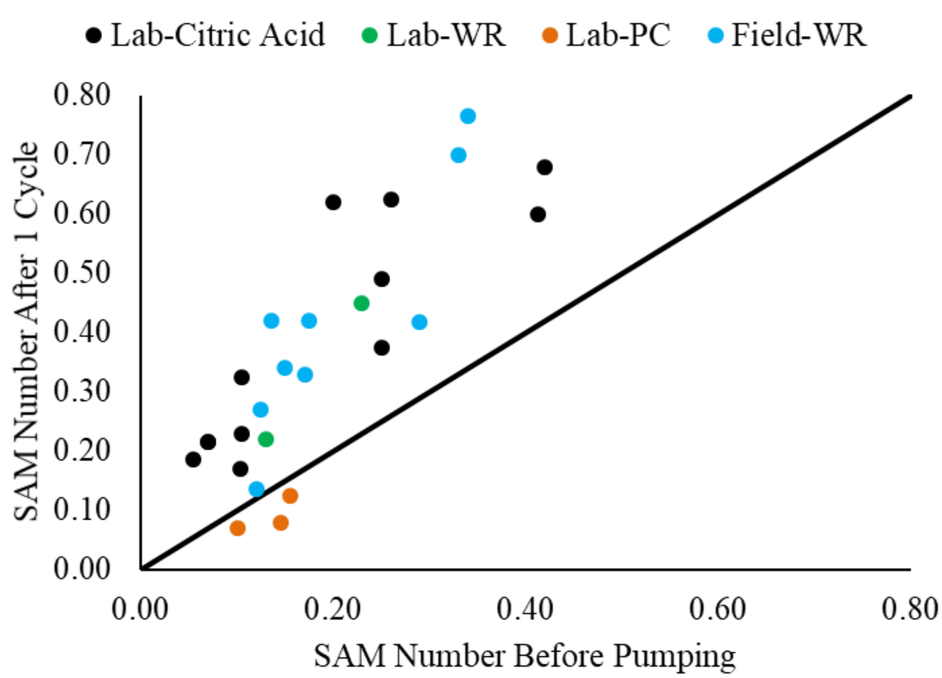

Figure 2-10 – Plot of SAM Number Before Pumping versus the SAM Number after pumping one cycle through pump and pipe network

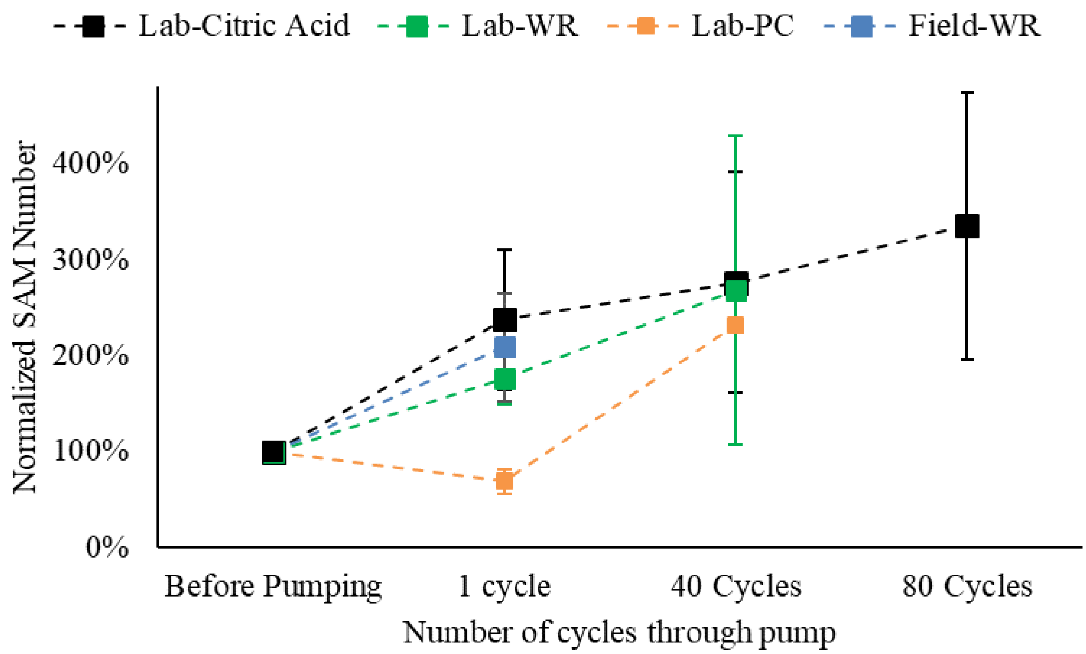

Figure 2-11 – Plot of SAM Number vs number of cycles through the pump and pipe network.

A plot of the SAM Number versus Air Content is in Figure 2-12. Based on previous work, this plot shows the efficiency of the air void system in concrete by plotting the air content and SAM Number [16]. The lower limit in the graph represents concrete with a high efficiency air-void system and the upper limit represents a low efficiency air-void system. Air-void efficiency determines the amount of air required to make a high-quality air-void system. A high efficiency air-void system has a larger amount of small bubbles and so it requires less air to reach a satisfactory air void system [16].

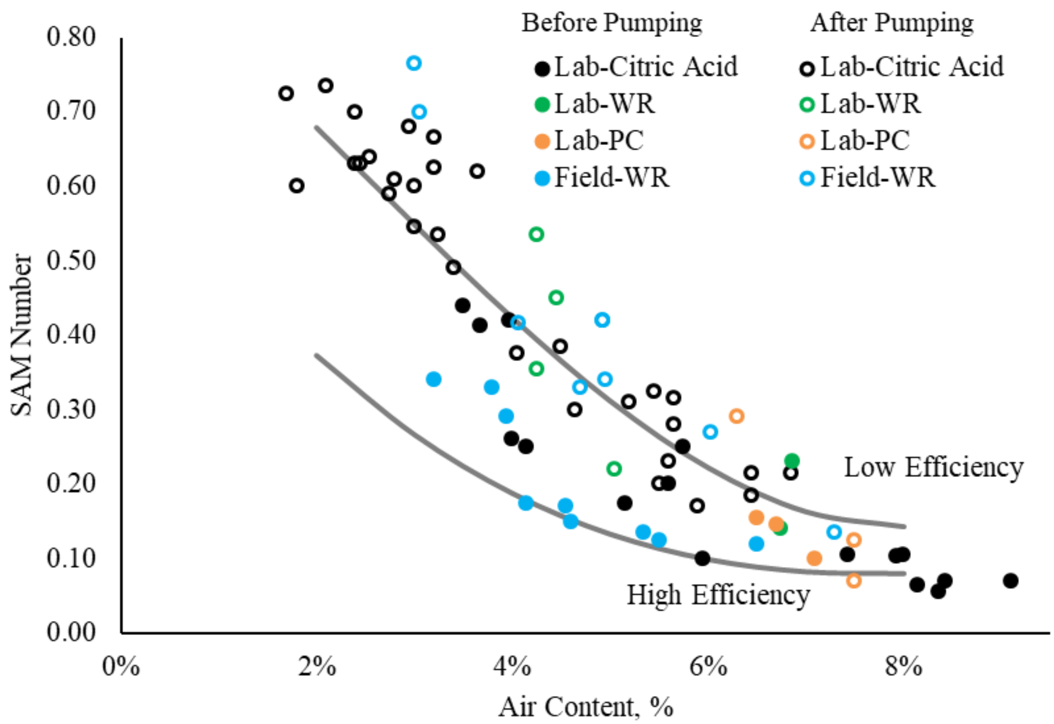

Figure 2-12 – Plot of SAM Number vs Air Content for laboratory and field samples before pumping and after one cycle through the pipe network.

The closed circles represent points before pumping, and open circles represent points after pumping. The plot shows that before pumping, most points fall closer to the lower limit, indicating a high efficiency air void distribution or a larger amount of small bubbles. After pumping, the points fall closer to the upper limit. This means that the pumping has changed the efficiency of the air void distribution. Details tracking the movement of individual mixtures on the SAM vs. Air plot are in Section A.5 in the Appendix.

2.2.2 Recovery of the Air Void System

To investigate how the air void system recovered over time. Mixtures were tested every 20-30 minutes after pumping. In the plots, the data at zero minutes corresponds to the measurement taken before pumping. The data at ten minutes corresponds to one cycle through the pipe network. A non-pumped sample has also been included for comparison. The results have been divided into mixtures that lost air during pumping and those that did not. These will be discussed separately.

2.2.2.1 Mixture with minimal change from pumping

The mixtures with minimal change in the air volume from pumping are shown in Figure 2-13 and Figure 2-14. In these mixtures there is minimal change in the air volume and SAM Number over time after pumping. Since the mixtures were not modified by the pumping process then we would not expect these values to change. This data confirms this and acts as a control.

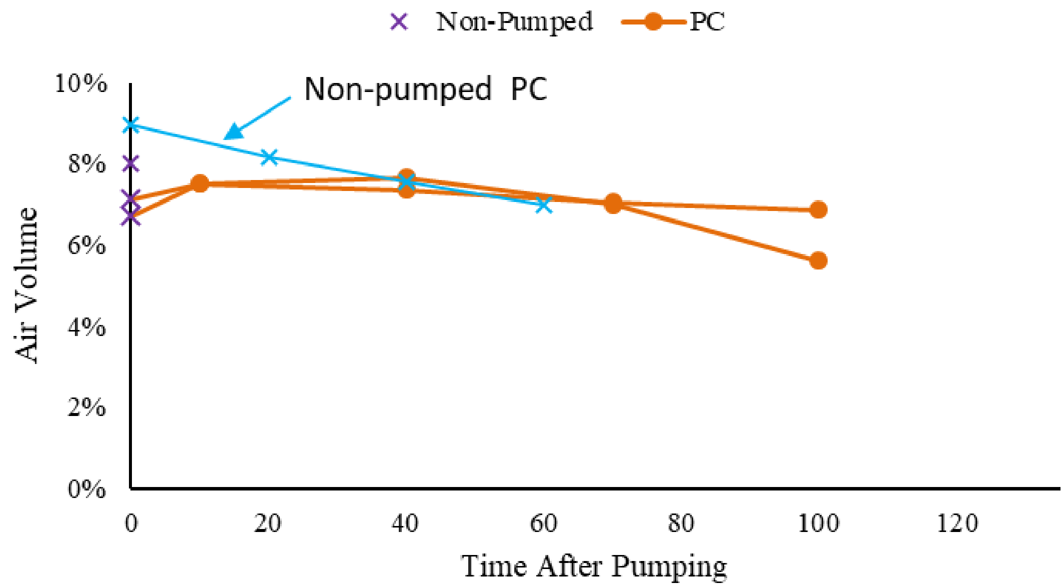

Figure 2-13 – Plot of fresh air content (%) versus time after pumping one cycle through the pump and pipe network.

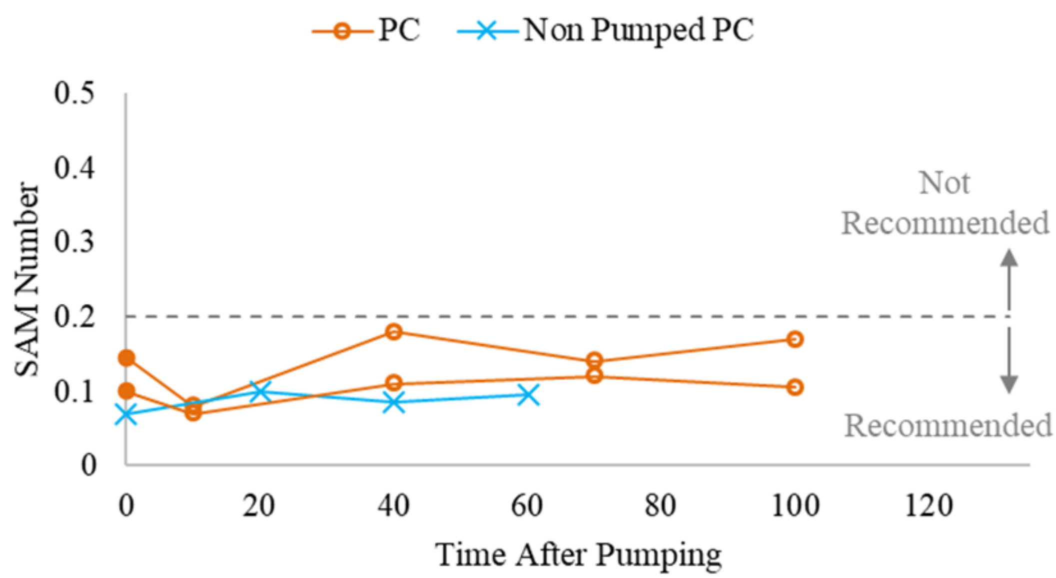

Figure 2-14 – Plot of SAM Number versus time after pumping one cycle for PC mixtures.

2.2.2.2 Mixtures with changes from pumping

Figure 2-15 shows the air volume change and Figure 2-16 shows the SAM Number change over time for mixtures that lost air after one cycle of pumping. As the concrete sat undisturbed, the SAM Number seems to improve over time. This could be caused by the pumping temporarily dissolving the smaller bubbles from the increased pressures. As the concrete sits statically, these smaller bubbles may reform. This is why the SAM Number improves over time.

An important observation is that the improvement in the SAM Number is observed without a significant change in the air volume. This may occur if the dissolved air bubbles are small and do not make a significant contribution to the total air volume but do change the size and spacing of the air void system. The SAM Number would be expected to decrease over time if the voids that are returning are small and well dispersed. This suggests that the air void system measured immediately after pumping is not representative of what is present in the hardened concrete for these mixtures.

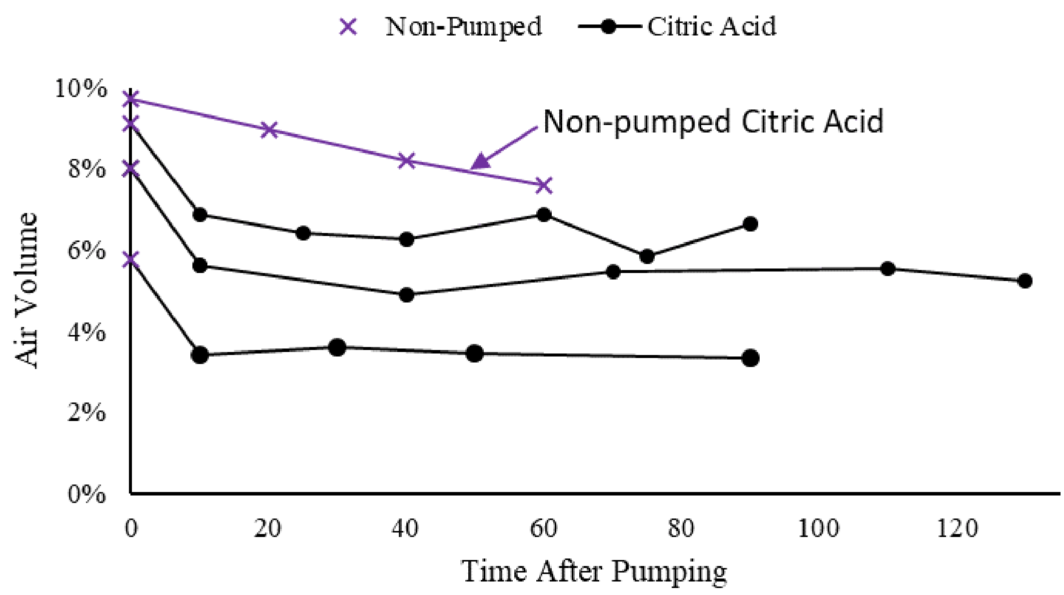

Figure 2-15 – Plot of fresh air content (%) versus time after pumping one cycle for citric acid mixtures.

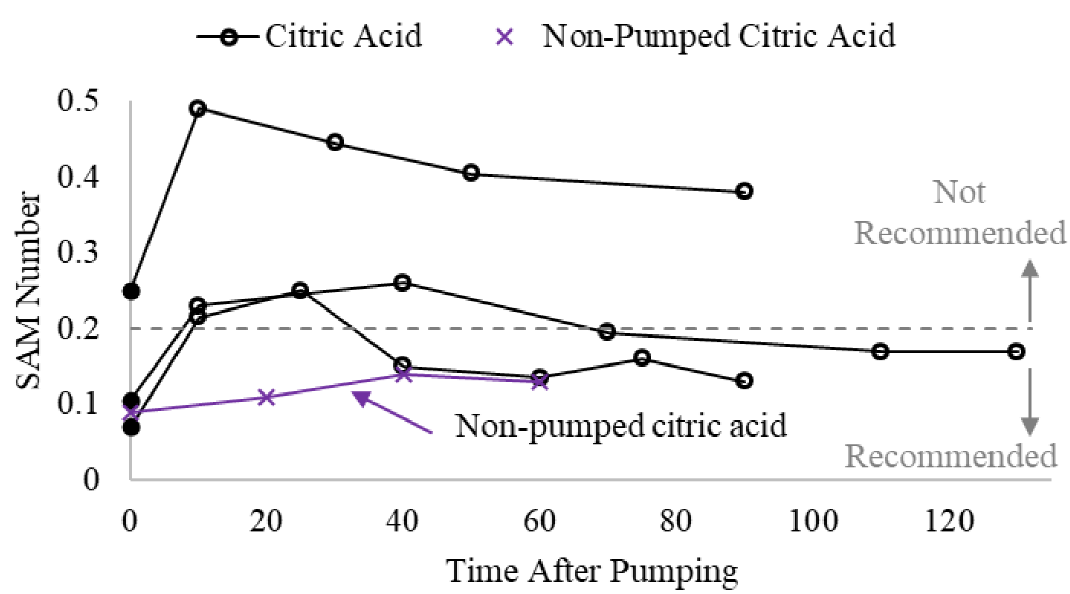

Figure 2-16 – Plot of SAM Number versus time after pumping one cycle for citric acid mixtures.

2.2.3 Freeze-thaw Durability

Most specifications require air contents to be greater than 4% when freeze-thaw durability is required. In addition, previous research has also shown a SAM Number less than 0.32 correlates to the point of satisfactory performance in ASTM C666 [3].

Figure 2-17 shows the relationship between air content and Durability Factor. A dashed vertical line shows 4% air content and a Durability Factor of 70%. The filled circles represent the air content measured before pumping and the open circles represent the air content measured after pumping. In addition, 64 data points are included from previous publications to show the typical relationship between the air content and Durability Factor for non-pumped samples [3]. The previous work used the same cement, fly ash, coarse aggregate, and fine aggregate described in Section 2.1.1.

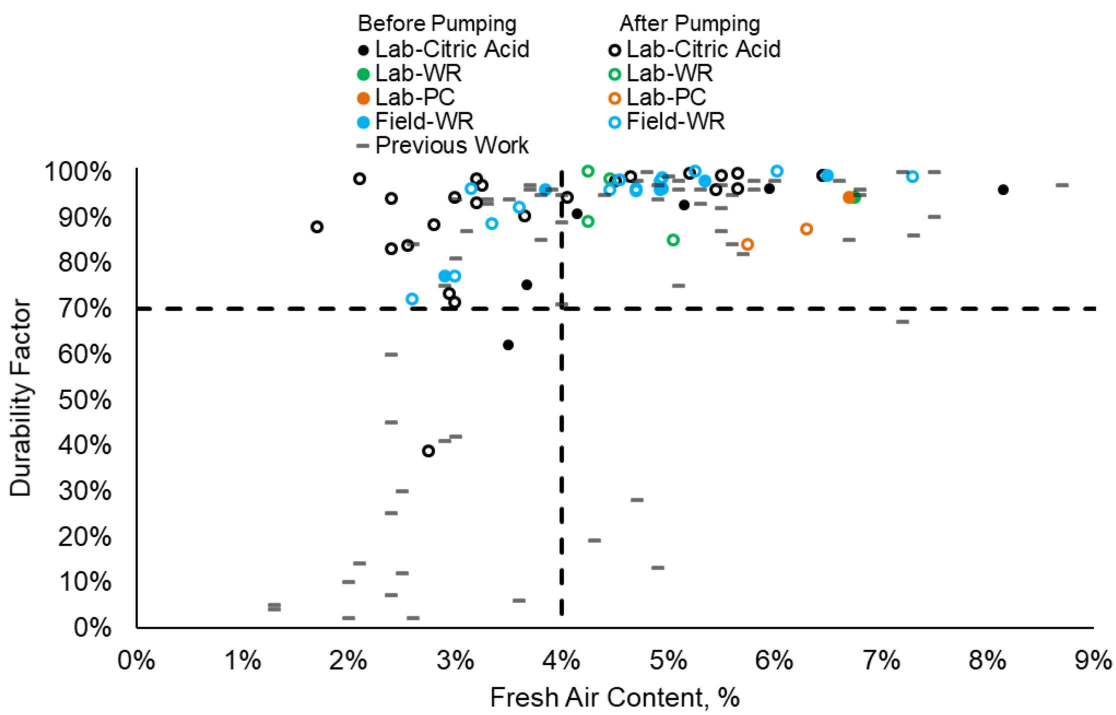

Figure 2-17 – Plot of fresh air volume measured after pumping versus Durability Factor

Pumping frequently reduced the air content below 4%; however, the ASTM C666 freeze-thaw performance was satisfactory. This shows the air content after pumping does not accurately predict the freeze-thaw performance based on industry standards.

Figure 2-18 shows the relationship between SAM Number and Durability Factor. The closed circles represent points measured before pumping, and the open circles represent points measured after pumping. In addition, 64 data points from previous publications and the SAM Number limit of 0.32 are included to show the typical relationship between the SAM Number and Durability Factor for non-pumped samples [3]. The previous work used the same cement, fly ash, coarse aggregate, and fine aggregate described in section 2.1.1.

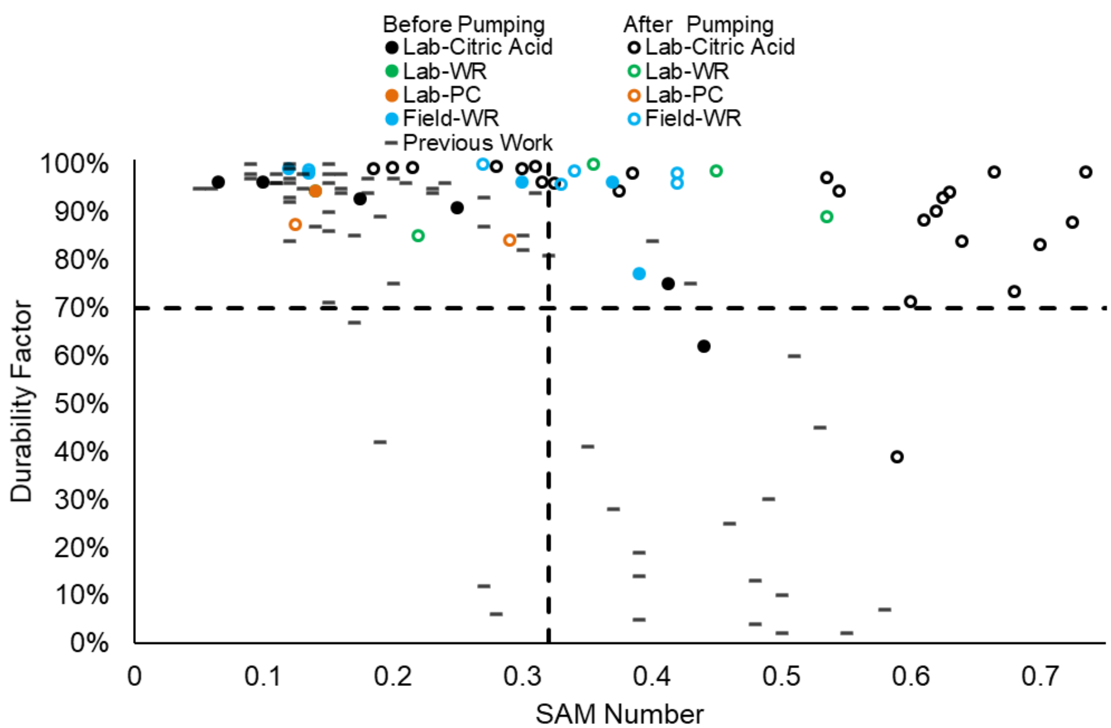

Figure 2-18 – Plot of SAM Number versus Durability Factor

Figure 2-18 shows that there is a large difference in freeze thaw performance between the SAM Number measured after pumping and the previously published data set. The previously investigated data points were not pumped and this could explain the large difference in performance. This will be discussed later in this document.

It is important to recognize that all samples that had an air content > 4% and a SAM Number < 0.32 *prior to pumping* showed satisfactory freeze thaw performance *after pumping*, regardless of the number of cycles through the pump, change in air content, or change in SAM Number due to pumping. For example, there were 33 ASTM C666 freeze-thaw samples that had a satisfactory air volume and SAM Number prior to pumping. After pumping 22 of these samples did not have a satisfactory air volume and SAM Number. Regardless, all 33 samples showed satisfactory freeze thaw performance. *This indicates the air void system measured after pumping is not representative of what is present in the hardened concrete.*

2.2.4 Hardened Air Void Analysis Results

Figure 2-19 shows a plot of the spacing factor before pumping versus the spacing factor after one pumping cycle for laboratory and field samples. Also shown on the graph is a line of equality and lines representing the accepted coefficient of variation for the hardened air void analysis. Just over 80% of the samples fall within the accepted coefficient of variation. This suggests pumping did not significantly change the spacing factor of the hardened concrete samples.

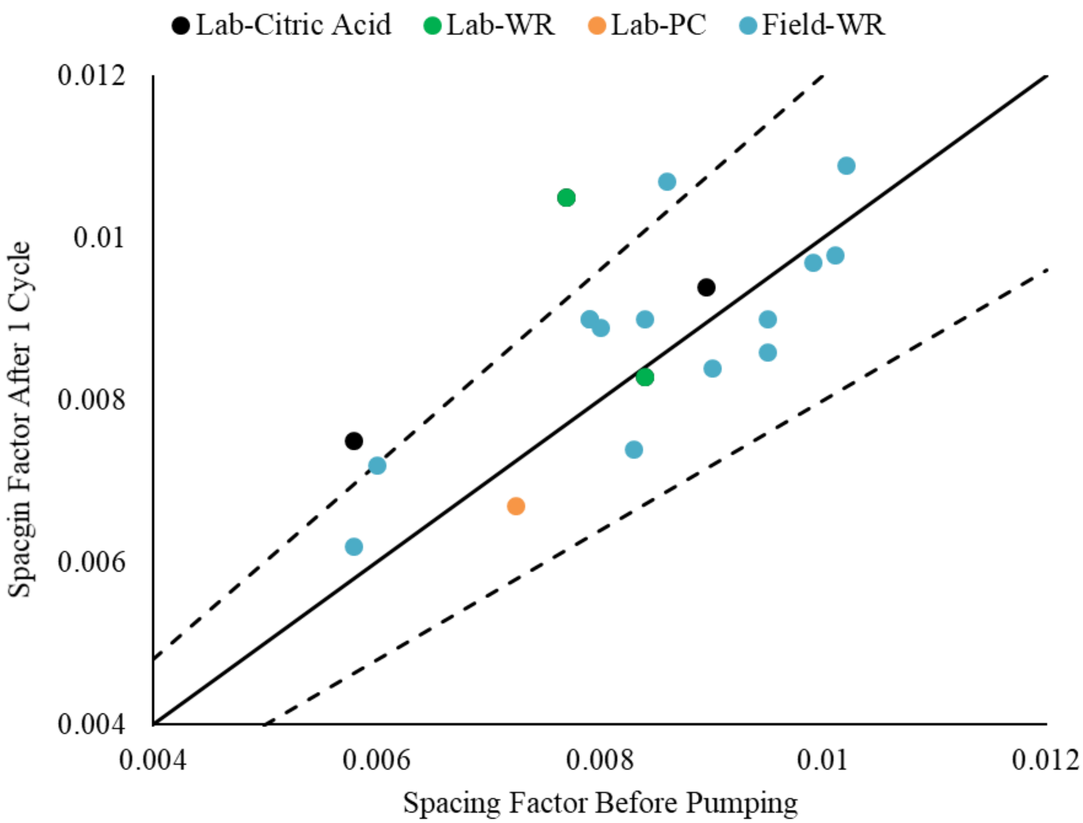

Figure 2-19 – Plot of spacing factor before pumping versus spacing factor after 1 cycle for laboratory and field samples.

Figure 2-20 shows a plot of the hardened air volume divided by the fresh air volume for samples before and after pumping. A number above 100% indicates the hardened air volume was higher than the measured fresh air volume. Included are 24 samples before pumping and 33 samples after pumping. The graph shows error bars from one standard deviation. The plot shows that on average, the hardened air volume matched the fresh air volume for samples before pumping. After pumping, the hardened air content was on average 11% higher than the fresh air content. This shows that, on average, the hardened air content is higher than the measured fresh air content after pumping. This suggests that the air dissolved during pumping returns over time. This supports previous measurements concerning the air content recovery.

It should be noted that this volume change is not large. For example, a concrete measured at 6% fresh air content after pumping would be expected to increase to 6.7% in the hardened concrete. Despite this small volume, the returning bubbles may be primarily smaller bubbles and so they may impact the air void spacing and SAM Number and not the volume.

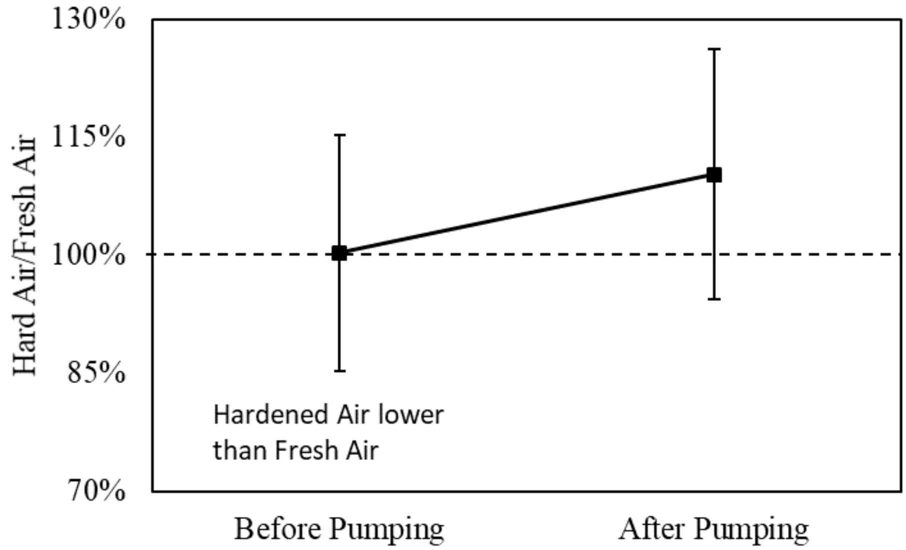

Figure 2-20 – Plot of hard air/fresh air for samples before pumping (24 samples) and after pumping (35 samples).

2.2.5 Predicting Freeze-Thaw Performance for Pumped Concrete

Pumping frequently caused the air contents and SAM Numbers to change due to pumping. Based on the 16 laboratory and 18 field mixtures investigated, 67% of the mixtures showed a change in air content greater than 0.5% and 91% of mixtures showed an increase in SAM Number greater than 50% due to pumping.

In practice, a high quality air void system is commonly identified as having an air content above 4.0% [17] and a SAM Number below 0.32 [3]. However, these limits do not seem to apply for concrete measured immediately after pumping as these measurements did not reflect the freeze-thaw durability of the hardened concrete for the laboratory and field samples investigated in this study. Furthermore, the measurements of SAM Numbers over time suggest the air is returning to the concrete, the hardened air void analysis shows an average increase in air content of 11% compared to the fresh measurements after pumping, and there is no statistical difference for 83% of the spacing factors investigated before and after pumping.

There were 22 samples that were found to have an air volume < 4% or a SAM Number > 0.32 when sampled after pumping. Based on industry standards, these samples would not be expected to be freeze-thaw durable. *However all of these samples showed satisfactory performance in freeze thaw testing.* This was observed regardless of the number of cycles through the pump, change in air content, or change in SAM number due to pumping. This freeze thaw testing combined with the hardened air void analysis and air recovery work suggests that the air returns to the concrete over time and provides a well-distributed air-void system that provides satisfactory freeze thaw durability.

This suggests the air content and SAM Number measurements after pumping may not be reliable indicators of the freeze-thaw durability for the materials and conditions investigated. This suggests the typical construction practice of investigating the air content after pumping concrete may not reflect the actual freeze-thaw performance of the concrete. This was observed in both laboratory and field testing.

2.2.6 Practical Significance

Based on the 16 laboratory and 18 field mixtures investigated in this work, it appears that the air that is lost during pumping are primarily smaller bubbles. However, these bubbles appear to return to the concrete over time as a small and well-distributed bubble system with a comparable spacing factor to the concrete prior to pumping. This means that the air volume and SAM Number measurements made after pumping are not representative of what will be within the hardened concrete and should not be used to predict freeze thaw durability of concrete.

This suggests that rejecting concrete after pumping for low air content or a high SAM Number is not a good practice. Instead, it is suggested to test the concrete before pumping for both air volume and SAM Number. When the mixtures had an air content > 4% and a SAM Number < 0.32 before pumping, all mixtures showed satisfactory freeze thaw durability regardless of any changes in the fresh air content or SAM Number due to pumping.

2.3 SUMMARY

Pumping frequently caused changes in the air void system of the fresh concrete. Regardless of the change in the air void system of the fresh concrete, the hardened air void parameters and freeze thaw performance did not show substantial change of the air void system due to pumping.

Based on the 16 laboratory and 18 field mixtures investigated the following conclusions have been made:

- For mixtures containing citric acid and WR, 67% of the mixtures showed a change in the air content of more than 0.5% and 87% showed an increase in SAM Number greater than 50% after one cycle of pumping.
- Of the three mixtures containing PC, the air content of one mixture was changed by more than 0.5% and no mixtures showed an increase in SAM Number after one cycle of pumping.
- An improvement in the SAM Number over time was seen in mixtures that initially lost air and increased SAM number after one cycle of pumping.
- If a mixture had and an air volume > 4% and SAM Number < 0.32 prior to pumping, the mixture showed satisfactory performance in ASTM C666 testing regardless of the change in the fresh air content or SAM Number from pumping. This was seen in laboratory and field testing regardless of the number of cycles through the pump, pumping pressure, or pump configuration.
- When comparing spacing factors before and after pumping, 83% of the data showed changes that were within the variation of the test method.
- The hardened air content of pumped samples on average 11% higher than the fresh air volume measured after pumping. For non-pumped samples, there was no difference between the hardened air content and fresh air content.

These findings suggest that the air volume and SAM Number measured immediately after pumping are not representative of the hardened concrete. Measurements taken after pumping should not be used to reject concrete for poor freeze-thaw durability. Instead, it is suggested to measure the air volume and SAM Number prior to pumping.

Care should be taken in extrapolating these findings as only a limited number of materials have been investigated. However, the results were consistent for both the lab and the field testing and all measurements suggest that measurement of the concrete prior to pumping was the best indicator of performance. Additional work is underway to expand these findings to a wider range of materials and pumping configurations.

CHAPTER III

INVESTIGATING THE PRESSURE DISSOLUTION MECHANISM AND AIR VOID RECOVERY AFTER PUMPING

3.0 INTRODUCTION

The proper air void system in concrete provides a microstructure that allows space for water to freeze and expand without damaging the concrete [3, 13]. There are concerns that pumping concrete can reduce the air content and therefore reduce the freeze-thaw durability of the concrete [6, 9]. In general, three mechanisms contribute to the change in air content during pumping. These are the vacuum, impact, and pressure dissolution mechanisms [6-9, 11]. An overview of these mechanisms is in Section 1.2. Although all of these likely contribute to decrease the air volume during pumping, it is suspected that the pressure dissolution mechanism decreases the air void quality of concrete mixtures during pumping [5, 6, 9, 11].

To learn about how pumping affects the air volume and air void distribution of concrete, this study investigated two testing methods. The first method investigates the location the air volume is lost during pumping and the second method investigates the air void changes in the fresh and hardened concrete with time after pumping. The work minimized all factors contributing to the vacuum and impact mechanisms, thus isolating the pressure dissolution mechanism. The work provided several useful observations.

3.1 EXPERIMENTAL METHODS

3.1.1 Materials

All concrete and grout mixtures described in this work used a Type 1 cement that meets the requirements of ASTM C150 and fly ash meeting the requirements of ASTM 618 Class C. The mixtures used a wood rosin based air entraining admixture (AEA) to stabilize air during mixing. This type of AEA has been the most common type of AEA used for air-entrained concrete. The mixtures used a citric acid, a mid-range water reducer meeting ASTM C494, or a polycarboxylate (PC) superplasticizer meeting ASTM C1017. Three mixtures contained a food grade citric by 0.25% weight of the cementitious material. Citric acid is the primary ingredient to several commercial set retarders. The citric acid ensured the concrete did not stiffen while testing. Two mixtures used a WR at a dosage of 7 oz/cwt. Two additional mixtures used a polycarboxlyate (PC) superplasticizer at a dosage of 2.5 oz/cwt. These dosages provided a 7 in. to 9 in. slump for all mixtures. The WR and PC is not expected to modify set time at these dosages.

Table 3-1 shows the oxide analysis for the cement and fly ash. All of the concrete mixtures had a water-to-cementitious material ratio (w/cm) of 0.45, 611 lbs/yd^3 of total binder with 20% Class C fly ash replacement by weight. In each mixture, the fine aggregate came from a single natural sand source and the coarse and intermediate aggregates came from a single dolomitic limestone available in Oklahoma approved for concrete production.

The mixtures used a wood rosin based air entraining admixture (AEA) to stabilize air during mixing. This type of AEA has been the most common type of AEA used for air-entrained concrete. The mixtures used a citric acid, a mid-range water reducer meeting ASTM C494, or a polycarboxylate (PC) superplasticizer meeting ASTM C1017. Three mixtures contained a food grade citric by 0.25% weight of the cementitious material. Citric acid is the primary ingredient to several commercial set retarders. The citric acid ensured the concrete did not stiffen while testing. Two mixtures used a WR at a dosage of 7 oz/cwt. Two additional mixtures used a polycarboxlyate (PC) superplasticizer at a dosage of 2.5 oz/cwt. These dosages provided a 7 in. to 9 in. slump for all mixtures. The WR and PC is not expected to modify set time at these dosages.

Table 3-1 – Type I cement oxide analysis

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	C_3S	C_2S	C_3A	C_4AF
Cement	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	-	-	56.7	17.8	8.2	7.8
Fly Ash	38.7	18.8	5.8	23.1	5.6	1.2	1.8	0.6	1.5	0.4	-	-	-	-

3.1.1.1 Mixture Design

All mixtures used a constant aggregate gradation. Figure 3-1 shows the total aggregate gradations along with the Tarantula Curve limits. Previous research shows the Tarantula Curve successfully guides the aggregate gradation to improve the pumpability of concrete [14]. The sum of the fine and coarse sand was approximately 38% and 27% respectively. The coarse sand is the sum of the material contained on the #8, #16, and #30 sieve. The fine sand is the sum of the #30, #50, #100, and #200 sieve. This falls within the recommended range for flowable concrete [15]. Table 3-2 displays a summary of the mixtures. All mixtures had the same paste properties. The paste content of each mixture was 28.9%; the air content was not included in determining the paste content.

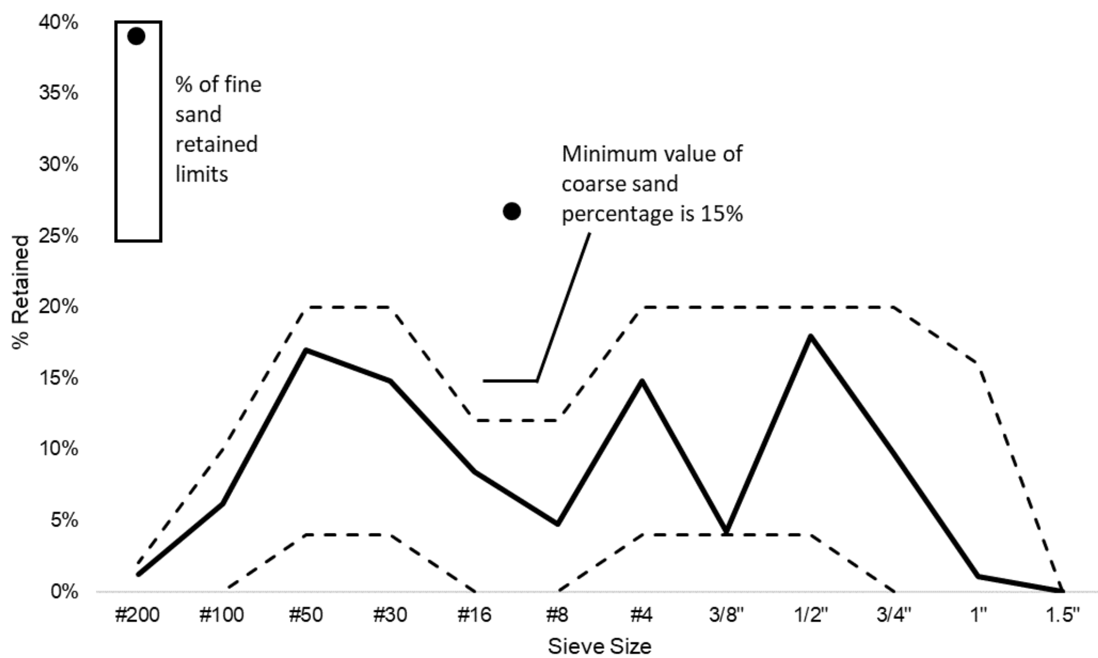

Figure 3-1 - Gradation used in the testing shown against the Tarantula Curve.

Table 3-2 – Concrete Mixture Summary

Cement (lbs/cy)	**Fly Ash (lbs/cy)**	**Water (lbs/cy)**	**Coarse (SSD lbs/cy)**	**Int. (SSD lbs/cy)**	**Fine (SSD lbs/cy)**	**Paste Content**
489	122	275	1113.2	551.7	1493.9	28.9%

3.1.2.2 Grout Mixtures

The pump and pipe network were primed with grout prior to each pumping session. Priming consists of lining the walls of the pump and pipe network with a thin lubricating layer of mortar [14]. The grout mixture used a Type 1 cement, meeting the requirements of ASTM C150, with a w/cm of 0.40, 1006 lb/ yd^3 of cement, and 2514 lb/yd^3 of sand from the same natural sand used in the concrete mixtures.

3.1.2 Equipment

3.1.2.1 Concrete Pump

The Putzmeister TK 50 concrete pump used for this research is in Figure 3-2. This pump provides an almost continuous concrete flow by two alternating pistons. One piston draws concrete from the hopper as it retracts, and the second piston pushes concrete out as it extends. An S-valve alternating delivery system shifts from one delivery cylinder to the other. This continuously delivers concrete from the pump. A remixer was included to continually agitate the concrete in the hopper. Each pumping session used the same engine revolutions per minute (RPM) and piston volume to maintain consistency between pumping sessions. The pump settings used in this work were 1500 RPM, and a piston volume set to full capacity, which was approximately 0.57 ft^3. Previous work determined these values [14]. Additional information on the Putzmeister TK 50 pump and the values used are included in Section A.2 in the Appendix.

Figure 3-2 – The Putzmeister TK 50 Concrete Pump used for all laboratory testing.

3.1.2.2 Pipe Configuration

The testing used a standard pipe network. Figure 3-3 shows an overview of the pipe network. The pipe network used 4.0 in. inside diameter (I.D.) single wall steel pipe. Rubber gaskets and couplings secured the sections of pipe together. The pipe network consists of a 3.3 ft. long single wall steel pipe reducer that reduces the 5.0 in. I.D. output of the pump to 4.0 in. After the reducer, there is 52.5 ft. of 4.0 in. I.D. steel pipe with three 1.5 ft radius 90° bends. At the end of the steel pipe network a 9.8 ft, 4.0 in. I.D. flexible rubber hose was used for easier placement. The total volume of the pipe network is approximately 6.0 ft^3. Along the pipe network, four sensors measured the pressures at the walls of the pipe during pumping. The locations of the four sensors are in Figure 3-3. Details about the pressure sensors are included in Section A.4 in the Appendix. Details about the pressure response from pumping was included in Section A.5 of the Appendix.

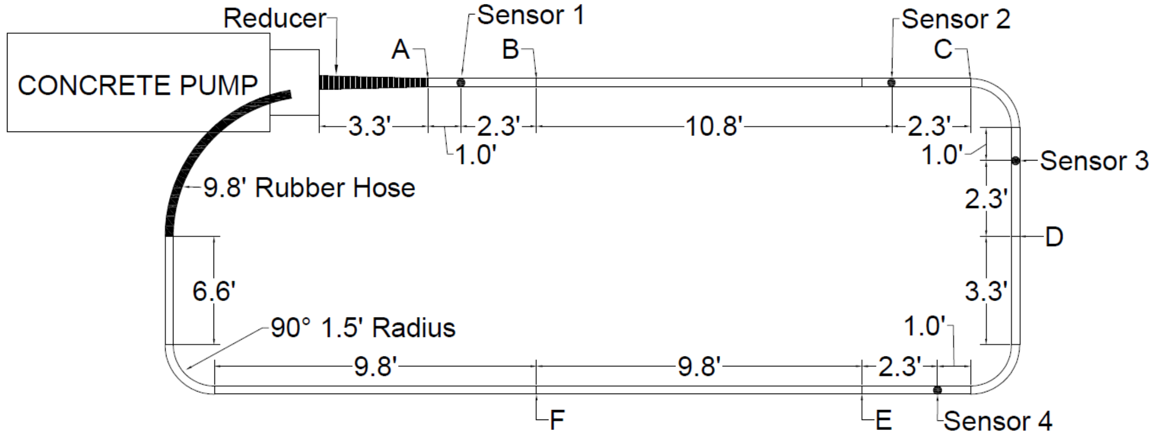

Figure 3-3 – Plan View of the pipe network and locations the pipe network was disassembled.

3.1.3 Evaluation of Air Entrained Pumped Concrete

To better understand the loss of air within the pipe network, the air content of the concrete was tested at different locations within the pipe network. An air entrained concrete mixture was prepared and then pumped to fill the concrete pipe network. The pump was then stopped and the pipe network disassembled while full of concrete. The locations the air content of the concrete inside the pipe network was measured is shown in Figure 3-3. In order to learn more about how air entrained concrete changes after pumping, a concrete mixture was first tested before pumping, and then tested over time after leaving the pipe network.

The Super Air Meter (SAM) measured the air volume and SAM Number in the fresh concrete in accordance with AASHTO TP 118. In addition, the slump (ASTM C143), and unit weight (ASTM C138) evaluated the workability and consistency of the concrete. A hardened air void analysis per ASTM C457 determined the air void parameters in the hardened concrete.

3.1.3.1 Mixing Procedure

For the laboratory mixtures, aggregates are brought from outside stockpiles into a temperature-controlled room at 72°F for at least 24 hours before mixing. The aggregates spun in a mixing drum for at least three minutes. A representative sample for moisture content testing was used to apply a moisture correction to the mixture. At the time of mixing, all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water mixed for three minutes. The resulting mixture rested for two minutes while scraping the sides of the mixing drum. After the rest period, the admixtures were added and mixing continued for three minutes. Information on charging the pump and pipe network, and how the concrete was gathered was included in Section A.3 of the Appendix.

3.1.3.2 Sampling Concrete

To investigate changes in air content during pumping, the concrete pump was turned off while the pipe network was full with flowing concrete. Unit weight and air volume was measured at joints located at 3.3ft, 6.6ft, 19.7ft, 25.4ft, 34.3ft, and 44.1ft from the outlet of the pump. The locations were shown in Figure 3-3Figure 3-3 – Plan View of the pipe network. This compared how the air content changed at different locations within the pipe network. These mixtures used AEA and WR at a dosage of 7oz/cwt. This test was repeated twice to validate the findings.

Next, concrete was pumped through the pipe network and allowed to sit without agitation. The concrete was tested approximately every 20 minutes to determine how the slump, unit weight, air volume, and SAM Number changed over time. A sample was also collected for hardened air void analysis. This testing procedure was performed three times using citric acid and twice using a polycarboxylate (PC) superplasticizer. Using citric acid or a superplasticizer affected the behavior of the concrete mixtures due to pumping.

3.2 RESULTS AND DISCUSSION

The raw data from testing is in section A.1 of the appendix in table format.

3.2.1 Change in Air Content within the Pipe Network

Figure 3-4 shows the air content measured at different points within the pipe network. The results show the air loss occurs between adding the concrete to the hopper and just after the reducer, with no further air loss after that point.

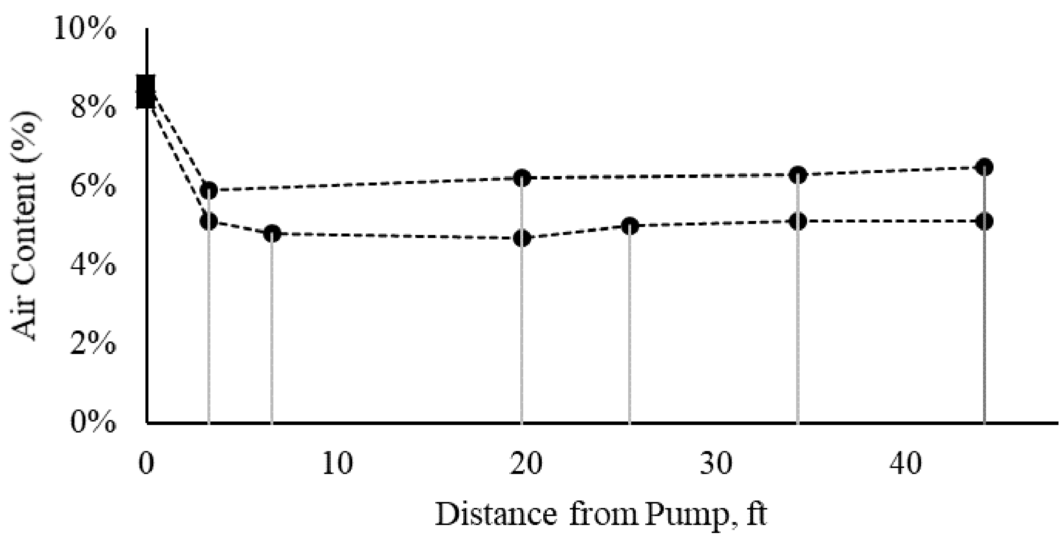

Figure 3-4 – Air content measured at different points and approximate pumping pressures along the pipe network.

In the first mixture, the air content measured prior to pumping was 8.0%. After pumping, the average air volume measured in the pipe network was 5.0%, with a standard deviation of 0.16%. In the second mixture, the air volume prior to pumping was 8.6% and after pumping the average air volume in the pipe network was 6.2%, with a standard deviation of 0.20%. The testing minimized any change in air content from a vacuum or drop height. A slight vacuum may occur as the piston draws the concrete into the piston and all drop heights were less than 3 ft. By isolating the pressure dissolution mechanism, the results support that the applied pressure from pumping causes the changes in air content for the equipment, pumping method, and the materials investigated.

The results show that all of the air loss occurred before the first point measured; which was at the end of the reducer, 3.3ft from the outlet of the pump. Testing after the reducer shows that the air content in the pipe network was almost constant, regardless of distance from the pump. This suggests the loss in air happens within the pump and reducer. Furthermore, this coincides with the point of the highest pressure.

Additional pressure cycles did not cause additional air loss. The concrete at the end of the pipe network has seen more pressure cycles than the concrete sampled right after the concrete pump. For example, the concrete sampled at 6.6 ft, 25.4 ft, and 44.1 ft away from the pump would be subjected to approximately one, four, and seven pressure cycles respectively. However, these subsequent pressure cycles did not result in additional air loss.

The air loss also occurred where we would expect the highest amount of shearing and the highest pressure in the concrete. Shearing concrete may cause air bubbles to find a surface and be removed from the concrete mixture. Research is needed to evaluate how shearing affects the air void system in concrete and the ways air bubbles can physically leave the system during pumping.

The volume of bubbles may shrink in size via Boyle's Law. Boyle's Law states that for a given amount of gas at a constant temperature, the volume occupied is inversely proportional to the pressure. Boyles Law is defined as:

$$PV = k$$

where P is the pressure, V is the volume, and k is a constant. This equation shows that for a given amount of air, as the pressure increases the volume decreases. There is an increase in pressure that could cause a decrease in volume during pumping. However, this would assume the rheology of the concrete, surface tension of the bubble shell, or other factors would hold the bubble at the smaller volume once the concrete returns to atmospheric pressure after pumping.

An increase in pressure can could also cause air to dissolve into solution via Henry's Law. Henry's Law states that the amount of a gas dissolved in a liquid is proportional to the partial pressure of the gas. Henry's law is defined as:

$$P = kC$$

where P is the partial pressure of the gas, C is the concentration of the dissolved gas in solution at equilibrium, and k is a constant [6, 9-11]. Henry's law shows at higher partial pressures, the concentration of the gas dissolved in the liquid is higher. In concrete pumping, this means that increases pressure will cause more air to dissolve into solution. The concrete encounters higher pressure closer to the pump. This can be seen in Figure A.5-3, as sensor one reported the highest pressure and pressure decreased with distance from the pump. This supports the findings, as the highest pressure seems to dissolve the most amount of air into solution.

3.2.2 Change in Air Content After Pumping

To investigate how the air void system recovered over time, mixtures were tested every 20-30 minutes after pumping one cycle through the pump and pipe network. The mixtures with citric acid and PC behaved differently despite having similar mixture designs. Three citric acid mixtures and two PC mixtures were tested. Historically, PC mixtures have coarser air void distributions; however, the PC dosage is low for the mixture investigated.

Figure 3-5 shows a plot of the average normalized air volume versus time after pumping, along with error bars showing one standard deviation. The slump, unit weight, air, and SAM measurements recorded were given in Table A.1-2 in Section A.1 of the Appendix. In the plot, the zero minute data corresponds to the measurement before pumping. A non-pumped citric acid and non-pumped PC mixture were tested over time for comparison. The non-pumped citric acid and PC mixtures behaved very similar to one another. Due to different sampling times for the pumped citric acid mixtures, linear interpolation was performed to determine the air content. This did not affect the results because the air content after pumping did not change significantly for the citric acid mixtures.

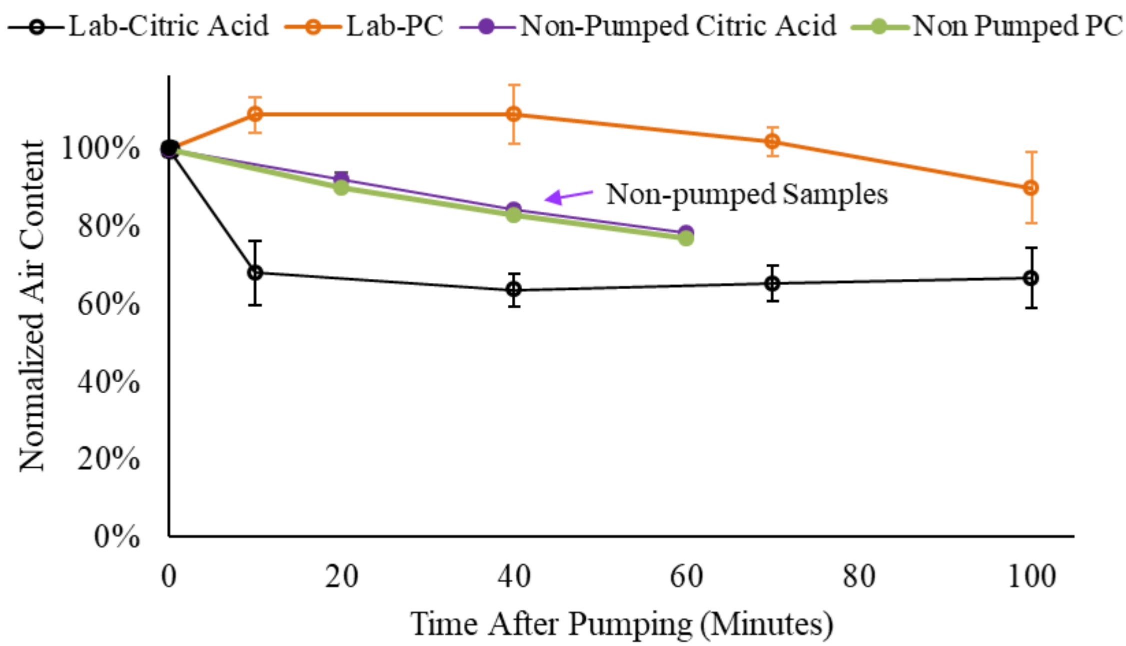

Figure 3-5 – Air volume (%) versus time after pumping

For the citric acid mixtures, the greatest change in air content occurred immediately after pumping once through the pipe network. As the pumped concrete rested undisturbed over time, the measured air content did not change. The mixtures containing PC showed an initial increase in air content due to pumping, and a slight decrease in air content over time. In comparison, the non-pumped citric acid and PC samples lost air at a constant rate, and at 60 minutes lost approximately 22% of their initial air content. It is common for concrete mixtures to lose air volume as the concrete sits over time [18]. Buoyancy effects suggest it is most likely the larger bubbles leaving the air void system. However, it is unclear how much air the non-pumped samples would lose over time.

For the pumped citric acid samples, approximately 32% of their initial air content was lost initially due to pumping, with a standard deviation of 8%. The PC samples initially gained 9% of their initial air content due to pumping, with a standard deviation of 4.5%. As the concrete sat over time, there was not a significant change in the air content for the pumped citric acid and PC samples. More work is needed to understand why the rate of air loss changes after pumping. However, the behavior seems to be consistent as it occurred for several mixtures.

3.2.3 Recovery of the Air Void System After Pumping

Figure 3-6 shows a plot of the SAM Number versus time after pumping for citric acid and PC mixtures. In the plot, the data at zero minutes corresponds to the measurement taken before pumping. The data at 10 minutes corresponds to one cycle through the pipe network. The SAM number indicates the quality of the air void distribution in the fresh concrete [3]. As the SAM Number increases, the air void quality decreases and vice versa. The samples containing citric acid behaved differently than the samples containing PC.

For all citric acid samples, the SAM Number at least doubled after one cycle through the pipe network. This matches previous findings and indicates pumping causes an initial coarsening of the air void system. As the concrete sat undisturbed, the SAM Number decreased for all citric acid pumped samples. This suggests the air void system seems to change over time by showing an improvement in the SAM Number. The decrease in SAM number indicates that the air void quality is improving. This is typically caused by the formation of fine air voids. This suggests that the air void system measured after pumping is not representative of what is present in the hardened concrete.

For the mixes containing a PC, the SAM number slightly decreased initially due to pumping. Over time, the SAM number increased to approximately the same SAM number measured before pumping. The small changes in SAM number indicate, for the PC mix investigated, pumping did not have a significant impact on the fresh air void parameters of the concrete.

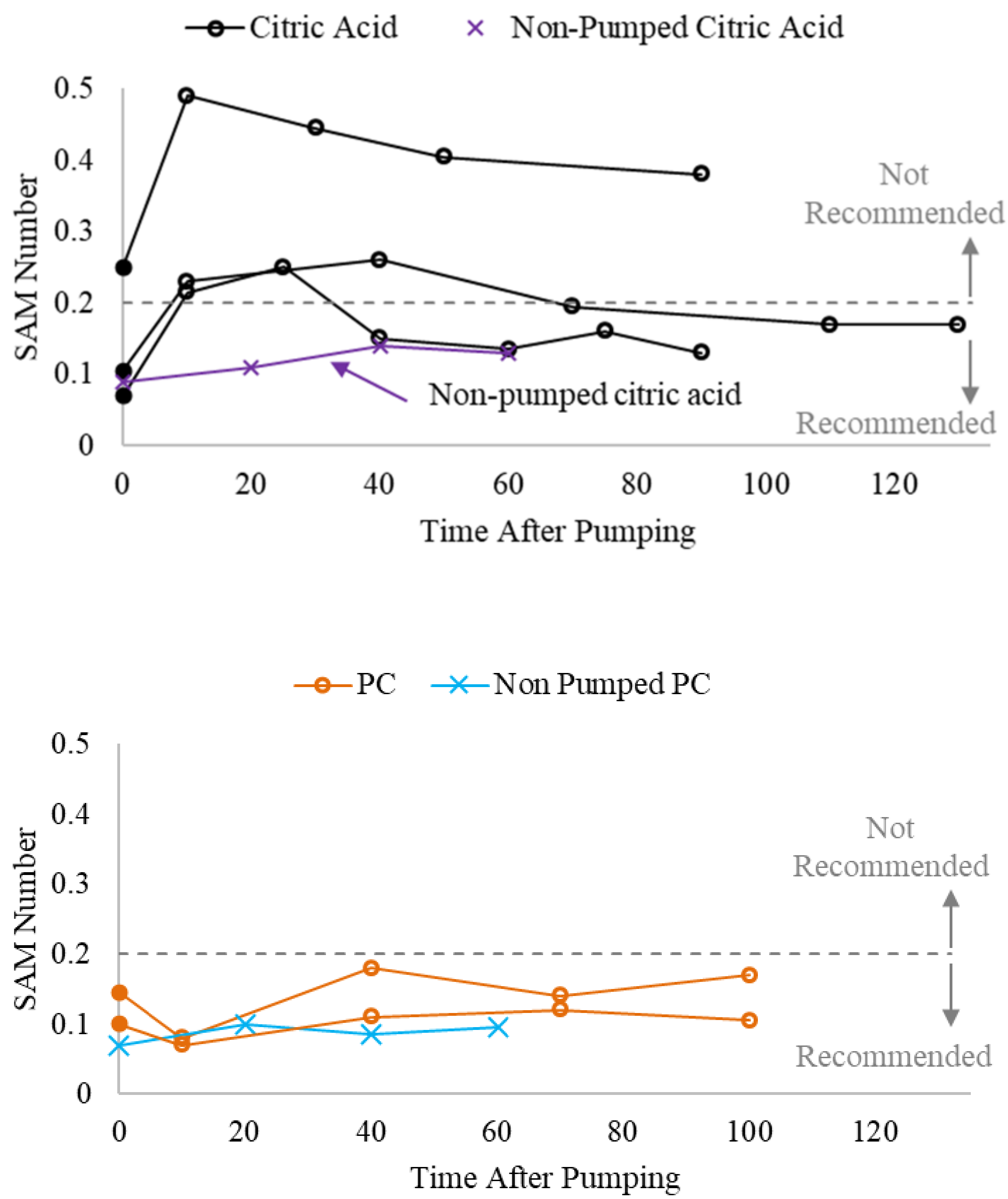

Figure 3-6 – SAM Number versus time after pumping

For the citric acid mixtures, the initial increase in the SAM number after 1 cycle through the pump and pipe network could be the result of the smaller bubbles dissolving into solution. The internal pressure of individual air bubbles in concrete varies according the Laplace-Young equation:

$$P_1 = P_0 + 2t/R$$

where P_1 is the internal pressure of the air in a bubble, P_0 is the pressure of fluid surrounding the air bubble, t is the surface tension of the bubble film, and R is the bubble radius [6, 9-12]. The equation shows that smaller bubbles are at higher internal pressures than larger bubbles. The higher internal pressure makes the smaller bubbles likely to dissolve before larger bubbles. If the increase in pressure causes the smaller bubbles to dissolve, this would reduce the quality of the air void system and cause the SAM Number to increase.

Over time, the SAM number decreased for all citric acid samples after pumping. This indicates the quality of the air void system is improving as the air void system is becoming finer. This could be the result of the dissolved air coming back out of solution after pumping; however, a significant change in the air content was not observed. This could be the result of the small bubbles returning to the mix. The volume of the fine bubbles is very small and do not greatly impact the total air volume of the mixture.

3.2.4 Hardened Air Void Analysis Results

The literature commonly states that the dissolved air, upon leaving solution, would likely add to existing bubbles rather than create new bubbles [6, 9, 11]. However, this shift would likely affect the spacing factor of the air void system, thus reducing the freeze-thaw durability of the concrete. Testing was performed in Chapter 2 on similar concrete mixtures that investigated how pumping changes air void parameters critical to freeze-thaw durability. The testing in chapter 2, a hardened air void analysis was performed per ASTM C457 on concrete taken before pumping and after pumping one cycle through the pump and pipe network. Figure 3-7 plots the spacing factor measured before pumping versus the spacing factor measured after pumping. Also shown on the graph is the published coefficient of variation per ASTM C457. The graph shows there was not a significant difference in the spacing factor measured before pumping versus the spacing factor measured after pumping, as 83% of mixtures fall within the published coefficient of variation. These results support that the air coming out of solution likely forms a fine air void distribution that is desirable for freeze-thaw durability. The air that returns to the concrete appears to be small and well distributed. This supports the SAM vs. time after pumping measurements show in Figure 3-6, as both graphs indicate the final air void system is consistent with what is measured before pumping.

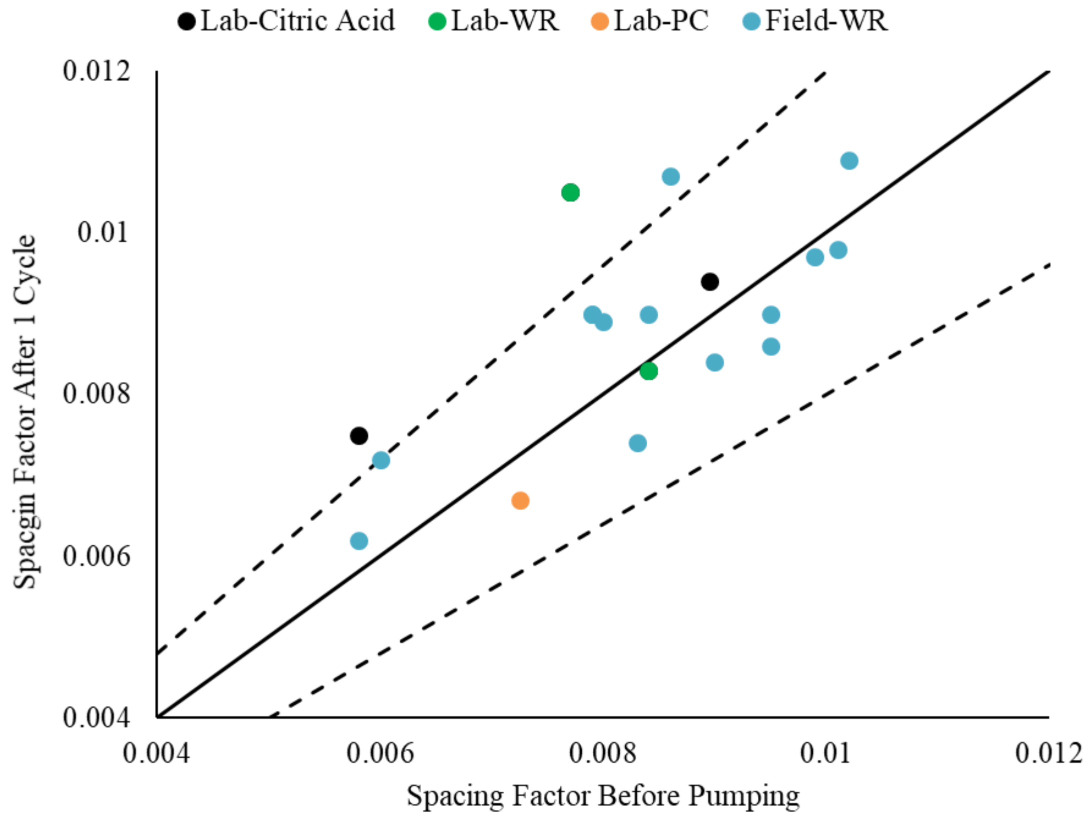

Figure 3-7 – Plot of spacing factor before pumping vs spacing factor after pumping

3.2.5 Factors Affecting Air Coming out of Solution

Many factors affect bubble formation of a dissolved gas. The literature commonly states that the dissolved air, upon leaving solution, would likely add to existing bubbles rather than create new bubbles [6, 9, 11]. However, the SAM decreasing over time in Figure 3-6, and the spacing factor results in Figure 3-7 suggest more is happening. Factors affecting bubble formation include: the partial pressure on the gas and liquid, the concentration of the gas in the liquid, temperature of the liquid, nature of the gas, ease of interchange between the bubble wall, localized saturation around the bubble, and the diffusivity of the gas in the liquid [6, 10, 11]. Likely the viscosity/stiffness of the concrete will also play a role. Bubble formation in the fresh concrete will respond to any change in equilibrium. Therefore, any of these variables, and likely variables that are not listed, will affect the rate of bubble formation in concrete. In addition, many of these factors may change with time as the pumped concrete hardens. More research is necessary to isolate the important mechanisms and factors governing bubble formation in pumped concrete.

The basics of Henry's Law and the Laplace-Young Equation, although fundamental in understanding the basic behavior, may not hold completely true for concrete. Air entrained bubbles in concrete are held together by a membrane composed of a hydrophyllic on one side and a hydrophobic on the other. The membrane forms a shell that acts as a vapor barrier that holds bubbles together and prevents bubbles from coalescing. An applicable theory of air dissolving and reforming in concrete must account for this membrane. Additionally, it is likely the properties of the membrane will change as concrete mixtures vary, causing the behavior of the air void system to vary.

3.3 SUMMARY

All testing used a similar mixture design with a small range of admixtures. One should be careful drawing strong conclusions from this work as the materials investigated were limited. However, this work created several useful observations. For the given pump and pipe configuration, the following conclusions were made:

- An average of 35% of the initial fresh air content was lost along the entire length of the pipe network with a standard deviation 6%. This indicates air was lost within the first 3.3ft of pumping, with no additional air loss measured after than point.

- The point of air loss coincides with the point where the highest pressure is expected.
- After discharge from the pump, a significant change in fresh air content was not observed over time.
- After pumping, the SAM Number regained stability, approaching the value measured before pumping over time, indicating the quality of the air void system is returning to the concrete.

These results indicate the pressure dissolution mechanism likely played a role in reducing the air content of the fresh concrete. This study also shows the super air meter may not be a useful tool in determining the air void quality of concrete immediately after pumping. The initial increase in SAM Number after pumping suggests a likely coarsening of the air void system due to pumping. Over time, the SAM number decreasing indicates the air dissolved during pumping is returning, and is developing a fine air void distribution that is desirable for freeze-thaw durability. These findings reinforce the recommendations of ASTM C94 to test air before the concrete pump.

CHAPTER IV

CONCLUSION

4.0 SUMMARY

The main goal of this research was to further advance the knowledge of pumping air entrained concrete. This thesis was composed of two main studies to investigate the effects pumping has on the fresh and hardened air void system of concrete. The first study investigated the direct impact pumping has on the fresh and hardened air void parameters directly related to freeze-thaw performance. The second study investigated the mechanisms affecting the fresh air content and how the air void distribution changes with time after pumping. All testing used a similar mixture design with varying air contents and pump configurations. One should be careful drawing strong conclusions from this work as the materials investigated were limited. However, this work created several useful observations.

The following conclusions were drawn from chapter two.

- For mixtures containing citric acid and WR, 67% of the mixtures showed a change in the air content of more than 0.5% and 87% showed an increase in SAM Number greater than 50% after one cycle of pumping.

- Of the three mixtures containing PC, the air content of one mixture was changed by more than 0.5% and no mixtures showed an increase in SAM Number after one cycle of pumping.

- An improvement in the SAM Number over time was seen in mixtures that initially lost air and increased SAM number after one cycle of pumping.

- If a mixture had and an air volume > 4% and SAM Number < 0.32 prior to pumping, the mixture showed satisfactory performance in ASTM C666 testing regardless of the change in the fresh air content or SAM Number from pumping. This was seen in laboratory and field testing regardless of the number of cycles through the pump, pumping pressure, or pump configuration.

- When comparing spacing factors before and after pumping, 83% of the data showed changes that were within the variation of the test method.

- The hardened air content of pumped samples on average 11% higher than the fresh air volume measured after pumping. For non-pumped samples, there was no difference between the hardened air content and fresh air content.

The following conclusions were drawn from chapter three.

- An average of 35% of the initial fresh air content was lost along the entire length of the pipe network with a standard deviation 6%. This indicates air was lost within the first 3.3ft of pumping, with no additional air loss measured after than point.

- The point of air loss coincides with the point where the highest pressure is expected.

- After discharge from the pump, a significant change in fresh air content was not observed over time.
- After pumping, the SAM Number regained stability, approaching the value measured before pumping over time, indicating the quality of the air void system is returning to the concrete.

The conclusions from these chapters suggest pumping may cause an initial coarsening of the air void system in the fresh concrete. However, the results indicate a portion of the air void system returns to the concrete. The hardened concrete did not show a significant trend of coarsening. This indicates that the changes to the air void system during pumping are not present in the hardened concrete.

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APPENDICES

A.1 CONCRETE TESTING RESULTS

The raw data from the mixtures are presented below.

The tables shows the type of water reducer used in each mixture. The prefix “L” indicates laboratory mixtures and the prefix “F” indicates field mixtures. The orientation of the boom is noted for each field mixture.

Table A.1-1 – Testing results for laboratory and field samples measured before and after pumping.

Test ID	Number of Cycles	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457			ASTM C666			Peak Pressure (psi)
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})	Durability Factor	Length Change	Mass Change (%)	
L-1 Citric Acid	Before	9.5	4.0%	0.26	4.1%							
	1	9.25	3.2%	0.63	3.6%	4.3%	0.0099	539.2	93.0%	0.00%	-0.84%	58
	40	9	2.1%	0.74	2.0%				98.3%	-0.03%	0.16%	65
	80	8.25	1.7%	0.73	1.6%	2.8%	0.0094	689.3	87.7%	0.02%	0.01%	80.5
	120	7.25	1.8%	0.60	1.8%							91

Test ID	Number of Cycles	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457			ASTM C666			Peak Pressure (psi)
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})	Durability Factor	Length Change	Mass Change (%)	
L-2 Citric Acid	Before	9	5.6%	0.20	5.5%							
	1	8.5	3.7%	0.62	2.8%				90.1%	0.06%	-0.88%	
	40	9	2.4%	0.63	1.5%	4.2%	0.0082	651.6	94.1%	0.02%	0.89%	66.75
	80	7.25	2.4%	0.70	1.3%	2.9%	0.0122	521.9	83.0%	0.07%	-1.18%	72.75
	120	4.25	2.5%	0.63	1.1%							90
L-3 Citric Acid	Before	9.5	7.4%	0.11	8.1%							
	1	8.25	5.5%	0.33	4.5%				95.9%	-0.03%	-0.16%	
	40	7.25	5.7%	0.32	5.2%	6.0%	0.0084	541.5	96.2%	0.00%	-0.06%	66.8
	80	3.5	4.5%	0.39	4.4%	4.5%	0.0093	553.5	98.0%	0.01%	-0.02%	85.6
L-4 Citric Acid	Before	9.75	5.4%	0.25	5.8%							
	1	9	4.1%	0.38	4.4%				94.3%	0.00%	-0.23%	41
	40	6.5	3.0%	0.55	2.5%				94.4%	0.00%	-0.19%	53.8
	80	2.75	3.3%	0.54	2.7%				97.1%	0.01%	-0.22%	62.7
	120	0.5	3.2%	0.67	96.3%	3.3%	0.0099	600.4	98.4%	0.00%	-0.06%	90.9
L-5 Citric Acid	Before	8	8.4%	0.07	8.8%	8.5%	0.0055	615.6				
	1	7.75	6.5%	0.22	6.9%				99.1%	0.02%	-0.63%	71
	40	6.5	5.5%	0.20	5.6%	6.2%	0.0088	510.6	99.2%	0.02%	-0.40%	82.4
	80	2.75	4.7%	0.30	4.2%	4.3%	0.0079	669.3	98.9%	0.02%	-0.48%	113.9
L-6 Citric Acid	Before	7	4.0%	0.42	4.2%							
	1	5.5	3.0%	0.68	2.7%				73.2%	0.07%	-1.94%	76.5
	40	4	2.6%	0.64	2.3%	4.7%	0.0091	557.1	83.8%	0.14%	-1.62%	82.6
	80	1.75	2.8%	0.61	2.7%	3.4%	0.0121	490.5	88.2%	0.04%	-1.25%	101
L-7 Citric Acid	Before	9	8.4%	0.06	8.8%							
	1	8	6.5%	0.19	6.1%	8.8%	0.0074	444.2	99.0%	0.01%	-0.08%	64.8
	40	6	5.7%	0.28	5.1%	7.1%	0.0083	487.2	99.5%	0.00%	-0.01%	68.6
	80	2.75	5.2%	0.31	4.9%	5.1%	0.0099	497.1	99.5%	0.01%	0.05%	82

Test ID	Number of Cycles	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457			ASTM C666			Peak Pressure (psi)
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})	Durability Factor	Length Change	Mass Change (%)	
L-8 Citric Acid	Before	7	3.7%	0.41	3.9%							
	1	5	3.0%	0.60	2.1%				71.2%	0.12%	0.14%	97.6
	40	3	2.8%	0.59	2.1%				38.8%	0.13%	0.32%	108
L-9 Citric Acid	Before	8.25	9.1%	0.07	9.5%	8.1%	0.0058	622.3				
	1	8.25	6.9%	0.215	6.6%	7.1%	0.0075	538				
L-10 Citric Acid	Before	7.75	8.0%	0.105	8.0%	7.5%	0.00685	575.9				
	1	6.5	5.6%	0.23	5.0%							
L-11 Citric Acid	Before	8	5.8%	0.25	4.8%	7.4%	0.007	507.3				
	1	7	3.4%	0.49	2.5%							
L-12 WR	Before	8	6.9%	0.23	6.8%	6.7%	0.0077	560.8				
	1	3.5	4.5%	0.45	4.6%	4.6%	0.0105	491.3	98.5%	0.02%	-0.79%	98.4
	40	2.25	4.3%	0.355	3.8%				100.0%	0.01%	-0.43%	128.9
L-13 WR	Before	8.5	6.8%	0.14	6.5%	6.2%	0.0084	536.2	94.3%	0.04%	-0.80%	
	1	6	5.1%	0.22	4.5%	4.1%	0.0083	648.4	85.0%	0.06%	-0.88%	75.9
	40	3.25	4.3%	0.535	4.0%				88.9%	0.03%	-0.47%	101.6
L-14 PC	Before	9	6.5%	0.155	6.1%				92.6%	-0.15%	-0.70%	
	1	8	6.3%	0.125	5.6%	6.5%	0.0092	476	87.3%	-0.09%	-1.11%	62.5
	40	6	5.8%	0.29	4.2%				84.0%	-0.02%	-1.25%	89.3
L-15 PC	Before	9.5	6.7%	0.145	6.2%	6.5%	0.00725	605.3				
	1	7.25	7.5%	0.08	6.9%	7.7%	0.0067	561.1				
L-16 PC	Before	9	7.1%	0.1	7.0%	5.8%	0.0067	686.5				
	1	7	7.5%	0.07	6.6%							
Additional Non-Pumped Citric Acid	Before	8	0.0595	0.1	5.5%	6.1%	0.0079	568.1	96.1%	0.30%	-0.42%	
	Before	9.25	0.0815	0.065	8.0%				96.1%	0.22%	-0.15%	
	Before	7	0.0515	0.175	3.8%	6.4%	0.0082	548.4	92.6%	0.50%	-0.62%	
	Before	6.75	0.035	0.44	2.2%				62.0%	0.27%	-1.11%	
	Before	7.5	0.0415	0.25	3.0%	4.5%	0.0094	552.1	90.8%	-0.13%	-0.65%	

Test ID	Number of Cycles	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457			ASTM C666			Peak Pressure (psi)
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})	Durability Factor	Length Change	Mass Change (%)	
F-17 WR Flat	Before	7.5	0.065	0.12	7.3%	6.2%	0.0058	777.7	99.1%	0.02%	0.23%	
	1	6.5	0.073	0.135	8.7%	9.7%	0.0062	476.4	98.9%	0.03%	0.09%	
F-17 WR Arch	Before	6	0.055	0.125	6.1%	6.0%	0.006	755.8				
	1	6.5	0.06025	0.27	7.7%	6.1%	0.0072	627.8	100.0%	0.01%	0.16%	
F-17 WR A-Frame	Before	6	0.046	0.15	4.3%	3.8%	0.0083	680.1				
	1	6	0.0495	0.34	5.4%	4.7%	0.0074	687.3	98.6%	0.02%	0.26%	
F-18 WR Flat	Before	7.5	0.0535	0.135	5.9%	4.9%	0.0099	503.9	98.0%	0.21%	0.02%	
	1	8.5	0.04925	0.42	5.2%	6.6%	0.0097	446.7	98.0%	0.11%	0.03%	
F-18 WR Arch	Before	6	0.0455	0.17	4.3%	3.6%	0.009	641.1				
	1	8	0.047	0.33	4.2%	5.9%	0.0084	543.2	95.7%	0.07%	0.03%	
F-18 WR A-Frame	Before	5.5	0.0415	0.175	4.4%	4.1%	0.0084	642.9				
	1	6.5	0.04925	0.42	5.2%	5.2%	0.009	536.6	96.0%	0.15%	0.03%	
F-19 WR Flat	Before	6	0.0395	0.29	4.1%	3.7%	0.0101	577.8				
	1	8	0.040667	0.416667	4.8%	4.8%	0.0098	510.8				
F-19 WR Arch	Before	4	0.038	0.33	3.5%							
	1	6	0.0305	0.7	2.6%	3.8%	0.0104	528				
F-19 WR A-Frame	Before	4	0.032	0.34	3.4%	4.2%	0.0102	514.9				
	1	5	0.03	0.765	2.8%	4.5%	0.0109	467.5				
F-20 WR Flat	Before	7.5	0.0385	0.37	4.6%	4.7%	0.0079	641.5	96.1%	-0.78%	-1.29%	
	1	8	0.0455		5.1%	4.5%	0.009	573	98.1%	-0.13%	0.06%	195.95
F-20 WR Arch	Before	7.25	0.044	0.34	5.5%	4.7%	0.0095	528				
	1	7.25	0.0445		5.2%	4.8%	0.0086	583	96.0%	-0.21%	0.02%	152.95
F-20 WR A-Frame	Before	7.75	0.05	0.235	6.1%	4.5%	0.0079	651.7				
	1	7	0.036		3.3%	3.8%	0.009	613.6	92.3%	-0.36%	0.04%	152.95
F-21 WR Flat	Before	5.25	0.029	0.39	2.2%	5.2%	0.008	606	77.0%	-0.51%	0.06%	
	1	7.25	0.0335		3.4%	4.8%	0.0089	565.7	88.6%	-1.64%	0.04%	184.2857
F-21 WR Arch	Before	3.75	0.026	0.43	1.7%	5.0%	0.0095	519.2				
	1	4.75	0.03		2.6%	4.6%	0.009	568.4	77.0%	-0.28%	0.07%	200.9444

Test ID	Number of Cycles	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457			ASTM C666			Peak Pressure (psi)
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})	Durability Factor	Length Change	Mass Change (%)	
F-21 WR A-Frame	Before	5.25	0.037	0.24	2.1%							
	1	5.25	0.0315		1.7%	3.8%	0.0109	512	72.1%	-0.04%	0.00%	191.55
F-22 WR Flat	Before	8	0.0495	0.3	5.1%	5.4%	0.0086	554.9	96.1%	-0.02%	-0.07%	
	1	8.25	0.0525		6.3%	5.6%	0.0107	438.2	100.0%	0.02%	-0.09%	191.65
F-22 WR Arch	Before	7.25	0.0405	0.42	3.7%							
	1	8	0.047		5.0%				96.1%	-0.06%	0.03%	175.6364
F-22 WR A-Frame	Before	3.25	0.0255	0.4	3.6%	0.0%						
	1	3.5	0.026		2.2%	4.4%	0.0086	610.1	96.1%	-0.42%	-0.02%	185.7222

Table A.1-2 – Testing results for the recovery of the air void system after pumping.

Mixture	Time After Pumping	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457		
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})
L-17 Citric Acid	Before	8.25	9.1%	0.07	9.5%	8.1%	0.0058	622.3
	10	8.25	6.9%	0.215	6.6%	7.1%	0.0075	538
	25	6.75	6.4%	0.25	6.0%			
	40	6.75	6.3%	0.15	5.6%			
	60	7.5	6.9%	0.135	7.4%			
	75	6	5.9%	0.16	5.2%			
	90	6	6.7%	0.13	6.9%			
L-18 Citric Acid	Before	7.75	8.0%	0.105	8.0%	6.7%	0.0076	574.2
	10	6.5	5.6%	0.23	5.0%			
	40	3.75	4.9%	0.26	4.8%	4.1%	0.0115	467.3
	70	6	5.5%	0.195	4.8%	3.9%	0.0115	477.9
	110	3.5	5.6%	0.17	4.9%			
	130	3.5	5.3%	0.17	4.4%			
L-19 Citric Acid	Before	8	5.8%	0.25	4.8%			
	10	7	3.4%	0.49	2.5%			
	30	6	3.6%	0.445	2.5%			
	50	4.5	3.5%	0.405	1.5%			
	90	3	3.4%	0.38	2.3%			
L-20 PC	Before	9.5	6.7%	0.145	6.2%	6.5%	0.00725	605.3
	10	7.25	7.5%	0.08	6.9%	7.7%	0.0067	561.1
	40	6.25	7.7%	0.18	6.8%	7.4%	0.0069	565
	70	3.5	7.0%	0.14	6.0%			
	100	1.5	5.6%	0.17	4.2%			
L-21 PC	Before	9	7.1%	0.1	7.0%	5.8%	0.0067	686.5
	10	7	7.5%	0.07	6.6%			
	40	5.5	7.4%	0.11	6.2%			
	70	4.25	7.1%	0.12	6.0%	5.8%	0.0068	672.4
	100	2.5	6.9%	0.105	5.9%	5.5%	0.0074	640.1

Table A.1-3 – Testing results for changes in non-pumped concrete mixtures over time.

Mixture	Time After Mixing	Slump (in)	Air from Super Air Meter (%)	SAM Number	ASTM C138	ASTM C457		
					Gravimetric Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in^{-1})
L-22 Citric Acid	0	7.25	10%	0.09	10.1%	5.9%	0.0076	601.1
	20	7	9%	0.11	8.6%	9.4%	0.0053	575.9
	40	6.5	8%	0.14	7.7%			
	60	6.25	8%	0.13	7.0%	7.8%	0.0054	690.8
L-23 WR	0	7.75	8%	0.1	7.6%	7.9%	0.0072	509.2
	20	5.75	7%	0.1	5.9%	7.8%	0.0061	609.4
	40	5.5	6%	0.11	5.7%	6.9%	0.0067	619.4
	60	4.25	6%	0.13	5.3%	7.3%	0.0066	595.3
L-24 PC	0	8.25	9%	0.07	7.9%			
	20	7.75	8%	0.1	7.0%			
	40	7.5	8%	0.085	6.5%			
	60	5.5	7%	0.095	5.7%			

Table A.1-4 – Testing results for change of air content in the pipe network.

		L-25 WR		L-26 WR	
		Air from Super Air Meter (%)	ASTM C138	Air from Super Air Meter (%)	ASTM C138
Point	Distance from Pump (ft)		Gravimetric Air (%)		Gravimetric Air (%)
Before Pumping		8.2%	8.0%	8.6%	8.9%
a	3.3	5.1%	4.2%	5.9%	5.5%
b	6.6	4.8%	3.8%	--	
c	19.7	4.7%	3.6%	6.2%	6.2%
d	25.4	5.0%	4.4%	--	
e	34.3	5.1%	4.0%	6.3%	6.0%
f	44.1	5.1%	4.8%	6.5%	6.7%
Average Air After Pumping		5.0%	4.1%	6.2%	6.1%
σ		0.2%	0.4%	0.2%	0.4%

A.2 ADDITIONAL INFORMATION ON THE TK50 CONCRETE PUMP

The Putzmiester TK50 concrete pump uses a 96 HP diesel engine to drive a main hydraulic pump and a secondary double-stage hydraulic pump. The main hydraulic pump is a variable displacement, load sensing hydraulic pump that powers two hydraulic cylinders that drive the delivery pistons. The first stage of the secondary hydraulic pump, in conjunction with an accumulator, shifts the delivery system from one delivery cylinder to the other. The second stage of the secondary hydraulic pump rotates the agitator. The pump has an approximate 7 cu ft. hopper.

The TK50 Pump has a throttle control and a piston volume control. The rpm of the engine can range from 900 to 2200 rpm. Testing by Seader, MS determined the maximum piston volume as 0.57 cu ft. The volume of the piston was measured by filling the pump's hopper with water and pumping a single piston stroke into a bucket that was then weighed. The volume of the piston was calculated by dividing the weight of the water in the bucket by the unit weight of water. This was done 30 times and the average was taken. The coefficient of variation was 6%. To maintain consistency between pumping session, 1500 rpm and the maximum piston volume were used. Preliminary testing by Seader, MS, determined 1500 rpm gave enough power and time between piston strokes to accurately measure the pressure in the line [14].

A.3 CHARGING THE PUMP AND PIPE NETWORK AND SAMPLE COLLECTION

One 4.0 ft^3 grout mixture followed by three 6.0 ft^3 concrete mixtures were prepared using the mixing procedure outlined in section 2.1.1.4. Prior to pumping the first concrete mixture, slump, unit weight, air, SAM, and hardened air void data were collected. The same tests were performed on the second concrete mixture. Unit weight and slump data on the third concrete mixture helped ensure consistency between concrete mixtures. To charge the pump, the grout mixture was added first and pumped approximately three strokes to lower the amount of grout in the hopper and fill the line. Next, the concrete mixtures were added and pumped through the line. The grout material was pumped into a waste container until concrete was seen exiting the line.

After discarding all of the grout from the line, the rubber discharge hose was moved to recirculate into the pump's hopper. This recirculated the material. After 10 piston strokes, $\approx 1ft^3$ of material was removed from the discharge line to collect slump, unit weight, air, SAM, hardened air void data, and ASTM C666 samples. The data collected at this time determined the impact pumping concrete once through a full pipe network has on the air void quantity and distribution. This data is labeled as "1 cycle" because it has only been through the pump and pipe network once. After gathering the material for testing, the pump was turned on and ran for 15 minutes.

After each 15-minute interval, the pump was stopped for ≈1 minute while $\approx 1ft^3$ of concrete was gathered for testing. Slump, unit weight, air, SAM, hardened air void sample, and C666 beams were completed. During the 15 minutes of pumping, the concrete was circulated approximately 40 times through the pipe network. This is the same as traveling through approximately 2400’ of 4” I.D. line and passing through the reducer 40 times. Line pressures were recorded during the entire testing procedure. The pumping session was terminated when the slump was less than 3.0”. This was chosen because concrete with low workability can lead to blockages in the line.

A.4 PRESSURE SENSOR CALIBRATION RESULTS

Table A.4-1 – Table of pressure sensor calibration values.

		Slope	y-int.	r^2
Sensor 1	1/23/2017	0.113	-29.2	0.9988
Sensor 2	1/11/2017	0.113	-31.5	0.9995
	1/12/2017	0.110	-25.9	0.9996
	1/13/2017	0.109	-23.7	0.9999
Sensor 3	1/10/2017	0.113	-33.6	0.9996
	1/11/2017	0.112	-29.7	0.9992
	1/12/2017	0.112	-28.0	0.9996
Sensor 4	1/10/2017	0.112	-28.0	0.9991
	1/11/2017	0.110	-23.1	0.9997
	1/12/2017	0.109	-19.9	0.9997

Table A.4-1 shows the available values from sensor calibration. Details about sensor calibration are included in section 2.1.2.2. Calibration data from previous sensor calibrations are not available. However, all slope values used before the dates shown are very comparable to the values presented in the table. Comparing the maximum and minimum slope calculations in the table of 0.113 and 0.109, at a reference voltage of 1000mV, the calculated pressure would be 113psi and 109psi respectively. Most of the error in measurement would come from selecting the proper zero psi voltage.

A.5 PRESSURE SENSOR OUTPUT AND EVALUATION OF THE PRESSURE CURVE

Figure A.5-1 shows a typical pressure curve, including values from the four sensors. The figure shows two piston strokes. Each piston stroke consists of two portions: the pressure initiating the movement of the concrete, and the pressure required to keep the concrete moving. The maximum pressure in each stroke occurs during the first portion of the curve. This is when piston initiates the movement of the concrete.

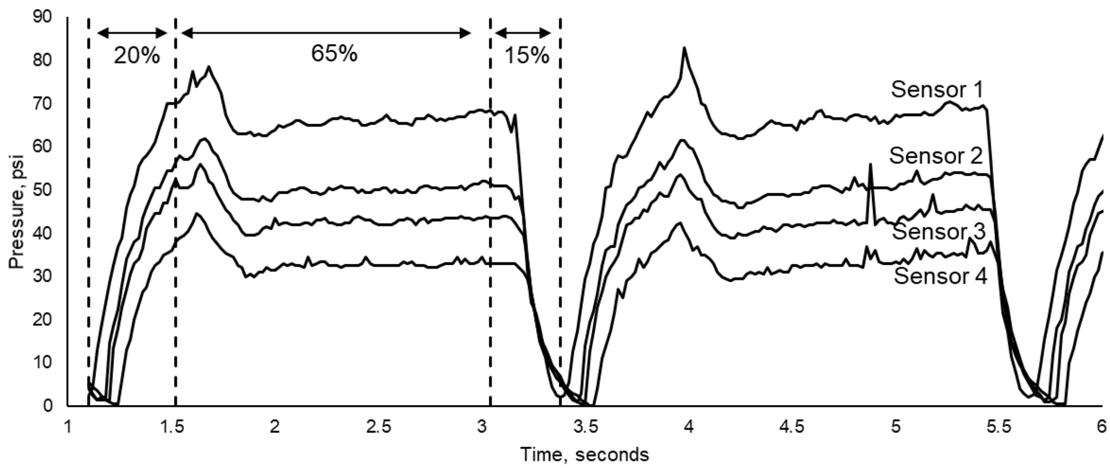

Figure A.5-1 - Typical pumping pressure curve and calculation.

A computer code determined the maximum, minimum, and average pressure values due to each piston stroke. The local minimums in the data determined the length of each pressure curve [14]. The peak pressure and minimum pressure were determined from analyzing maximum and minimum pressure values from the entire duration of each pressure curve. The peak pressure was used to describe mixtures in this work. To determine the average pressure, the first 20% and last 15% of the pump curve were not included. This excluded the non-uniform pressure changes at the beginning and end of each stroke. A graphical representation of this is in Figure A.5-1.

To determine the peak pressure at different sampling times, the peak pressure from the last 10 full piston strokes before sampling were averaged. This allows the comparision of peak pressures between mixtures. Note that the coefficient of variation between the peak pressure of the last 10 strokes was always less than 5%, with common coefficients of variation of 2% to 4%.

In all mixtures, the pressure measured within the pipe network increased with cycles through the pipe network. Table A.1-1 reports the sensor 1 peak pressure at the different sampling times for laboratory and field mixtures. Figure A.5-2 shows a typical plot of the peak pressure for sensor 1 for laboratory mixtures. The peak pressure is the maximum pressure recorded during each piston stroke. The peak pressures for the laboratory mixtures varied between 50 and 120 psi. The curve follows an increase in pumping pressure over time. The gaps in the data are where the pump was stopped to test the concrete. A typical plot of the average pressure, is in Figure A.5-3. The values for each of the four sensors are shown.

For the field mixtures, peak sensor 1 pressures ranged from 150 to 200 psi. The field mixtures showed substantially higher pressures than laboratory mixtures; however, the amount of air lost was not comparable. The increase in SAM Number in laboratory and field mixtures also appears to be independent of the applied pressure. This is possibly the result the much of the air available to be dissolved will be dissolved at lower pressures, and higher pressures not having much of an impact to dissolve additional air.

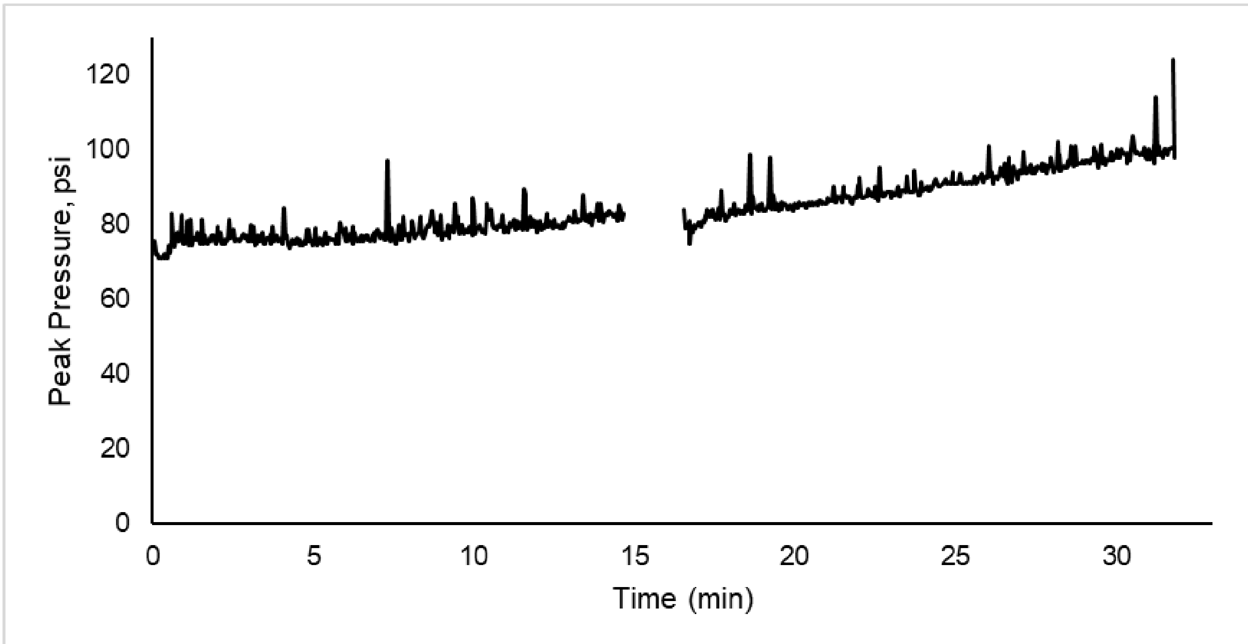

Figure A.5-2 – Plot of Typical Sensor 1 Peak Pressure vs. Time

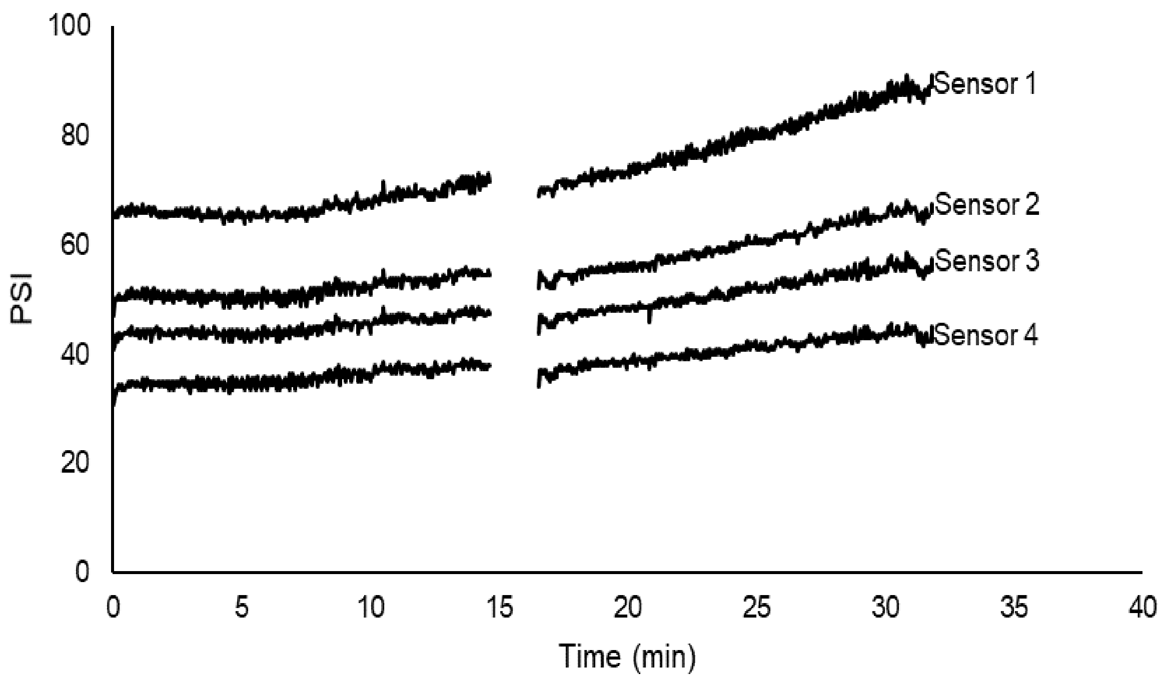

Figure A.5-3 – Plot of Typical Average Pressure Plot versus Time

A.6 MOVEMENT OF THE SAM VS. AIR FOR INDIVIDUAL MIXTURES

Figure A.6-1 shows the movement of the SAM vs Air data after one cycle through the pump and pipe network. This shows how the individual mixtures change due to pumping. There was a general upward trend for this data indicating that pumping causes a coarsening in the air void distribution. The PC mixtures showed a general downward trend with pumping; indicating the air void system is becoming finer. In general, before pumping the mixtures fall close to the high efficiency line. Indicating a distribution of smaller bubbles. After pumping, the mixtures fall close to the low efficiency line, indicating a distribution of larger bubbles.

For the citric acid, WR, and field mixtures, the greatest movement was after cycling once through the pipe network. The field mixtures were not recirculated. Figure A.6-2 shows with additional pumping, the movements on the air content versus SAM Number plot were small and did not show a general trend. This indicates the most significant damage to the air void system in the fresh concrete happens during the first cycle of pumping. Additional cycles did not have a significant impact of further coarsening the air void system in the fresh concrete.

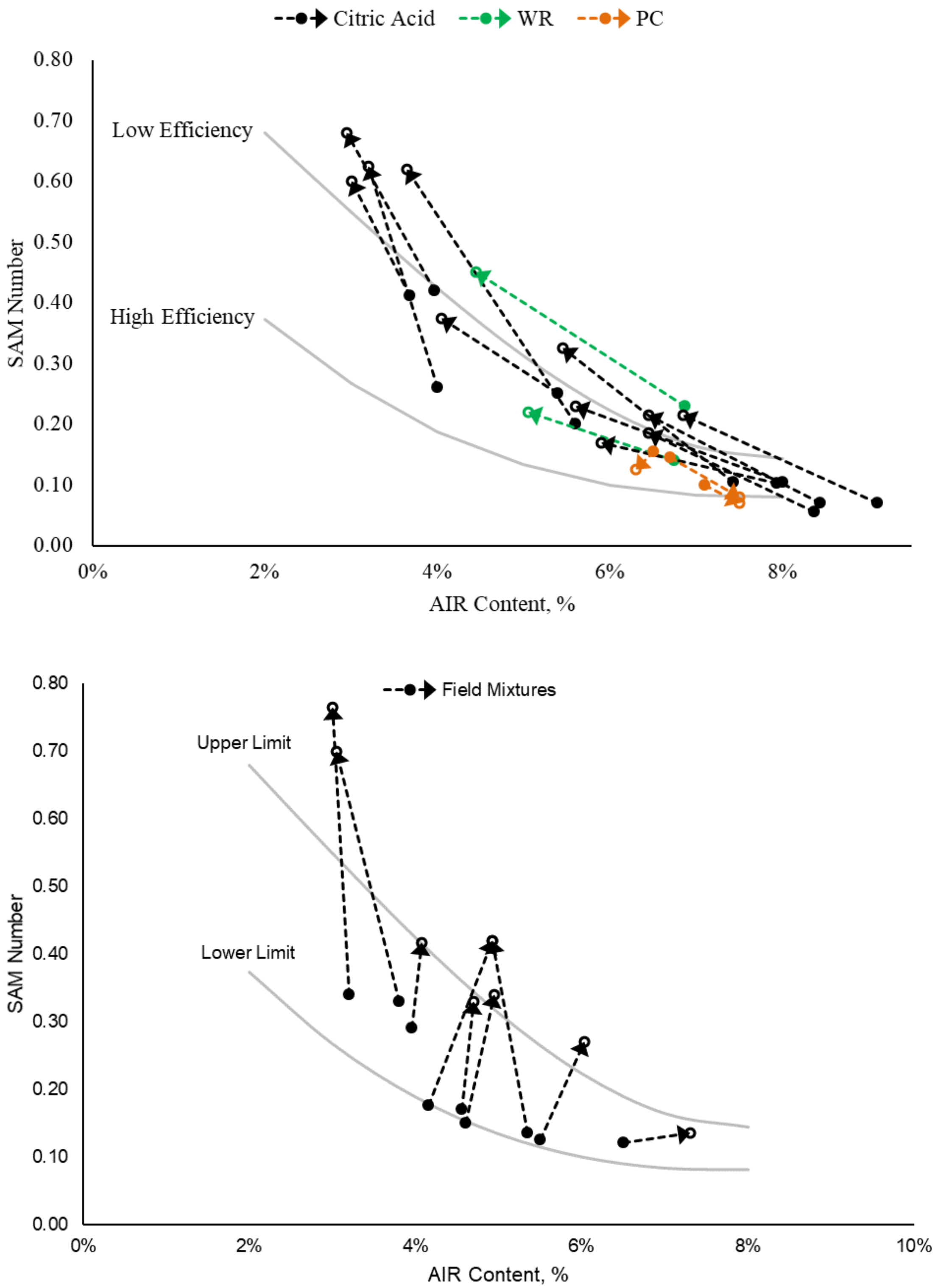

Figure A.6-1 – Movement of SAM vs. Air after between measurement taken before pumping and 1 cycle through the pump and pipe network for lab and field samples

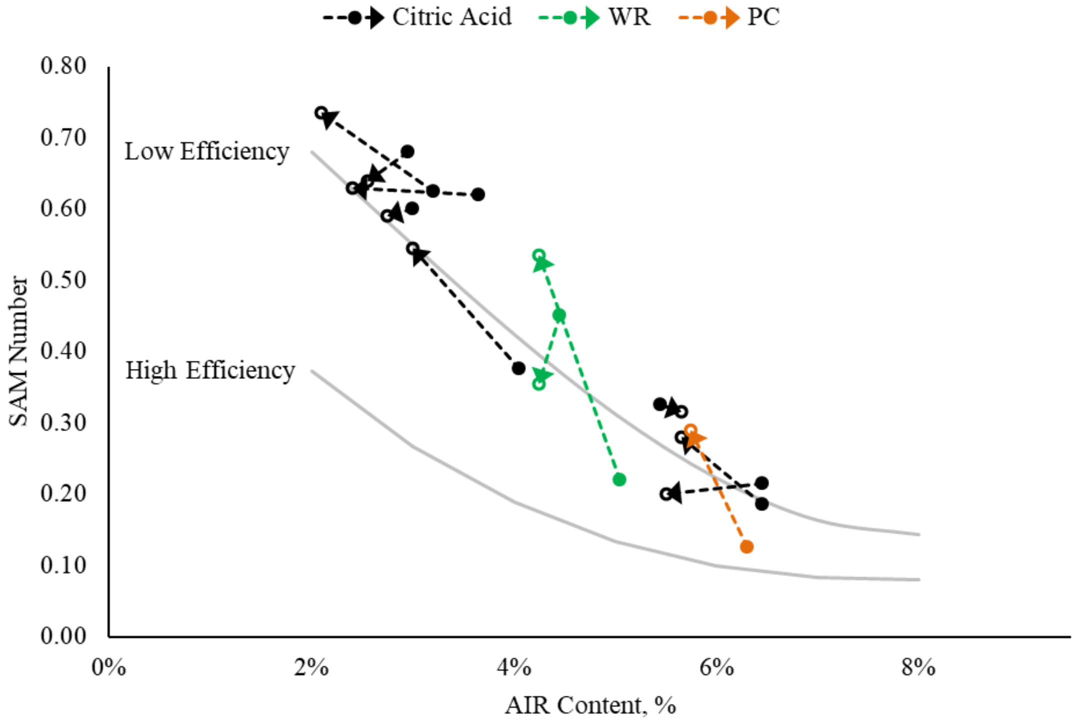

Figure A.6-2 – Movement of the SAM Number vs. fresh air content for individual mixtures between measurements taken at 1 and 40 cycles through the pump and pipe network.

A.7 PUMPING ADDITIONAL CYCLES AND THE IMPACT ON THE DURABILITY FACTOR

Additional pumping had little impact on the Durability Factor. Figure A.7-1 shows the average Durability Factor after pumping for laboratory mixes. Each point represents the average Durability Factor and standard deviation for samples taken at 1, 40, 80, and 120 cycles for each mixture. The graph shows pumping additional cycles through the pump and pipe network did not greatly change the Durability Factor. That is the durability factor measured after 1, 40, 80, or 120 cycles were very close to one another. All standard deviations are within the limits of ASTM C666 expect for mixture L8. This suggests that additional pumping did not cause additional coarsening of the hardened concrete.

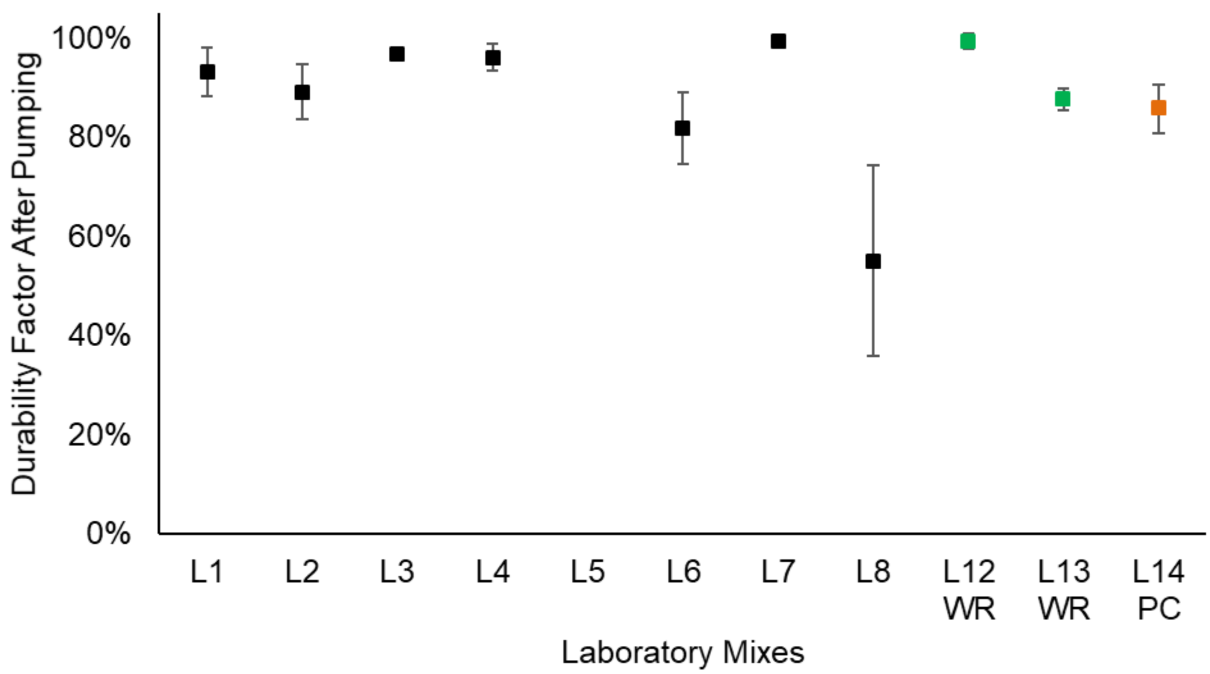

Figure A.7-1 – Average Durability Factor and standard deviation after pumping for laboratory mixes.

A.8 COMPARING THE DURABILITY FACTOR BEFORE PUMPING VERSUS THE DURABILITY FACTOR AFTER PUMPING.

It is beneficial to compare how the Durability Factor changes from pumping. ASTM C666 samples prior to pumping were tested for 1 WR, 1 PC, and 15 field mixtures. In order to gain insight into how the Durability Factor changed as a direct result of pumping, the difference was determined by subtracting the Durability Factor before pumping from the Durability Factor after pumping. A positive number indicates an increase in Durability Factor and a negative number indicates a decrease in Durability Factor. Figure A.8-1 shows a plot of the average percent difference along with error bars showing one standard deviations. The graph shows that pumping did not cause a significant change in Durability Factor, indicating pumping did not significantly coarsen the air void system for the mixtures investigated.

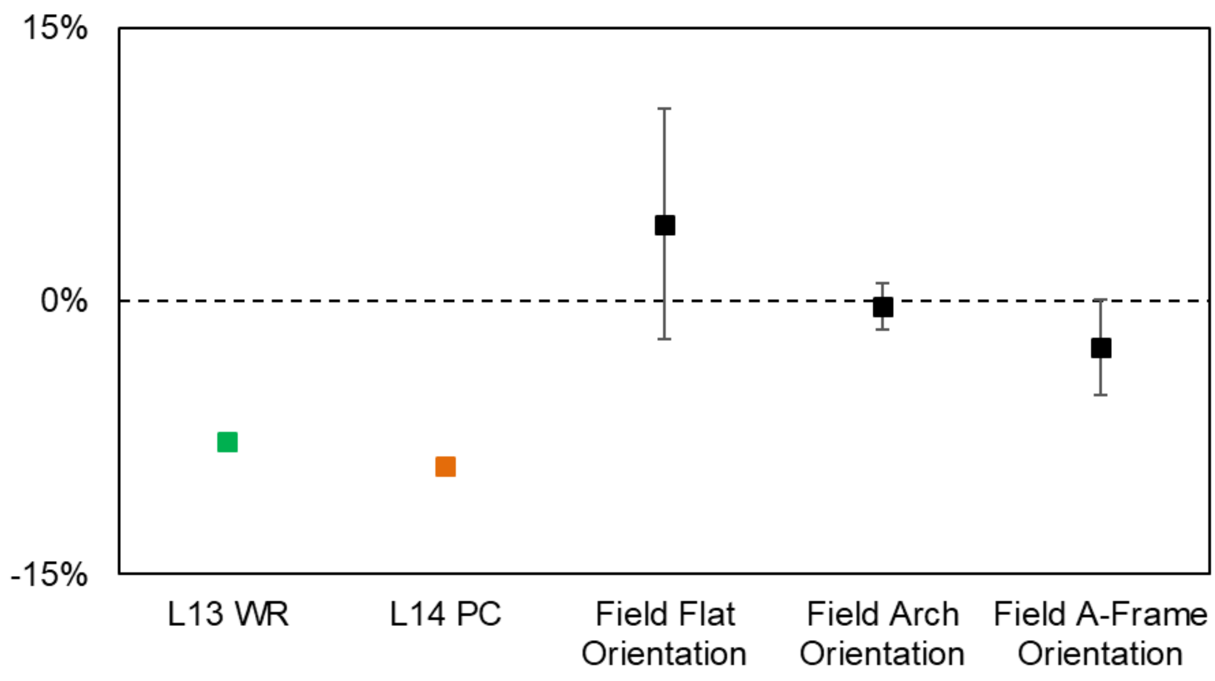

Figure A.8-1 – Percent difference between Durability Factor before pumping and Durability Factor after pumping

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