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Concrete Pumping Effects on Air-Entrained Voids in Concrete Mixtures

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16. ABSTRACT

Placing concrete using a concrete pump has placement advantages due to the increased speed, accessibility, and convenience of operation. Unfortunately, the pumping of air-entrained concrete is known to affect the fresh air content in the fresh concrete. This has caused concern about the durability of concrete in environments where the concrete will experience repeated freezing and thawing cycles.

The research described in this report investigated the impact concrete pumping has on air-entrained voids in concrete. The study examines the effects of different air contents, pumping time, and pressure has on the air volume and the stability of the air void system. The laboratory tests conducted show a significant amount of air volume was lost in the fresh concrete as a result of pumping. In many cases, the quality of the air void system in the fresh concrete would predict the concrete would have poor performance in freeze-thaw testing; however, all mixtures showed satisfactory performance in ASTM C666 freeze-thaw testing. This indicates the quality of the air void system in the fresh concrete after pumping is not representative of the hardened concrete for the materials and procedures used in this testing. The results suggest that if a high-quality air void system is present prior to pumping, that the air void system after pumping should be sufficient f or freeze-thaw durability.

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Concrete Pumping Effects on Air-Entrained Voids in Concrete Mixtures

Final Report

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1.0 INTRODUCTION

Since the 1930's, concrete pumps have been used to efficiently transport and place concrete [1]. Pumping has advantages due to the increased speed, accessibility, and convenience. Unfortunately, pumping of air-entrained concrete is known to impact the fresh air content [2, 3]. This has caused concern in environments where the concrete will experience repeated freezing and thawing cycles.

Pumping can cause air to increase, decrease, or stay almost constant. However, it is common to report a decrease in air content from pumping. Typical air losses range from 0.5 to 3%, with less frequent larger losses [2, 3]. These variations depend on numerous factors that make it hard to predict the air content after pumping. In general, the mechanisms during pumping thought to change the air content are the vacuum, impact, and pressure dissolution mechanisms [3]. The literature discusses all of these mechanisms and all likely play a role in the change of air during pumping. In practice, contractors try to minimize circumstances that contribute to these mechanisms [2].

The research conducted investigates the impact that pumping has on the air void system of a concrete mixture. This study examines the effects of different air contents, pumping time, and pressure has on the air volume and stability of the air void system. During testing, all circumstances that contribute to the vacuum and impact mechanisms were kept to a minimum; thus isolating the pressure dissolution mechanism. This isolation of variables provided important insights.

2.0 EXPERIMENTAL METHODS

2.1. MATERIALS

2.1.1 Concrete Mixtures

All of the concrete mixtures described in this work were prepared using a Type I cement that meets the requirements of ASTM C150 and a fly ash that meets the requirements of ASTM 618 Class C. Table 1 shows the oxide analysis for cement and fly ash used. All of the concrete mixtures investigated were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 611 lb/CY of the 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. It was the goal of the project to use an almost constant aggregate gradation. This was not possible since gradation varied within a stockpile. Figure 1 shows the total aggregate gradations for all mixtures along with the Tarantula Curve limits. The sum of the fine and coarse sand was approximately 38% and 27% respectively for all mixtures, which falls within the recommended range [4]. Table 2 displays a summary of the mixtures investigated. All mixtures have a paste content of 28.9% with the exception of mixture A-1 and A-2. Table 2 shows the paste content for all the mixtures.

Table 1 - Type I cement oxide analysis

	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	-	-	-	-

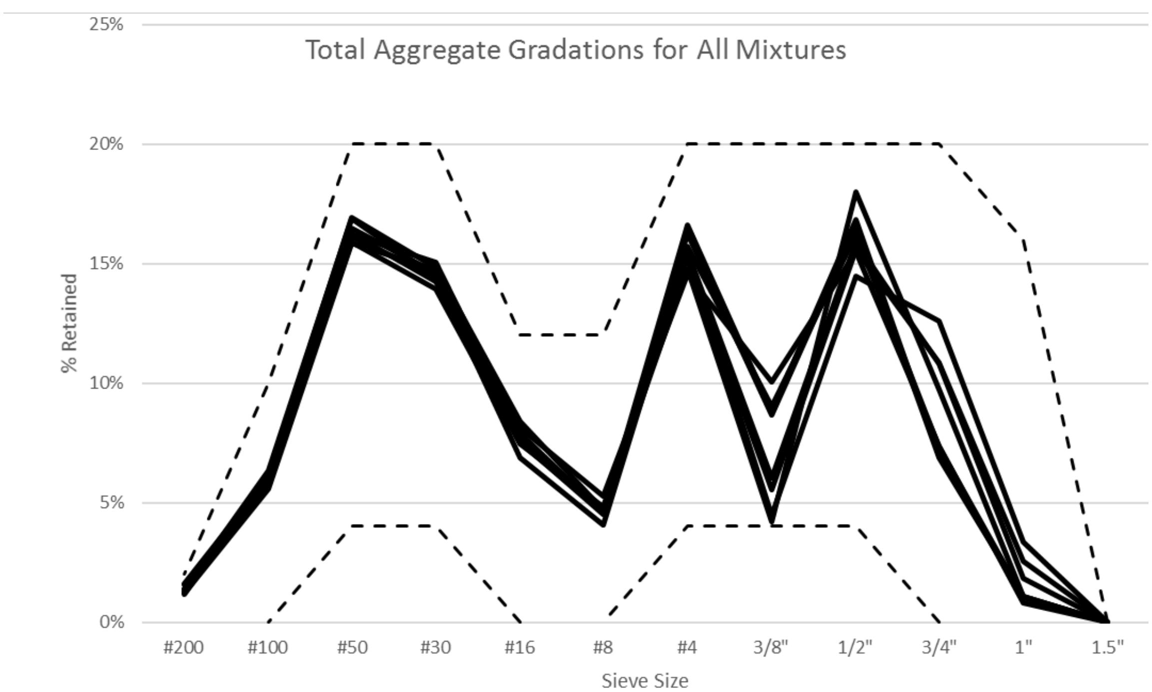

Figure 1 – Baseline Gradation

Table 2 – Concrete Mixture Summary

Mixture	Cement (lbs/cy)	Fly Ash (lbs/cy)	Water (lbs/cy)	Coarse (lb/cy)	Intermediate (lbs/cy)	Fine (lbs/cy)	Paste Content
A-1	489	122	275	1309	413	1331	29.6%
A-2	489	122	275	1183	359	1415	30.2%
A-3	489	122	275	1212	551	1401	28.9%
A-4	489	122	275	1236	492	1434	28.9%
A-5	489	122	275	1214	511	1437	28.9%
A-6	489	122	275	1218	508	1502	28.9%
A-7	489	122	275	1264	426	1471	28.9%
A-8	489	122	275	1113	552	1494	28.9%
A-9 (No Citric Acid)	489	122	275	1535	213	1417	28.9%
B-1	489	122	275	1335	391	1438	28.9%
C-1	489	122	275	1311	380	1471	28.9%
C-2	489	122	275	1113	552	1494	28.9%
C-3	489	122	275	1335	391	1438	28.9%

2.1.2 Grout Mixtures

Prior to each concrete pumping session, a grout was used to prime the pump and pipe network. This is the most common method of preparing the pump and pipe network to pump concrete. Priming consists of lining the walls of the pump and pipe network with a thin lubricating layer of mortar [1]. The grout mixture was prepared using a Type I cement that meets the requirement of ASTM C150. The grout mixture was designed with a w/cm of 0.40, 1006 lb/CY of cement, and 2514 lb/CY of sand from the same natural sand source used in the concrete mixtures.

2.1.3 Admixtures

An air-entraining admixture (AEA) was used to entrain air during mixing. The AEA was from the wood rosin family and is the most common type of AEA used for commercial air entrained concrete. For the majority of the concrete mixtures investigated a food grade citric acid dosage of 0.25% by cementitious weight was used as a set retarder. The citric acid also acted as a water reducer in the concrete and grout mixtures. In mixture A-1 and

A-2, a mid-range water reducer was used at a dosage of 1 oz/cwt in addition to the citric acid dosage. In mixture A-9, a citric acid was not used and instead a midrange water reducer (WR) was used at a dosage of 7 oz/cwt. At this dosage, this admixture is not expected to modify set time.

2.2 EQUIPMENT

2.2.1 Concrete Pump

The Putzmeister TK 50 concrete pump used for this research is in Figure 2. This pump provides an almost continuous concrete flow through two alternating pistons that draw in concrete from the hopper as the piston retracts, and push concrete out as the piston extends. A rotating delivery system shifts from one delivery cylinder to the other. This allows concrete to be continuously delivered by the pump. An agitator was included in the hopper to continually agitate the concrete in the hopper.

Figure 2 - Putzmeister TK 50 Concrete Pump

This pump is powered by a 96 HP diesel engine that drives a main hydraulic pump and a secondary double-stage hydraulic pump. The main hydraulic pump is a variable displacement, load sensing hydraulic pump that is used to power two hydraulic cylinders that drive the delivery pistons. The first stage of the second hydraulic pump, in conjunction with an accumulator, is responsible for shifting the delivery system from one cylinder to the other. The second stage of the second hydraulic pump is responsible rotating the remixer.

The TK 50 Pump has a throttle control that varies the engine revolutions per minute (RPM) and a piston volume control. To maintain consistency between pumping sessions, a constant engine rpm, and piston volume was selected. The pump settings used in this work were 1500 rpm, and a piston volume set to full capacity, which is approximately 0.57 ft^3. These values were based on previous work [1].

2.2.2 Pipe Network

An instrumented pipe network was used to transport material during testing. For the majority of work, 4.0" single wall steel pipe was used. During one test, 5.0" diameter single wall steel pipe was used. Sections of pipe are connected using a rubber gasket and couplings securing the pipes together. A more detailed description of the pipe layouts used in each testing procedure is given in the section describing the testing procedure.

2.2.3 Pressure Sensor Assembly and Calibration

Four pressure sensor assemblies were used along the pipeline to measure the pressure in the concrete line during pumping. Figure 3 shows a typical sensor assembly. The GE 5000 pressure sensor was used 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 0.5 psi accuracy by converting pressures into voltage readings between 0 and 5000 mV. The sensor would be damaged if directly subjected to concrete and therefore a buffer chamber was required. The buffer chamber consists of a hydraulic fluid-filled chamber with a flexible rubber membrane on one end, with the other end connected to the GE 5000 sensor. As pressure increases on the rubber membrane, this pressure is transferred to the fluid in the chamber and to the GE 5000 sensor, which yields a voltage reading.

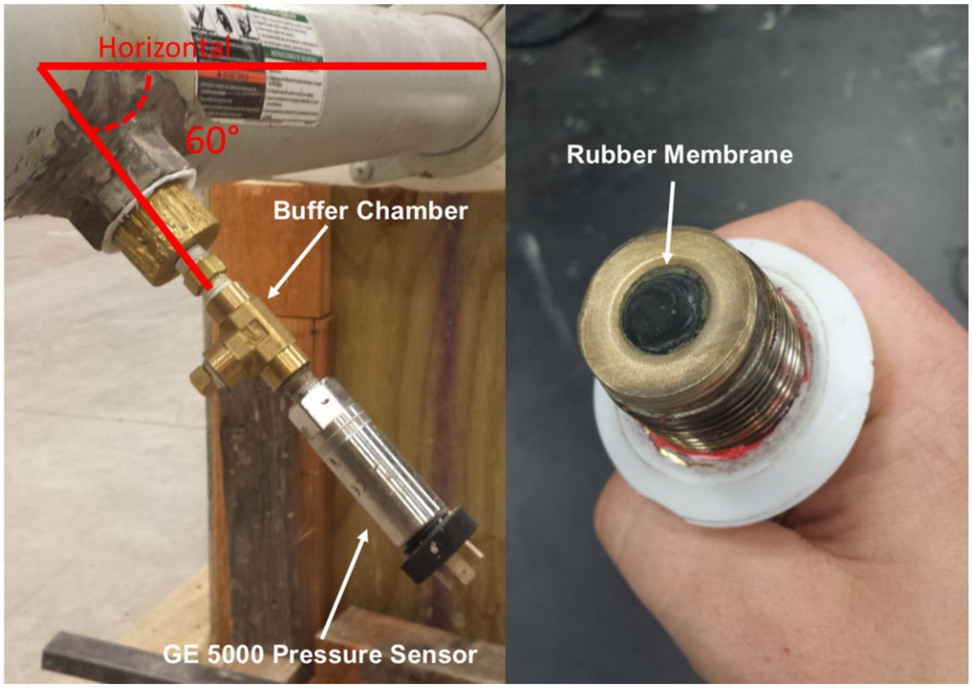

Figure 3 - Overview of the pressure sensors.

To connect the sensor to the pipe, a 1.125 in. diameter hole was drilled with a nut welded to the outside of the pipe. The buffer chamber was threaded and then screwed inside the nut until the rubber membrane was adjacent to the walls of the pipe. The pressure sensors were rotated approximately 60° from the horizontal, as seen in Figure 3. This was done to keep aggregate, paste, and water from collecting on top of the membrane during pumping. During pumping, voltage readings were taken every 0.02 second.

To determine how the voltage readings correlate to pressure in the pipeline, the sensor assemblies were calibrated by connecting the sensors to a water-filled section of pipe and pressurizing the section between 0 and 110psi. By systematically changing the pressure in the pipe and recording the voltage output from the sensor, calibration curves were developed. Typical results from the sensor calibration are in Figure 4. The curves developed show a linear relationship between the subjected pressure and voltage readings.

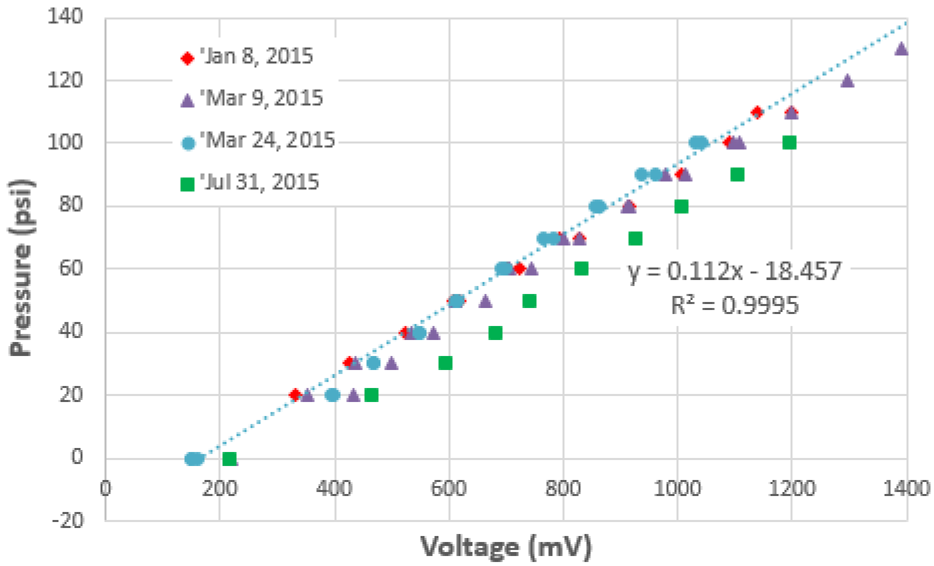

Figure 4 - Typical Sensor Calibration Curve

A linear line was fit to the graph to determine the slope of the calibration data. The slope of the different lines remained very similar. The maximum difference in slope would lead to an approximate 5 psi difference at a reference voltage of 1200 mV. This is an estimate of the possible error measurement. The y-intercept shifted slightly between measures, but the slope of the calibration line was not affected. To account for this a measurement was taken in the pipeline when it was empty. This value was set to 0 psi and the slope from the calibration was used to calculate the change in pressure.

2.3 EVALUATION OF AIR ENTRAINED PUMPED CONCRETE

In evaluating the pumping performance of air entrained concrete, there is a concern with how the total air volume, air void quality, and freeze-thaw resistance of the concrete was affected due to pumping. On the fresh concrete, the Super Air Meter (SAM) was used in accordance with AASHTO TP 118 to give the total air volume and an indication of the air void quality in the fresh concrete. In addition, the slump, ASTM C143, and unit weight, ASTM C138, were performed on the fresh concrete as an indication of the workability and consistency of the concrete. On the hardened concrete, ASTM 666 was used to determine the freeze-thaw resistance and ASTM C457 was used to determine the air void parameters of the hardened concrete.

2.3.1 Laboratory Testing

In order to evaluate the pumping performance of air entrained concrete, three different laboratory testing configurations were investigated. These are the recirculation, disassemble, and segment testing procedures.

In the recirculation procedure, concrete was tested after mixing, after one cycle through the pipe network, and then after every 15 minutes of recirculating the concrete through the pump and pipe network. The purpose of the recirculation testing procedure was to determine how the air volume, air void quality, and freeze-thaw resistance of the concrete changes as the concrete is continuously pumped over time. This procedure is discussed in detail in section 2.3.3. This method may not be representative of what would happen on a bridge deck but may be more applicable for high-rise building construction where pumps used at different floors to transfer the concrete up the building. This was done because it was convenient to recirculate the concrete in order to get more insight into the performance of air entrainment in pumped concrete.

In the disassemble method, concrete was pumped once through the pipe network. The pump was then stopped and the pipe sections were removed while full of concrete. Samples from several different locations were then tested to see how the air content of the concrete varied at different locations within the pipe network. More information is given in section 2.3.4.

In the segment method, concrete is tested before and after being pumped through straight lengths of pipe of various length with and without a reducer. The output from the pump was 5". Concrete was sampled after leaving the pump with no pipes, after a 6.6 ft and 19.7 ft long 5" diameter pipe. Next, a 3.3 ft reducer was used to decrease the 5" output of the pump to 4" pipe. Concrete was sampled right after the reducer, after 6.6 ft and 19.5 ft of 4" diameter pipe. The method investigated how the air volume, air void quality, and pumping pressure change with different pipe lengths and sizes. This method is known as the segment method and is described in detail in section 2.3.5.

2.3.2 Mixing Procedure

The mixing procedure was the same for all tests. To complete each mixture aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24 hours before mixing. Aggregates were placed in a mixing drum, spun for a period of time, and a representative sample was taken to determine the moisture content 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 was 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 was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the desired admixtures were added and the mixer was turned on and mixed for three minutes.

2.3.3 Recirculation Testing Procedure

2.3.3.1 Pipe Network Configuration

An overview of the pipe network used is in Figure 5. The network consists of a 3.3 ft long single wall steel pipe reducer from the 5.0" output diameter of the pump to 4.0". This is followed by 52.5 ft of 4.0" diameter steel line with three 1.5' radius 90° bends. At the end of the steel pipe network a 9.8', 4.0" diameter flexible rubber hose was attached. This allowed for the repositioning of the discharge of concrete during pumping. The total volume of the pipe network is approximately 6.0 ft^3. Along the pipe network, four sensors were placed to measure an estimate of pumping pressures in the line. The locations of the four sensors are in Figure 5.

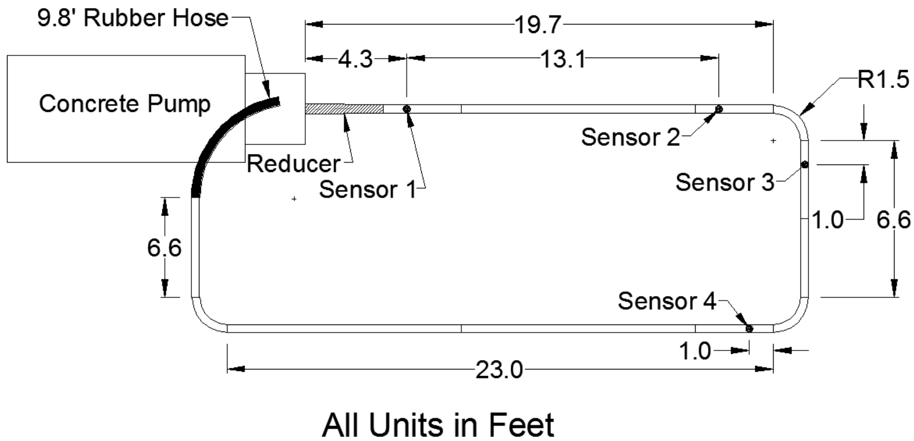

Figure 5 – Plan View of the pipe network.

2.3.3.2 Charging the Pump and Pipe Network

After configuring the pipe network, 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 2.3.2. Prior to pumping the first concrete mixture, slump, unit weight, air, SAM, and hardened air void data was collected as a baseline for the rest of the pumping. Unit weight and slump data were collected on the second and third concrete mixtures to 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.

2.3.3.3 Data Collection

After all of the grout was discarded from the line, the rubber discharge hose was moved to recirculate into the pump's hopper. This allowed the material to be recirculated during pumping in a continuous loop. Recirculating the concrete over time subjected the concrete to more pressure cycles and pumped the concrete over longer lengths; serving to exaggerate the effect pumping has on the concrete.

The pump was then cycled through ten piston strokes, after which ~1.0ft^3 of material was removed from the end of the discharge line to collect slump, unit weight, air, SAM, hardened air void data, and ASTM C666 samples. The data was collected at this time to determine the impact pumping concrete once through a full pipe network has on the air void quantity and distribution in the concrete. This data is labeled as 0 minutes and most accurately represents what the concrete will be subjected to in a bridge deck placement 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 ~2 minutes while concrete was gathered for testing. In order to collect the sample of concrete at each time interval, the pump was stopped and the flexible hose moved to discharge ~1.0ft^3 of concrete. 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 6 times through the pipe network. This is the same as traveling through 315 ft of 4.0" diameter line and passing through the reducer 6 times. Line pressures were recorded during the entire testing procedure. The pumping session was terminated when the slump was less than 2.5". This was chosen because concrete with low workability can lead to blockages in the line.

2.3.4 Disassemble Testing Procedure

The pump and pipe network were assembled in accordance with section 2.3.3.1. This is the same pipe network setup as the recirculation testing procedure. The pump and pipe network were charged with concrete in accordance with Section 2.3.3.2. After discarding the grout from the line, the hopper was filled and pumping continued until the hopper was almost empty. The pump was then stopped and the pipe network disassembled while it was full of concrete.

Concrete from inside the pipes was collected and unit weight and air measurements were performed for each section. This was done to determine how the air void quantity and distribution changes with distance from the pump. Pipeline pressures were recorded during the testing. Figure 6 shows the points where the concrete was sampled. These points are labeled a - f.

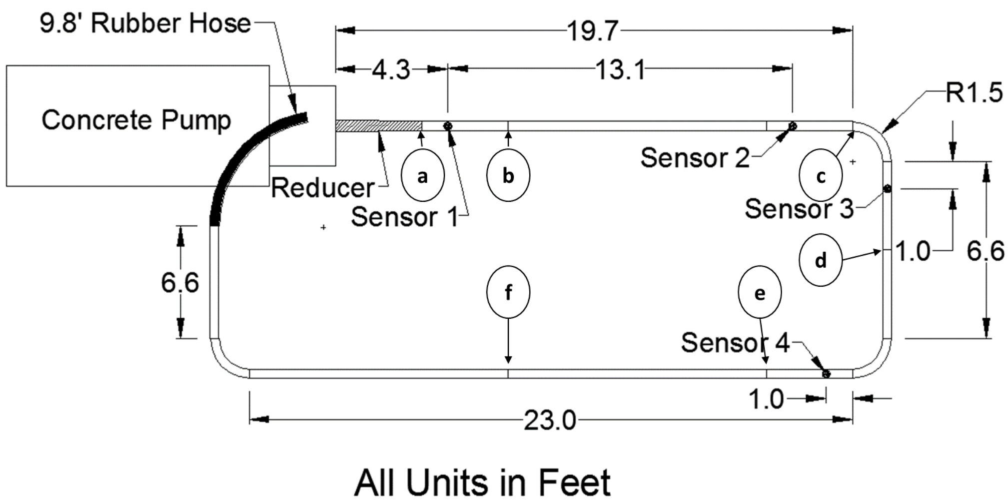

Figure 6 – Points where the pipe network was disassembled

2.3.5 Segment Method

Concrete was pumped through pipes of varying lengths and sizes and tested for changes in the air parameters of the concrete. The lengths, pipe sizes, and sensor locations are in Figure 7. Concrete was pumped without any pipe attached, with a 3.3 ft reducer + 3.3 ft of 4.0” line, 3.3 ft reducer + 16.4 ft of 4.0” line, 6.6 ft of 5.0” line, and 19.3 ft of 5.0” line. The lengths and sizes of pipe were increased to investigate how longer lengths and larger diameters of pipe changes the pumping pressures and the subsequent air volume and air void distribution. To accomplish this, three 6.0 ft^3 concrete mixtures were made in accordance with section 2.3.2. For this testing, approximately 2 ft^3 of the concrete mixture was left undisturbed to compare the change in air volume and air void distribution over time. The remaining concrete was emptied into the pump’s hopper and continuously pumped through the pipe and into a collection bin. After collection, slump, unit weight, air volume, SAM, and ASTM C457 tests were performed on the control concrete and the pumped concrete at the same time. This was done to ensure that the results indicate the changes directly due to pumping. In addition, ASTM C666 samples were collected from the pumped concrete.

The pump and pipe segment was charged with concrete in accordance with Section 2.3.3.2. After discarding the grout from the line, the hopper was filled and pumping continued until the hopper was almost empty. To test the same concrete before and after pumping, both the volume of the piston chamber and pipe were calculated. By dividing these two values then the number of piston strokes could be determined to deliver the concrete from the hopper to the end of the pipe. When fractions of a piston stroke were needed to empty the pipe, then an additional piston stroke was added.

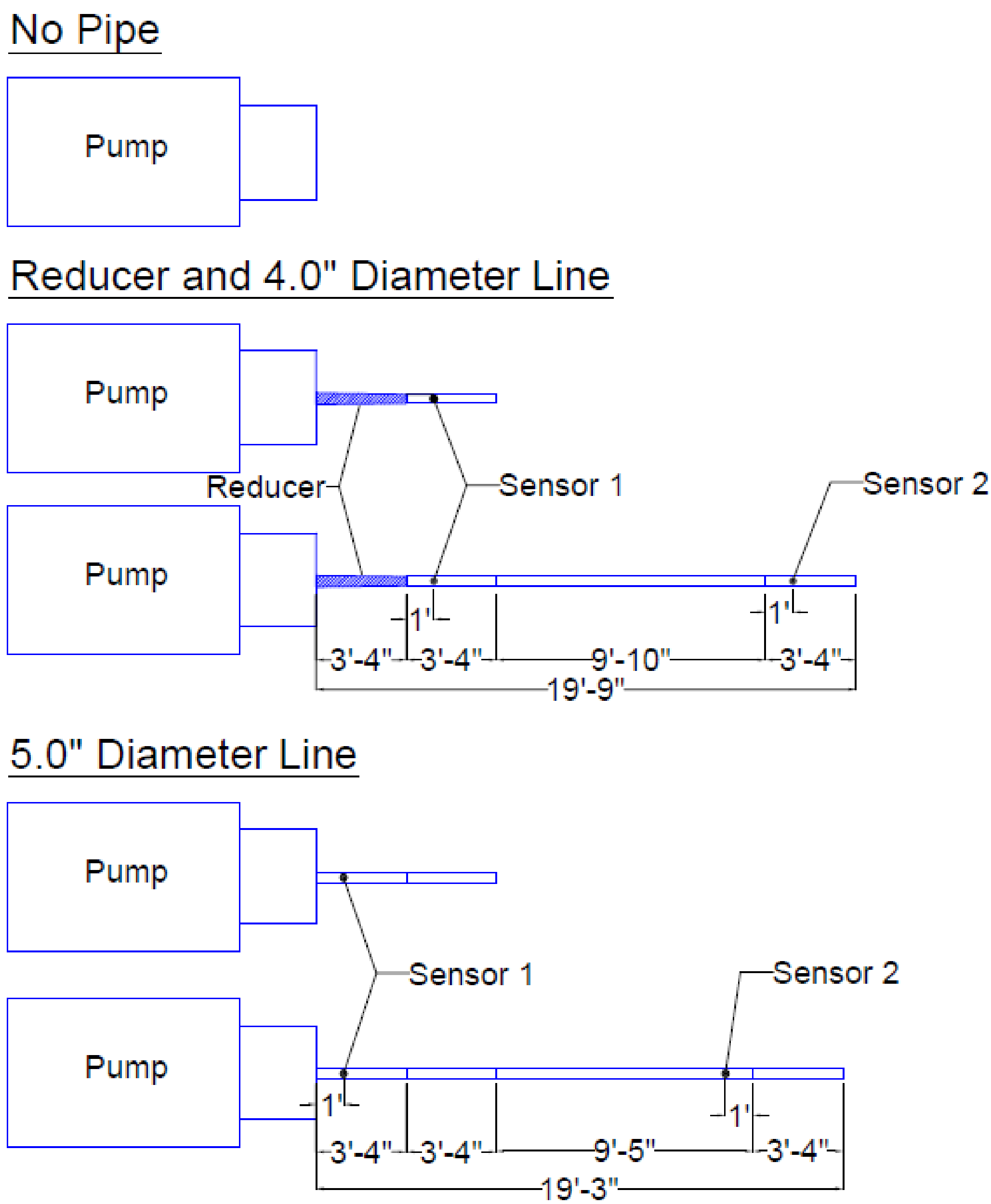

Figure 7 – Pipe Segment Layouts

2.3.5 Pressure Sensor Output

At the end of each pumping session, the data from each pressure sensor is retrieved and then processed. A typical pressure curve, showing values from all four sensors, is in Figure 8. This figure shows two piston strokes.

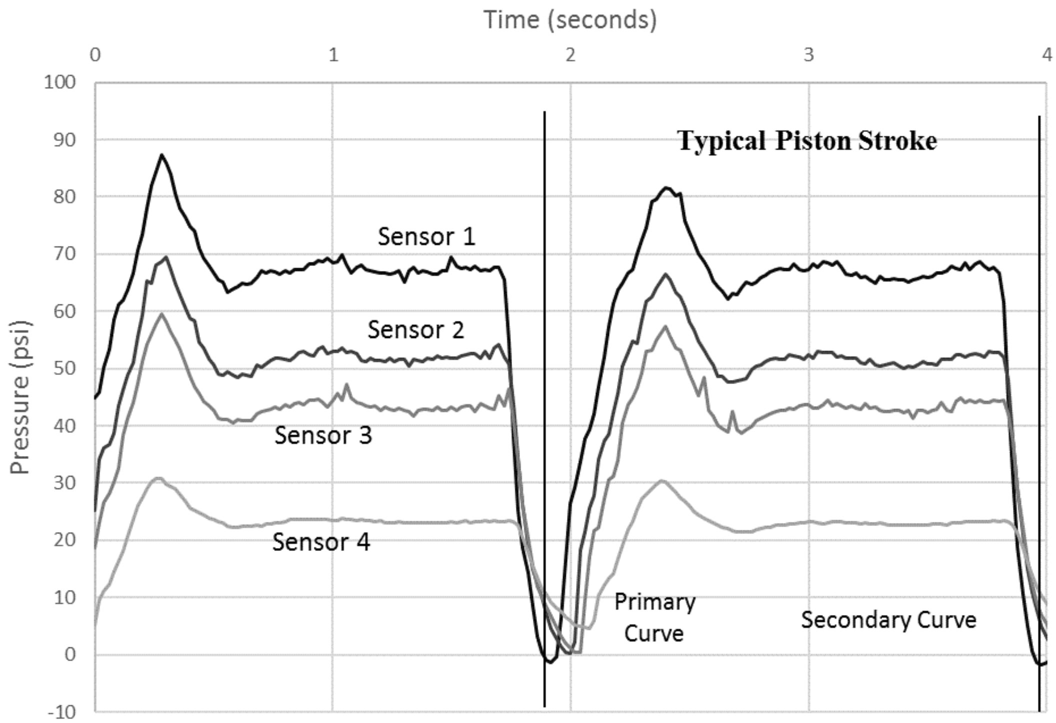

Figure 8 - A typical pumping pressure curve has a primary and secondary curve.

One piston stroke consists of a primary curve and a secondary curve. The primary curve is the initial pressure when the piston begins to move in the cylinder. The secondary curve is typically a smaller pressure that occurs while the piston is moving in the cylinder. In other words, the primary curve is the pressure required to initiate the movement of the concrete and the secondary curve is the pressure required to keep the concrete moving. A computer code was used to analyze the data for the primary and secondary curves [1]. For each of the four sensors, the maximum value of the primary curve and the average and coefficient of variation of the secondary curve is measured. The end of the primary curve and beginning of the secondary curve is separated by using a local minimum value after the primary curve. The middle 70% of the secondary curve was averaged and used to evaluate the pumping pressure. By not using the first and last 15% of the secondary curve this removed the non-uniform pressure changes right after the primary curve and at the end of the secondary curve. A graphical representation of this is in Figure 9. When the pump was running as expected and when the concrete had good workability, this methodology worked well and the coefficient of variation was low. At times when the mixes caused the pumping pressures to become erratic, there were irregular pressures during the secondary curve. This caused the coefficient of variation to increase [1].

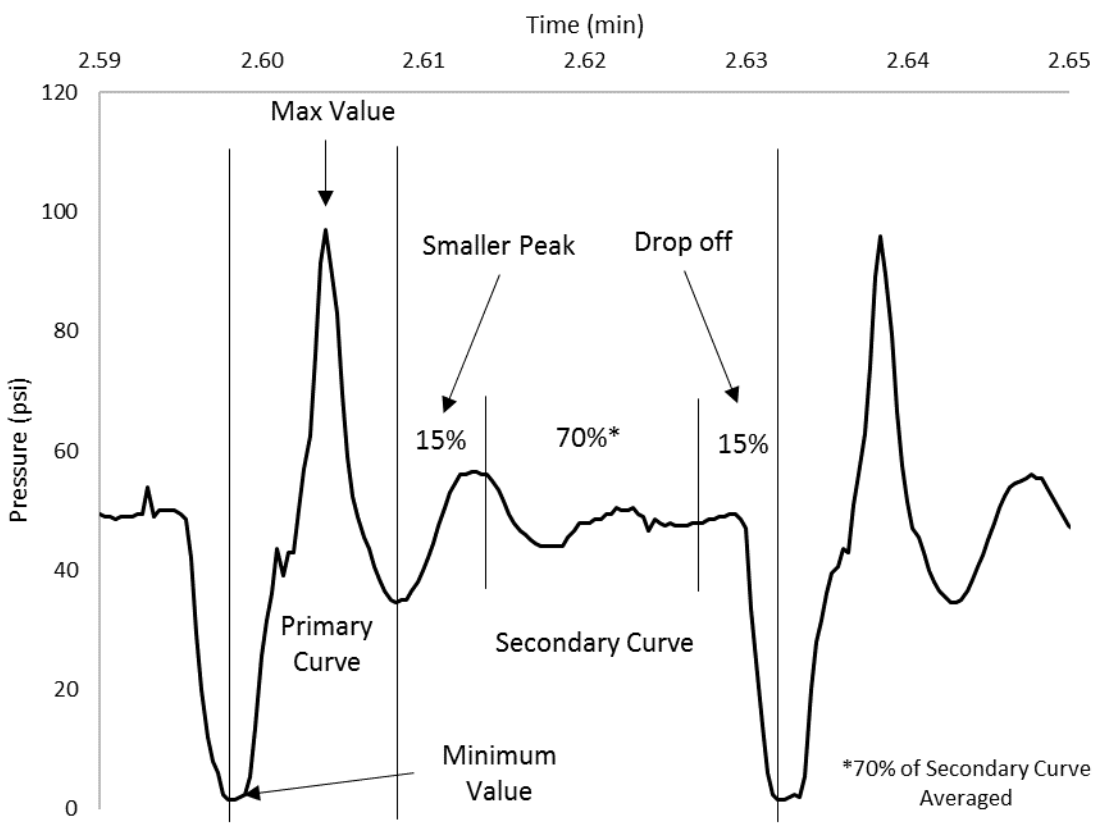

Figure 9 - The maximum value of the primary curve is found, and an average of the center 70% of the secondary curve.

3.0 RESULTS

3.1 RECIRCULATING TESTING PROCEDURE RESULTS

3.1.1 Super Air Meter Numbers and Air Volume

The slump, air, and SAM Number and ASTM C666 Durability Factors are in Table 3. Some values at 30 min and 45 min were not recorded because the concrete became too stiff to pump safely. When comparing the concrete before and after pumping the air content decreased and the SAM Number increased for all of the mixtures investigated.

A plot of the air content vs. time increment is in Figure 10. After adding the concrete to the pump it was cycled through the pipe network once. This is approximately 10 piston strokes. This is called the 0 min for this work. All mixtures showed the greatest decrease in air content between the measurements right after mixing and the measurements at 0 min. After 0 min, the air content of the mixtures either decreased at a slower rate or remained approximately constant.

Figure 11 shows the air content of each mixture relative to the approximate number of times through the pipe network. The most significant loss of air seems to occur during the first time through the pipe network. A plot of the SAM Number vs time increment is in Figure 12. In all mixtures, the SAM Number increased at the 0 min mark. This suggests the air void system is becoming more coarse. With continuing to pump the concrete, the SAM Number remained either approximately constant or increased.

Table 3 – Slump, Air Content, SAM Number, and Durability Factor during recirculation procedure

Test ID.	Test Parameter	Sample Taken Before Pumping	Sample Taken After Pumping 0 min	Sample Taken After Pumping at 15 min	Sample Taken After Pumping at 30 min	Sample Taken After Pumping at 45 min
A-1	Slump	9.25	9.25	9.00	8.25	7.25
	Air	4.1%	3.2%	2.1%	1.7%	1.8%
	SAM	0.26	0.625	0.735	0.725	0.6
	D.F.	--	93%	98%	88%	--
A-2	Slump	9.0	8.5	8.5	7.25	4.25
	Air	5.6%	3.7%	2.4%	2.4%	2.5%
	SAM	0.2	0.62	0.63	0.7	0.63
	D.F.	--	90%	94%	83%	
A-3	Slump	9.5	8.25	7.25	3.5	-
	Air	7.4%	5.5%	5.7%	4.5%	-
	SAM	0.11	0.325	0.315	0.385	-
	D.F.	--	96%	96%	98%	
A-4	Slump	9.5	9.0	6.5	2.75	0.5
	Air	5.4%	4.1%	3.0%	3.3%	3.2%
	SAM	0.27	0.38	0.55	0.54	0.67
	D.F.	--	94%	94%	97%	98%
A-5	Slump	8.0	7.75	6.5	2.8	-
	Air	8.4%	6.5%	5.5%	4.7%	-
	SAM	0.07	0.215	0.2	0.3	-
	D.F.	--	99%	99%	99%	-
A-6	Slump	7.5	5.5	4.0	1.75	-
	Air	4.0%	3.0%	2.6%	2.8%	-
	SAM	0.42	0.68	0.64	0.61	-
	D.F.	--	73%	84%	88%	-
A-7	Slump	9.0	8.0	6.0	2.75	-
	Air	8.4%	6.5%	5.7%	5.2%	-
	SAM	0.05	0.185	0.28	0.31	-
	D.F.	--	99%	100%	100%	-
A-8	Slump	7.0	5.0	3.0	-	-
	Air	3.9%	3.0%	2.8%	-	-
	SAM	0.42	0.6	0.59	-	-
	D.F.	-	-	-	-	-
A-9 (No Citric)	Slump	8.0	3.5	2.25		
	Air	6.9%	4.5%	4.3%	-	-
	SAM	0.20	0.45	0.355	-	-
	D.F.	-	99%	100%	-	-

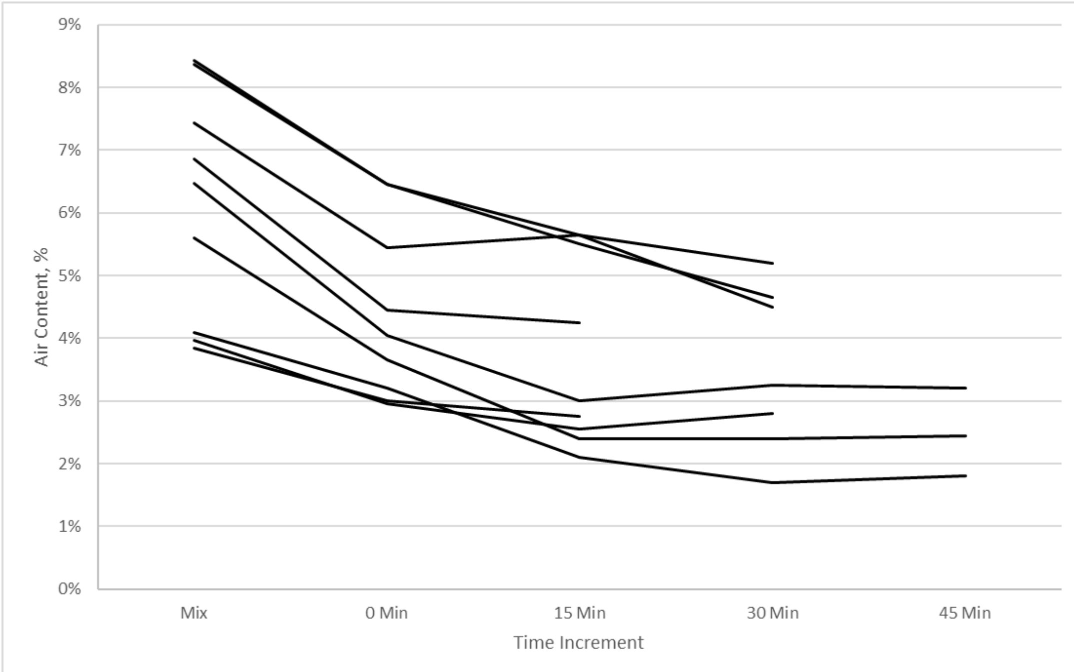

Figure 10 – Plot of Air Content vs. Time Increment

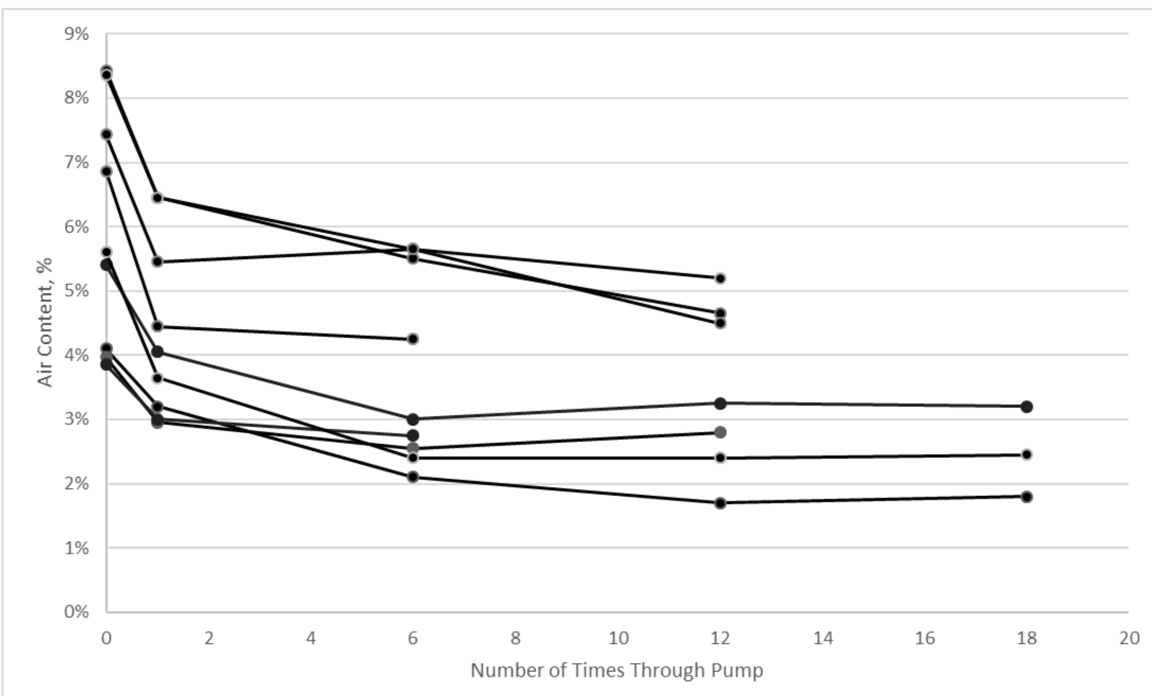

Figure 11 – Air Content versus Number of Times Through the Pump

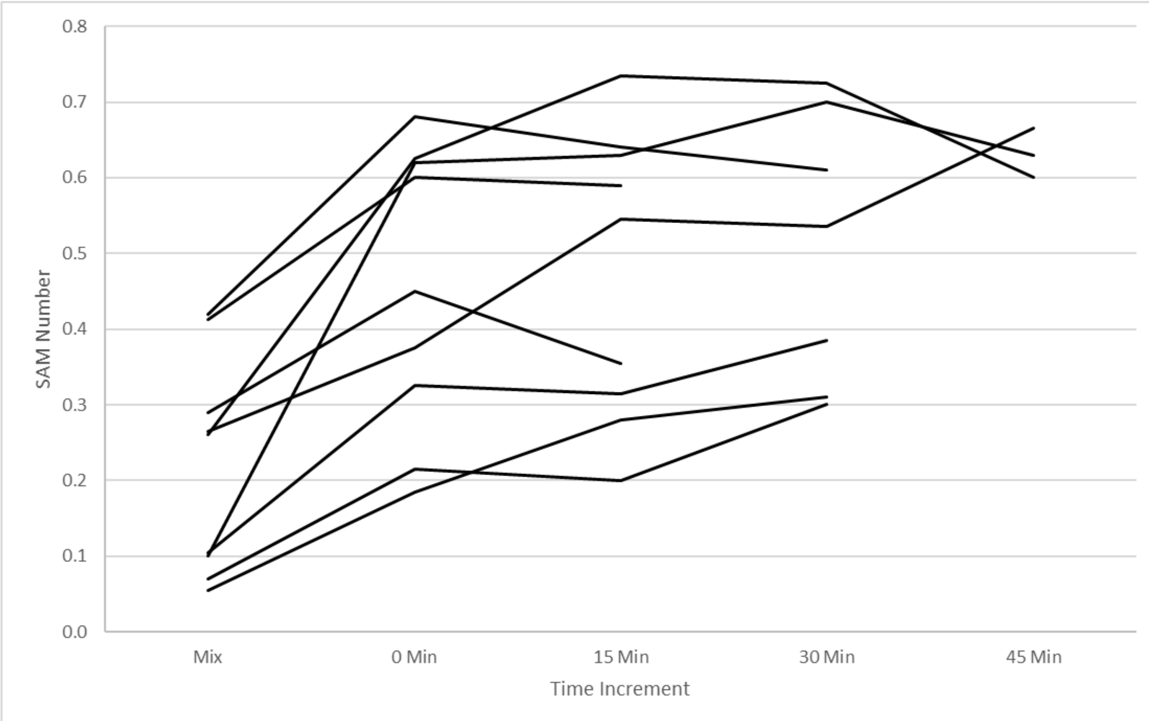

Figure 12 – Plot of SAM Number vs. Time Increment

A plot of the SAM Number versus Air Content is in Figure 13. This plot was shown in previous work to correlate to the air void quality of the concrete [5]. The lower limit in the graph represents concrete with a fine air void distribution and the upper limit represents a coarse air void distribution. The data is separated into two sets: before pumping and after pumping. Trendlines for each data set is shown in the figure. The trendline before pumping falls close to the lower limit, indicating a higher quality air void distribution. After pumping many of the data points fall closer to the upper limit, indicating a coarser air void distribution. The air void distribution of mixtures with air contents of 6% or greater does not seem to be as impacted as the mixtures with lower air contents.

Figure 14 shows the movement of the SAM vs Air data shows how the data changes due to pumping. The greatest movement was after cycling once through the pipe network. This data shows a general upward trend indicating that pumping causes a coarsening in the air void distribution. With additional pumping, the movements on the air content versus SAM Number plot were small and did not show a general trend. The SAM vs. Air movement from 0 min to 15 min is in Figure 15.

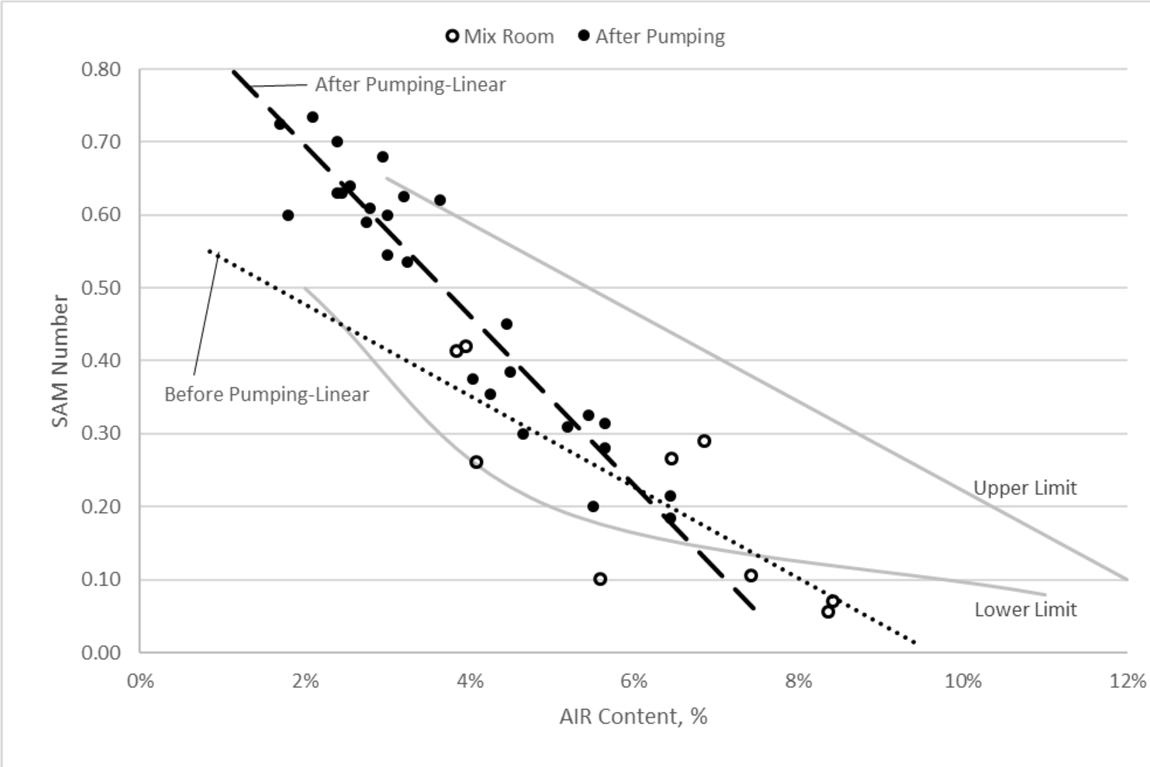

Figure 13 – Plot of SAM v Air Content

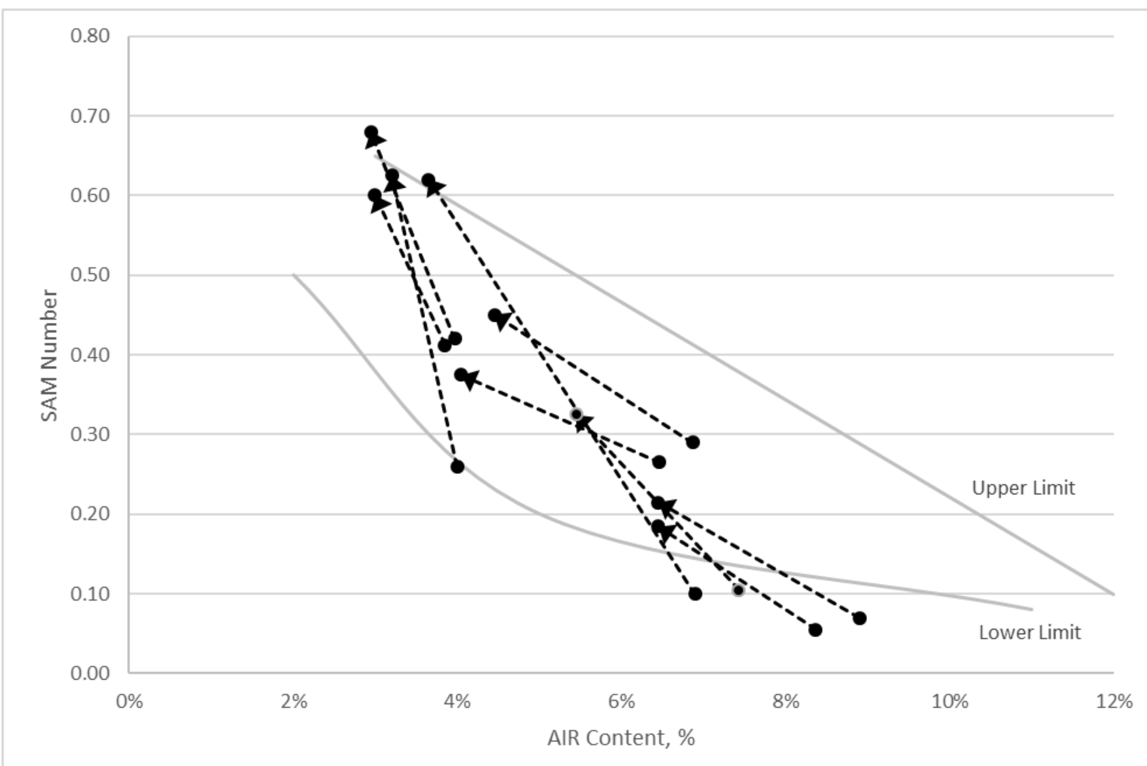

Figure 14 – Movement of SAM vs. Air from before pumping to 0 min mark.

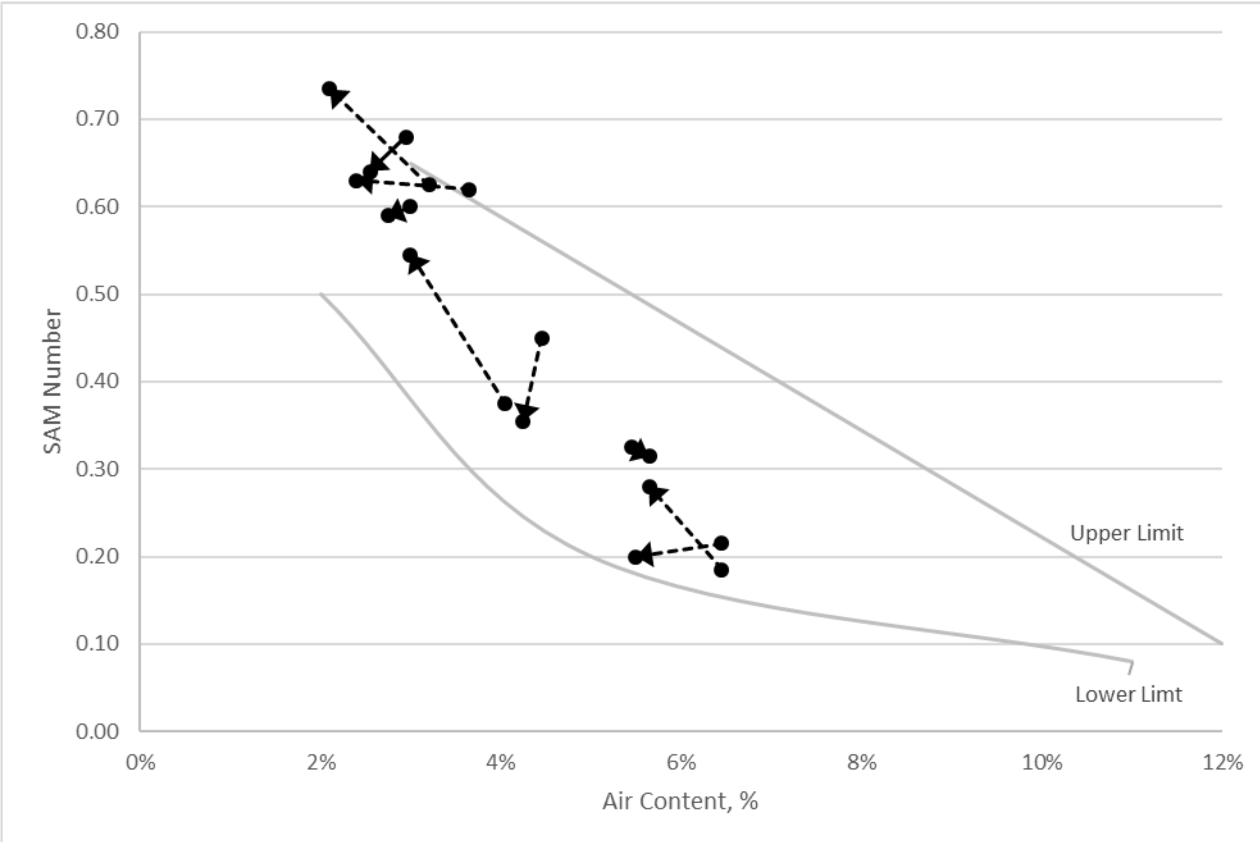

Figure 15 – Movement of SAM vs. Air from 0min mark to 15 min.

3.1.2 Pressure Data

In all mixtures, the pressure measured within the pipe network increased with time. Figure 16 shows a typical plot of the peak pressure for sensor 1. The curve follows an increase in pumping pressure over time. There are some gaps in the data where the pump stopped to test the concrete. There are also pressures measured that are above the others. It is not clear if these are real pressure values or are caused by some other artifact. A typical plot of the average pressure of the secondary curve is in Figure 17. The values for each of the four sensors are shown. As expected, sensor 1 showed the highest pressure.

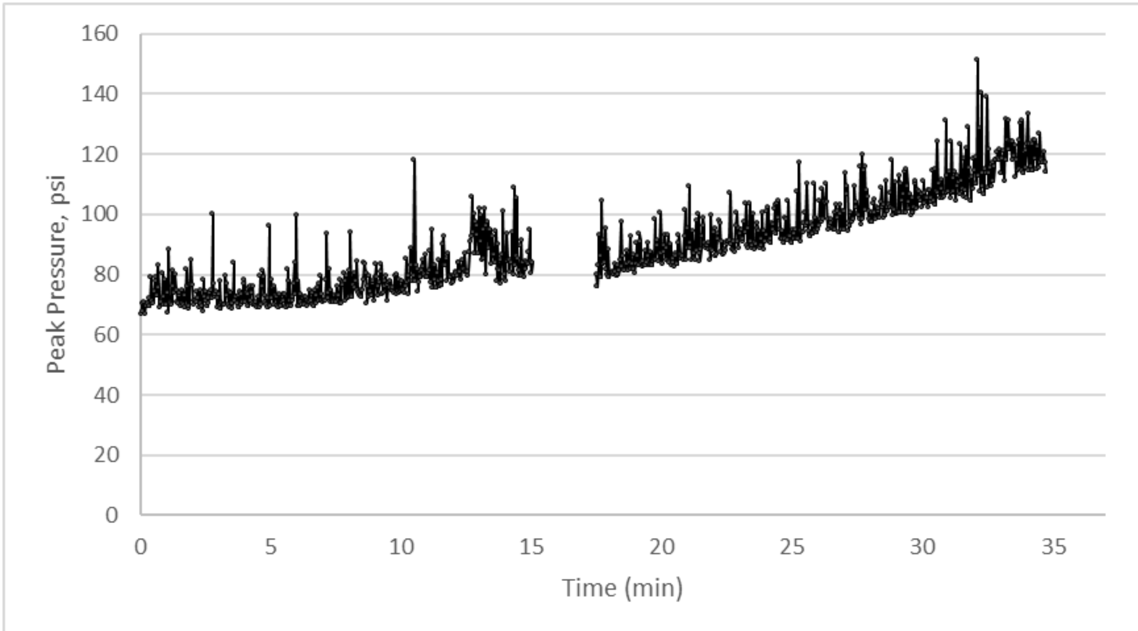

Figure 16 – Plot of Typical Peak Pressure Plot versus Time

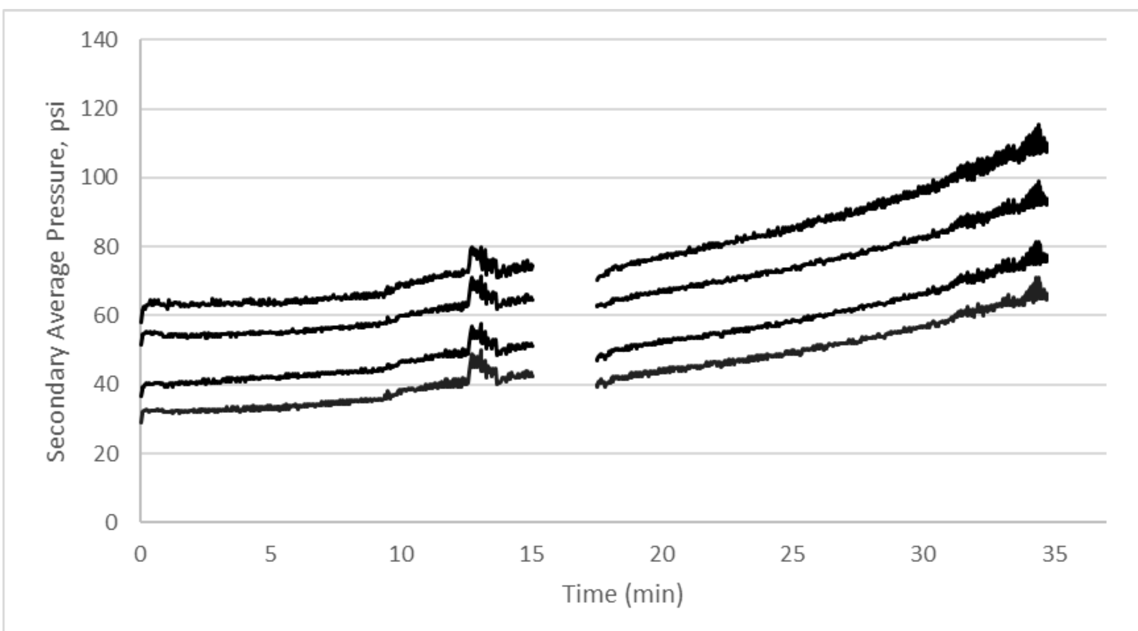

Figure 17 – Plot of Typical Secondary Curve Average Pressure Plot versus Time

To determine the peak pressure on the concrete at different sampling times, the last 10 full piston strokes were averaged. This provides a useful basis for comparing pressures between mixtures and reduces the impact of outliers. Note that the coefficient of variation of the last 10 strokes was always less than 10%, with common coefficients of variation of 2-4%. Figure 19 shows a plot of air content vs peak pressure for the samples where the pressures during pumping. Zero psi represents the air content of the concrete prior to pumping. Figure 19 plots the normalized air content versus peak pressure. The normalized air content was determined by dividing the air content prior to pumping by the measured air contents after pumping. These plots show the percentage of air loss during the first cycle through the pump is similar for all mixtures.

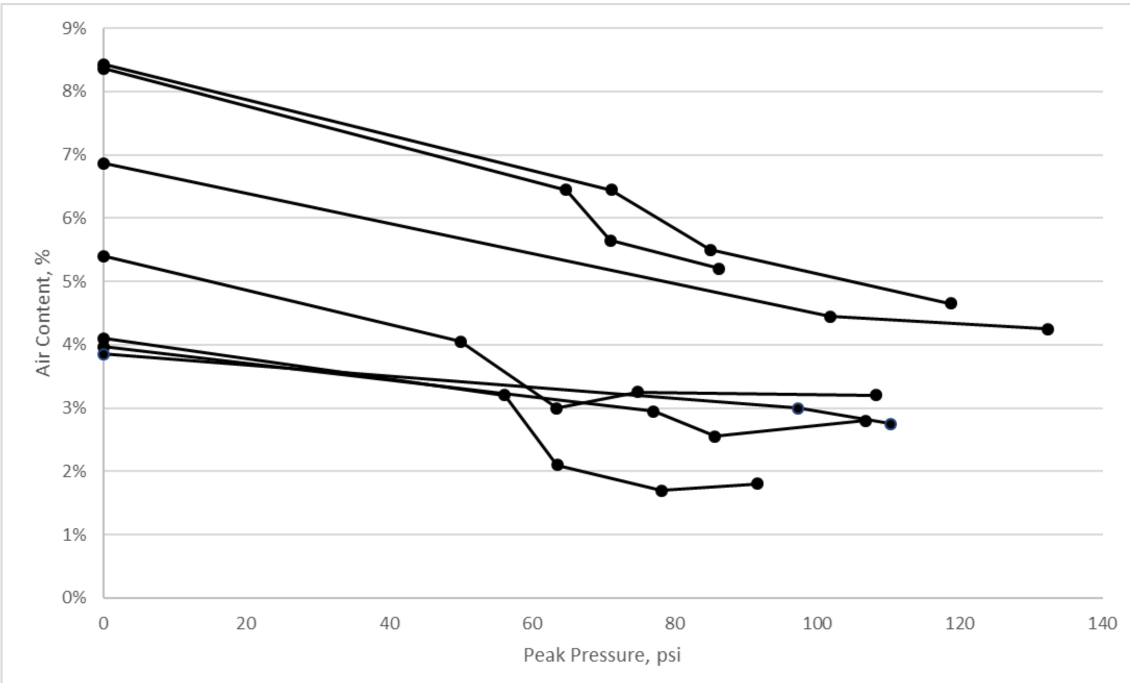

Figure 18 – Plot of Air Content vs. Peak Pressure

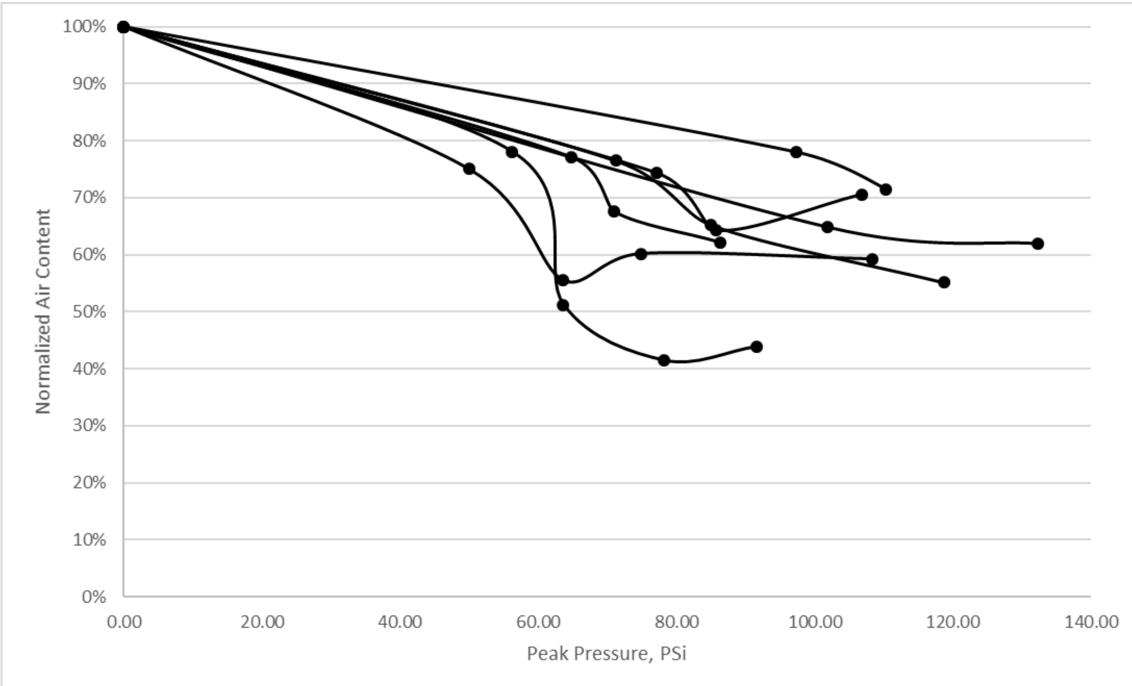

Figure 19 – Normalized Air vs. Peak Pressure

3.1.3 ASTM C666 – Durability Factor Data

The ASTM C666 results are in Table 3. It was decided that a Durability Factor less than 70% after 300 freeze-thaw cycles would be considered failing for this study. A Durability Factor of 70% is consistent with previous work [6]. All samples investigated showed a Durability Factor greater than 70% and would be satisfactory. This is surprising as the air contents for some of these mixtures were less than 2.5%. Figure 20 shows a plot of air versus Durability Factor. Most specifications require air contents to be greater than 4% when freeze-thaw durability is required and so this point has been highlighted with a dashed vertical line. Pumping frequently reduced the air content below these values and ASTM C666 freeze-thaw performance was satisfactory. Previous research has also shown a SAM Number less than 0.32 correlates to the point of satisfactory performance in ASTM C666 [6]. Figure 21 plots SAM Number before pumping and after pumping versus Durability Factor. Also shown on the graph is a line denoting a failing Durability Factor and a line denoting the recommended SAM Number for freeze-thaw performance. In addition, data points are included from previous publications to show the typical relationship between the SAM Number and Durability Factor [6]. The previous work was performed using the same cement, fly ash, coarse aggregate, and fine aggregate describes in section 2.1.1. Figure 21 shows that there is a large difference in freeze-thaw performance between samples taken after the pump and the previously published data set. The previously investigated data points were not pumped and so this could explain the large difference in performance. This will be discussed later in this document.

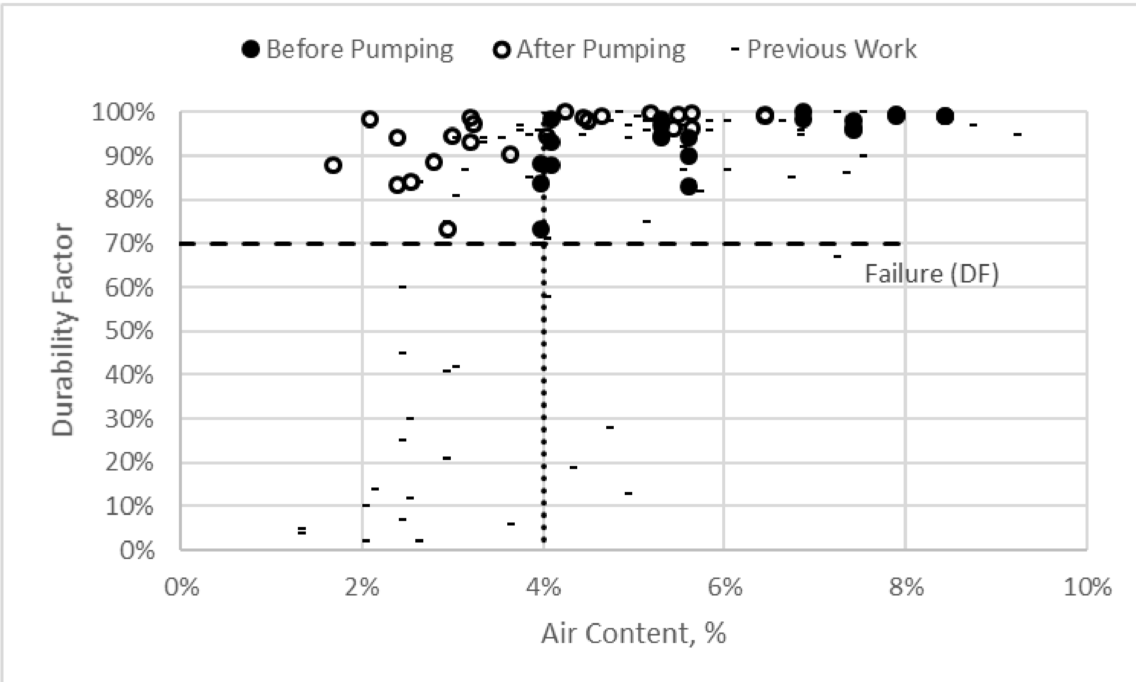

Figure 20 – Plot of Air versus Durability Factor

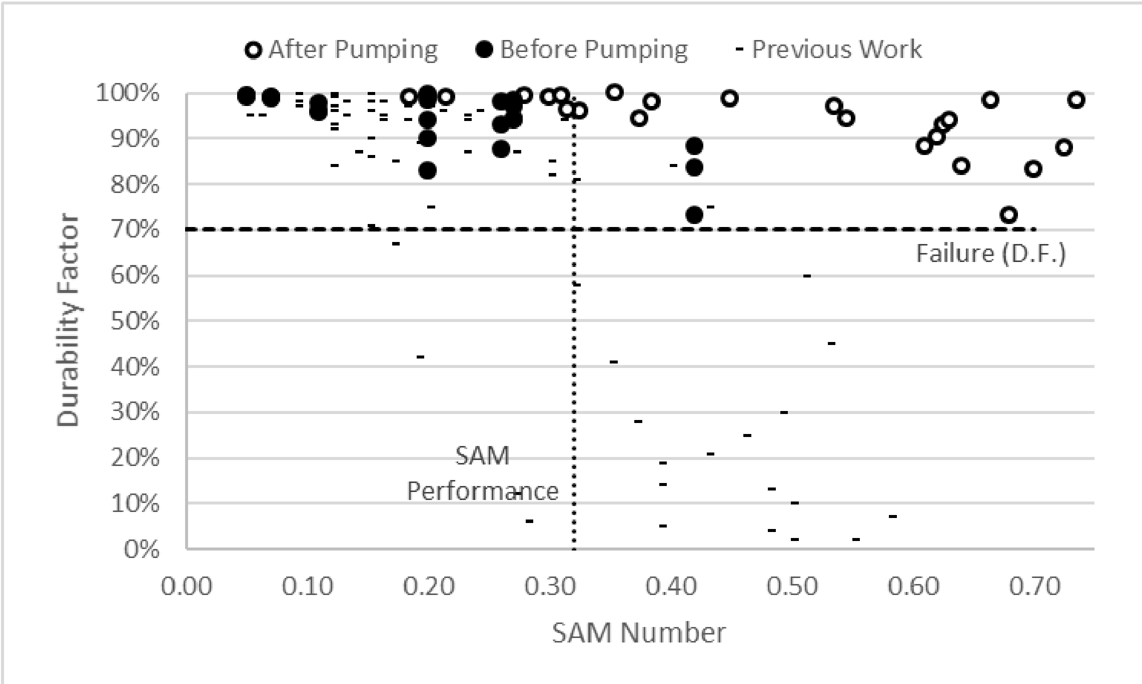

Figure 21 – Plot of SAM versus Durability Factor

3.1.4 ASTM C457 – Hardened Air Void Analysis Data

The hardened air void analysis was not complete at the publication of this report but this information will be included in future publications.

3.2 DISASSEMBLE TESTING PROCEDURE RESULTS

Table 4 shows the air content measured at different points in the pipe network, the average of all measurements, and the standard deviation. The disassemble testing procedure is outlined in section 2.3.4. The purpose of this procedure was to determine how air content changes with distance from the pump. Figure 6 in section 2.3.4 shows the points of sampling.

Table 4 – Measured Air content (%) at different points in the pipe network

Point	Air	Distance from Pump (ft)
Prior to Pumping	8.0%	----
a	5.1%	3.3
b	4.8%	6.6
c	4.7%	19.7
d	5.0%	25.4
e	5.1%	34.3
f	5.1%	44.1
Average Air	5.0%	
σ (Std. Dev.)	0.16%	

The air content measured prior to pumping was 8.0% and the air content was consistently 5.0% with minor variation at the different sample locations. This suggests that there is an approximately 3.0% air loss between the pump and just after the reducer, with no further air loss after that point.

3.3 SEGMENT RESULTS

This testing investigated how different pipe lengths and pipe diameters affected the air void system in concrete. The different pipe lengths and pipe sizes tested are in Table 5. Citric acid was not used in any of the mixtures. Table 5 includes the results for the segment testing procedure. Included is the slump, air content, and SAM Number before and after pumping. Table 6 includes the peak and secondary average pressures for pressure sensor 1 for the 5.0” pipe diameter testing. Pressures for the 4.0” pipe diameter testing were not recorded. As expected, the longer lengths of pipe resulted in higher pressures. To summarize the results, the longer length of pipe produced a greater SAM Number increase, and the smaller diameter pipe resulted in lower air contents.

Table 5 – Segment Division Testing Procedure Results

Pipe System Layout	Test Method	Sample Taken Before Pump	Sample Taken After Pump
Layout 1 - No Pipe	Slump (in.)	6.75	6.75
	Air	6.5	6.1
	SAM	0.1	0.14
Layout 2 - Reducer & 3.3ft of 4.0" Line	Slump (in.)	8.5	4.25
	Air	6.8	5.6
	SAM	0.16	0.28
Layout 3 - Reducer & 16.6ft of 4.0" Line	Slump (in.)	8	4.25
	Air	6.8	5.3
	SAM	0.16	0.31
Layout 4 - 6.8ft of 5.0" Line	Slump (in.)	6.5	5.5
	Air	6.6	6.4
	SAM	0.11	0.17
Layout 5 -19.3ft of 5.0" Line	Slump (in.)	6.25	5
	Air	6.6	6.4
	SAM	0.08	0.25

Table 6 – Pumping Pressures from the Segment Division Testing

Pipe System Layout	Sensor Information	Pressure (psi)
Layout 4 - 6.8ft of 5.0" Line	Sensor 1 Peak Pressure	7
	Sensor 1 Avg. of Secondary Pressure	5.5
Layout 5 -19.3ft of 5.0" Line	Sensor 1 Peak Pressure	18.9
	Sensor 1 Avg. of Secondary Pressure	17

4.0 DISCUSSION

All testing used a very similar mixture design with varying air contents and different 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.

4.1 USING AIR VOLUME AND THE SAM TO PREDICT FREEZE-THAW PERFORMANCE FOR PUMPED CONCRETE

The fresh air content and SAM Number measured after pumping did not reflect the freeze-thaw durability of the hardened concrete. In practice, an acceptable air void system is commonly identified as having an air content above 4.0% [7] and a SAM Number below 0.32 [6]. Lower SAM Numbers provide a safety factor against failure.

Only eight of the mixtures sampled after pumping met the recommended criteria, however, all 25 of the mixtures investigated after pumping had a Durability Factor greater than 73%. This outstanding freeze-thaw performance with air contents as low as 2% and high SAM Numbers above 0.40 does not match the performance of concrete that was not pumped as can be seen in Figure 20 and Figure 21.

This significant difference suggests that the air content and SAM Number measurements made immediately after pumping are not reliable indicators of freeze-thaw durability for these materials and conditions. This does not mean that these tests give incorrect measurements. However, it may mean that the air void system that the tests measure do not represent the air void system in the hardened concrete.

This data questions the practice of investigating the air content after it has been pumped. Further research is underway to investigate mixtures with substandard air void systems to see if this finding holds.

4.2 REDUCTION IN AIR CONTENT

During this testing, all circumstances that contribute to the vacuum and impact mechanisms of air modification were minimized. A slight vacuum may occur as the piston draws the concrete from the hopper. All drop heights were kept to less than 3 ft in the testing and so this should not cause air loss. By isolating the pressure dissolution mechanism, the results support that the applied pressures from pumping caused the changes in air content.

Both the disassemble procedure and segment testing showed that the air loss occurred after the reducer. Testing completed on the dissembled pipe network showed that the air content was constant after the reducer. Furthermore, a pipe segment with no reducer showed a minimal decrease in air content.

A reducer in a pipe network locally constricts the volume and so there is a significant amount of shearing or pressure increase of the concrete in the line. We feel that this disturbance of the concrete is an important factor in the air loss that occurs. Furthermore, this may not be the only loss of air reduction caused by pumping. This is an area of further research.

4.3 EVOLUTION OF THE AIR VOID SYSTEM

Figure 14 and Figure 15 shows that the air void system becomes coarser after pumping. This seems to occur with a single cycle through the pipe network, and then only small changes occur with additional pumping. These coarse air void systems suggest that the freeze-thaw durability of the concrete should be poor but satisfactory Durability Factors were found for all tested samples.

This may be caused by increased pumping pressures and shearing from the concrete traveling through the reducer and causing air bubbles to dissolve into the solution. This would explain the lower air contents measured immediately after pumping. However, the satisfactory freeze-thaw testing shows that the air bubbles likely return to the concrete before the concrete hardens. More research is needed to better understand this phenomenon.

5.0 CONCLUSION

The laboratory tests conducted show a significant amount of air volume was lost in the fresh concrete as a result of pumping. By isolating the pressure dissolution mechanism, the results suggest it was pumping the concrete in the reducer that took the concrete from 5.0” to 4.0”. In many cases the air volume and SAM Number measured after pumping predict that the concrete would have poor performance in ASTM C666 testing; however, every mixture showed outstanding ASTM C666 performance. This suggests that the air volume and SAM Number after pumping is not representative of the hardened concrete for these materials and procedures used in this testing. The results suggest that if a high-quality air void system is present prior to pumping then the air void system after pumping should be sufficient for freeze-thaw durability. Additional testing is underway and will be presented in future publications.

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