THE PUMPABILITY OF OPTIMIZED GRADED AGGREGATES

By

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THE PUMPABILITY OF OPTIMIZED GRADED AGGREGATES

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I could not have pumped concrete on my own. Completing this research required a large volume of concrete and a large team to complete testing. This work was as much managerial as it was academic; thankfully I had the honor of working with a group of undergraduates who were both intellectual and hardworking. Their competency brought respect to our team and benefitted all of Cooper Laboratory.

To everyone who worked long hours, cleared jammed pipelines, chipped concrete, fixed sensors, and shoveled rock; thank you.

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Abstract: This work validates the gradation boundaries presented by Dr. M. Daniel Cook in his 2015 dissertation. A large variety of concrete gradations were pumped through a pipeline and their pressures were measured, analyzed, and compared. From this, recommendations for aggregates gradations were made to reduce required energy to pump a concrete mixture. A widely used field test, called the Slump Test, was used extensively in this project. Recommendations for slump were also given as a means to determine if a concrete is pump-able. Also, concrete containing air-entraining admixtures were tested to determine what happens when pumping air-entrained concrete. Along with these mixtures, a novel Rapid Shear Test was created as a means for determining whether shear properties of fresh concrete is a major factor in the property changes of pumped concrete. Together, these tests and results provide general recommendations and a framework for further comparative testing in the future.

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CHAPTER I

INTRODUCTION TO OPTIMIZED GRADED CONCRETE

1.0 INTRODUCTION

Concrete is part of our every-day lives. Streets, sidewalks, foundations, and walls are made from concrete. Concrete makes up the floors of towering skyscrapers and provides piers and decks for expansive bridges. Even with this multitude of uses concrete is made of simple materials: rock, sand, cement, and water. While the science that goes behind the reactions between cement, water, and aggregates (rock and sand) is complex, the theory is simple; the blend of cement and water work together to form a binding paste that holds rock and sand together to form man made solid stone, concrete.

Large amounts of funding have been poured into the research between these reactions to learn how the concrete can be made stronger, more durable, and more efficient. Part of that research involves the study of aggregates; more specifically how the combination of aggregates sizes can affect the properties of concrete. This project is part of a much larger one that is investigated.

Recent research at Oklahoma State University has contributed to our understanding of aggregate gradation knowledge. This has allowed important recommendations to be made for aggregate gradation to optimize the positive properties of concrete (i.e. higher strength, durability, workability). Cook (2015) provides methods for determining maximum and minimum boundaries for specific aggregate sizes to better create consistent, workable concretes. This thesis extends on his work to investigate how these mixtures perform while pumping.

1.1 OPTIMIZED GRADED CONCRETE

Controlling the amount of each sieve size of aggregate in a concrete mixture in order to control or optimize certain properties of concrete is called optimized graded concrete. In 2015, specifications were developed for the maximum and minimum boundaries as well as effects for breaking those boundaries for each sieve size (Cook 2015). Figure 1 shows those specifications, known as the Tarantula Curve, because it resembles the silhouette of a tarantula.

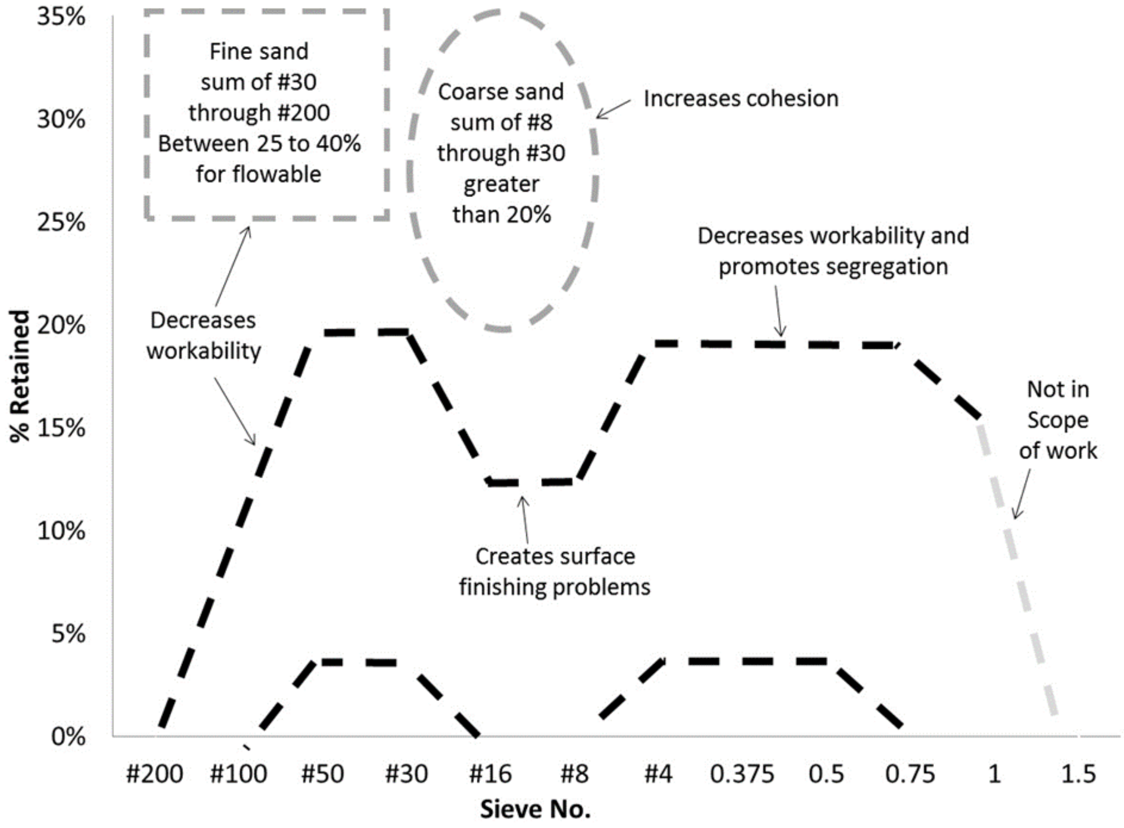

Figure 1: The Tarantula Curve gives conservative boundaries for determine the maximum and minimum quantities of each aggregate.

In addition to the Tarantula Curve, the total sum of fine sands in the mixture were given boundaries as well. Fine Sands include sieve sizes #200 to #30. The total percent of those relative to the concrete mixture drastically affects the workability properties of concrete. Too little fine sands and the concrete segregates, causing a non-homogenous mixture. Too much fine sands and the concrete become too stiff to work, or too stiff to flow through the pipeline. In Dr. Cook's dissertation, he also reports a limit for minimum and maximum fine sand content, shown in Figure 2 (Cook 2015). For this research project, sand from Source A was used.

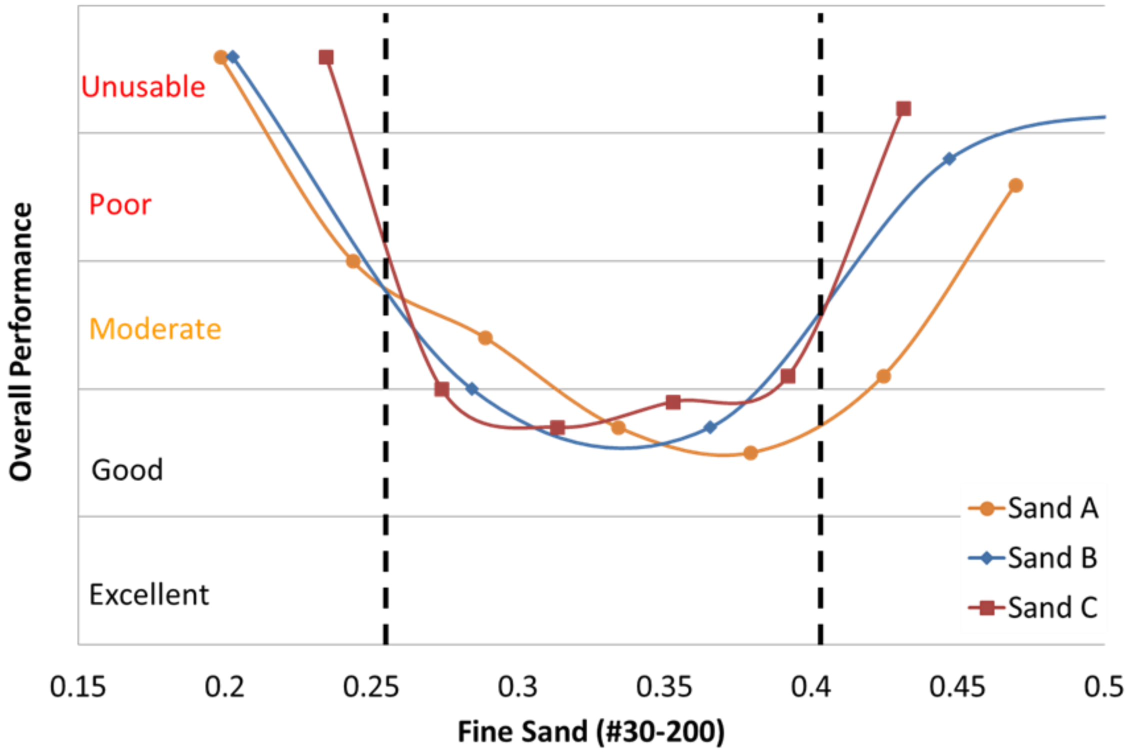

Figure 2: Fine sand limits help determine a range for workable concretes.

Using these two figures in combination for aggregate gradation provides a useful tool for creating workable concretes quickly. All one needs to do is proportion their coarse aggregates, sands, and possibly intermediate aggregates properly to achieve a gradation within these bounds.

As part of the testing process to determining these bounds, a rheometer was used to find static and dynamic yield stresses in concretes with varying aggregate gradations. Low static and dynamic yield stresses, paired with industry testing methods such as the slump test, provide numerical values to indicate which gradations provide the most flowable, or workable, concrete. After a close to 200 different concrete mixtures were tested, a rating system was devised by Cook (2015) to provide insight to the most workable concretes. This system is seen in Table 1.

Table 1: Ranking system for workability of concrete. A is optimal, F is failure.

Workability Performance Scale	**Slump Test** (in)	**Visual Observation**	**ICAR Rheometer**		
			Static Yield Stress (psi)	Dynamic Yield Stress (psi)	Plastic Viscosity (psi/sec)
Excellent (A)	8 to 6	A or 1	< 0.145	< 0.036	< 0.001
Good (B)	6 to 4	B or 2	0.145-0.218	0.036-0.073	0.001 to 0.002
Moderate (C)	4 to 2	C or 3	0.218-0.290	0.073-0.145	0.002 to 0.003
Poor (D)	2 to 0	D or 4	> 0.290	> 0.145	> 0.004
Unusable (F)	0	F or 5	Too stiff	Too Stiff	Too Stiff

The goal of this project is to determine if these specifications work on pumpable concretes. A wide variety of gradations will be used. Later, the amount of paste, cement and water, will be changed as well as air-entrainers that increase the amount of air bubbles in a concrete mixture. The combination of tests hope to provide a framework and series of tests that have the ability to specify the amount of aggregates, cements, and admixtures needed to create a concrete that is both pumpable and cost-effective (reducing the amount of cement in the mixture).

CHAPTER II

LABORATORY EVALUATIONS OF PUMPABLE CONCRETE MIXTURES

2.0 INTRODUCTION

Since the 1930s, concrete pumps have been used to move the concrete from the ready-mix truck to the final destination on the jobsite (Kosmatka 2011, Neville 2012). Modern day concrete pumps have horizontal hydraulic pistons to push the concrete through rigid and/or flexible piping (Kosmatka 2011, Neville 2012). Since these concrete mixtures can be required to travel long distances through these pipes, this has required special concrete mixtures. These mixtures are required to be cohesive, flowable, and still able to be finished. While admixtures, secondary cementitious materials, and paste volume contribute to these pumpable concrete mixtures, a major focus has been placed on aggregate gradation. It would be helpful to develop a gradation specifically for pumping concrete. If the gradation is designed incorrectly then this will cause segregation, higher chance pipe jams, problems with surface finishability (The Contractor's Guide 2005).

While concrete pumps are amazing machines that are capable of handling a lot of different materials, it is important that the concrete mixtures do not require the machines to work excessively where they require a greater amount of repair or increase the likelihood for pipe jams. This means a desirable performance of a mixture should have minimal pressures, low segregation, and meet other performance requirements.

2.1 EXPERIMENTAL METHODS

2.1.1 Materials

2.1.1.1 Concrete Mixture Design

All the concrete mixtures described in this work were prepared using a Type I cement that meets the requirements of ASTM C150 with 20% ASTM C618 class C fly ash replacement by weight. To investigate the impact of the aggregate gradation, all of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 611 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 28.4% for the mixture volume. A citric acid was used at a dosage of 0.25% by weight of cementitious materials. When added to the concrete mixture the citric acid acted as a setting retarder and also a water reducer. In each mixture the sand came from a single natural sand (sand A) source and the course and intermediate aggregates came from a single dolomitic limestone (limestone A) . The aggregate proportions were purposely varied between each pump session and the paste parameters were held constant, this allowed comparisons between the workability of the mixtures of different combined gradations.

2.1.1.2 Grout Mix Design

The most common method of starting to pump concrete through the line is to start with a grout mixture (Neville 2012 and The Contractor’s Guide 2005).

The grout is used to line the walls of the pipe and reduce the amount of segregation that occurs in the concrete from pumping (Neville 2012 and The Contractor’s Guide 2005). Using a Type I cement that meets the requirements of ASTM C150, the grout mixture was designed with a w/cm of 0.40, 1006 lbs/cy of cement, 2514 lbs/cy of sand. A citric acid dosage of 0.25% by weight of cementitious materials was added to the grout mixture to help retard the hydration. The grout aggregate also came from Sand A.

2.1.2 Equipment

2.1.2.1 Concrete Pump and Pipe Network

A Putzmeister TK50 concrete pump was used for this research and is shown in Figure 3. This pump has a 96 HP diesel engine and 5 ft^3 hopper. The pump has two cylinders that draw in concrete from the hopper and then force it through the pipeline via a shifting cylinder in the hopper.

Figure 3: The concrete pump used in this work (Putzmeister TK 50).

An instrumented 52.5 ft. pipe network with three 90° bends, and a 9.8 ft. rubber hose was used to evaluate each concrete mixture. An overview of the pipe network is shown in Figure 4. The output diameter of the pump is 5 in. while the pipe network has a diameter of 4 in. A 3.3 ft. long reducer pipe was attached at the pump to make this transition in diameter. Sensor 1 is immediately after the reducer and measures pressures in the line most directly related to the output pressure. Sensor 2 measures pressure in the line 13.1 ft. away from Sensor 1 and is also directly in front of the first 90° bend. Sensor 3 is right after the first bend and thus using the pressure from Sensor 2 and 3, the loss in pressure caused by the bend can be measured. Sensor 4 is placed after the second 90° bend and can be used with Sensor 3 to measure pressure changes between the second bend. The pump loops on itself in order to recirculate material while testing. This also allows the change in material over time to be measured. At the end of the pipeline a 9.8 ft. rubber hose is attached. This hose repositions the flow of concrete either to large waste barrels or back into the hopper to recirculate the concrete through the pipe network.

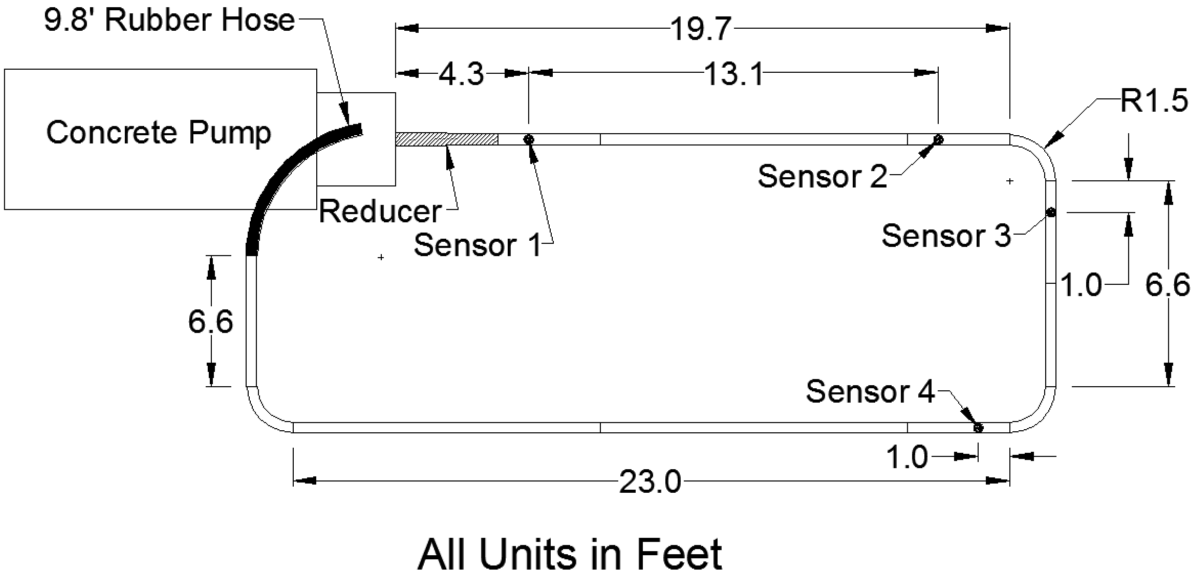

Figure 4: Plan view of the pump layout.

The TK 50 pump has two primary settings, engine revolutions per minutes (rpm) and piston volume. The rpm of the engine can range from 900 to 2200 rpm and the maximum piston volume is 0.57 ft^3. The volume of the piston was measured by filling the pump's hopper with water and then pumping out a single piston stroke into a bucket that was then weighed. The volume of the piston was calculated by using the unit weight of water. This was done 30 times and the average was taken. The coefficient of variation was 6%.

The TK 50 pump has dual pistons that force concrete into the line. As one piston pushes material into the pipeline, the other piston is pulling concrete from the hopper into a cylinder. Then a sealed, rotating coupling with a diameter of 5 in. switches between the pistons allowing the piston full of material to force it into the line and the recently empty piston to pull more material from the hopper. In some preliminary testing it was found that 1500 rpm gave enough power and time between piston strokes to accurately measure the pressure in the line. In order to maintain consistency between investigations it was easiest to use the full capacity of the piston. This gave us the pump settings used in this work, 1500 rpm and 0.57 ft^3.

The total volume of the pipe network, including the reducer, 90°, and rubber hose, is 6.0 ft^3. Since the average piston stroke moves 0.57 ft^3 of material, it would require 10.5 piston strokes to move concrete through the entire line and have it discharge again into the pump.

2.1.2.2 Pressure Sensor Assembly

Four pressure sensor assemblies were used along the pipeline to measure pressure in the concrete while pumping. A typical assembly can be seen in Figure 5. The GE 5000 pressure sensor is capable of measuring pressures between -14.5 to 507 psi with 0.5 psi accuracy by converting pressures into a voltage that ranges between 0 and 5000 mV.

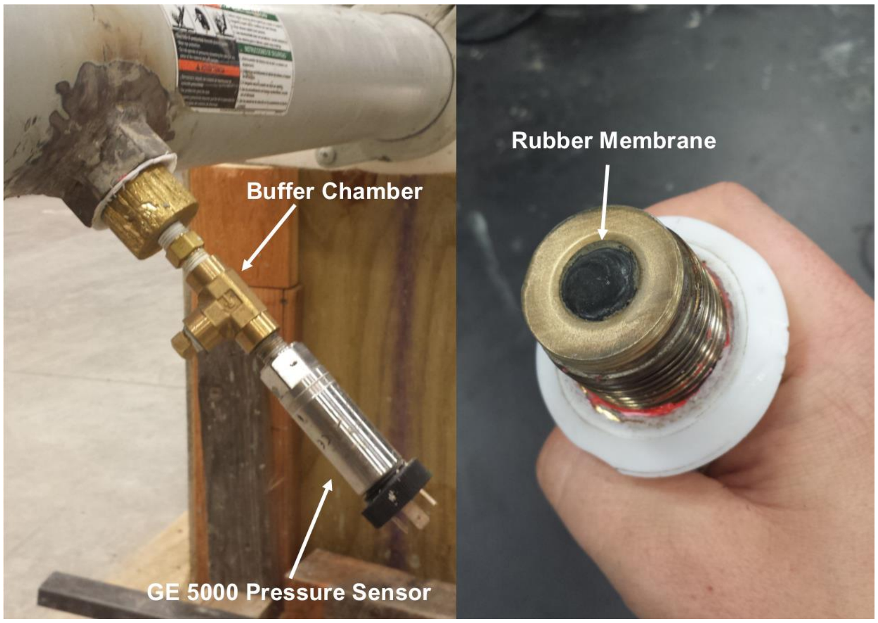

Figure 5: An overview of the pressure sensor is shown. Oil fills the buffer chamber and as the rubber membrane moves the pressure can be read by the pressure sensor.

These pressure sensors would be damaged if they were directly subjected to the concrete. Because of this, a buffer chamber was created and filled with an incompressible oil. While a flexible membrane was made at one end of the chamber, the sensor was used at the other end of the chamber. As the concrete pressure in the line increased it would move the membrane, and then in turn would cause the oil pressure to increase the GE 5000 pressure sensor. The sensor would then read these changes in the pressure of the oil and convert them to a voltage.

To attach the sensor to the pipe, 1.125 in. diameter hole was drilled in the pipe. Next, a nut was welded to the outside of the pipe and the end of the buffer chamber was threaded and then screwed into the nut until the flexible membrane was adjacent to the walls of the pipe. The pipe was rotated so that the sensors were 30° away from pointing directly downward. This kept aggregate, paste, and water from collecting on top of the flexible membrane which might reduce the sensitivity and accuracy of the sensor. Pressure in the pipeline is taken over the entire data collection period at 0.02 second intervals.

To ensure each sensor was performing correctly and repeatable, the sensor assemblies were calibrated by hooking them to a water filled pipe where the pressure was systematically changed. Typical results of this calibration curve is shown in Figure 6.

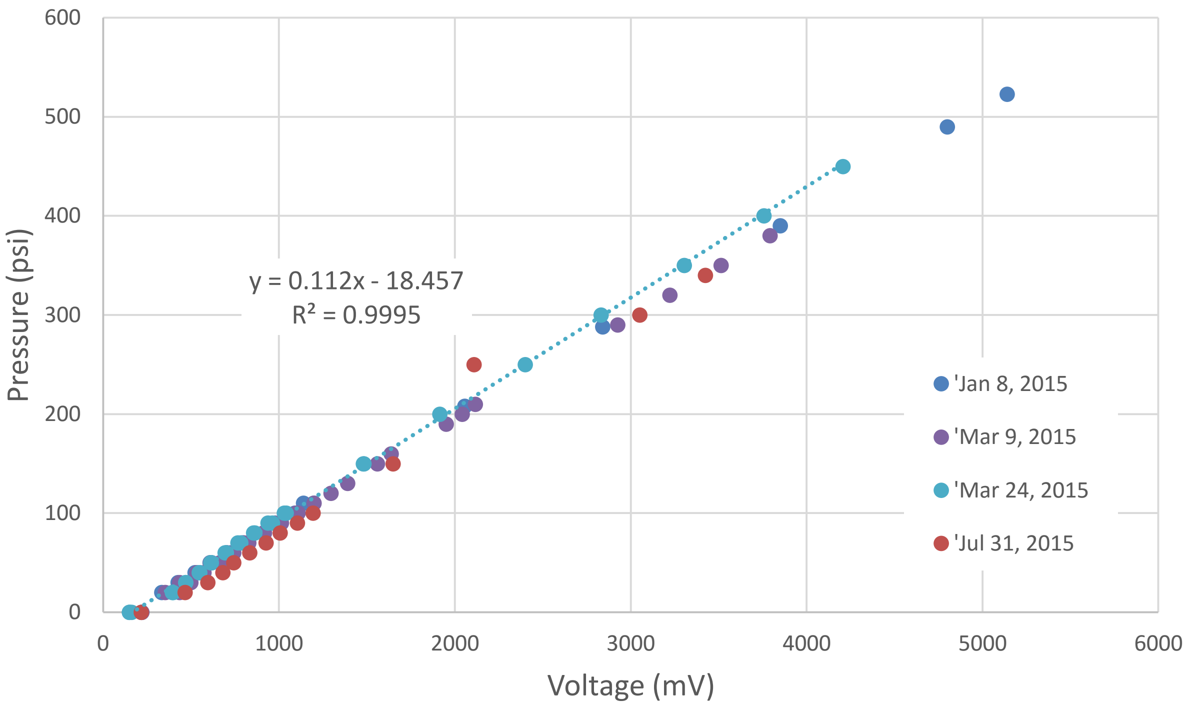

Figure 6: The sensors were calibrated using a pressure chamber filled with water and then using a best fit line.

It should be noted the y-intercept values slightly shift over time but the slope of the calibration lines remains constant. Because of this a "zero pressure" sensor reading was determined by recorded the sensor's internal pressure value when the pipelines were empty. This gauge reading was set equal to the zero pressure value. Measured increases in pressure were then added to these initial values. These increases were developed based on the water pressure calibration curves for each sensor.

2.1.3 Testing Methods

2.1.3.1 Pumping Procedure

Every pumping session consists of three parts: mixing, data collection, and clean up. Mixing consists of one 4 ft^3 grout mixture and three identical 5 ft^3 optimized graded concrete mixtures. All of the aggregate proportions for each mixture can be seen in Table 2.

Table 2: The concrete mixtures that were used during testing.

Mixture Design	Cement (lbs./cy)	Fly Ash (lbs./cy)	Water (lbs./cy)	Coarse limestone A (SSD lbs./cy)	Intermediate limestone A (SSD lbs./cy)	Sand A (SSD lbs./cy)
C-01	489	122	275	1150	539	1450
C-01 6S	451	113	253	1447	530	1183
C-01 5.5S	414	103	233	1464	531	1263
C-02	489	122	275	1610	58.8	1470
C-03	489	122	275	1460	210	1460
C-04	489	122	275	882	813	1440
C-05	489	122	275	964	728	1440
C-06	489	122	275	1550	753	864
C-07	489	122	275	1450	698	1010
C-08	489	122	275	1330	638	1180
C-09	489	122	275	1240	589	1310
C-10	489	122	275	1020	474	1630
C-11	489	122	275	760	941	1440
C-12	489	122	275	1820	52.2	1280
C-13	489	122	275	723	313	2070

2.1.3.2 Mixing

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 and spun and a representative sample was taken to determine the moisture content to apply the correction. 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 material and the remaining water with the citric acid was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes.

The grout mixture had a typical slump of 8.25 in. and a unit weight of 137 lbs./ft^3. Again, the grout was used to create an initial mortar layer around the pipes to reduce friction in the line and reduce segregation as is typical in the concrete pumping industry. To charge the pump, the grout was added first and a few strokes were used to lower the hopper and fill the lines. Next, the concrete was added. The end of the flexible hose was placed in a waste container as the pump was run. The waste container first filled with grout, and then as soon as concrete started exiting through the hose the pump was stopped and the flexible hose was moved to discharge back into the hopper. The pump continued to run for at least 10 piston strokes to remove any air gaps that may have occurred while adding concrete to the hopper. After the air was removed the material testing was started and the time is marked at 0 minutes.

Each concrete mixture was tested with the Slump Test, Unit Weight, and the ICAR Rheometer. For the Stress Growth Test, the first three values were taken and then averaged. The Rheometer's Flow Curve Test was conducted until three test values with an r^2 value higher than 0.75. If less than three values were able to be acquired, the average of the values was still recorded but marked as "undesirable" as the mixture was close to the lower range of workability able to be measured by the rheometer. If no values with an r-squared value above 0.75 were acquired, the mixture was considered failed and no value was recorded.

2.1.3.3 Data Collection

In order to sample concrete, the pump is stopped and the rubber hose is disconnected from the hopper. Concrete from the flexible line is then collected by holding the rubber hose over a large plastic bin and pumping for approximately two piston strokes. Concrete falls from the hose into the bin and then slump and unit weight tests are completed from that material. This same method is used to fill the container used for rheometer testing. Conducting the rheometer tests requires approximately 45 seconds per test and the test must be done multiple times to ensure accurate measurements. To accommodate this, the time intervals are spaced at approximately 15 min to allow for the testing. After these tests are completed then the material is returned to the hopper to recirculate.

After the material is gathered for testing at its respective time interval, the pump is run at 1500 rpm for 30 piston strokes and then 1200 rpm for 30 piston strokes. After that, the rpms are returned to 1500 until the next testing interval to ensure that the pump has enough energy to keep from seizing if the mixture stiffens. See Figure 7 for the pumping testing procedure over time.

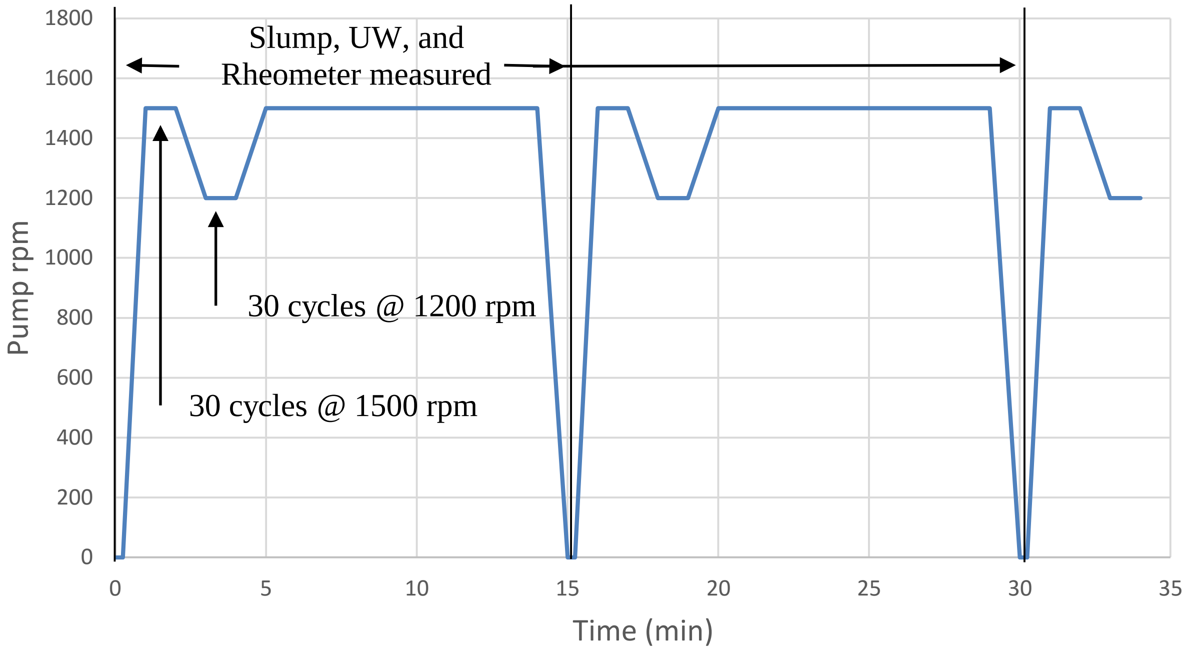

Figure 7: A typical pump cycle over time and the tests completed at different intervals.

If the pump needed more than 1500 rpm to keep pumping, then the mixture is considered too stiff. When a mixture becomes too stiff, the rpms of the pump will decrease and the piston will stop until the rpms of the engine are increased high enough to resume pumping. This rarely happens, and only occurs when the workability is very low. Throughout testing, a slump ranging from 3 in. to 1.5 in. corresponded to poor pumping performance. Also, if it is noticed that only aggregates are coming out of the rubber hose with no paste, then the concrete is segregating. When a mixture segregates, the line will block and the flow loop must be taken apart to clean the pipes. This would not be acceptable in industry and so is deemed a failure in the testing. Since we are interested in not causing premature failure of the pump, concrete pressures that are higher than the average would be reasons to call the mixture "undesirable" for pumping, though not considered failing in most cases.

2.1.3.4 Pressure Sensor Output

The data from each pressure sensor is retrieved and then processed. A typical pressure curve, showing values from all four sensors, is shown in Figure 8. This figure shows two piston strokes.

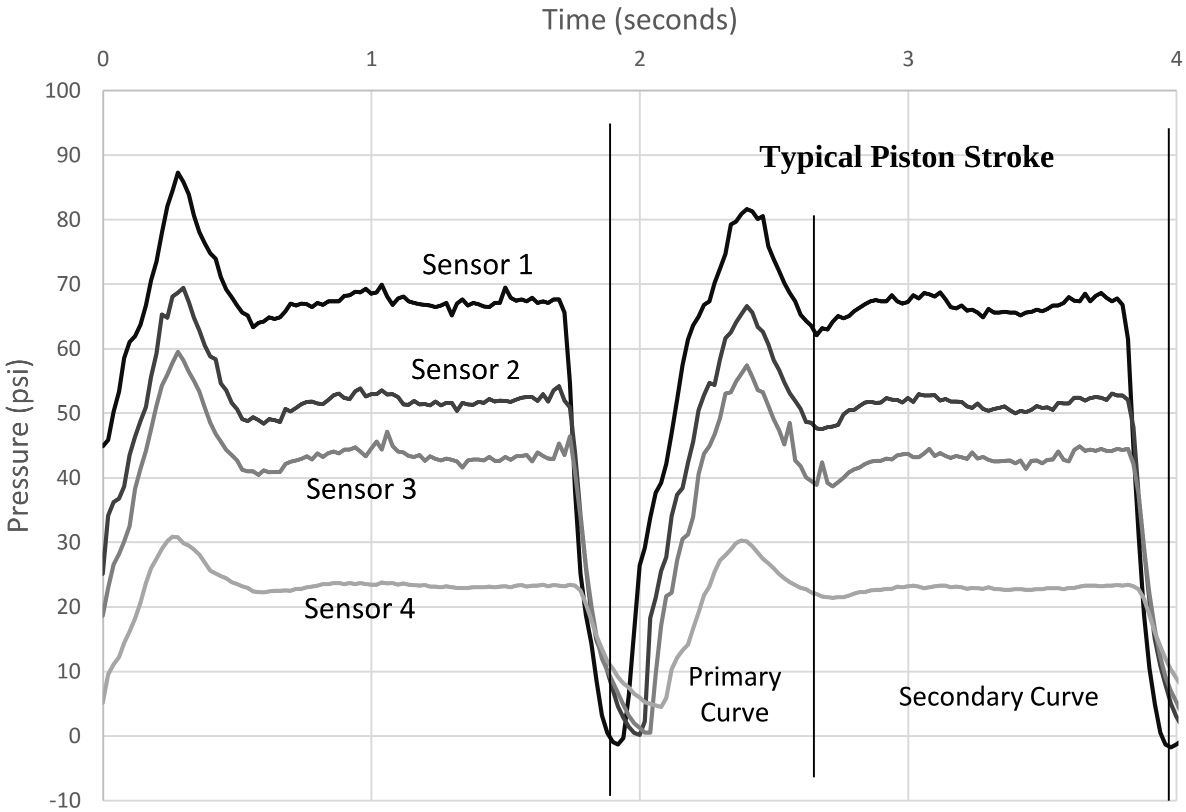

Figure 8: A typical pumping pressure curve has a primary and secondary curve.

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.

Self-authored computer code is used to analyze the data for the primary and secondary curves. For each of the four sensors the maximum value from 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 found by finding a local minimum value after the primary curve. The middle 70% of the secondary curve is analyzed as this portion is relatively flat. 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 can be found in Figure 9. When the pump was running as expected 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 greatly increase.

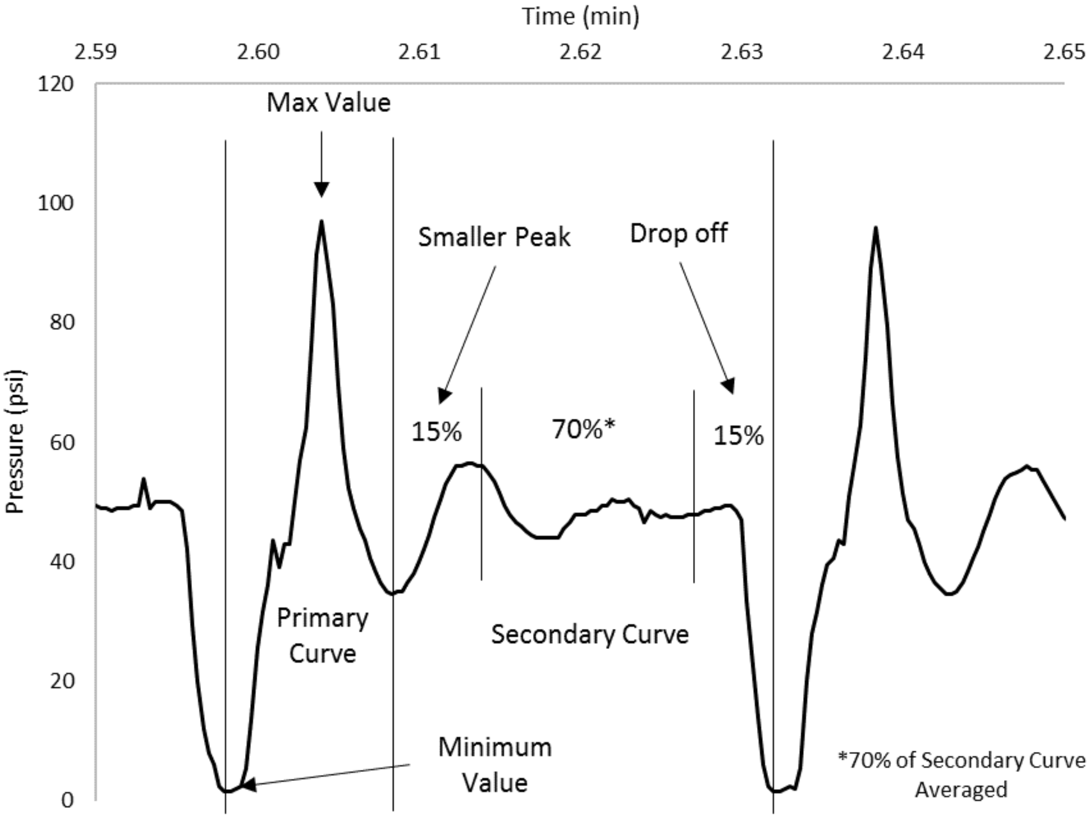

Figure 9: The maximum value of the primary curve is found as well as average of the center 70% of the secondary curve.

A typical coefficient of variation value, when both the smaller peak and the drop off are properly excluded, ranges from 0.2% to 10%. When a value is higher than 10%, it usually means that the buffer zones did not properly exclude the two problem areas in the secondary curve. Since there are around 750 piston strokes in a normal pump session lasting around 40 minutes, secondary curve averages with a coefficient of variation greater than 10% were excluded from the data reported. When this was done the text mentions it.

2.2 RESULTS AND DISCUSSION

In all cases the pressure in the line decreased with distance away from the pump. This is most likely due to an experienced friction against the walls of the pipeline. Recall that both Sensor 1 and Sensor 2 were measured in straight pipe that are 13.1 ft. apart. Next, there is a 90° bend and then Sensor 3. Then there was another 90° bend and then Sensor 4. This decrease in pressure is caused by friction of the pipe walls and losses from the change in direction caused by the 90° bend. In some cases, when the line contained large pockets of air, a segregating mixture, or concrete that was too stiff, then the pressure curves looked erratic. Figure 10 shows examples of erratic curves from different observed phenomenon. These curves were found when pressure data was obtained from the sensors after pumping ended.

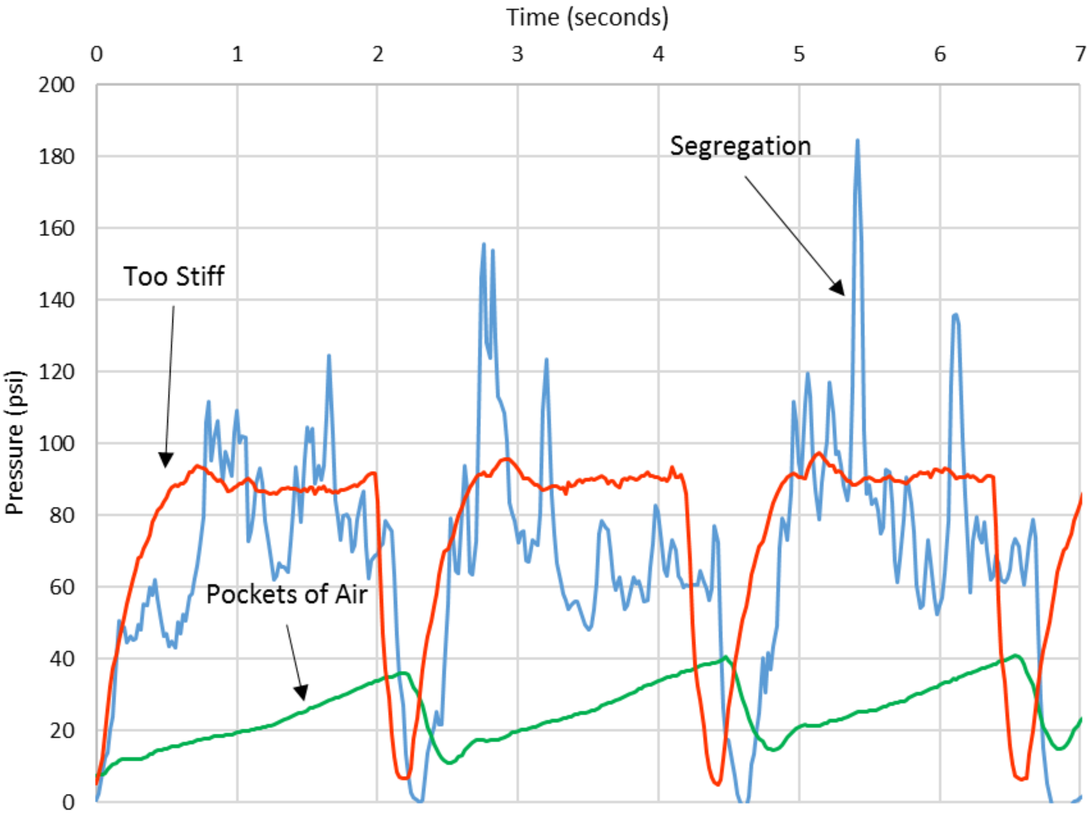

Figure 10: Air gaps, low workability, and segregation can be seen on the pump curves.

2.2.1 Mixture Repeatability

One mixture was repeated three times. Their secondary pressure curves were tabulated in Table 3 to analyze the pressure variability for a single mixture.

Table 3: Secondary pressure curve values from Sensor 2 (units in psi).

	C-01_02 3 min	**C-01_04** 2 min	**C-01_05** 1 min	
	50.0	42.0	44.0	
	50.5	42.5	47.0	
	51.0	42.0	47.5	
	51.5	42.0	48.5	
	51.5	42.0	48.0	
	51.5	42.5	48.5	
	51.5	41.5	48.0	
	51.0	42.0	48.0	
	50.5	41.5	47.5	
	50.0	41.5	48.0	
	50.0	42.0	47.5	
	49.5	41.5	48.0	
	49.5	42.0	47.5	
	49.5	41.5	48.0	
	49.5	42.0	47.5	
	50.0	41.5	48.0	
	50.0	42.0	48.0	
	50.5	42.5	48.0	
	51.0	42.0	48.0	
	51.5	42.5	48.0	
	51.5	42.5	48.0	
	51.5	42.0	48.5	
	51.5	42.5	48.0	
	51.5	41.5	48.0	
	51.0	42.5	47.5	
	51.0	42.0	48.0	
	50.5	42.0	47.5	
	50.5	42.0	48.0	
	50.5	42.0	47.5	
	50.5	42.0	47.5	**Totals**
Average	**50.7**	**42.0**	**47.7**	**46.8**
Std. Dev	**0.7**	**0.3**	**0.8**	**3.6**
c_v	**1.38%**	**0.81%**	**1.62%**	**7.7%**

These results show that within a given measurement of a mixture that the variance is very small with the largest coefficient of variation of 1.62%. However, between measurements the coefficient variation was larger at 7.7%. This data suggests that there is more variation in replicating a concrete mixture than making a repeated measurement with the pipe loop. This data also suggests that two mixtures can vary by about 7 psi (this is twice the standard deviation between the three mixtures) and their performance can be considered similar.

2.2.2 Average Pressure of the Secondary Curves

The pressure curves were variable depending on the concrete mixture but in most cases a primary and secondary curve could be identified. To determine the average values reported in this paper, 30 values, each with a coefficient of variation less than 10%, were used unless otherwise specified. In all cases, these measurements were made at 0, 15, and 30 minutes after pumping began. The coefficient of variation was never greater than 4% in a pressure average. Table 4 shows the recorded pressure data at 1500 rpm for each mixture at each time interval.

When all results were compiled, a Sensor 2 value of 60 psi was a conservative estimate for when a concrete mixture became undesirable to pump. This is about a 25% increase from the initial pumping pressure for well performing mixes. Also, coincidentally the mixture's slump was typically less than or equal to 3 in. and acquiring values from the ICAR Rheometer became difficult. All testing time intervals that yield a pressure greater than 60 psi for Sensor 2 are highlighted in yellow. Events that caused the mixture to become unusable are highlighted in red to signify an unacceptable mixture.

Table 4: Secondary curve averages for each mix on each sensor over time. Undesirable values are marked in yellow. Mixtures where the pump stopped are marked in red.

		Time (min)	Sensor 1 (psi)	Sensor 2 (psi)	Sensor 3 (psi)	Sensor 4 (psi)	Comments
Coarse Agg Gradations	**1/2" - 15.7%**	0	**Sensor Error**	48.0	39.5	26.5	
		15		42.0	36.5	25.5	
		30		45.5	41.0	29.5	
		45		54.5	50.0	37.5	
	1/2" = 20%	0	64.0	48.0	43.0	38.0	
		18	87.5	70.5	61.0	53.5	
	1/2" = 22%	0	63.0	55.5	43.0	38.0	
		15	87.5	75.0	61.5	54.0	Air Gaps
	1/2" = 25%	0	41.5	35.0	30.0	24.5	Segregation
		15	43.5	37.5	31.5	21.5	
		30	55.0	48.0	40.0	28.0	
		45	72.0	63.0	52.0	37.0	
Int Agg Gradations	**#4 = 15.6%**	0	**Sensor Error**	48.0	39.5	26.5	
		15		42.0	36.5	25.5	
		30		45.5	41.0	29.5	
		45		54.5	50.0	37.5	
	#4 = 20%	0	67.5	52.5	44.0	29.5	
		12.5	81.0	63.5	54.2	35.0	
	#4 = 22%	0	58.0	46.0	38.0	29.0	
		15	78.5	62.5	53.5	41.5	Air Gaps
	#4 = 25%	0	54.0	42.5	35.5	22.0	
		15	55.5	45.5	37.5	23.5	
		30	76.0	64.0	52.5	34.5	
		37	97.0	82.5	68.0	47.5	
Fine Sand Gradations	**FS = 24%**	0	**Pipe Jam**				
	FS = 28%	0	68.0*	55.5*	45.0*	30.5*	
		15	78.5	64.0	53.5	35.5	
		30	96.5	81.5	71.0	45.5	
	FS = 32.5%	2.5	76.0	59.0	49.0	32.5	
		15	83.5	65.0	55.0	36.5	
		27	101.5	80.0	68.5	45.0	
	FS = 36.1%	3.5	**Sensor Error**	50.0	42.5	26.5	
		17		55.0	47.0	29.5	
		30		68.0	58.5	36.0	
	FS = 39.8%	0	**Sensor Error**	48.0	39.5	26.5	
		15		42.0	36.5	25.5	
		30		45.5	41.0	29.5	
		45		54.5	50.0	37.5	
	FS = 44.6%	4	**Sensor Error**	64.0	54.5	32.6	
	FS = 56.5%	3.5	94.5	77.0	62.5	50.5	Unworkable

* Only 23 values instead of the typical 30 could be gathered at this time period due to secondary curves with an unacceptable coefficient of variation.

Table 5: Secondary curve averages for variable sack contents. Undesirable values are marked in yellow.

		Time (min)	Sensor 1 (psi)	Sensor 2 (psi)	Sensor 3 (psi)	Sensor 4 (psi)
Paste Content	**5.5 Sack**	0	93.5	66.5	64.5	59.0
	6.0 Sack	0	89.0	63.5	58.5	52.5
		15	89.0	66.5	60.0	57.5
		30	107.0	82.5	73.5	73.5
	6.5 Sack	0	**Sensor Error**	48.0	39.5	26.5
		15		42.0	36.5	25.5
		30		45.5	41.0	29.5
		45		54.5	50.0	37.5

2.2.2.1 Changing Pump Settings

As discussed previously, during testing the rpms of the engine were changed. This would vary the pressure from the initial piston stroke and the secondary pressure caused by the advancement of the piston. At the 1200 rpm two mixtures caused the pump to form air gaps. This was determined by examining their pressure curves. These were mixtures with high intermediate aggregate (22% retained on the #4) and one mixture with high coarse aggregate (22% retained on the ½”). These are noted above in Table 3. When the rpms were increased to 1500 rpm, the air gaps disappeared. It is interesting that both of these occurred when cases of #4 and 1/2” sieve sizes were increased to 25% retained.

2.2.3 Workability Measurements

Rheometer data was taken using the ICAR Rheometer. These measurements are typically taken at 0, 15, and 30 minutes. The results are shown below in Table 6 and Table 7. A classification scheme developed by previous research at OSU is shown in Table 4 (Cook 2015, Cook et al. 2015). In Tables 6 and 7, an asterisk by a value means less than three measurements were able to be attained.

Table 6: Classification of concrete mixture based the various workability tests.

Workability Performance Scale	**Slump Test** (in)	**Visual Observation**	**ICAR Rheometer**		
			Static Yield Stress (psi)	Dynamic Yield Stress (psi)	Plastic Viscosity (psi/sec)
Excellent (A)	8 to 6	A or 1	< 0.145	< 0.036	< 0.001
Good (B)	6 to 4	B or 2	0.145-0.218	0.036-0.073	0.001 to 0.002
Moderate (C)	4 to 2	C or 3	0.218-0.290	0.073-0.145	0.002 to 0.003
Poor (D)	2 to 0	D or 4	> 0.290	> 0.145	> 0.004
Unusable (F)	0	F or 5	Too stiff	Too Stiff	Too Stiff

Table 7: Rheometer and slump values with pump rating for the investigated mixtures. Times where Sensor 2 pressure exceeded 60 psi are highlighted in yellow. Events that stopped pumping are highlighted in red.

		Time (min)	Static (psi)	Dynamic (psi)	Plastic Viscosity (psi/s)	Slump (in)	Pump Comments
Coarse Agg Bounds	**1/2" = 15.7%**	0	0.0896 A	0.0307 A	0.00218 B	8.25	
		15	0.0863 A	0.0379 B	0.00116 A	8.25	
		30	0.1356 A	0.0412 B	0.00116 A	7.50	
		45	0.2437 C	0.0757 C	0.00131 A	5.25	
	1/2" = 20%	0	0.3495 D	0.0078 A	0.00290 C	5.50	
		15	0.6164 D	0.0702 B	0.00551 D	2.50	
	1/2" = 22%	0	0.1276 A	0.0257 A	0.00232 C	8.00	
		15	0.2335 C	0.0751 C	0.00232 C	6.50	Air Gaps
	1/2" = 25%	0	0.0660 A	0.0209 A	0.00203 B	9.00	Segregation
		15	0.0747 A	0.0270 A	0.00174 B	8.50	
		30	0.1552 B	0.0592 C	0.00131 A	6.50	
Int Agg Bounds	**#4 = 15.6%**	0	0.0896 A	0.0307 A	0.00218 B	8.25	
		15	0.0863 A	0.0379 B	0.00116 A	8.25	
		30	0.1356 A	0.0412 B	0.00116 A	7.50	
		45	0.2437 C	0.0757 C	0.00131 A	5.25	
	#4 = 20%	0	0.1740 B	0.0332 A	0.00406 D	5.50	
		15	0.4525 D			2.50	
	#4 = 22%	0	0.1711 B	0.0350 A	0.00334 D	7.25	
		15	0.2379 C	0.0799 C	0.00203 B	4.50	Air Gaps
	#4 = 25%	0	0.1153 A	0.0344 A	0.00232 C	7.50	
		15	0.1595 B	0.0535 B	0.00160 B	4.00	
		30	0.6309 D	0.1552 D	0.00131 A	2.50	
Fine Sand Bounds	**FS = 24%**	0	0.1204 A	0.0228 A	0.00218 B	8.50	Segregation
	FS = 28%	0	0.1038 A	0.0590 B	0.00348 D	5.00	
		15	0.4134 D	0.1065 C	0.00218 B	3.75	
		30	0.6527 D			2.00	
	FS = 32.5%	0	0.3989 D	0.0703 B	0.00479 D	4.50	
		15	0.4554 D	0.1217 C	0.00247 C	3.50	
		30	0.6150 D	0.1639 D	0.00363 D	1.50	
	FS = 36.1%	0	0.1210 A	0.0374 B	0.00305 D	5.00	
		15	0.2060 B	0.0783 C	0.00218 C	4.50	
		30	0.4743 D	0.1213 C	0.00116 A	2.50	
	FS = 39.8%	0	0.0896 A	0.0307 A	0.00218 B	8.25	
		15	0.0863 A	0.0379 B	0.00116 A	8.25	
		30	0.1356 A	0.0412 B	0.00116 A	7.50	
		45	0.2437 C	0.0757 C	0.00131 A	5.25	
	FS = 44.6%	0	0.3539 D	0.0911 C	0.00305 D	4.00	
		10	0.4743 D	0.1356 C	0.00348 D	2.00	
	FS = 56.5%	0	0.5976 D	0.0992 C	0.00290 C	1.50	Unworkable

Table 8: Rheometer and slump values for the C-01 gradation at different sack contents.

	Time (min)	Static (Pa)	Dynamic (Pa)	Plastic Viscosity (Pa/s)	Slump (in)	Pump Comments
6.5 Sacks	0	0.0896 A	0.0307 A	0.00218 B	8.25	
	15	0.0863 A	0.0379 B	0.00116 A	8.25	
	30	0.1356 A	0.0412 B	0.00116 A	7.50	
	45	0.2437 C	0.0757 C	0.00131 A	5.25	
6.0 Sacks	0	0.2149 B	0.0526 B	0.00363 D	5.25	
	15	0.2616 C	0.0817 C	0.00276 C	4.75	
	30	0.6248 D	0.1611 D	0.00261 C	2.00	
5.5 Sacks	0	0.3305 D	0.0564 B	0.00986 F	3.00	Unworkable

Times where Sensor 2 pressure exceeded 60 psi are highlighted in yellow. Events that stopped pumping are highlighted in red.

Using the rheometer as a guide for the pumpability of concrete, both 6.5 sack concrete mixes (repeats of each other) produced acceptable values as they were pumped through the pipeline. A 6 sack concrete mixture of the same gradation also pumped within acceptable values for about 15 minutes. The 5.5 sack mixture failed immediately.

In industry, using a 6 sack concrete mixture would be acceptable as long the gradation is within the bounds specified in the first chapter and the slump is above 5", but enriching the concrete mixture just half a sack more of cementitious materials provides more room for error with gradation as well as lower yield stresses for longer periods of time.

2.2.4 Pressure versus Slump Data

Slump was taken at each time interval during pumping. The slump was plotted against the measured pressure with a best fit line and is shown in Figure 11.

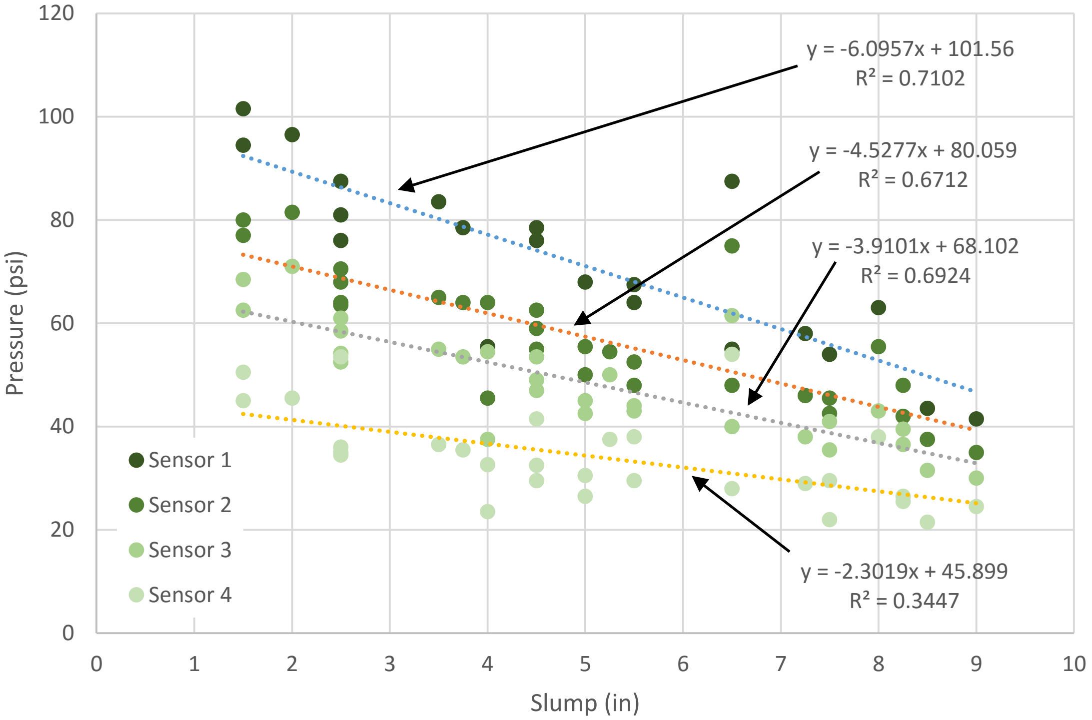

Figure 11: Pumping pressure versus slump.

Sensors 1 through 3 show a strong correlation between slump and pressure in the pipeline. Even though the pressures drop as concrete flows through the pipe, each sensor kept a similar slope. Sensor 4, the sensor after the second 90^o, has more scattered data and a best fit line with a slightly lesser slope but still shows a correlation between slump and pressure in the line. As the slump increased then the resistance to flow decreased and so the measured pressures also decreased. The unique slope of each of the lines suggests that regardless of the amount of pipe or bends before a location there is a linear change in the pumping pressures with a change in slump. The larger scatter observed at Sensor 4 may be caused by the very shallow slope of the slump versus pressure response. This data shows that slump provides a good indicator of pumping pressures as long as segregation is not occurring.

2.2.5 Pressure versus Rheometer Data

Figure 12, 13, 14, 15 show the rheometer values for both static and dynamic stresses plotted against the pressure in each sensor along with lines of best fit.

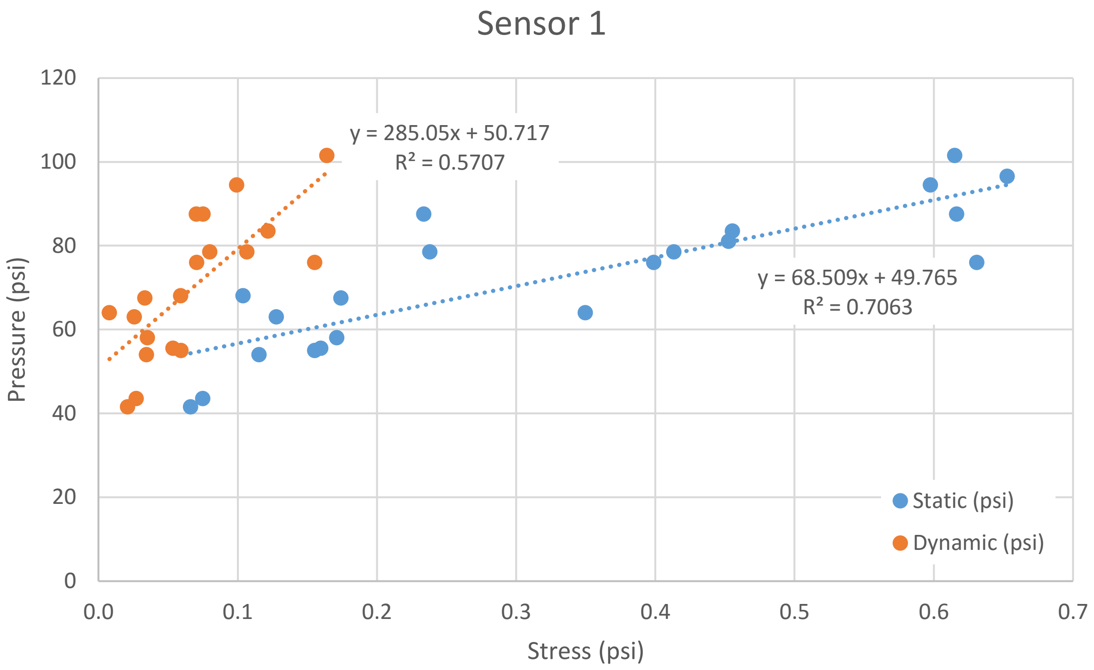

Figure 12: Sensor 1 pressure at 1500 rpm versus yield stresses.

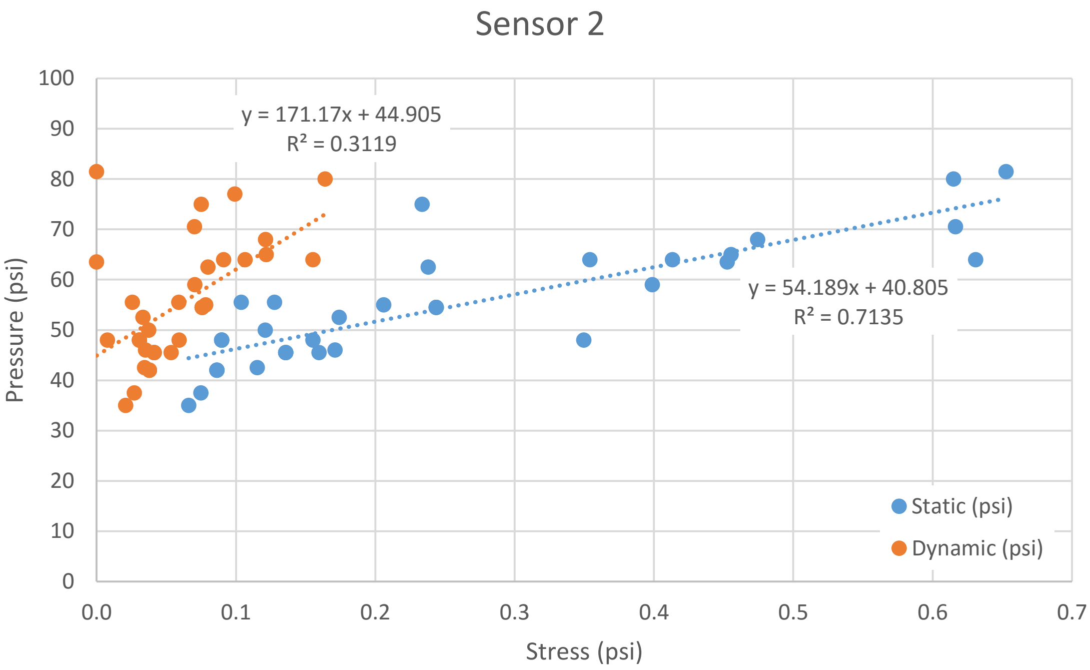

Figure 13: Sensor 2 pressures at 1500 rpm versus yield stresses.

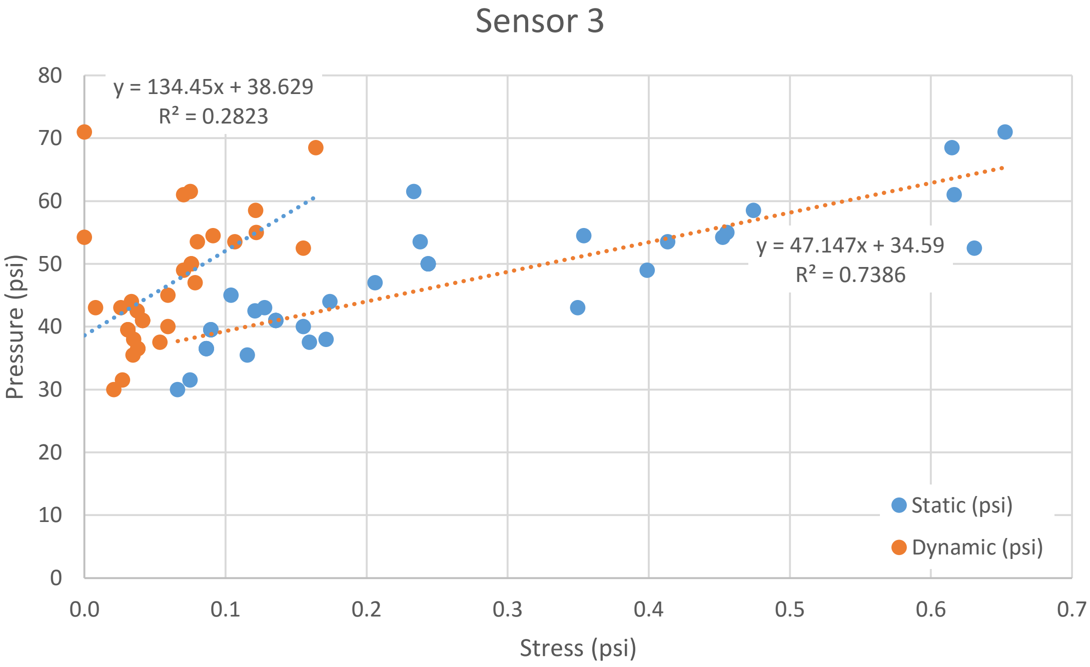

Figure 14: Sensor 3 pressures at 1500 rpm versus yield stresses.

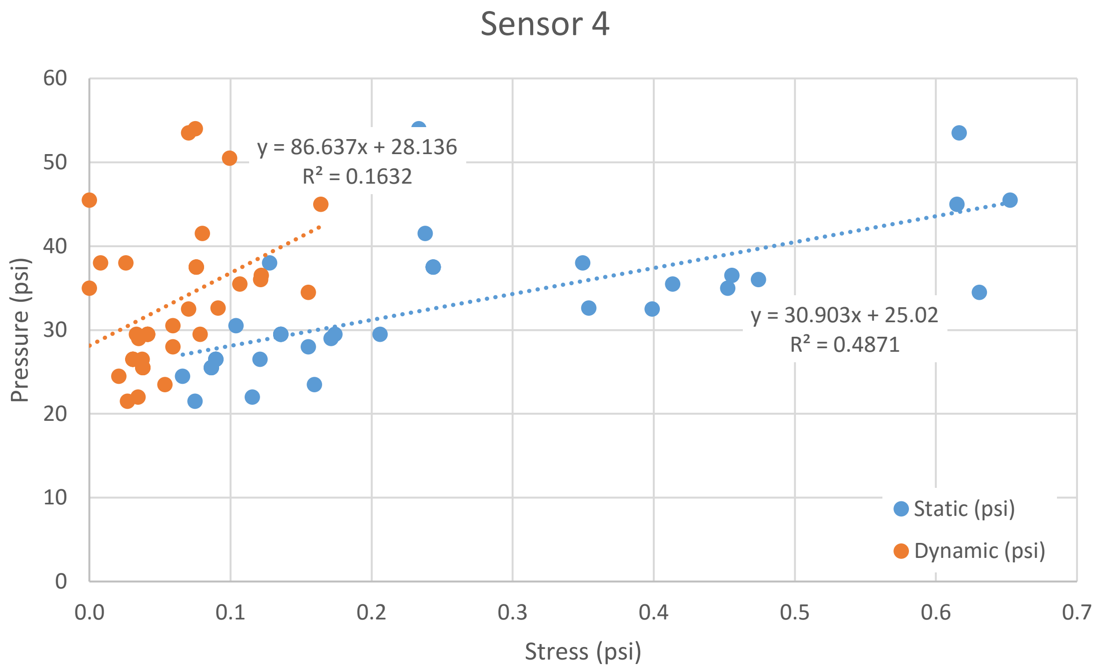

Figure 15: Sensor 4 pressures at 1500 rpm versus yield stresses.

As the static and dynamic yield stresses increased, the measured pressure in the lines also increased. These results are expected because as yield stresses in the concrete increase then so will the cohesion between the pipe walls and the mixture. This will require higher pressures to move the concrete forward in the pipe. These graphs show an acceptable correlation between pressure and static and dynamic yield stress. The data from Sensor 4 is more scattered than the other three sensors. This could be because the friction losses are so large that the correlation between the mixture rheology and pump pressure is masked. It could also be caused by something else not yet understood.

2.2.6 Comparing Pump Pressure to Gradation Limits

In this section, the gradations of each mixture will be shown with the average pressure of the secondary curve from Sensor 2 at the start of pumping. This is done to display how the pressures change as the gradations reach and surpass the bounds of the Tarantula Curve.

Recall that Table 4 shows the Sensor 2 data for each mixture at 0 minutes and 1500 rpm with the corresponding percent retained curves. As shown in Figures 12 through 15, Sensors 1, 2, and 3 have similar correlations between pressure, yield stresses, and slump. Even though the pressures from Sensor 2 are lower than Sensor 1, the results are expected to be comparable between the mixtures.

In this section the mixtures are divided into three data sets: Coarse Aggregate, Intermediate Aggregate, and Fine Sands. The mixtures are separated like this to highlight the portion of the gradation that is variable. Unacceptable performance is shown in red, mixtures with undesirable performance are shown in yellow, and mixtures with acceptable performance are shown in black. Recall that undesirable mixtures reach a slump of 3 inches or less at any time during the pumping session.

2.2.6.1 Examining the Coarse Limits

The 1/2” sieve size was adjusted to meet and then breach the bounds of the Tarantula Curve for the suggested maximum percentage. Each gradation is plotted in Figure 16 with their average pressure values from Sensor 2 at 0 minutes. In order for one of the mixes to reach 25% retained, the sand content had to be slightly adjusted to keep the gradation curve from breaking the bound in other areas. Gradations that exceeded 65 psi at any time during pumping are shown in yellow as this is not desirable.

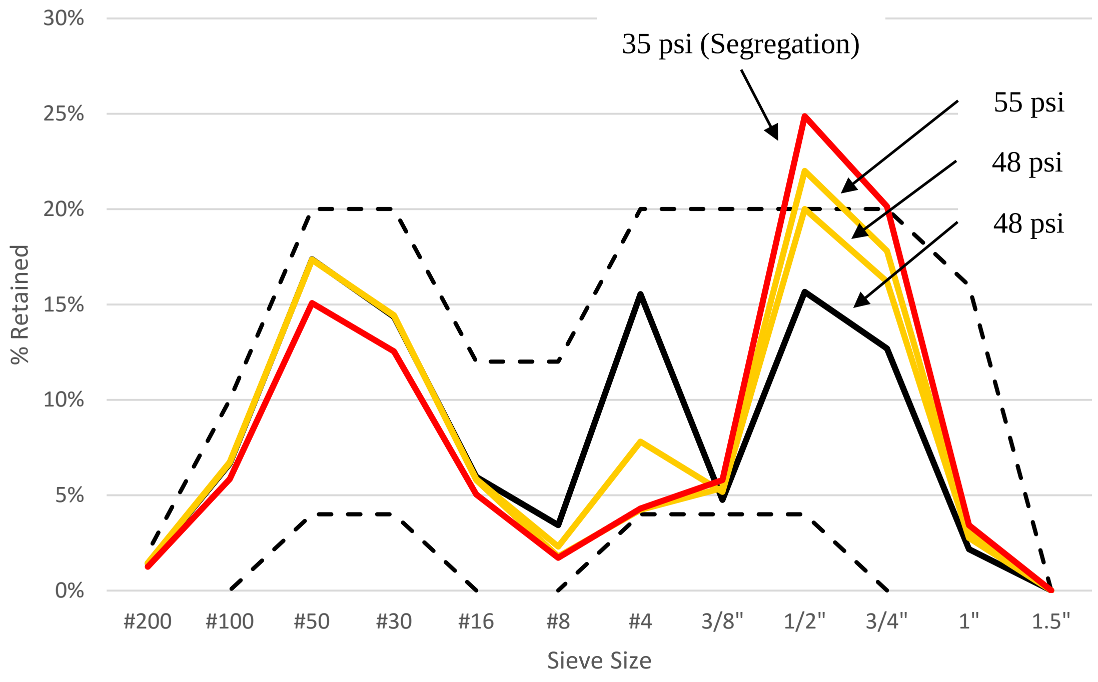

Figure 16: Sensor 2 pressures at 0 minutes per coarse gradation.

None of the coarse aggregate gradations had a substantially high initial pressure value. In fact, the concrete mixture with the lowest pressure has the highest percent retained value. While this mixture had a low pumping pressure it was observed to segregate as highlighted in red in Figure 16. An image of the mixture segregating is shown in Figure 17. The aggregate discharging from the line can be seen sitting on top of the concrete in the hopper. Because of this segregation this mixture was deemed to not be acceptable. Even if the concrete is used strictly because it can be pumped, aggregates remain in the pipeline after pumping due to segregation, this would require heavy cleanout for each pipe section. This observation of segregation matches observations made in previous research for mixtures with similar gradations (Cook 2015).

Figure 17: Coarse aggregate exiting the pipeline and showing segregation.

2.2.6.2 Examining the Intermediate Limits

The #4 sieve size was adjusted to meet the bounds of the Percent Retained Chart and then breach the suggested maximum percentage. Each gradation is plotted in Figure 18 as well as their respective average pressure values from Sensor 2 at 0 minutes at 1500 rpm.

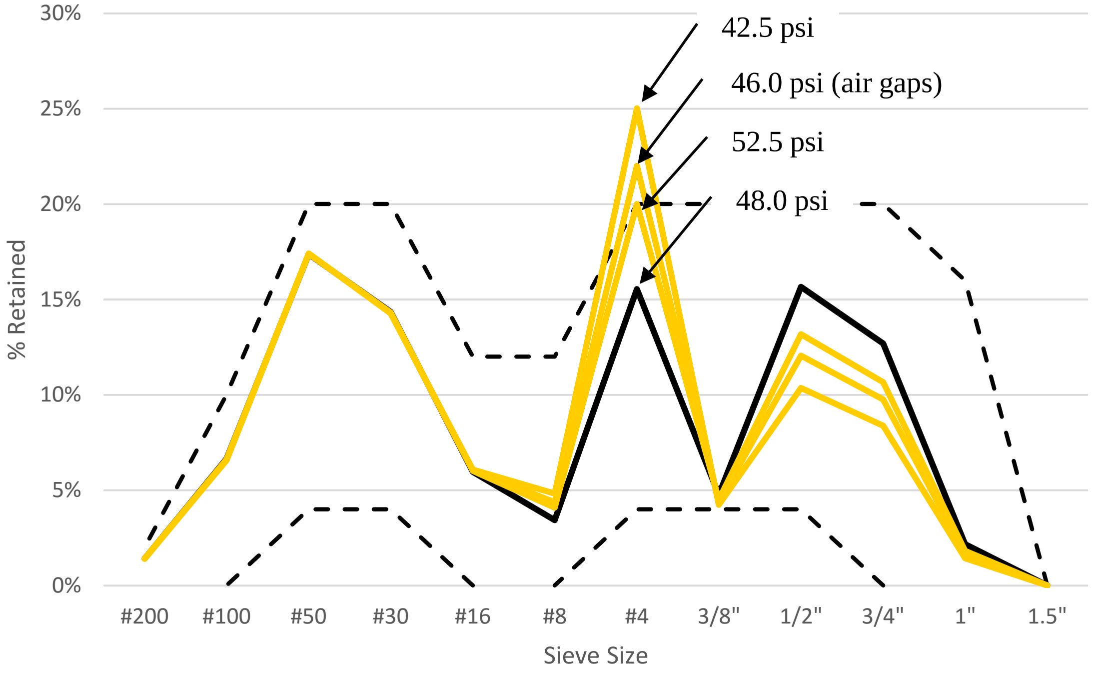

Figure 18: Sensor 2 pressures at 0 minutes per intermediate gradation.

The greatest difference in pressure is 10 psi between the higher pressure at 20% of #4 and the lower pressure gradation at 25% of #4. This difference is 3 psi higher than the variation that can be expected between mixtures. The range of intermediate aggregates doesn't seem to affect the pump pressure in any noteworthy way with 1500 rpm. But when the rpm is dropped to 1200, air gaps form in the line at 22% retained. Even so, these mixtures remained pumpable over time with no dramatic effects except that gradations highlighted in yellow broke 65 psi at some point during pumping, rendering them undesirable, but no segregation was observed in these mixtures.

2.2.6.3 Examining Fine Sand Limits

Recall that Percent Fine Sands are a sum of retained #30, #50, #100, and #200 sieves. Using a 6 sack mixture, the total amount of fine sand volume was recommended to be between 25% and 40% (Cook 2015). The amount of Fine Sand was adjusted for this data set to try to determine how this impacts pumping. A collection of the gradations and their respective Sensor 2 pressures at the 0 minutes and 1500 rpm is shown in Figure 19 below.

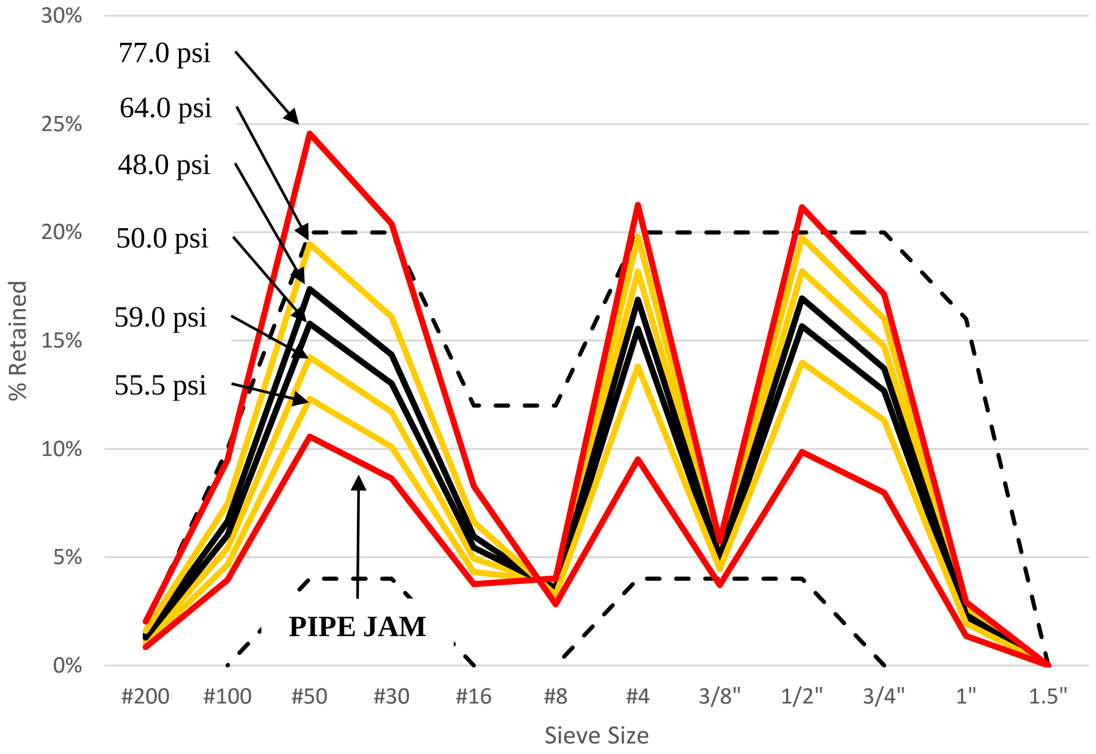

Figure 19: Sensor 2 pressures at 0 minutes per percent fine sands.

Two concrete mixtures are of major importance in this figure. The first is the 24% Fine Sand mixture (highlighted in red and labeled “PIPE JAM”). It segregated in the pipeline causing the pump to seize and thus it provides a lower fine sand boundary for required sands in a certain gradation. The mixture design with 44.6% fine sands brings the gradation right below the upper boundary. Here the concrete can still flow through pipe network but requires a higher pressure to do so. While this works, it is not recommended because the mixture can only be pumped for about 10 minutes. The mixture with a fine sand content of 56.5% breaks the fine sand volume and has a higher fine sand content than the upper limit of the curve. This mixture had a pumping pressure that was 60% higher than the mix that has a 48.0 psi average value. During pumping this mixture was so stiff it would not flow in between the grate and into the hopper. Rather, it was forced into the hopper with a shovel. Also, both the static and dynamic yield stresses received unacceptable values immediately after the pumping started.

2.2.6.3.1 24% Fine Sand Mixture Design

In Table 6, the rheometer data gives the 24% Fine Sand concrete mixture an A rating for static and dynamic stress. Even so, the mixture jammed the pipe. Initially, the mixture was observed to have very poor cohesion and during pumping the mixture segregated causing the coarse rock to get jammed in the reducer. Figure 20 shows the slump test conducted on the 24% fine sands concrete mixture with a comparison of a slump test ran on 39.4% fine sands concrete. As can be seen the slump with the low fine sand will have a high slump measurement but the mixture breaks apart in the slump test and not stayed cohesive. *This is an example where the rheology tests did not correlate with the performance.* These observations match those in other chapters and further support the importance of the lower Fine Sand limits. Once the reducer was detached the aggregate was tightly packed in it. See Figure 21 to see the jam in the pipeline.

Figure 20: Concrete with 24% fine sands breaks apart when the slump test is conducted.

Figure 21: Concrete with 24% fine sands has insufficient mortar to coat the pipeline, causing a jam.

After 14 piston cycles the rock had backed up all the way to the pistons, seizing the pump. See Figure 22 for an example of the pressure data while segregation occurred.

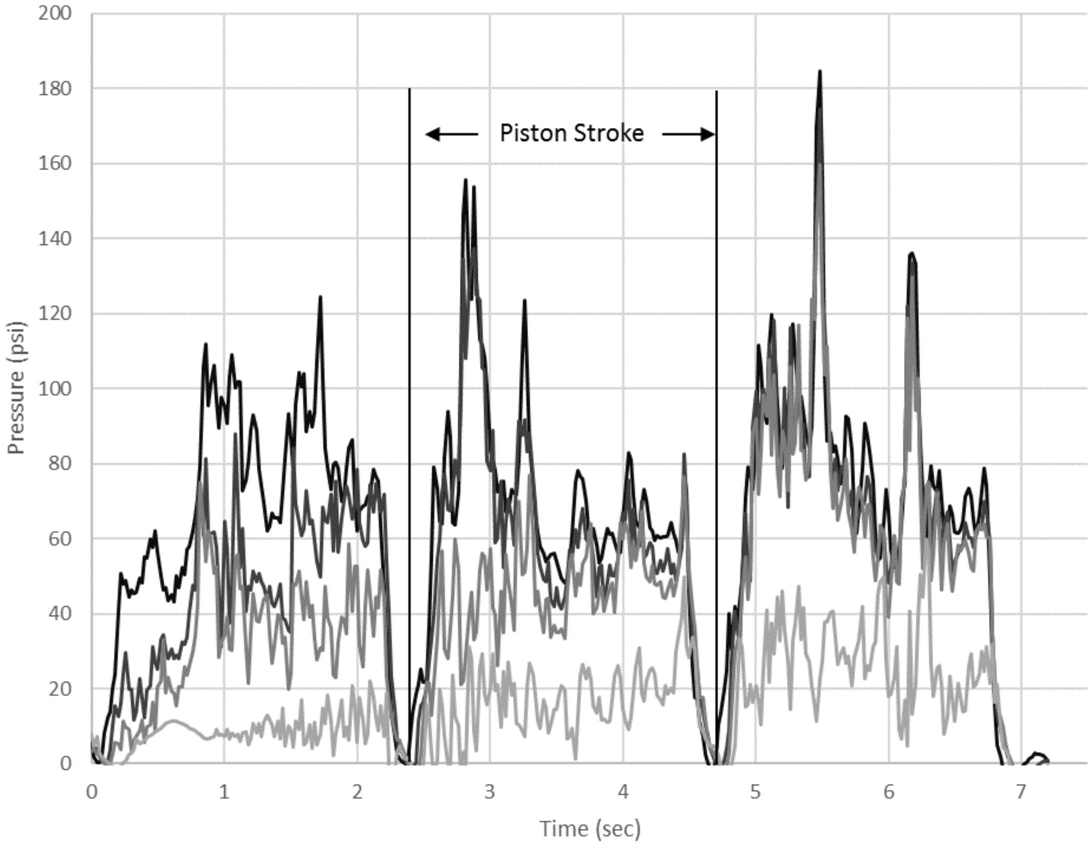

Figure 22: Segregation in the line causes erratic, unpredictable pressure curves.

The piston strokes don’t follow the typical pressure curve. Rather, it’s noisy and jagged with large pressure spikes throughout the stroke. No other tested concrete mixture had pressure curves similar to this and thus is considered a non-pumpable concrete mixture.

2.2.7 Pumping Pressures for Percent Fine Sand Mixtures with Time

Each mixture was pumped for at least 30 minutes or until it was deemed unacceptable based on the standards stated previously. As shown in Figure 19, the percent of fine sands seemed to play the biggest role in the pumpability of concrete. Below, the range of fine sands are compared to pressure, yield stresses, and slump for the period of their testable time in Figures 23, 24, 25, and 26. Again for pressure, note that the data points are from Sensor 2. If a mixture failed a data point was not plotted. In almost all cases, pressure and yield stress increase over time with slump decreasing as well. Also these values form a curve that remains similar through each figure.

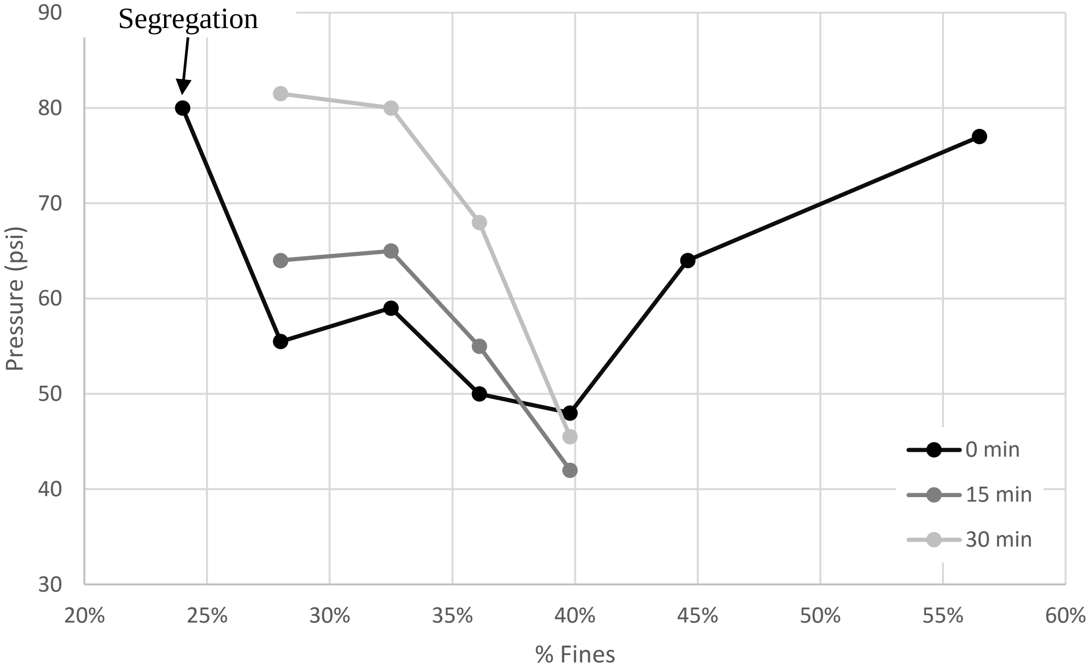

Figure 23: Sensor 2 pressures over time versus % fine sands.

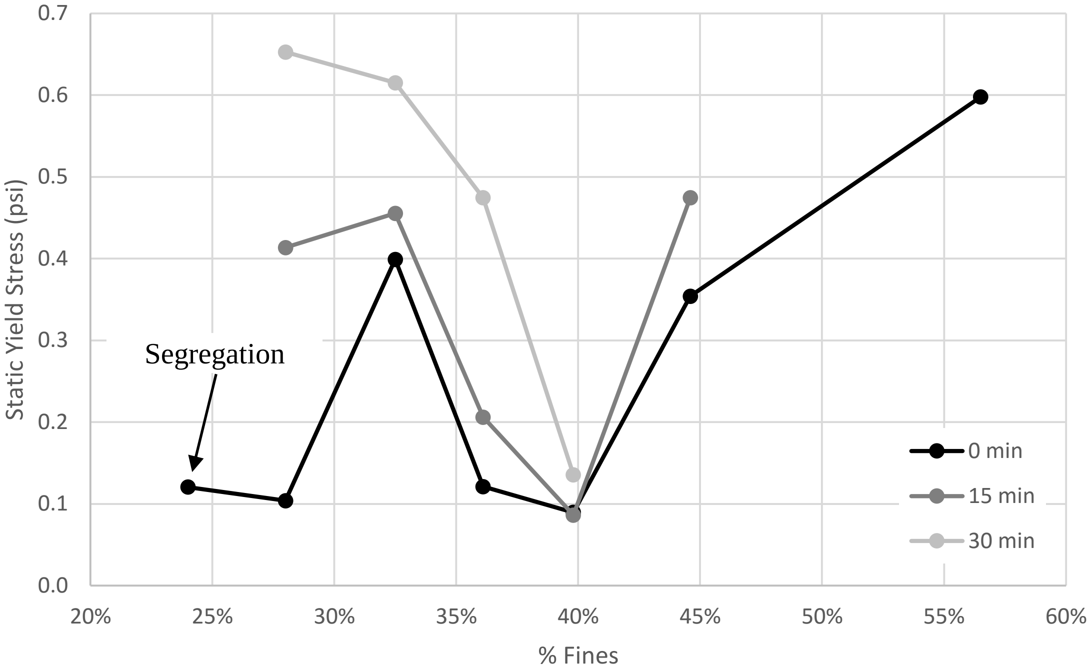

Figure 24: Static yield stress over time versus % fine sands.

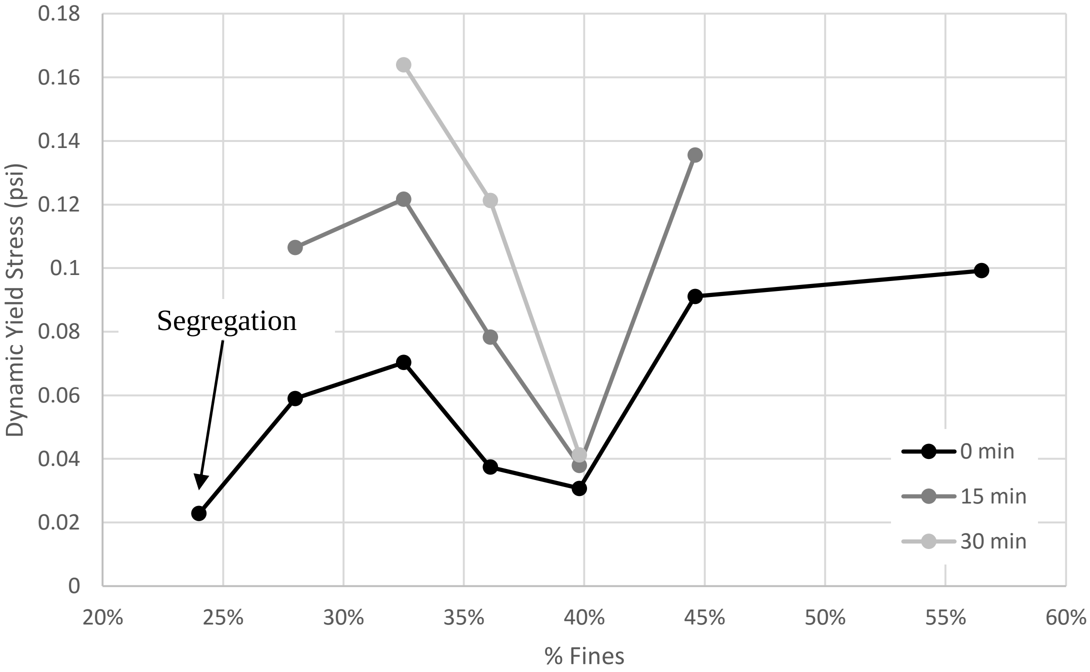

Figure 25: Dynamic yield stress over time versus % fine sands.

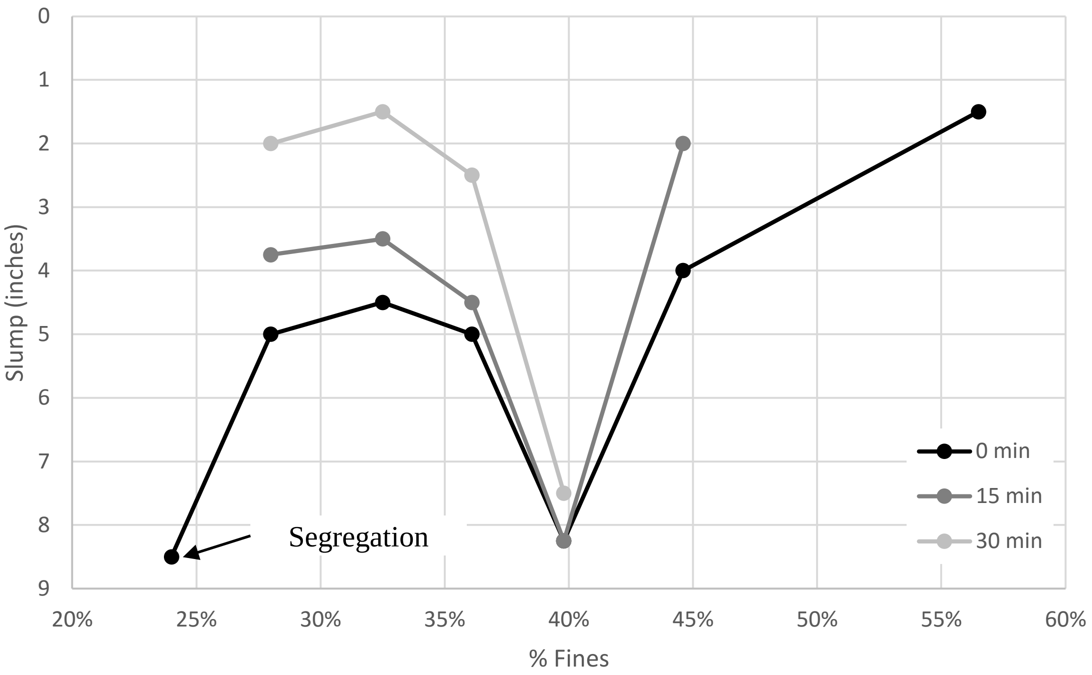

Figure 26: Slump over time versus % fine sands.

In general, the pumping pressure, slump, and rheometer values increased with pumping time. Also mixtures that had a Fine Sand content between 32% and 40% showed the best performance. This suggests that mixtures with Fine Sand contents in this range are more robust and should be able to be pumped for longer periods and therefore longer distances than mixtures with other fine sand contents.

2.2.7.1 Discussion of Fine Sand Range

Figure 27 shows the percent fine sands and their respective pressures. Note how reducing your fine sands to about 24% causes crippling segregation and increasing to over 55% creates very low, unusable workability.

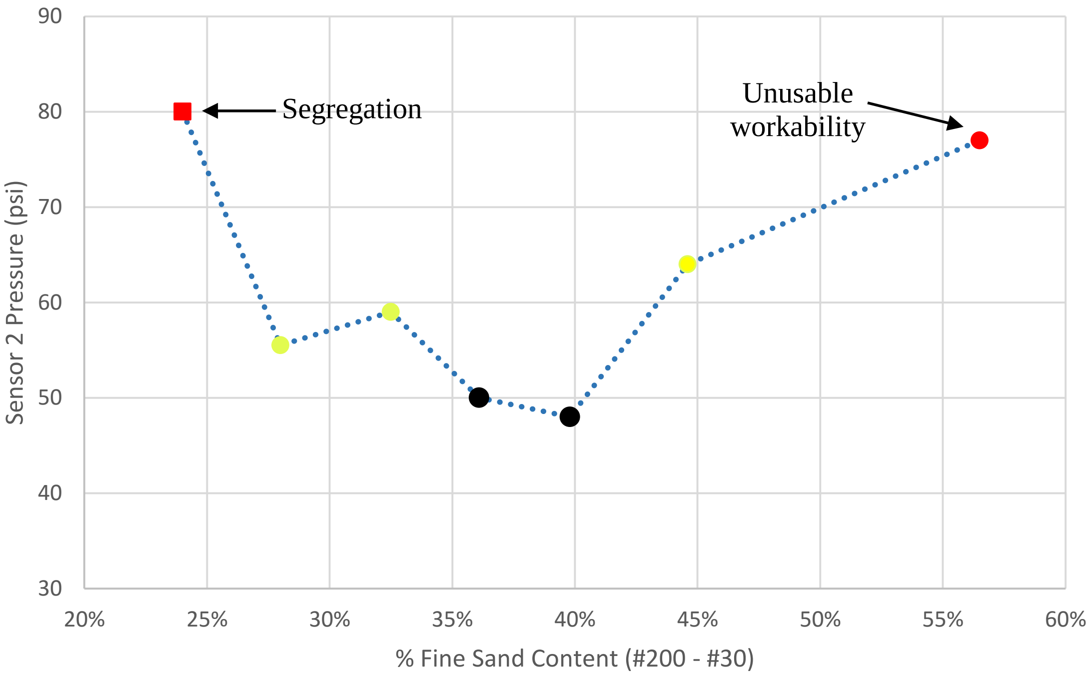

Figure 27: Sensor 2 pressures at 0 minutes versus fine sand content. Desirable contents are in black. Undesirable contents are in yellow. Unacceptable contents are in red.

Note that this curve matches Figure 2 from Chapter 1, and is shown again below. Recall that Sand A was used in the pumping tests. Looking only at that sand source the bounds slightly shift to the right. Looking at Figure 27, the percent of Fine Sand content marked undesirable in yellow follows closely with Moderate Overall Performance shown in Figure 28. This remains true for those mixes deemed unacceptable, both from segregation and poor workability. Those percent fine sand contents, marked red, follow closely with Poor Overall Performance. It is not clear why Sand A has a different performance than Sand B and Sand C. However, it is comforting that the performance of Sand A in the previous testing closely matches the performance in the pump testing. Because of these differences in performance it makes it challenging to pick one set of recommendations for the fine sand limits. In order to be conservative the limits from 25% to 40% will be recommended as they worked for the three sands investigated. Ideally additional research should be completed to continue to look at why different sands performed differently in this testing. It may have to do with the shape of the individual sand particles.

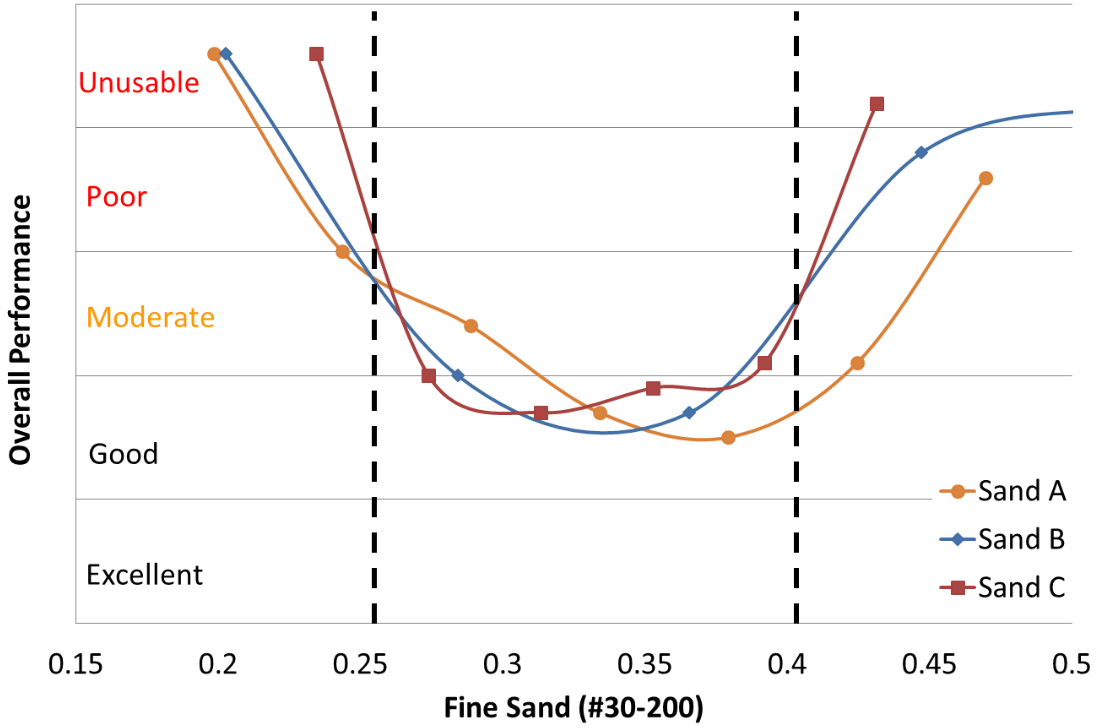

Figure 28: The overall performance of three different sands versus the fine sand content in the mixture. The results from Sand in the pumping test gives a similar result to Sand A performance.

From this it is seen that the bounds of both the Tarantula Curve coupled with the bounds of the Fine Sand Chart provide a conservative gradation range for pumpable concretes. These recommendations are similar to the results for the fine sand boundaries previously found. Mixtures within the range from 28% to 44% Fine Sands for Sand A have a reasonable range of workability. As you increase the total sands past 44% the yield stress values and pump pressures greatly increase indicating that the mixture has become too stiff. Mixes with total fine sands less than 28% may have lower yield stresses and pressures but they become subject to the high risk of segregation.

2.3 SUMMARY

The grout part of concrete, the combination of paste and fine sands, helps to both reduce friction as concrete travels through the pipeline as well as hold the whole mixture including aggregates together so the concrete is carried through the pipeline. There is a wide range of acceptable coarse and intermediate aggregates volumes that can be used but the gradation limits for the coarse aggregate of 20% recommended by others served as a useful limit for these mixtures. The following conclusions were made:

- The concrete pump and instrumented pipe loop system provided a useful tool to evaluate the impact of different aggregate gradations on the ability to pump concrete mixtures.
- There is a relationship between slump, static yield stress, and dynamic yield stress and the pumping pressures for the constant part of the pressure versus time curve and sensors located immediately after the pump and after a 90^o bend.
- The pumping pressures after the second 90^o bend did not show a good relationship, likely from the higher pressure losses at this point.
- The Tarantula Curve provides a useful limit for coarse, intermediate, and fine aggregates where the concrete mixture becomes undesirable and may also cause failure.
- A percent Fine Sand content of 24% caused segregation and jammed the pipeline and a percent Fine Sands content greater than 44% creates a mix that would be too stiff to pump, especially for long periods of time.

While more investigations on different aggregate sources and shapes of aggregates is necessary, this study still provides useful limits that can have positive impacts on the concrete industry.

CHAPTER III

ANALYSIS OF PUMP PRESSURES OVER TIME

3.0 INTRODUCTION

Analyzing secondary pressure curves at different time intervals only begins to explain the changes in pressure in a concrete pump. The pressure curves have minimums, maximums, lengths, and plateaus. Each of these values may change over time while the concrete's properties are changing as it is being pumped.

In a single pump session lasting around 45 minutes, around 584,000 data points are gathered. To analyze all these data points efficiently software and coding is required. MATLAB's Curve Fitting Tool can be used once the different sections of the pressure curves have been analyzed (stated above). The pressure curves from each mix design can be compared against each other by using regression curves of the same form. That is, if an equation can be found that yield an acceptable line of best fit for all pressure curves, then it can be determined if one mix is better performing.

In this chapter a regression analysis procedure will be recommended and then applied to all pressure curves. Sensor 2 will be used as the main sensor for comparison because it is the closest sensor to the pump that worked for every pump session. Then the four sensors will be compared against each other in terms of pressure loss per foot, a standardized unit, and slump to see if a simple testing method can estimate pressures in the pipeline.

3.1 EXPERIMENTAL METHODS

The methods from Chapter 2 were used to collect all pump data described in this chapter. The piston stroke interval, minimum pressure, peak pressure, and secondary curve averages were collected from the data. Data points that yielded a recognizable piston stroke shape were used in this analysis. Given that the concrete pump is a piece of construction equipment and that pressure curves are not identical (sometimes even chaotic) some data points from the sensors were considered erroneous and were excluded. This could be done because each pumping session, lasting about 40 minutes, yielded close to 900 pressure curves per sensor. With so many data points one could exclude some data without sacrificing the overall trends.

3.1.1 Regression analysis

Regression analysis is used to show the trends in this work by using the average secondary curve pressures. In all cases the pressure was higher at the end of the pump session than at the beginning. In some cases, the increase in pressure didn't increase until fifteen minutes into the session.

In order to compare these factors, a single, robust regression curve is needed to show these trends over time. Many regression curves were tried, including power, exponential, and linear, but two curves matched all of the data the closest; a second degree polynomial and an exponential function with an additional coefficient. This curve also had to have easily comparable coefficients. A polynomial curve in the form $y(x) = p_{1*}x^2 + p_{2*}x + p_3$ is not easily comparable because p_1 and p_2 work together to shape the slope and the curvature. Using the function $y(x) = a \cdot x^b + c$ is easier to compare: 'a' controls how quickly or slowly the function begins the curve upward, 'b' controls the curvature once the line begins to slope upward, and 'c' controls the initial y-intercept. Also, by limiting the lower bound of 'b' to one, the curve can be controlled to have a positive curvature in cases where regression analysis creates an almost linear line.

3.2 RESULTS AND DISCUSSION

The parts of the pressure curves will be discussed in this section. This includes the change in piston stroke intervals, the change in peak pressures, the change in minimum pressures, and lastly the change in the secondary curve pressures. The change in secondary curves will be graphed for changes in the course aggregate, intermediate aggregate, percent fine sands, and paste content. The data is grouped in this way to provide clarity.

3.2.1 Changes in Intervals, Peak Pressures, and Minimum Pressures

3.2.1.1 Piston Stroke Intervals

In the pumping sessions, the time interval for each piston stroke remained relatively constant with little variability and no general increase or decrease in intervals over time. In all cases, except the baseline mix which was well within the bounds of the Tarantula Curves, the time interval averaged 2.15 seconds with a standard deviation across all pump sessions of 0.20 seconds. In the case of the base line mixture the averaged time interval was 2.05 seconds with a standard deviation over 1181 piston strokes of 0.15 seconds.

3.2.1.2 Peak Pressures

Peak pressures occur at the beginning of the piston stroke when extra force is required to break static friction. They were highly variable and did not show any particular trends. In most cases, peak pressures where higher the closer their respective sensors were to the concrete pump. Figure 29 shows a representation of the changes in peak pressures per sensor over time.

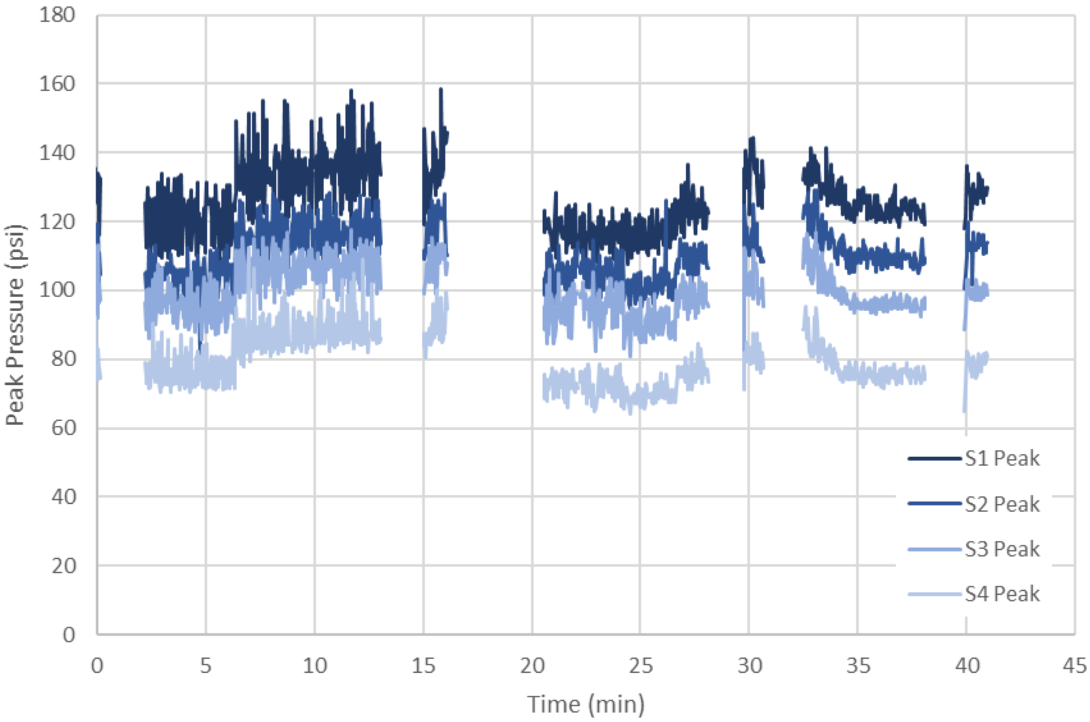

Figure 29: While peak pressure move up and down, they don’t move in a predictable way.

In this particular pump session, the sensor 1 peak pressure averaged 126.5 psi and had a coefficient of variation of 7.5%. While other pump sessions yield peak pressures of different values, none of them show trends that can be used to select a mix design that will created a better pumpable concrete. Also, no peak pressure experience any drastic drops or increases over time. While more research can be done in the future to explain theses small hills in the data, it was decided the other parts of the pressures curve might better show predictable trends.

3.2.1.3 Minimum Pressures

In the case of minimum pressures, the data is split into two sections: half the pump sessions showed a slight increase in minimum pressures over time, and the other half showed steady minimum pressures over time. An example of the piston stroke minimums can be seen in Figure 30.

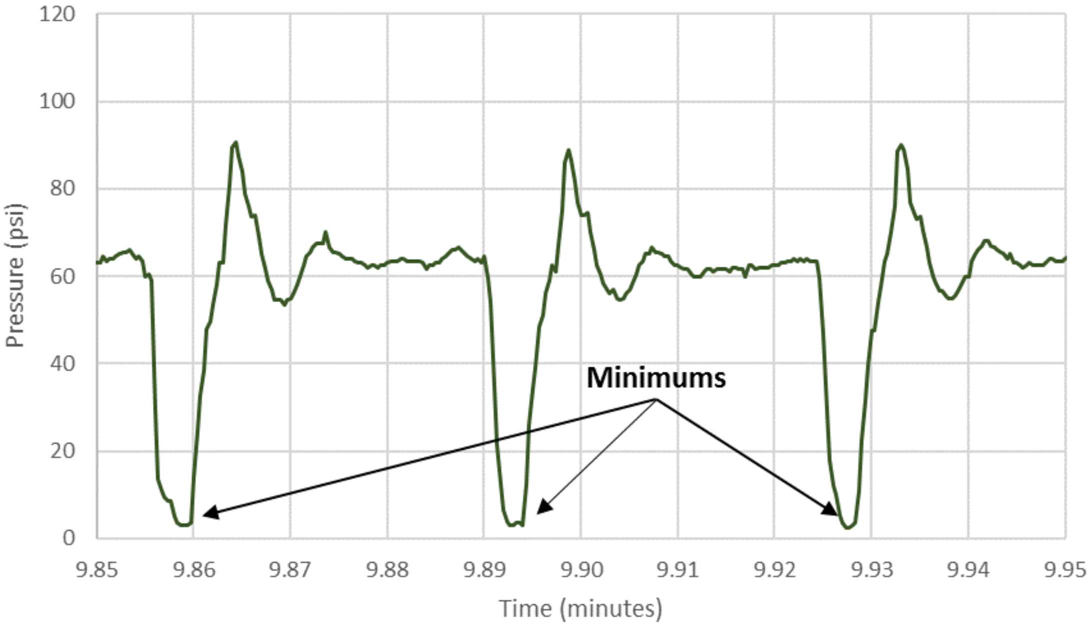

Figure 30: Minimum pressures occur at the beginning of each piston stroke.

The greatest minimum pressure per piston stroke was 8 psi; except for one case, the 56.5% fine sands where the minimum pressure remained steady at an average of 10 psi with a standard deviation of 1 psi. Even with the pump sessions that experienced an increase in minimum pressure, the increase is too small to define pumpable mixes against non-pumpable mixes. Likewise, some mixtures that performed well in the pump experienced an increase in pressure while some mixes that failed in the pump experience no increase in pressure. Like the peak pressures, research can be done at a later time to explore minimum pressures, but no trends can be found in this section of the data to specify a pumpable concrete mixture.

3.2.2 Secondary Curve Averages

In three of the pump sessions, Sensor One – the sensor closest to the pump – broke in a way that it could not produce data. Thus Sensor Two was used to compare all of the pump sessions as it was always running correctly. All of the curves from Sensor Two were analyzed and compared against each other using the selected regression curve. Table 9 shows all the mixes with the value of each content as well as its r-squared value and ending times.

Table 9: Each constant of the regression curve is shown along with its r-squared value and ending time. If the mixture couldn't produce data, it's marked "Fail" in the table.

f(x) = a*x^b + c		a	b	c	r^2	End Time (min)
Coarse Agg Bounds	1/2" = 15.7%	5.517E-09	5.67	44.58	0.8747	45
	1/2" = 20%	1.169E+00	1.00	50.99	0.9572	25
	1/2" = 22%	4.630E-01	1.33	55.78	0.9805	18
	1/2" = 25%	1.596E-02	2.05	32.20	0.9875	42
Int Agg Bounds	#4 = 15.6%	5.517E-09	5.67	44.58	0.8747	45
	#4 = 20%	1.979E-02	2.47	52.21	0.9871	14
	#4 = 22%	8.734E-01	1.06	45.34	0.9825	20
	#4 = 25%	4.137E-03	2.54	40.41	0.9928	38
Fine Sand Bounds	FS = 24%	Fail	Fail	Fail	Fail	Fail
	FS = 28%	1.783E-01	1.535	53.24	0.9810	28
	FS = 32.5%	7.122E-02	1.733	57.59	0.9871	28
	FS = 36.1%	1.482E-02	2.064	49.35	0.9846	34
	FS = 39.8%	5.517E-09	5.67	44.58	0.8747	45
	FS = 44.6%	Fail	Fail	64.00	Fail	6
	FS = 56.5%	Fail	Fail	77.50	Fail	5
Sack Content	6.5 Sacks	5.517E-09	5.67	44.58	0.8747	45
	6.0 Sacks	1.496E-02	2.095	61.80	0.8803	33
	5.5 Sacks	Fail	Fail	74.50	Fail	5

f(x) = a*x^b + c		a	b	c	r^2	Time (min)
Coarse Agg Bounds	1/2" = 15.7%	5.517E-09	5.67	44.58	0.8747	45
	1/2" = 20%	1.169E+00	1.00	50.99	0.9572	25
	1/2" = 22%	4.630E-01	1.33	55.78	0.9805	18
	1/2" = 25%	1.596E-02	2.05	32.20	0.9875	42
Int Agg Bounds	#4 = 15.6%	5.517E-09	5.67	44.58	0.8747	45
	#4 = 20%	1.979E-02	2.47	52.21	0.9871	14
	#4 = 22%	8.734E-01	1.06	45.34	0.9825	20
	#4 = 25%	4.137E-03	2.54	40.41	0.9928	38

Fine Sand Bounds	**FS = 24%**	Fail	Fail	Fail	Fail	Fail
	FS = 28%	1.783E-01	1.535	53.24	0.9810	28
	FS = 32.5%	7.122E-02	1.733	57.59	0.9871	28
	FS = 36.1%	1.482E-02	2.064	49.35	0.9846	34
	FS = 39.8%	5.517E-09	5.67	44.58	0.8747	45
	FS = 44.6%	Fail	Fail	64.00	Fail	6
	FS = 56.5%	Fail	Fail	77.50	Fail	5
Sack Content	**6.5 Sacks**	5.517E-09	5.67	44.58	0.8747	45
	6.0 Sacks	1.496E-02	2.095	61.80	0.8803	33
	5.5 Sacks	Fail	Fail	74.50	Fail	5

A regression curve could not be fit to four cases: three fine sand content mixes and one paste content mix. The mixture with a fine sand content of 24% failed entirely, as was discussed in the previous chapter. The other two fine sand mixtures did produce data but only for a short time period. An average with a standard deviation is used instead of a regression curve for that data and is shown on the table, highlighted in light red.

By grouping these curves these curves together by data set and plotting them over time, trends can be seen in the pumping pressures.

3.2.2.1 Course Aggregate Data Set

Figure 31 shows the secondary average pressure of Sensor 2 along with its regression curve plotted over time. Each line shows the percent retained for the ½” sieve size along with its r-squared value.

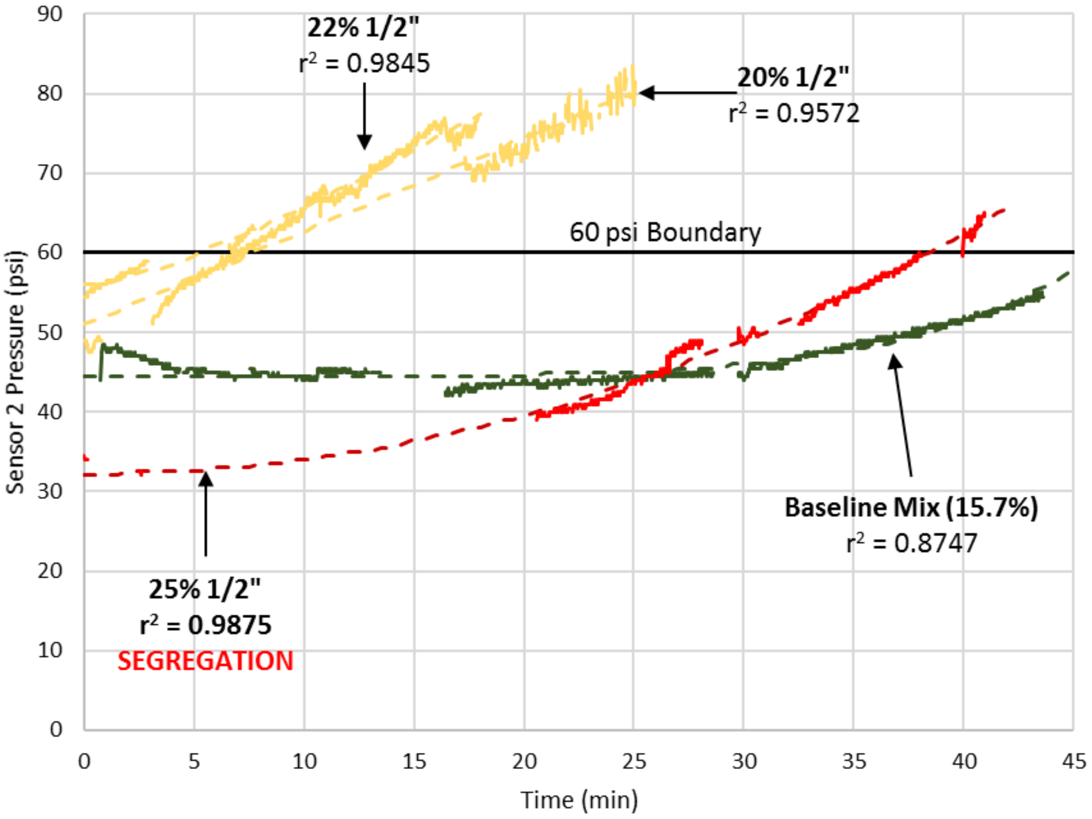

Figure 31: Increasing the coarse aggregate content to unacceptable levels yielding higher pump pressures or segregation.

The 60 psi boundary is shown on Figure 31 to mark when the concrete mixtures became unacceptable to pump. When the retained ½” sieve size begins to break the upper boundary of the Tarantula Curve the pressures increase and pumping time decreases. These mixtures were at an acceptable pressure for about five to six minutes whereas the Baseline Mix, well within the bounds of the Tarantula Curve never break 60 psi and lasts for 45 minutes of pumping.

When ½” aggregate was increased to 25% retained, the pressures dropped lower than the baseline mix, to about 32 psi, but the mixture segregates.

3.2.2.2 Intermediate Aggregate Data Set

Figure 32 shows the secondary average pressure of Sensor 2 along with its regression curve plotted over time. Each line shows the percent retained for the #4 sieve size along with its r-squared value.

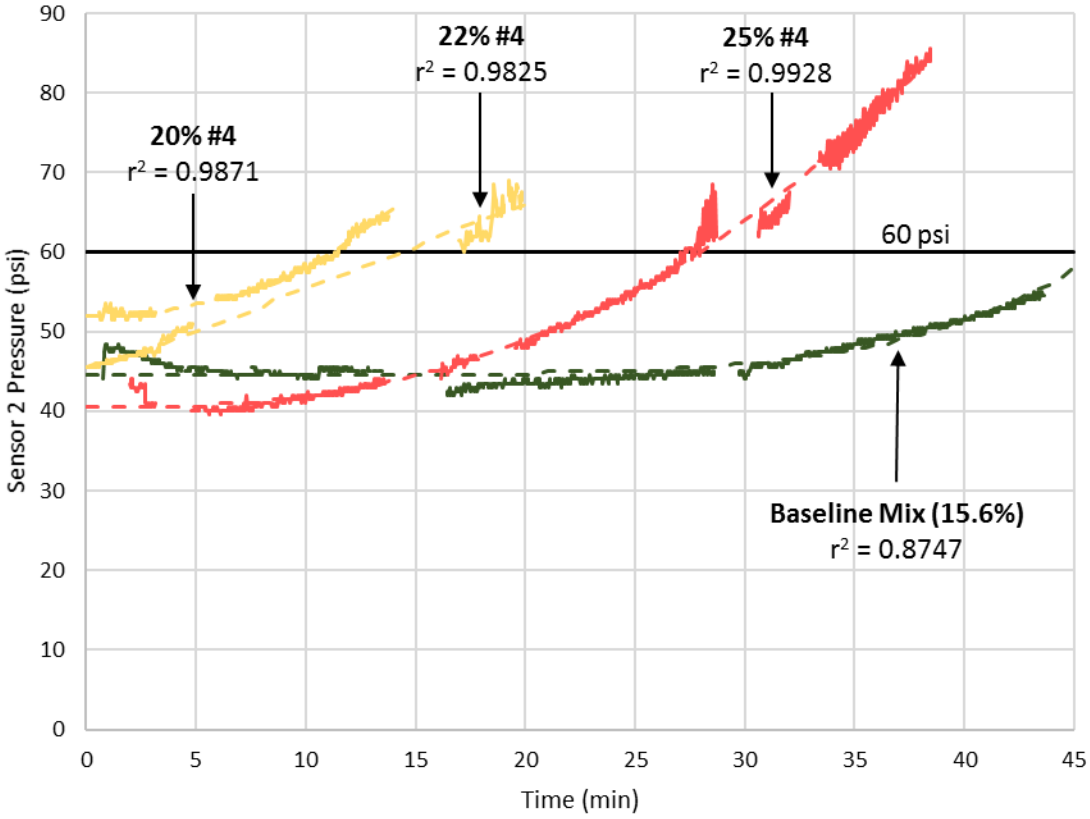

Figure 32: Increasing the #4 sieve size can create pressures higher than 60 psi over time but don't drastically effect pumpability.

In the case of increasing the percent retained of the #4 sieve size, the results are counter-intuitive. It could be assumed that increasing the #4 sieve size would increase pressure and decrease pump time – as in the case of the coarse aggregate data set – but instead the pump time increased as the #4 value was increased, but pressures did increase as more #4 was added to the concrete mixture. It took the concrete mixture with 25% of the #4 sieve size an additional fifteen minutes to reach a 2.5" slump and equivalent pressure than the 20% mixture.

This data suggests that there is no correlation to a decrease in pump time with an increase in the retained #4 aggregate, though there may be a correlation to a maximum pressure with an increase in #4 aggregate. This data show that pumping 25% retained #4 aggregate is possible, but doing so runs the risk of decreasing the pumpable time or greatly increasing the required pump pressure. The best performing gradation was still one that was well inside the bounds of the Tarantula Curve.

3.2.2.3 Percent Fine Sands Data Set

Figure 33 shows the secondary average pressure of Sensor 2 along with its regression curve plotted over time. Each line shows the percent of total fine sands along with its r-squared value. In the cases of 44.6% and 56.5% total fine sands, the standard deviation is displayed instead of an r^2 value.

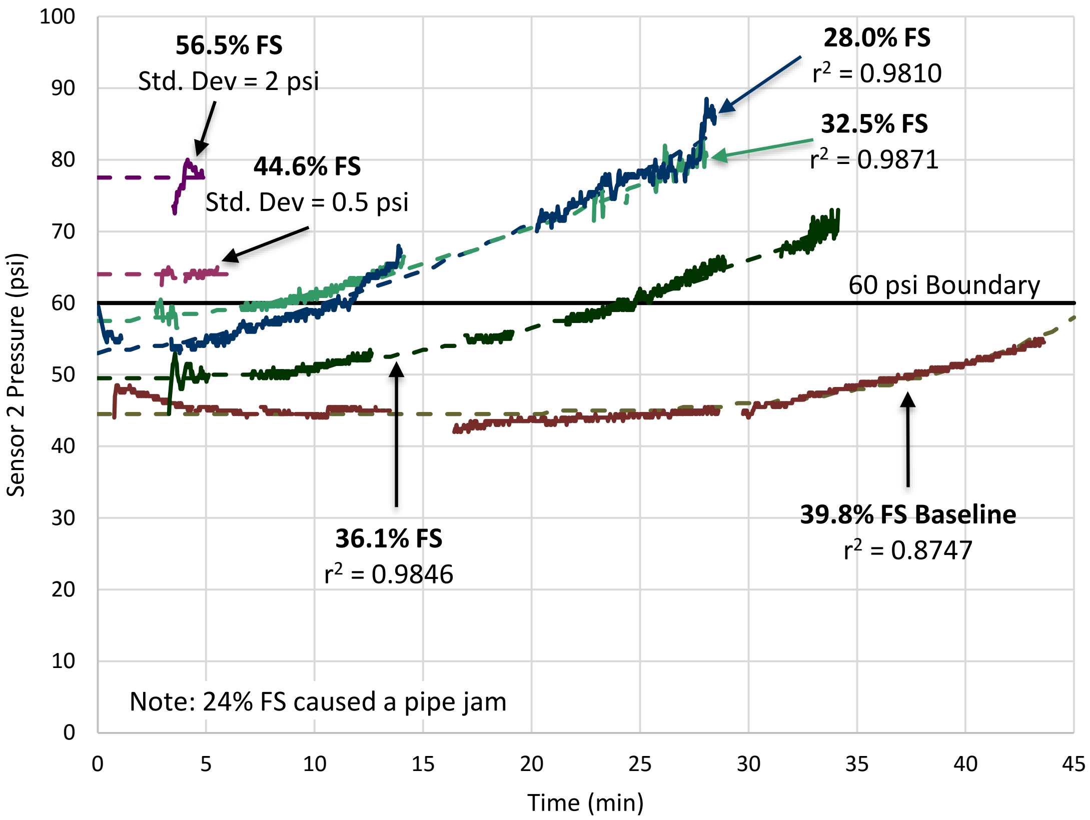

Figure 33: The percent fine sands content has a big and predictable effect on pumpability.

Note that a pump session was done on 24% fine sands and the concrete jammed the pipeline. The next data set, the 28% fine sands mixture was pumpable and yielded the highest pressure. Right beneath it was the 32.5% fine sands mixture with a slightly lower pumping pressure but lasting the same amount of time. From there, increasing in pumpable time and decreasing in required pressure, is 36.1% and 39.8% (our Baseline) mixes. After that, two mixes were tested that greatly exceeded the bounds of the suggested total fine sand content in a concrete mixture. Both of these mixes quickly failed. As fine sane content increased, so did the average secondary pressure along with its standard deviation. Too much fine sands in a mix, greater than about 40%, greatly increases the pressure, variation in pressure, and chance of a mixture failing to be pumpable.

A trend in the successful pump sessions can easily be seen in Figure 34 by excluding the failing concrete mixtures.

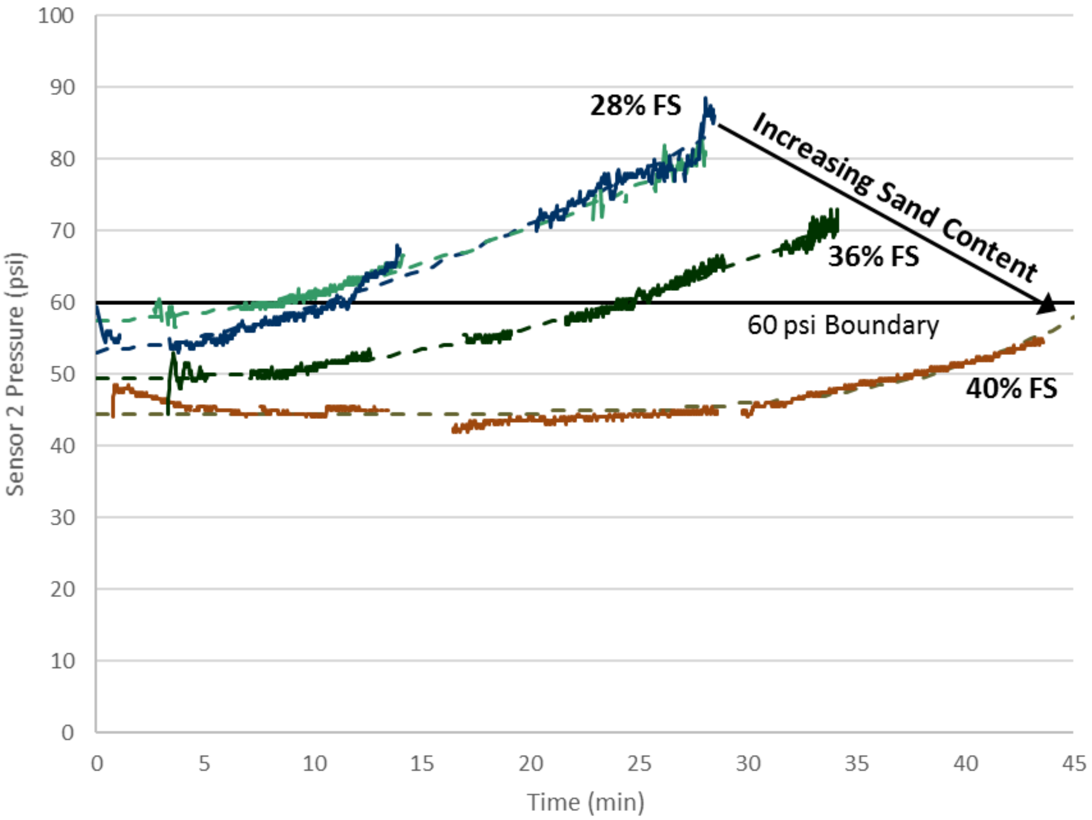

Figure 34: Within the bounds of 28% and 40% total fine sands, increasing sand content decreases pressure and increases pumping time.

This strongly suggests – along with the data from Chapter 2 – that the amount of fine sand in a concrete mixture effects pumpability. As the total fine sands increase from 28% to 40% the concrete mixture becomes more pumpable. 40% is a conservative boundary since other tests closest to this value are only 36% and 44%. Further research is required to determine if values between 36% and 44% also follow this trend and to see if 40% is the optimal fine sand content.

3.2.2.4 Paste Content Data Set

Using the same gradation as the baseline concrete mixture, well within the bounds of the Tarantula Curve, the paste content was reduced to determine its effect on the mixtures pumpability. Mixtures with a 6.0 sack and 5.5 sack paste content were tested and their secondary curve averages, along with their respective regression curve, are plotted over time in Figure 35.

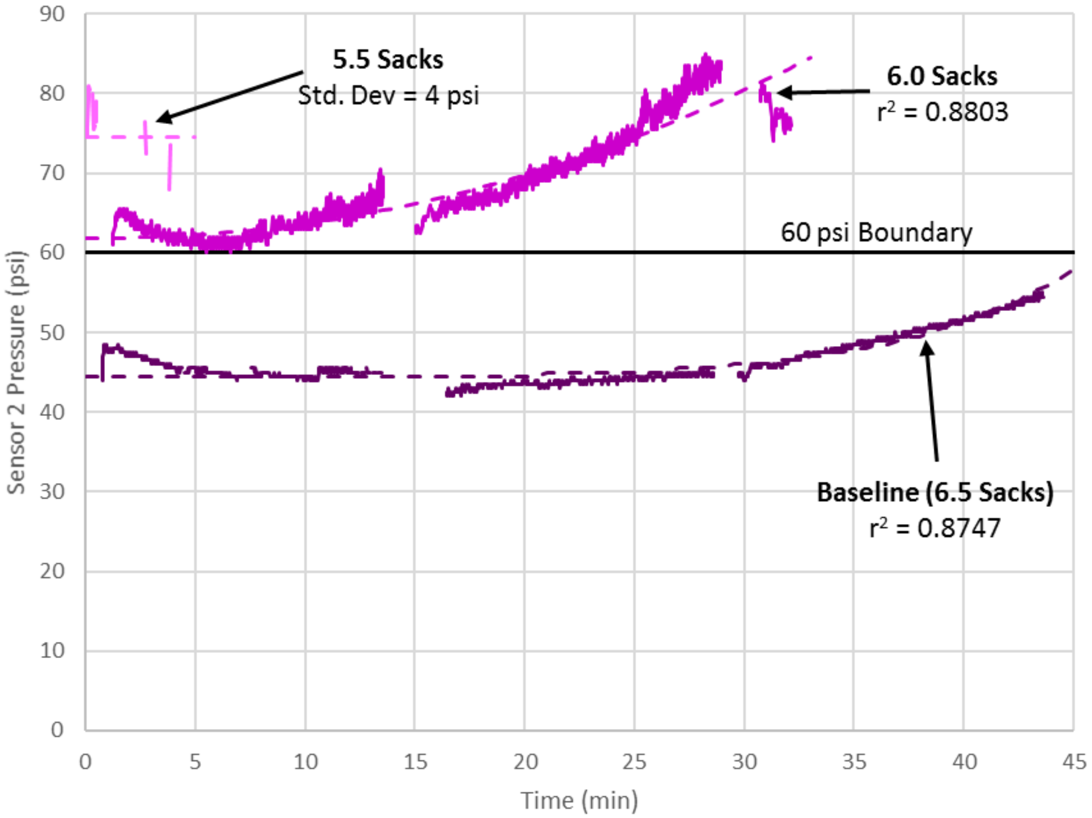

Figure 35: As paste content decreases, so does the mixture's pumpability.

Figure 35 strongly suggests that sack content affects pumpability. Even with optimal gradation, decreasing the sack requires a pump pressure above the 60 psi boundary. While a paste content of 6.0 sacks is pumpable – also cheaper to produce – there is less room for error with gradation.

Using a content of only 5.5 sacks, the mixture fails to pump. The pump session lasted only five minutes and graphed 75 psi pressures. Even with an optimized gradation, pumping with a paste content of 5.5 sacks is not suggested.

3.2.3 Pressure Loss between each Sensor

Recall that the space between Sensors 1 and 2 is a straight section of pipeline with a length of 13.4 feet. The space between Sensors 2 and 3 is a 90-degree bend with a total pipeline length of 5.4 feet. The space between Sensors 3 and 4 is a straight section that is 3.3 feet long followed by a 90-degree bend that is 2.09 feet. This makes the entire distance between the sensors to be 8.7 feet. Figure 36 from the previous chapter is shown below.

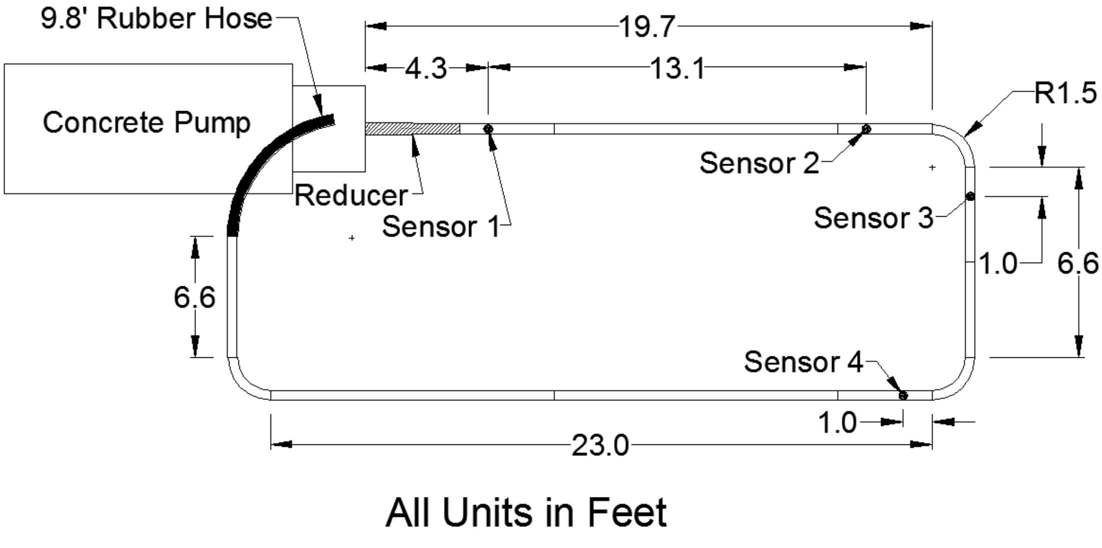

Figure 36: The pipe network with sensor distances.

Also recall that unless a concrete failed early, having an unusable slump of less than 3 inches, slump and unit weight measurements were taken at 15 minute intervals during pumping. Slump data from every time interval was combined and plotted with the pressure drops between each sensor. These pressure drops were found using the regression curve equations shown previously in the chapter. Figure 37, 38, and 39 show the pressure loss per foot for each set of sensors. Data points from failed mixtures, highlighted in orange, were removed from regression analysis but are still plotted in the figures.

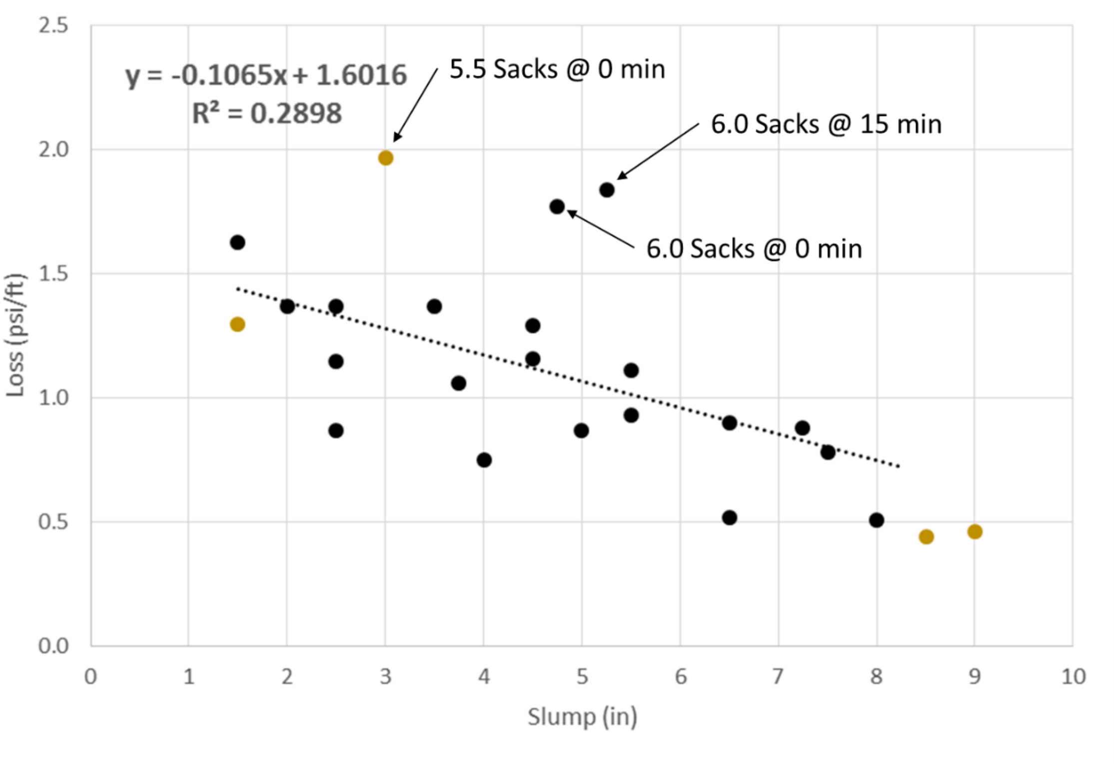

Figure 37: Correlation between slump and the straight section of pipeline.

There are three major outliers in the data: two from the 6-sack paste content mixture and one from the 5.5-sack paste content mixture. This suggests that slump can be used reasonably well for predicting pressure losses in a straight section of pipe as long as the sack content is 6.5 sacks. Perhaps mixtures with different sack contents follow different trends; future research is needed to determine if there are such trends.

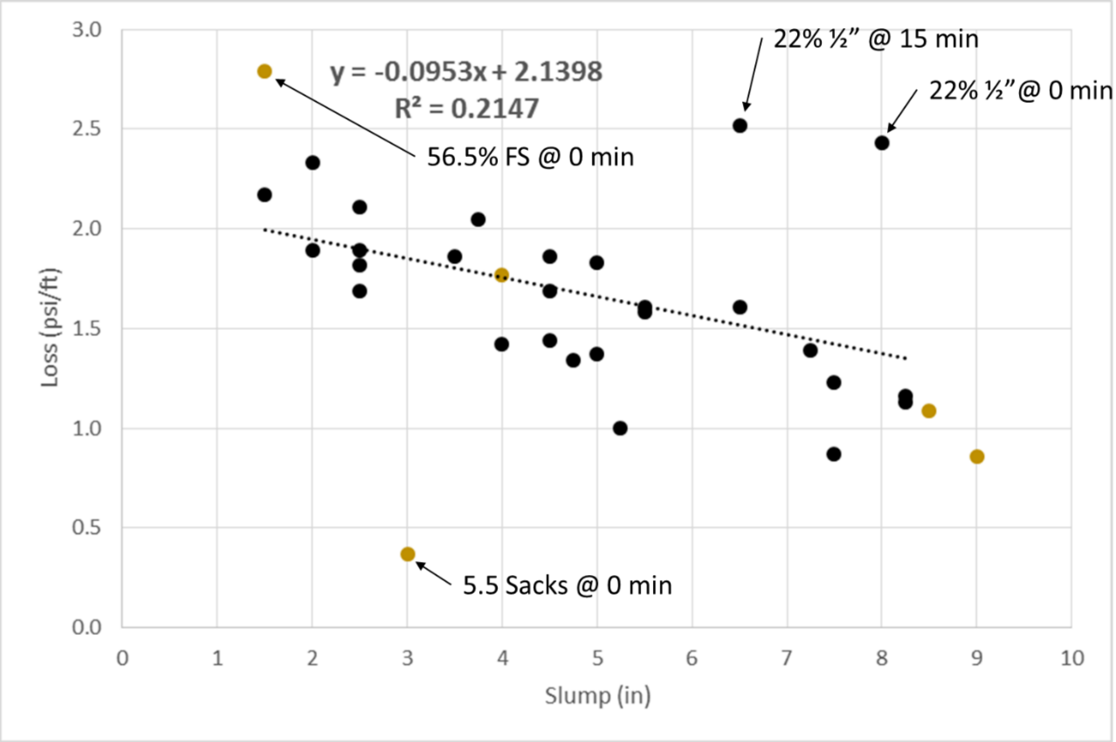

Figure 38: Correlation between slump and first 90-degree bend.

In this data set there are also four major outliers; three from variable gradation mixes and again one from the 5.5 sack content mixture. Two are from the 22% ½" sieve size data, the shortest-lived mixture from the coarse aggregate data set. The other is from the 56.5% fine sand data set, the mixture that yielded the highest initial pressures. Thus, it's notable these extreme gradations and paste contents produce unpredictable pressure losses and in the case, especially around a bend in the pipeline.

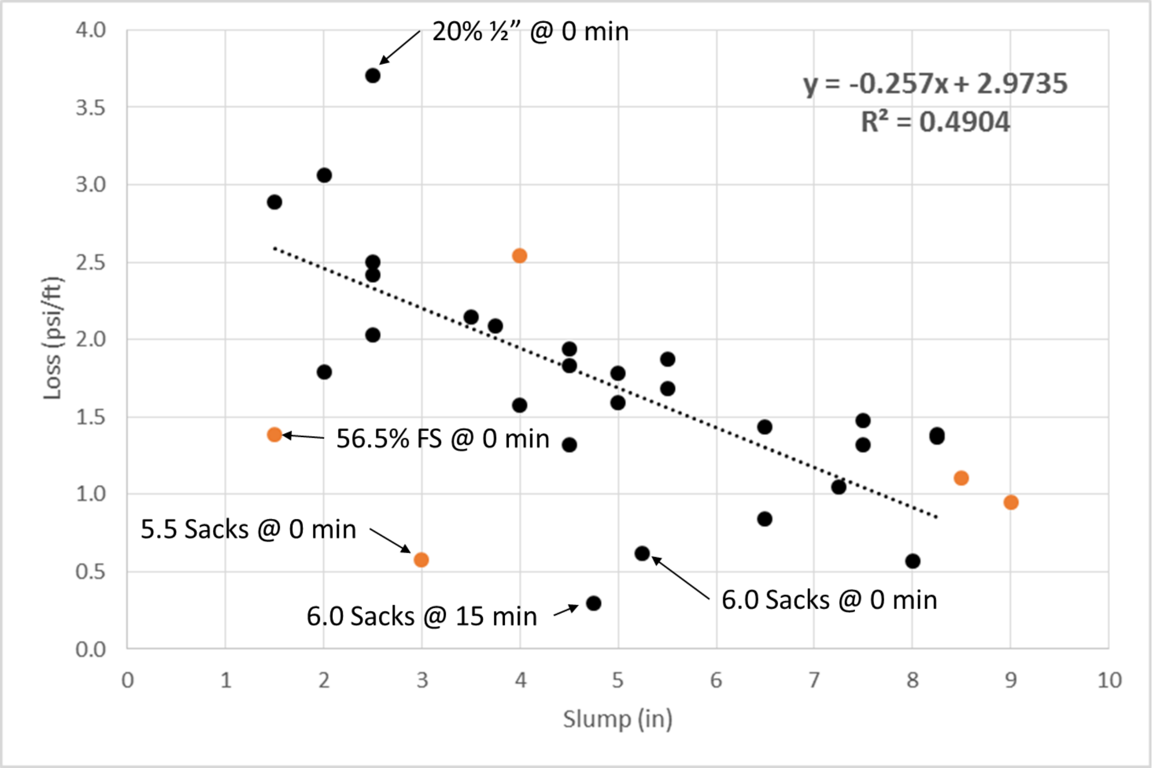

Figure 39: Correlation between slump and a small straight section and the second 90-degree bend.

Again the major outliers in the data include concrete mixtures with lower sack contents, suggesting that a different trend line may be needed after future research is completed. There is some trend that suggests that as a concrete's slump increases, the pressure loss in the pipeline decreases. This would occur because of the reduced stiffness, thus friction, the occurs between the pipeline wall and the concrete. The regression curves also suggest that losses are greater in a 90-degree bend than in a straight section of pipeline by about 0.5 psi at the y-intercept. With the given r-squared values, confidence intervals are large. No significant recommendations can be made in order to reach an exact loss in a unit length of pipeline. Only the most general recommendation can be made; using a concrete with a higher slump will most likely reduce pressure loss in a pipeline because it requires less force to overcome the friction against the concrete and the walls of the pipeline.

3.3 SUMMARY

Gradation is a major factor in pumpable concretes. By applying regression curves to the secondary curve averages of the pump data it has been shown that increasing a certain size aggregate above its recommended bounds will cause higher pumping pressures and shorter pumping times than can be acquired by creating gradations well within the bounds of the Tarantula Curve.

Fine sand content in concretes has the most drastic effect. By keeping the total fine sand content between the recommended boundaries of 28 to 40%, the concrete should be pumpable. These boundaries are not exact; further research is necessary to incrementally change the total fine sands in order to determine the optimal content.

Providing enough paste for the concrete to flow is also important in a pumpable concrete. It was shown that pumping with a 6.5 sack paste content produced the lowest pump pressures. It is assumed that pumping with 7 sacks of cement is also achievable but at the additional cost of more cement. Pumping with a 6 sack past content mixture is also achievable, but will require more energy and an optimized graded concrete. Pump any concrete with less than a 6 sack paste content is not recommended. Our research suggests that will cause a jammed pipeline.

A higher slump indicates lower pressure losses in a concrete pipeline, assuming gradations are not drastically overstepping the suggested boundaries for any particular sieve size. Further research is needed to determine pressure loss trends in concretes with paste contents different than 6.5 sacks.

CHAPTER IV

SHEARING AND PRESSURE EFFECTS ON PUMPABLE CONCRETE

4.0 INTRODUCTION

After finding that pump pressure, slump, and rheology correlate with pumpable concretes, the next step is to determine the causes of these effects. Slump values start very high, around 8 to 9 in. before pumping, but after cycling the concrete through the pump the slump drops drastically. While the total changes varied, in all cases the slump decreases and the yield stress increases as concrete was pumped.

To our knowledge concrete is subjected to two major forces in a concrete pump: pressure and shear. One or both factors could have a major effect on the pumpability of concrete. Those variables must be separated to determine their individual effects on concrete. A method was devised to test the shearing of concrete. This method hopes to provide some insight into what causes the workability to decrease as concrete is pumped.

4.1 EXPERIMENTAL METHODS

4.1.1 Materials

4.1.1.1 Concrete Mixture Design

All the concrete mixtures described in this chapter were prepared using a Type I cement that meets the requirements of ASTM C150 with 20% ASTM C618 class C fly ash replacement by weight. All of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 611 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 28.4% for the mixture volume. In each mixture the sand came from a single natural sand (sand A) source and the course and intermediate aggregates came from a single dolomitic limestone (limestone A). The aggregate proportions were held the same between each concrete mixture. A citric acid dosage of 0.25% by weight of cementitious materials was added to help retard the hydration.

4.1.2 Equipment

4.1.2.1 Rapid Shear Drill Press

Typically, the ICAR Rheometer conducts its tests by rotating its paddle at 30 rpm. To examine how a high shearing rate impacts the rheology of concrete, the paddle from the ICAR rheometer is attached to the drill press and then rotated at 300 rpm. This is 10 times the normal shearing rate. The same pot and vane is used in this testing as was used by the ICAR Rheometer, except that the vane is rotated by the drill press instead of the motor from the ICAR Rheometer. Figure 40 shows the test setup.

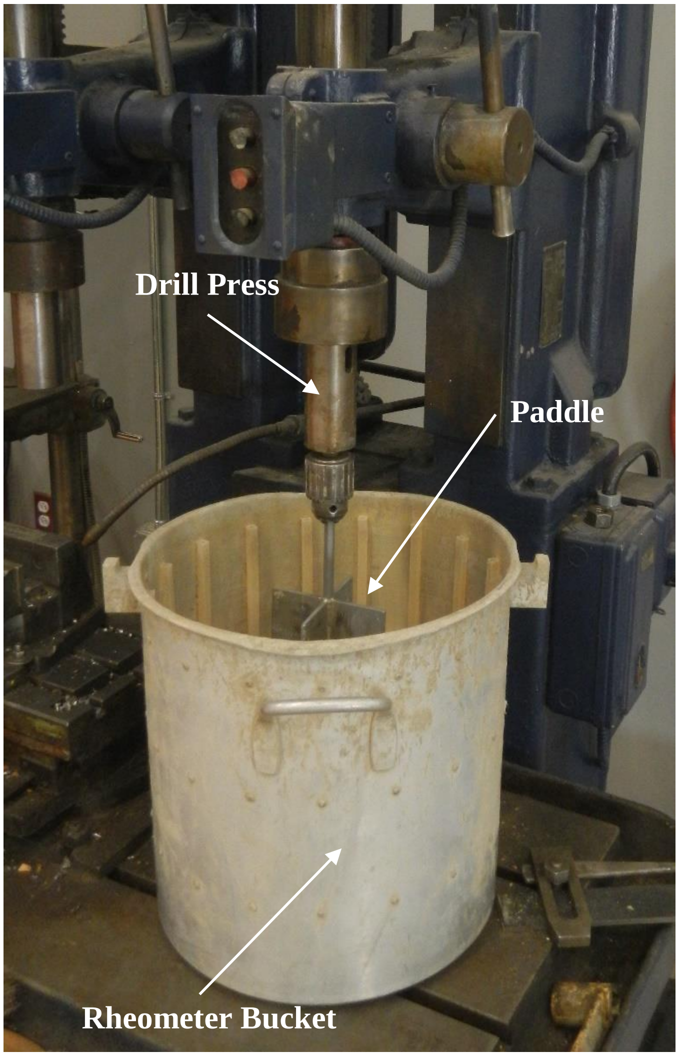

Figure 40: With the rheometer paddle attached to a drill press, concrete is sheared at 300 rpm, 10 times the speed of the ICAR Rheometer.

4.1.3 Testing Methods

4.1.3.1 Rapid Shear Drill Press Test

An initial slump and ICAR rheometer measurement is taken. Some material is left in the wheelbarrow to rest and the material from the rheometer pot is placed under the drill press. The vane from the rheometer is placed in the drill press and it is lowered down into the concrete and locked into place. The drill press then shears the concrete at 300 rpm for 10 minutes. This high shear rate simulates the friction between the walls and the concrete during pumping. After shearing the concrete for 10 minutes the vane is detached from the drill press and it is placed on the ICAR rheometer. The Static and Dynamic Yield stresses are found using the rheometer's typical speed of 30 rpm. Slump is also recorded with the sheared concrete in the rheometer pot as well as the material that has been resting in the wheelbarrow. The time required to run these tests is recorded and included in the total time calculations for the test.

After the slump is recorded the concrete is returned to the rheometer pot and is sheared by the drill press for another 10 minutes. Rheometer measurements and slump are taken again and the material is returned to the rheometer pot. This is done until the slump is less than 3". This slump value was chosen because this is the slump limit when the material was unacceptable for pumping.

4.2 RESULTS AND DISCUSSION

4.2.1 Rapid Shear

Figure 41 shows the slump data from the concrete that rested, concrete from the high shear rate testing, and the performance of the concrete from the pump.

4.2.1.1 Slump Data

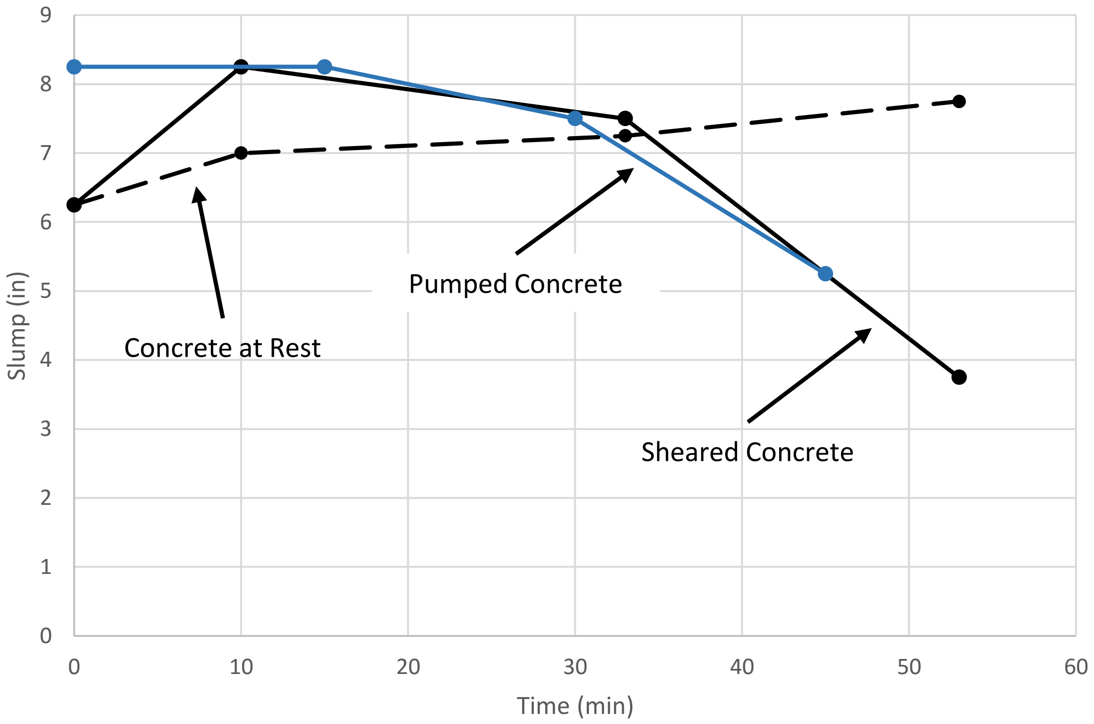

Figure 41: The slump change over time between sheared concrete and pumped concrete is similar.

Over the course of the test the slump in the control concrete increased 1.5 in. This could be due to bleeding in the wheelbarrow. Regardless, this slump gain is not considered significant relative to the changes that occurred in the sheared concrete.

The sheared concrete experienced a slump gain within the first ten minutes. But then the slump decreased by almost 4 in. over the course of the entire shearing test. When comparing the slump data gathered while pumping concrete of the same gradation and citric acid dosage, the results look similar. The biggest difference between the two data sets is the initial slump value, which is 2 in. apart. Even so, the slump changes in both the pumped concrete and the sheared concrete suggest that shearing is a major factor of slump loss in pumped concretes that use citric acid.

4.2.1.2 Rheometer Data

Two to three tests were run to acquire each value and the greatest coefficient of variation in any of the data points was 10%. Figure 42 shows the static and dynamic yield stress averages over time from the pump session and the high speed rheometer test. The white dots indicated the range of data that was collected.

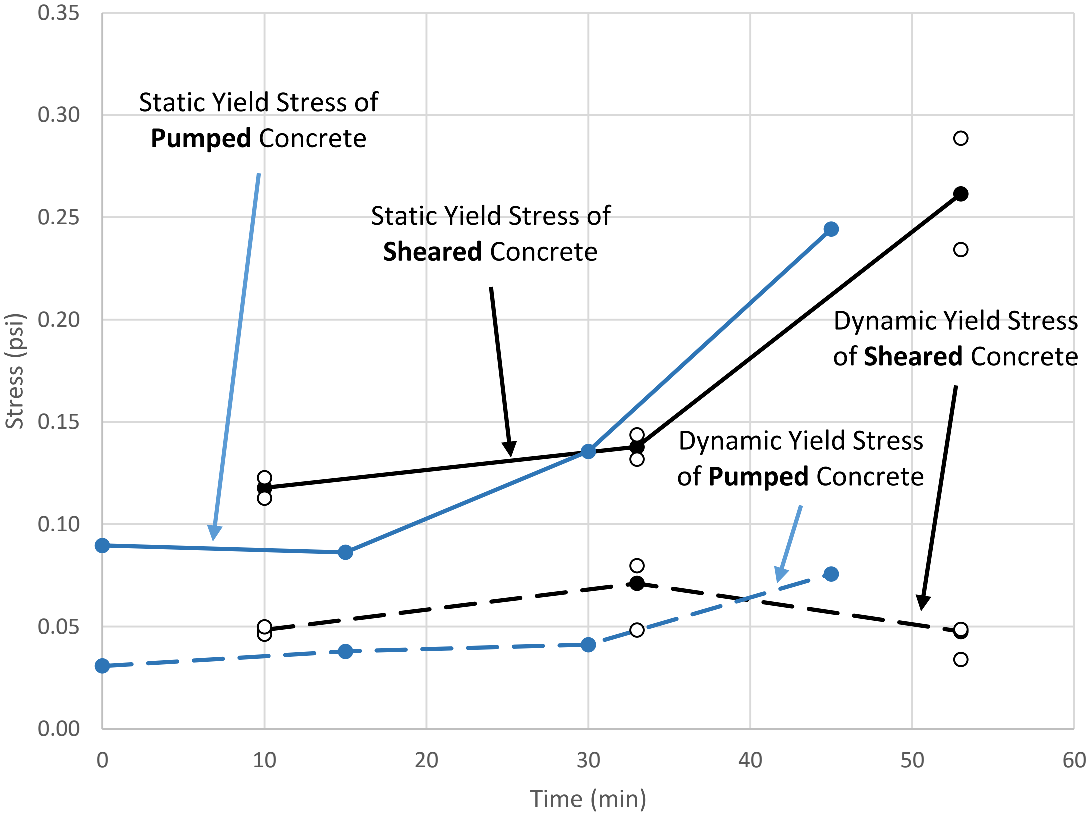

Figure 42: Pumping and high speed shearing return similar yield stress values over time.

In both pumped and high shear concrete the static and dynamic yield stress show similar performance. Since the dynamic yield stress doesn’t change greatly this could mean that the shearing does not have a significant impact on this parameter. But with the given trends, shearing the concrete increases the static yield stress. An increase in static yield stress means it would require more energy to initially get the concrete moving through the pump.

4.3 SUMMARY

The shearing of concrete has a conclusive effect on its pumpable properties. The aggregate’s movement within the cement paste could be the greatest mechanism for property changes. The cement grains suspended in the concrete mixture are likely to be sheared and broken apart by the rapid movement. When the cement grains are broken, new surfaces are exposed that could absorb both free water and other admixtures, including citric acid. This absorption would decrease the overall water to cement ratio, decreasing slump. It would also reduce the citric acid dosage ratio, reducing both its retardation and workability properties.

Using a rapid shear drill press at 300 rpm created changes in concrete’s slump very similar to what occurred in the concrete pump’s pipeline. Further research should include shearing the concrete at other rates to determine if the slump change is more time dependent, changing the same amount when sheared at different rates, or more shear dependent, decreasing in slump far quicker if the shear rate is increased.

CHAPTER V

LABORATORY EVALUATIONS OF PUMPABLE, AIR-ENTRAINED CONCRETE MIXTURES

5.0 INTRODUCTION

Proper air content in concrete can provide a microstructure that allows space for water to freeze and expand without cracking or damaging the supporting structure. Concrete bridge decks are highly susceptible to this sort of damage (called freeze/thaw) due to the rapidly changing weather conditions in Oklahoma and other states. Cold, freezing winds pass both over and under the concrete bridge deck causing quick freezing that could potentially destroy the structure. Thus, it is important that the concrete has the proper air structure to combat these effects.

In many cases the fresh concrete used for making bridge decks is pumped up to the building elevation. In the past, industry has recognized that pumping concrete destroys the air structure due to its high pressures (NRMCA 2005). Regardless of the “destroyed” air structure the bridges remain standing even after excessive freeze/thaw reactions. This must mean that there is more to be learned about the air content of pumped concretes.

In this chapter, two industry standard air contents will be pumped and analyzed. The Super Air Meter Test, designed by Dr. Ley, will be used to analyze the air content and air structure of these concretes after they have been pumped in hopes of finding trends to explain the cause of air loss during pumping.

5.1 EXPERIMENTAL METHODS

5.1.1 Materials

5.1.1.1 Concrete Mixture Design

All the concrete mixtures described in this work were prepared using a Type I cement that meets the requirements of ASTM C150 with 20% ASTM C618 class C fly ash replacement by weight. To investigate the impact of the aggregate gradation, all of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 611 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 28.4% for the mixture volume. In each mixture the sand came from a single natural sand (sand A) source and the course and intermediate aggregates came from a single dolomitic limestone (limestone A). The aggregate proportions were purposely held the same between each concrete mixture. In doing so, the pump's effect on air content could be analyzed.

5.1.1.2 Grout Mixture Design

The most common method of starting to pump concrete through the line is to start with a grout mixture (Neville 2012 and The Contractor's Guide 2005). The grout is used to line the walls of the pipe and reduce the amount of segregation that occurs in the concrete from pumping (Neville 2012 and The Contractor's Guide 2005). Using a Type I cement that meets the requirements of ASTM C150, the grout mixture was designed with a w/cm of 0.40, 1006 lbs./cy of cement, and 2514 lbs./cy of sand. The sand used in the grout mixture also came from Sand A.

5.1.1.3 Admixtures

For the grout mixture, a citric acid dosage of 0.25% by weight of cementitious materials was added to the grout mixture to help retard the hydration. For the concrete mixture, a citric acid dosage of

0.15% by weight of cementitious materials was used. This dosage was reduced to allow for the extra slump gain when using air-entrainers and mid-range water reducers.

5.1.2 Equipment

Equipment that was used in testing is the same as discussed in Chapter 2 and 4: concrete pump, pressure sensors, and the ICAR Rheometer with the high shear drill press. In this chapter an additional tool was used, a Super Air Meter (SAM).

5.1.2.1 The SAM

The SAM is an air pressurization system that measures an initial air content and air structure of a concrete by using a sequential pressurization method (14.5 psi, 30 psi, and 45 psi). By pressurizing the concrete to these different levels smaller air bubbles in the system will dissolve and larger air bubble will decrease in size. Equipment and procedure for this process is specified in AASHTO TP 118 ("*Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method*"). The equipment used is per that specification.

5.1.3 Testing Methods

5.1.3.1 Pumping with Air-Entrained Concrete

In addition to the pumping procedure from Chapter 2, air content data was also collected.

A specified dosage of air-entrainer was added to the concrete during its initial mixing. Before the concrete was dumped into the pump, it was tested using the SAM which additionally gathers unit weight and air content.

During pumping, two SAM test are run simultaneously during the standard testing interval times of 0, 15, 30, and 45 minutes and the data is recorded. Samples for hardened air void analysis is gathered with the concrete used by the SAM and will be reported in later publications.

5.2 RESULTS AND DISCUSSION

Two pump sessions were conducted: The first with 4% air content, and the second with 7% air content. Slump and SAM data were gathered during these sessions along with the data from the pressure sensors in the pipeline.

5.2.1 Pump Data

Both pump sessions lasted 45 minutes. The 4% air mix had a slump loss of only 2 inches while the 7% air mix had a slump loss of 4.5 inches. Even so, both mixtures remained above the 3-inch slump threshold. Table 10 shows the performance of both mixtures over each time interval. The two SAM tests are averaged together and presented on the table. Any average that yielded a coefficient of variation higher than 15% is highlighted in red.

Table 10: Summary of pumping data. In both cases, air content dropped significantly.

	4% Air Data Set			**7% Air Data Set**		
	Slump (in)	**Air (%)**	**SAM**	**Slump (in)**	**Air (%)**	**SAM**
Initial	9.25	4.0%	0.26	8.75	6.9%	0.10
0 min	9.25	3.2%	0.63	8.50	3.6%	0.62
15 min	9.00	2.1%	0.74	9.00	2.4%	0.63
30 min	8.25	1.7%	0.73	7.25	2.4%	0.70
45 min	7.25	1.9%	0.87	4.25	2.4%	0.63

Both concrete mixes experienced a loss in air content. The higher SAM number indicates low quality air void system. The SAM number had a coefficient of variation higher than 15% at the 45-minute mark in each session. The change in the air void system quality begins to occur immediately after pumping starts. This suggests that when concrete is pumped, the air void system becomes increasingly unstable.

5.2.1.1 Sensor Data

As discussed in the previous chapter, peak pressures, piston stroke intervals, and minimums pressures were not the best means towards a usable analysis. Data from the secondary curves was averaged and any secondary curve that had a higher coefficient of 10% was filtered out.

In the 4% air content concrete mixture, there was an error in the baseline value of Sensor 4 and possibly Sensor 3. In Figure 43, the plot of secondary curve averages over time, the values from Sensor 4 overtake the values from Sensor 3 at the end of the pump session. This suggests that a small negative pressure existed in the pipeline between the sensors. This is not possible. A new baseline for Sensors 3 and 4 could not be set because evidence of a better baseline could not be found in the data. Note in the figure where pressures from Sensor 4 overtake Sensor 3.

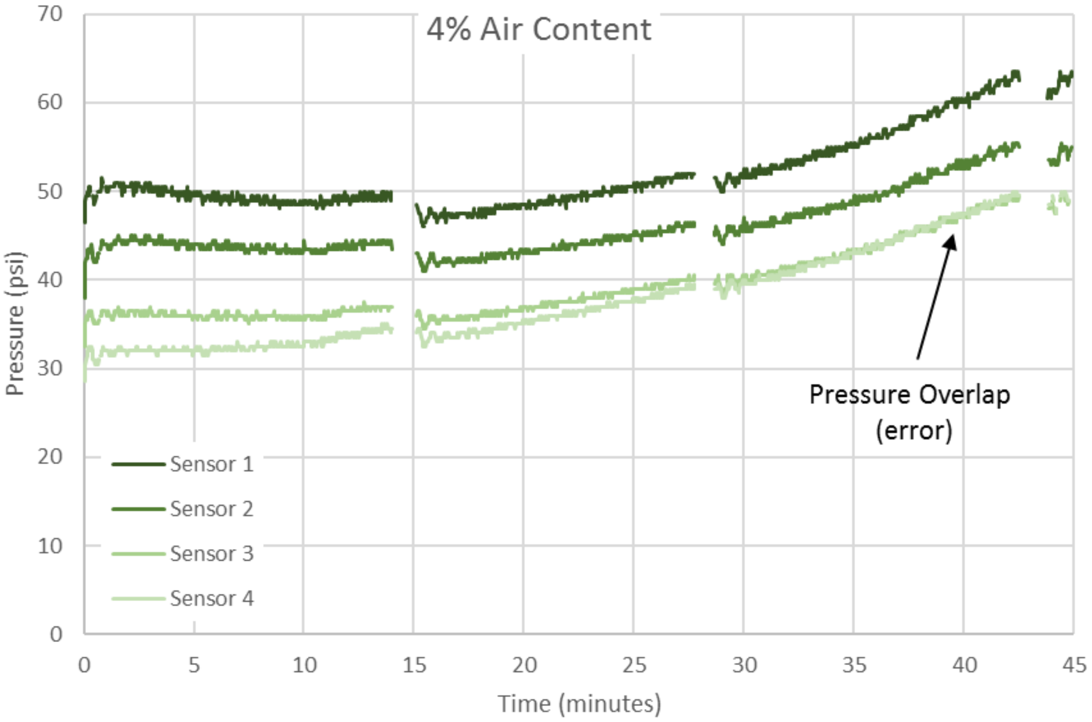

Figure 43: Error in Sensor 3 and 4 aside, concrete with air-entrainers perform at lower pressures.

In the 7% air pumping session, the first 5 minutes of pumping were lost. Even so, the sensors caught an unexplainable drop in pressure at the 12-minute mark. This cannot be an error in the sensors because all four sensors caught the phenomenon.

Secondary curve pressures were slightly higher than in the 4% air content concrete. Sensor 2 crosses the 60 psi boundary at 40 minutes while in the 4% air mixtures, Sensor 2 never exceeds 60 psi. Figure 44 shows the secondary curve data along with a box marking where data was lost and also the pressure drop in the system.

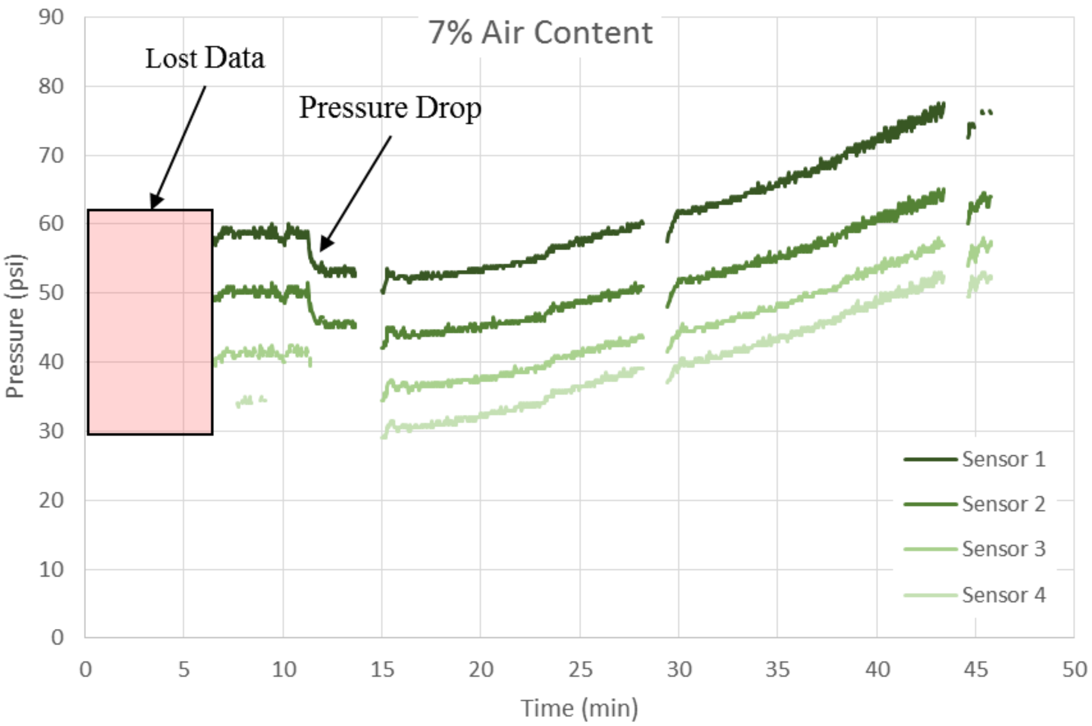

Figure 44: With 7% air content, the mixture performs at slightly higher pressures than 4% air content.

Pressures in the secondary curves seem to have similar values to the baseline concrete gradation. The baseline mixture has the same gradation but does not have any air-entrainers, only citric acid. Figure 45 shows the Sensor 2 secondary curves over time from the baseline mix and the two air-entrained mixes. Note the similarities.

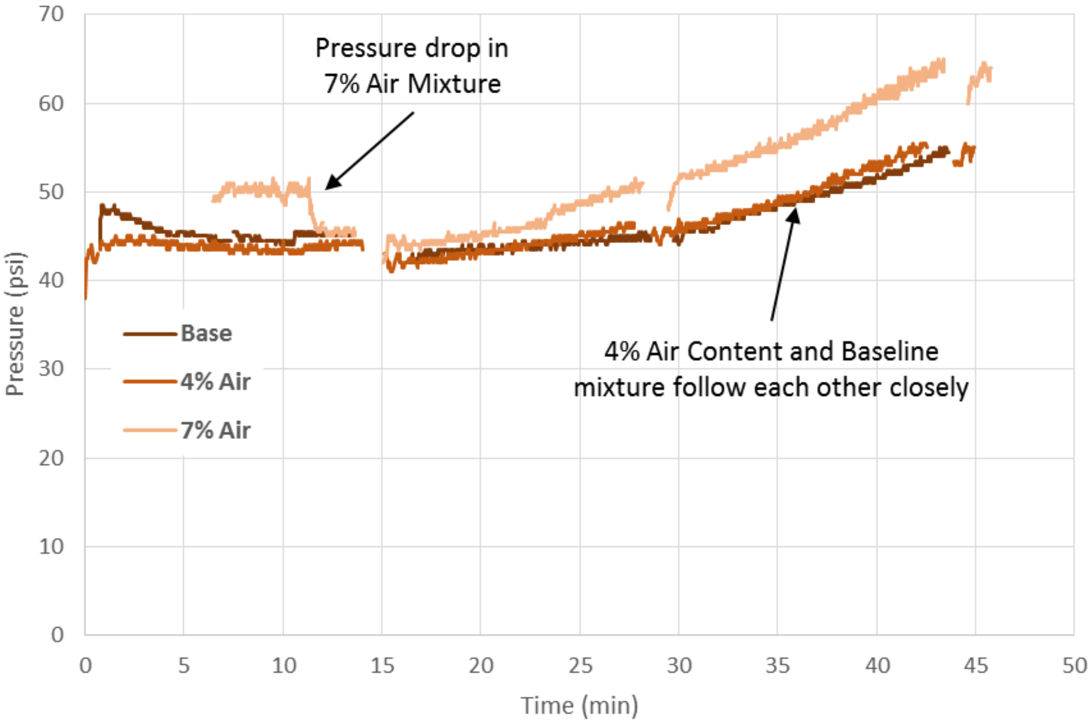

Figure 45: Once the pressure drops in the 7% air mix, it falls into line with the other mixes.

Even though the cause of the pressure drop is unknown, it falls alongside the pressures from the other two curves. The other two mixes, the baseline and the 4% air content, remain at similar pressures throughout the pump session. From 15 minutes onward, pressures from the 7% air content mixture get steadily higher than the other two.

5.2.2 High Velocity Shear Data

Slump, air content, and SAM number has the same initial value as before and the tests were done again after the concrete has been sheared. Figure 46 is a graphical representation of the slump change and air change in both the sheared and pumped concretes. The SAM number of the sheared concrete changed from 0.11 to 0.35, indicated that the air void system became slightly unstable after excessive shearing. The SAM number for each data point can also be seen in the figure.

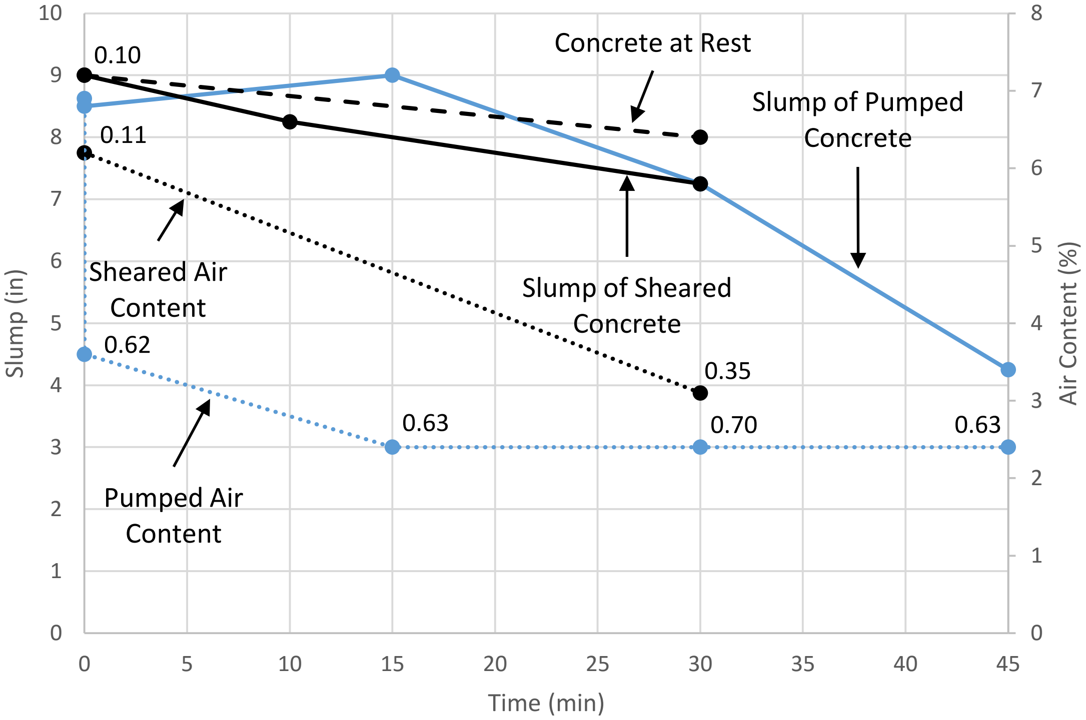

Figure 46: Slump in the sheared concrete follows similarly to the pumped concrete, as does the measured air content.

While both the slump and air content seem to follow closely between the pump and the shear test, the SAM numbers differ. In the pump that SAM number was 0.70 at the 30-minute time interval. The SAM number change from the initial value to the 30-minute mark was 0.60, much higher than the 0.24 change in the high velocity shear test. This suggests that while shearing contributes to the destruction of the air void system the pumping may be more important. Further testing is needed.

5.3 SUMMARY

Our tests have shown that a significant amount of air content is lost in concrete during pumping. Shearing, along with other factors, may be the cause of this air loss. To combat this loss, a contractor could overload the concrete with air-entrainers and hope to get a more desirable air content (NRMCA 2005). Even so, using the SAM in these tests suggest that pumping creates a very unstable air void system. No durability would be gained by overloading the concrete with air-entrainers, only weaker concrete.

Rapid shearing is a major cause of air loss in pumping. Our data suggests that shearing destroys the air bubbles in the concrete but the SAM numbers indicate that other factors may be the cause of the unstable air void system. That is, shearing decreases air content but not stability.

Air-entrainers do not reduce the pressures in a concrete pump. Rather, our test of 7% air content suggests that too much air causes higher pressures over time. More research is required to confirm this theory.

CHAPTER VI

CONCLUSION

6.0 SUMMARY

This thesis was mainly composed of three parts: comparing pump pressures to standard concrete testing methods, analyzing the parts of a pressure curve to compare the pumpability of a variety of concrete mix designs, and then attempting to create tests to determine what factors effect concrete the most during pumping.

We pumped concretes with 13 different gradations to determine if the Tarantula Curve provided conservative limits for aggregate gradations. Our team was able to show that staying within the bounds of the Tarantula Curve along within the total fine sand recommendations will yield the lowest comparable pump pressures.

Further analysis using regression curves were able to show that mixtures with aggregates gradations outside of the recommended boundaries behaved unpredictably, especially in terms of fine sand content. Staying within 28 to 40% total fine sands will tend to yield a pumpable concrete. Using those same regression curves, we were able compare pressure losses between sensors at exact moments in time and compare them to their slump value. By doing this, we were able to determine that pressure loss can be estimated by slump value, assuming the mixture has not segregated and the paste content is 6.5 sacks.

Lastly, by creating a testing method where concrete is rapidly sheared our team was able to show that shearing causes a loss in slump as well as air content. The Rapid Shear Drill Press Test created slump values very similar to those acquired by pumping. It also created similar air contents as well but had lower SAM numbers, indicating that other factors effect air content during pumping.

The most important, though simple finding, is that slump can be an excellent method for determining if a concrete is pumpable. Our data has shown that optimal slump for pumping is about 7.5”, plus or minus an inch. This slump must come from a cohesive concrete, not a mixture that has segregated. Slump, save for a few extreme gradation outliers, also proves to be a good method for predicting pressure losses in the pipeline, at least for a 6.5 sack paste content mixture.

Further research is required to learn more about the effect of pumping on air content as well as creating more precise boundaries for gradations. But this thesis has provided a strong skeleton to begin building a comprehensive data set for pumpable concretes.

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