Oklahoma Department of Transportation
200 NE 21st Street, Oklahoma City, OK 73105-3204

FINAL REPORT ~ FHWA-OK-15-07

INVESTIGATION OF OPTIMIZED GRADED CONCRETE FOR OKLAHOMA - PHASE 2

Marllon D. Cook
J. Nick Seader
M. Tyler Ley, Ph.D., P.E.
Bruce W. Russell, Ph.D., P.E.
School of Civil and Environmental Engineering
Oklahoma State University
Stillwater, Oklahoma

October 2015

Oklahoma Department of Transportation

Transportation Excellence through Research and Implementation
ODOT-spr@odot.org
Materials and Research Division
Research & Implementation Branch

INVESTIGATION OF OPTIMIZED GRADED CONCRETE FOR OKLAHOMA - PHASE 2

FINAL REPORT-FHWA-OK-15-07

ODOT SP&R ITEM NUMBER 2253

Submitted to:
John R. Bowman, P.E.
Director of Capital Programs
Oklahoma Department of Transportation

Submitted by:
Marllon D. Cook
J. Nick Seader
M. Tyler Ley, Ph.D., P.E.
Bruce W. Russell, Ph.D., P.E.
School of Civil and Environmental Engineering
Oklahoma State University

October 2015

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT=S CATALOG NO.
FHWA-OK-15-07		

4. TITLE AND SUBTITLE	5. REPORT DATE
Investigation of Optimized Graded Concrete for Oklahoma- Phase 2	**October 2015**
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) **Marllon D. Cook, Nick Seader, M. Tyler Ley, and Bruce W. Russell**	8. PERFORMING ORGANIZATION REPORT
9. PERFORMING ORGANIZATION NAME AND ADDRESS **Oklahoma State University Civil and Environmental Engineering 207 Engineering South Stillwater, Oklahoma 74078**	10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. **ODOT SP&R Item Number 2253**
12. SPONSORING AGENCY NAME AND ADDRESS **Oklahoma Department of Transportation Planning and Research Division 200 N.E. 21st Street, Room 3A7 Oklahoma City, OK 73105**	13. TYPE OF REPORT AND PERIOD COVERED **Final Report October 2013 – October 2015** 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Optimizing aggregate usage has been a subject widely discussed through the history of concrete. Since aggregates make up over 70% of the volume in a concrete mixture, the aggregate gradation is critical to the strength, workability, and durability of concrete. In practice, there is little quantitative guidance given to practitioners on aggregate proportioning in a mixture to meet the desired performance. The ACI 211 Mixture Design Procedure maybe the most widely taught mixture design method, but still is not widely used in practice due to limitations with the method. In fact, the ACI 211 method only contains a handful of aggregate parameters that many argue about the validity. One of the largest obstacles preventing the development of aggregate parameters and guidance comes from only a few test methods that are capable of providing quantitative data about the workability of concrete. This work focused on creating practical test methods and using them to understand how the aggregate gradation changes the workability of concrete.

A series of workability tests for concrete were developed/used to investigate mixtures for bridge deck applications. Each test is used to evaluate various aggregate gradations and develop a new set of design recommendations and specifications.

The ultimate product of this work is a new specification for the state of Oklahoma for mixtures with a greater durability at reduced cost and with improved sustainability. Based on 2015 production this design method has the potential to save the state of Oklahoma over $1.5 million per year, enough power for 440 Oklahoma homes, and reduce long term costs through reduced maintenance from durability issues.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Optimized Graded Concrete, Aggregate Gradation	**No restrictions. This publication is available from the Materials & Research Division, Oklahoma DOT.**

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	**Unclassified**	**156**	**N/A**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
In	Inches	25.4	millimeters	mm
Ft	Feet	0.305	meters	m
Yd.	Yards	0.914	meters	m
Mi.	Miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
Floz	fluid ounces	29.57	milliliters	mL
Gal	Gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
Oz	Ounces	28.35	grams	g
Lb.	Pounds	0.454	kilograms	kg
T	short tons (2000 lb.)	0.907	mega grams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
Fc	foot-candles	10.76	lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
Lbf	Pound force	4.45	newtons	N
lbf/in^2	Pound force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
Mm	millimeters	0.039	inches	In
M	Meters	3.28	feet	Ft
M	Meters	1.09	yards	Yd
Km	Kilometers	0.621	miles	Mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	Hectares	2.47	acres	Ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	Milliliters	0.034	fluid ounces	Floz
L	Liters	0.264	gallons	Gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
G	Grams	0.035	ounces	Oz
Kg	Kilograms	2.202	pounds	Lb
Mg (or "t")	mega grams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
ºC	Celsius	1.8C+32	Fahrenheit	ºF
ILLUMINATION				
Lx	Lux	0.0929	foot-candles	Fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	Fl
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	Pound force	Lbf
kPa	kilopascals	0.145	Pound force per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Acknowledgments

The research team would like to thank Kenny Seward, Matt Romero, Walt Peters, Gary Hook, and Bryan Hurst for all of their help with this project. In addition, we would like to say a special thanks to Dean Paul Tikalsky for his help in obtaining the concrete pump and for our outstanding conversations about concrete.

TABLE OF CONTENTS

List of Figures

List of Tables

CHAPTER 1 - INTRODUCTION

When Duff Abrams wrote *Proportioning Concrete Mixtures in 1922*, it outlined the basic fundamental concepts of a concrete mixture design that people still use today. Mixture designs are designed to meet certain specifications such as water-to-cementitious material (w/cm) ratio, compressive strength, durability, sustainability, permeability, and workability (Abrams 1922, Powers 1968). For many concrete producers, the goal has been to not only meet the basic specifications of a mixture design, but also create a lower paste content and still obtain a certain workability. To reduce paste, concrete producers look towards using aggregates effectively in a mixture design, which has been called optimized graded concrete (Shilstone 1990 and Taylor et. al. 2007). However, the development and implementation of reducing the paste content becomes a very complex subject due to the effects on the workability of the concrete (Shilstone 1990, Powers 1968, Abrams 1922). Duff Abrams stated, “Workability of concrete mixes is of fundamental significance. This factor is the only limitation which prevents the reduction of cement and water in the batch to much lower limits than are now practicable.” (Abrams 1922)

Only a limited amount of quantitative guidance can be given to practitioners on aggregate proportioning in a mixture to obtain the desired performance. Furthermore, the ACI 211 mixture design procedure has been the most widely taught mixture design method, but has not been commonly used in practice due to the method only containing a handful of aggregate parameters and many argue about their validity. This has been due to the lack of reliable tests to provide quantitative data about the workability of concrete. This work focused on establishing useful test methods and then using them to better understand how aggregate gradation impacts concrete workability.

The main goal of this report was to further advance the knowledge of aggregate proportioning, developed practical workability tests, and create a practical specification for optimized graded concrete in the application of structural concrete such as a bridge deck. This was done by creating and validating various workability tests in Chapter 2. The workability tests were used to investigate the combined gradations of bridge deck mixtures in Chapter 3 and 4. The following is an outline of the chapters presented.

- Chapter 2: Developing and validating workability tests.
- Chapter 3: Investing the combined gradation of coarse aggregate.
- Chapter 4: Investing the combined gradation of fine aggregate.
- Chapter 5: Using a concrete pump to further investigate limits.
- Chapter 6: Recommended Aggregate Gradations for Flowable Concrete.

CHAPTER 2 – WORKABILITY TESTS

2.1 INTRODUCTION

The workability of concrete describes the ability of a concrete mixture to be mixed, placed, consolidated, and surface finished for a specific application (Taylor et. al 2007, ACI 211 1991, Kosmatka et. al 2011, Neville 2012, Mehta and Monteiro 2006, Powers 1968, and NSSGA 2013). These tasks require a mixture to obtain a certain stiffness, flow, cohesiveness, richness, and surface finishability (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, and Powers 1932). If a concrete mixture does not obtain the required performance, the workability of the concrete cannot be obtained and therefore the concrete is not suitable for the application (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, and Powers 1932). This is why many concrete producers make a trial batch and measure the workability of the designed mixture before using the mixture in production (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, and Powers 1932).

One of the most sought-after achievements in the concrete industry has been a test or series of tests to measure the workability of the concrete (Powers 1932, Powers 1968, Wong et. al. 2001, Fulton 1961). Most workability tests measure various properties of fresh concrete (Powers 1968, Wong et. al. 2001, Fulton 1961), but very few tests measure a useful workability property for a certain application (Cook et. al. 2014). For example, the Slump Test (ASTM C 143) has been the most specified workability test, but it measures the consistently of fresh concrete to fall under its own weight (Shilstone 1989). The ability of a mixture to fall will not dramatically indicate if the mixture will be suitable for building a floor slab or bridge deck. This inability to adequately measure the workability of concrete has created much controversy over the impacts of various mixture components effecting the workability of concrete and the dependability of any workability test to measure the workability of fresh concrete (Powers 1932).

To complicate the issue further, various applications require completely different workability properties of fresh concrete. For example, a slip formed pavement requires a mixture to be flowable for consolidation, but stiff enough to hold an edge after the vibration has stopped (Taylor et. al. 2007 and Cook et. al 2014). Yet, pumped concrete applications require higher flow mixtures for placement, which significantly reduces the emphasis on the consolidation behavior of fresh concrete (Kosmatka et. al. 2011). Some current workability tests may give insights into this performance but they are not specific enough to give direct insights into how the concrete will be used.

2.1.1 Objectives

The focus of this work will be on the various workability properties of structural concrete. Structural concrete for use in a bridge deck must be able to be pumped, but still stiff enough to be molded to have a slope to allow drainage. Also, the surface finishability of the mixture is also important. It is challenging for a test to measure both the flowability and surface finishability of a mixture. This chapter presents four ways to help evaluate the workability of structural concrete.

2.2 EVALUATION TECHNIQUES FOR THE WORKABILITY OF STRUCTURAL CONCRETE

The goal of a workability test should be to provide a standard measurement that precisely evaluates the important performance parameters of a mixture in the desired application. Unfortunately, a single workability test may not be able to measure every important workability property for an application. Four different tests were used to help evaluate the behavior of the concrete. These include: i) Slump Test (ASTM C 143/ AASHTO T119), ii) visual observations, iii) the Float Test, and iv) ICAR Rheometer.

2.2.1 The Slump Test

The Slump Test (ASTM C143/ AASHTO T119) has been the most specified test for the workability of concrete. It was developed to help monitor the consistency of plastic and cohesive fresh concrete. Using a 12” tall cone with the radius varying from 4” to 8”, three equal volumes of concrete was added to the cone and rodded 25 times per layer. Then the cone was lifted off the concrete within 3 to 5 seconds and a measurement was taken from the distance the top of the concrete deformed as shown in Figure 2-1. Even though the Slump Test has been used to measure all concrete applications from roller compacted concrete to highly flowable concrete, the standards only recommend using the Slump Test on plastic and cohesive mixtures of 0.5 in. to 9 in. Some applications such as a footing may require a 2 in. Slump while a floor slab may require a 6 in. Slump. For this reason, structural concrete slumps can commonly be specified to range between 2 in. and 8 in.

Figure 2-1: The Slump Test conducted on a structural concrete mixture.

While the Slump Test has been widely used as a specification to evaluate workability, it has been commonly believed to be inadequate at measuring the workability of concrete in the field (Powers 1933). Shilstone had this to say about the Slump Test, “The highly regarded Slump Test should be recognized for what it is: a measure of the ability of a given batch of concrete to sag.”(Shilstone 1989). While this “sag” property of the concrete may have other uses in the quality control department, this property does not measure the ease at which a mixture can be mixed, placed, consolidated, or surface finished. Despite the Slump Test being simple, work has been shown to suggest that the performance of concrete in the test is related to the static yield stress of the material (Roussel 2012, Kosmatka et. al. 2011). Other tests are needed to measure the workability of concrete.

2.2.2 Visual Observations

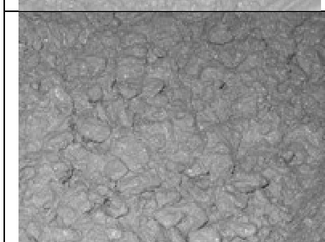
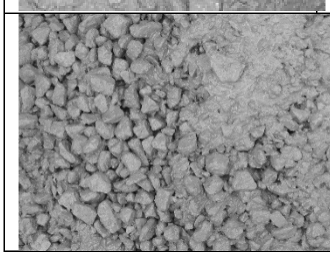
Since additional workability tests are needed, contractors often use visual observations to evaluate the workability of a concrete mixture (Powers 1932, Collins 2006, The Contractor's Guide 2005). The observations can be conducted by watching the concrete flow down a concrete chute, dragging the concrete with a come-along, or using a float to smooth the surface of the concrete to evaluate the surface finishability. These tasks require a mixture to obtain certain behavior characteristics such as a certain stiffness, flow, cohesiveness, richness, and surface finishability (Taylor et. al. 2007, Kosmatka 2011, Neville 2012, Powers 1932). While stiffness describes the resistance of concrete to movement, flow describes the ability of the concrete to continuously move (Kosmatka et. al. 2011, Neville 2012, Powers 1932). Also, richness describes the amount of sand and paste in the mixture for proper workability (Neville 2012, Powers 1932). Mixture with poor richness may struggle to meet the desired workability requirements. Another important behavior of concrete is the cohesiveness of the mixture to be homogenous and not segregate (Taylor et. al. 2007, Kosmatka 2011, Neville 2012, Powers 1932). This can have a dramatic impact on stiffness, flow, and surface finishability. The proceeding subsections discuss each performance behavior.

2.2.2.1 Cohesion

One of the most important properties of concrete is cohesion. This is the ability of the mixture to be a homogenous mixture while moving or at rest. Many times people refer to poorly cohesive mixtures as highly segregated mixtures. To assess the ability of the mixture to stay together, the five following performances were used: a mixture can be cohesive uniformly homogenous mixture (A), close to a homogenous mixture

(B), minor amounts of segregation occur at rest, but not during motion (C), major amounts of segregation at rest, but only minor amounts in motion (D), and extreme amounts of segregation at rest or while in motion (F). Table 2-1 contains A, C, and F performance ratings with a visual example and description of the performance rating.

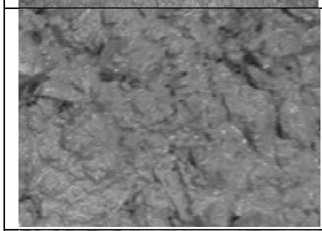
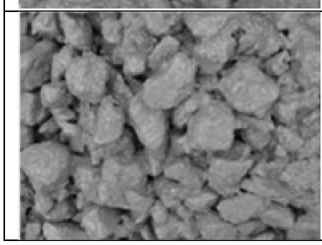
Table 2-1: Different cohesion performance ratings.

Visual	Rating	Description
	A	Uniformly homogenous mixture
	C	Minor amounts of segregation occur at rest, but not during motion
	F	Extreme amounts of segregation at rest or while in motion

2.2.2.2 Richness

Another important behavior property of the concrete is richness. This describes the ability of a mixture to properly proportion enough sand and paste to achieve the required workability performance of the concrete. Five different performance ratings were used to assesses the richness of a mixture and were as follows: well-proportioned amount of sand and paste (A), sufficiently proportioned amount of sand and paste (B), slightly Inadequately proportioned amount of sand and paste (C), inadequately proportioned amount of sand and paste (D), and impractically proportioned amount of sand and paste (F). Table 2-2 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 2-2: Different richness performance ratings

Visual	Rating	Description
	A	Well-proportioned amount of sand and paste
	C	Slightly Inadequately proportioned amount of sand and paste
	F	Impractically proportioned amount of sand and paste

2.2.2.3 Finishability

Finishability of a mixture describes the effort required to adequately finish the surface. A scoop of concrete was placed on a flat surface and smoothed using a magnesium hand float. Five different performance ratings were used to assesses the finishability of a mixture and were as follows: Insignificant effort was required to adequately finish the surface (A), reasonable effort was required to adequately finish the surface (B), significant effect was required to adequately finish the surface (C), excessive effort was required to adequately finish the surface (D), unattainable effort was required to adequately finish the surface (F). Table 2-3 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 2-3: Different finishability behavior performance ratings

Visual	Rating	Description
	A	Insignificant effort was required to adequately finish the surface
	C	Significant effect was required to adequately finish the surface
	F	Unattainable effort was required to adequately finish the surface

2.2.2.4 Flowability

Flowability of a concrete mixture describes the effort required to continuously move the concrete. Five different performance ratings were used to assesses the flowability of a mixture and were as follows: insignificant effort was required to continuously move the concrete (A), reasonable effort was required to continuously move the concrete (B), significant effect was required to continuously move the concrete (C), excessive effort was required to continuously move the concrete (D), and unattainable effort was required to continuously move the concrete (F). Table 2-4 contains A, C, and F performance ratings with a visual example and description of the performance rating.

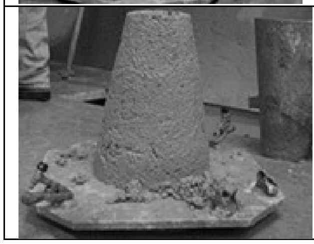
Table 2-4: Different flowability performance ratings

Picture	Visual Rating	Description
	A	Insignificant effort was required to continuously move the concrete
	C	Significant effect was required to continuously move the concrete
	F	Unattainable effort was required to continuously move the concrete

2.2.2.5 Stiffness

Stiffness of a concrete mixtures describes the effort required to initiate movement of the concrete. Five different performance ratings were used to assesses the stiffness of a mixture and were as follows: insignificant effort was required to initiate movement of concrete (A), reasonable effort was required to initiate movement of concrete (B), significant effort was required to initiate movement of concrete (C), excessive effort was required to initiate movement of concrete (D), and unattainable effort was required to initiate movement of concrete (F). Table 2-5 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 2-5: Different stiffness performance ratings

Visual	Rating	Description
	A	Insignificant effort was required to initiate movement of concrete
	C	Significant effort was required to initiate movement of concrete
	F	Unattainable effort was required to initiate movement of concrete

2.2.2.6 Procedure for Using Visual Observations

Currently, these visual observation methods are more qualitative measurements. However, visual observations remain the most widely used method of concrete workability evaluation at the jobsite. This work aims to start to standardize some of these visual observations. Table 2-6 contains a basic description of each behavior and the laboratory evaluation method for each property of fresh concrete. The operator gives a performance rating of an A through F scale for each of the five behavior characteristics. Table 2-1 through Table 2-5 can aid the operator in determining the rating of each behavior. After each performance behavior rating was determined, an average performance rating was calculated for the mixture. This average performance rating will be used as the final rating of the visual observation and describes the workability as: high (A), good (B), useable (C), inadequate (D), and not practical (F).

Table 2-6: Visual observation evaluation methods for each behavior

Behavior Characteristic	Visual Observation Evaluation
Stiffness	• Assessing effort required to initiate movement of the concrete Laboratory Evaluation Method: ➢ *How difficult is it to insert a hand scoop into the concrete?*
Flowability	• Assessing effort required to continuously move the concrete Laboratory Evaluation Method: ➢ *How well does the concrete flow while mixing in the drum?*
Finishability	• Assessing effort required to adequately finish the surface Laboratory Evaluation Method: ➢ *How difficult is it to float the surface of the concrete?*
Richness	• Assessing proportioned amount of sand and paste Laboratory Evaluation Method: ➢ *Will the mixture achieve proper flow and surface finishing requirements?*
Cohesion	• Assessing ability of the mixture to stay together Laboratory Evaluation Method: ➢ *Does this mixture segregate while mixing, discharging from the mixer, or setting in the wheelbarrow?*

2.2.3 The Float Test

The workability of concrete not only describes the ability of how a mixture flows, but also how easy it is to finish the surface. The surface of the concrete can be floated, troweled, straight-edged, broomed, tinned, edged, and jointed depending on the applications (Concrete finishers guide 2005). The initial surface process of floating removes voids, decreases texture, and further levels the concrete surface. This floating process is required before any of these other processes can be later accomplished (Concrete finishers guide 2005). In other words, if the concrete was not adequately floated, it will later affect the other finishing processes.

2.2.3.1 Concept of the Float Test

A very common way to float the surface of the concrete has been to use a bull-float for removing surface voids and creating a smoother surface texture. As shown in Figure 2-2, this involves a flat rectangular piece of metal that glides over the surface of the concrete to fill in voids, remove texture, and further level the surface. Multiple passes can be required to glide over the surface of the concrete to achieve the desired surface finish. If a large number of passes was required to achieve the desired surface finish, the mixture had a poor ability to be surface finished. This number of passes required to fill in the surface voids and smooth the concrete surface can measure the ability of a mixture to be surface finished.

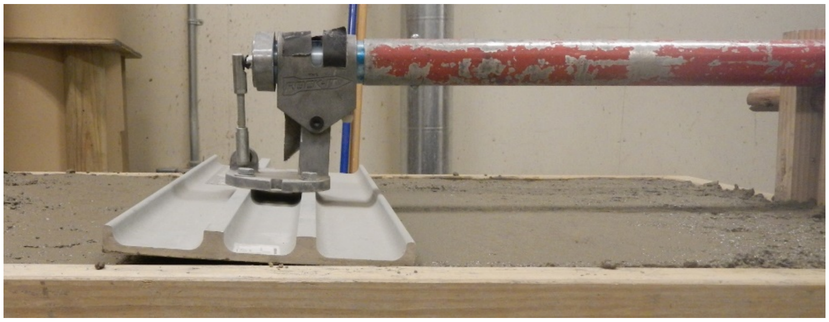


Figure 2-2: A bull-float is used to smooth the surface of the concrete

2.2.3.2 Developing the Float Test

To further develop the process of bull-floating into a laboratory test, the preparation of concrete samples and the parameters of the bull-float process had to be consistently controlled. As shown in Figure 2-3, the sample dimensions of 2 ft. by 3 ft. with a thickness of 3.5 in. were chosen to provide enough room to adequately evaluate the surface finishability, to give proper aggregate cover, and to still limit the amount of concrete used. The fresh concrete was slightly overfilled into the sample form. Then any excess concrete can be removed with a strike-off board siting on the top of the forms at one end and being pulled to the other end of the forms with a consistent forward motion as shown in Figure 2-4. This strike off motion was only a forward motion and not a sawing action due to this sawing action helps create a smooth surface. If any low spots were created after the strike off, enough concrete was added to fill in the hole. Then using a template, three standard holes with a 1 in. diameter and depth of 1 in. were created in the concrete surface of the concrete.

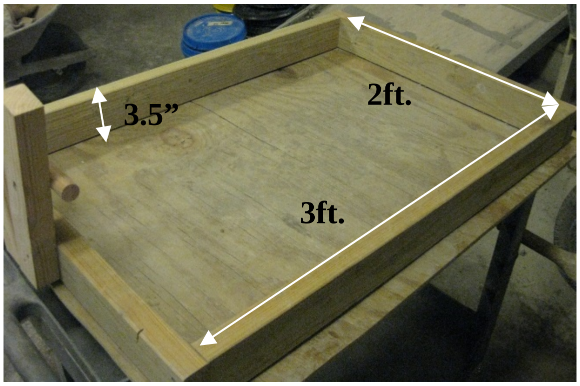


Figure 2-3: The dimensions of the float test forms

Figure 2-4: The concrete is leveled with a board

Then a modified bull float can be placed on the surface. This bull-floated was modified because in the field a bull-float may have a range of angles, weights, and speeds to allow for proper surface finishability of the concrete. However, to create a more consistent and repeatable workability test, the angle, weight, and speed of the bull-float was fixed to the following parameters: a fixed bull-float angle of the 2^{o} allowed a slight height tilt of less than 0.25 in., the bull-float self-weight of 7.1 lbs. created a stress of 0.08 psi on the surface of the fresh concrete, and a constant speed of 0.5 ft. / sec using a metronome. These parameters were selected to consistently and adequately allow the bull-float to properly finish the surface (Collins et. al. 2006 and The Contractor's Guide 2005). Figure 2-5 describes the four steps involved in the Float Test.

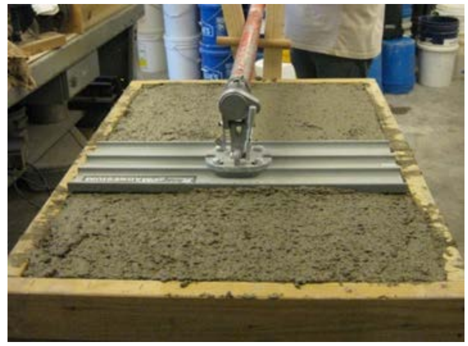
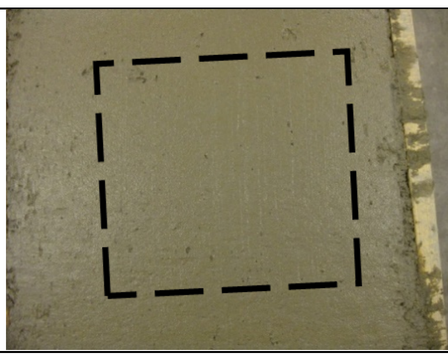
	
Step 1	Step 2
After placing and leveling the concrete with a strike off board, place template on the form and insert the 1" diameter dowel into the concrete to create a hole.	Place bull float on the surface. With a fixed upward tilt of 2 degree, move the bull float at a constant forward motion of 0.5 ft/sec until it reaches the form. (This is one pass.)
	
Step 3	Step 4
Using only the middle 1.5 ft. square area, determine the texture scale and closing of the holes with Figure 2.6 and Figure 2.7.	If the texture was a 3 or greater or the hole was not removed, the bull float passed back and forth until the texture was 2 or smaller <u>and</u> the hole closed.

Figure 2-5: The four steps of the Float Test

2.2.3.3 Evaluation of the Float Test

Multiple passes can be required to glide over the surface of the concrete to achieve the desired surface finish. If a large number of passes was required to achieve the desired surface finish, the mixture had a poor ability to be surface finished. The number of passes to remove texture from the concrete surface and the number of passes to fill in the three created holes provides a quantitative way to evaluate the finishability of the surface of the concrete. Figure 2-6 was used to quantify the surface texture. It shows a numerical textured scale value. Two values were recorded for each test. The number of passes required to smooth the surface and the number of passes required to fill in the hole.

Another quantifiable measurement was to determine the ability of the concrete to fill in the created holes. To further measure this behavior, three standard holes with a 1 in. diameter and depth of 1 in. were created in the concrete surface. These holes are supposed to represent holes that are sometimes present from removing large aggregate by striking off the surface. Figure 2-7 shows the removal of the holes through the bull-float passing over the surface each time.

	
4	**3**
Over 50% of area was textured	30 to 50% of area was textured
	
2	**1**
10 to 30% of area was textured	Less than 10% of area was textured

Figure 2-6: Examples of the amount of surface texture from Float Test samples

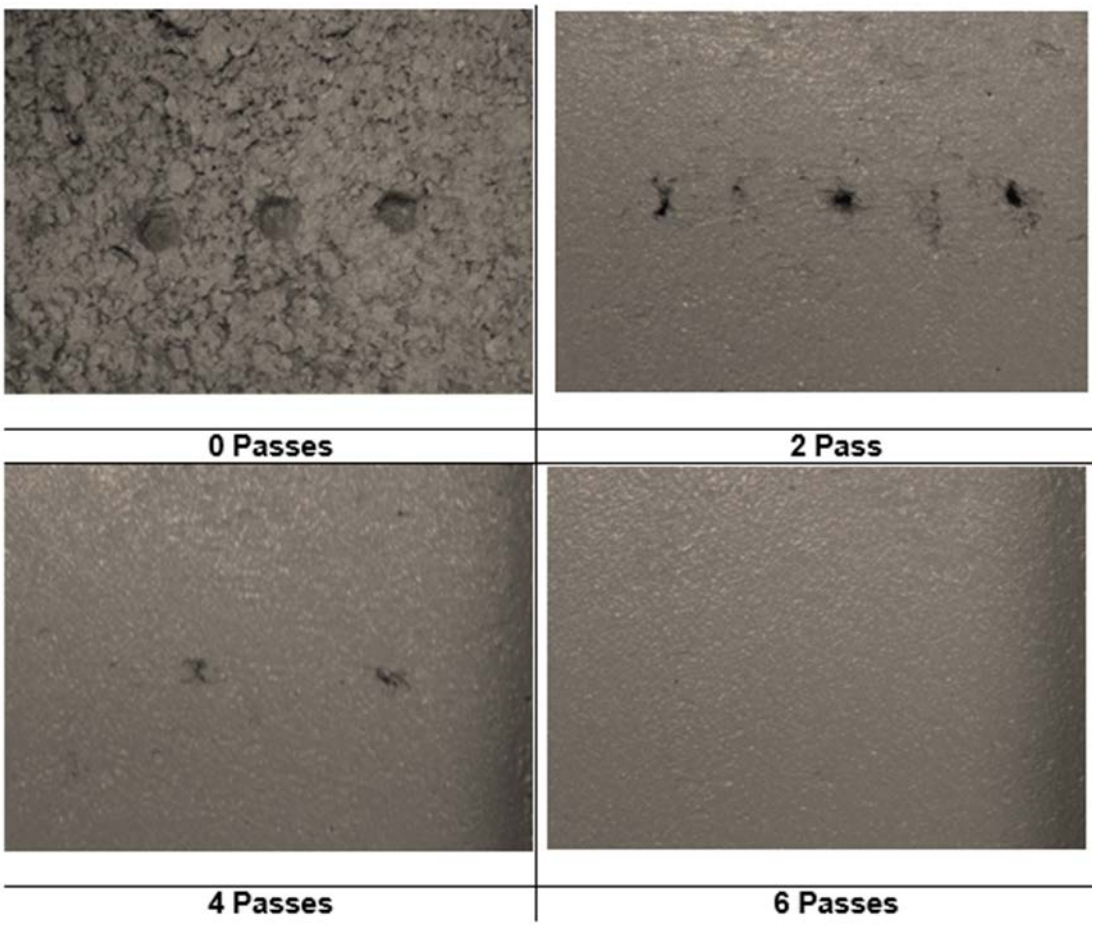


Figure 2-7: Examples of the three surface holes closing from each bull-float pass

2.2.4 Rheology

Critical workability parameters of fresh concrete has been the flowability properties of a mixture, which are also called the rheological properties of fresh concrete. Since concrete is a thixotropic fluid (Barnes 2000, Roussel 2012), the rheological measurements can be broken down into the static yield stress, dynamic yield stress, and the plastic viscosity (Roussel 2012, Koehler and Fowler 2004). While the static yield stress measures the minimum stress to initiate flow, the dynamic yield stress is the minimum stress to maintain flow. The plastic viscosity can be described as the ability to resist flow. A description and example of each parameter is described in Table 2-7.

Table 2-7: Rheological parameter

Rheological Parameter	Description
Static Yield Stress	• The minimum stress to initiate flow. Examples: ➢ *What is the difficulty of dragging concrete with a come-along?* ➢ *Will the concrete leave the mixing drum?*
Dynamic Yield Stress	• The minimum stress to maintain a constant flow. Examples: ➢ *How hard does the pump have to work to keep the flow constant?* ➢ *Will the concrete get stuck in the chute?*
Plastic Viscosity	• The ability to resist flow. Examples: ➢ *How fast does the concrete flow in the pipe of the pump?* ➢ *How fast does the concrete flow down the chute?*

To measure the rheological properties in a concrete mixture, the ICAR rheometer (Koehler and Fowler 2004) uses a 4 blade paddle vane as shown in Figure 2-8. Previous work has been done to standardize the vane type, vane dimensions, container dimensions, stress growth test speed, and flow curve test speeds (Koehler and Fowler 2004). The procedure for using the ICAR rheometer is:

1. After mixing, hand scoop the concrete into the rheometer container.
2. Place the ICAR rheometer on an empty bucket and reset it.
3. At 2 min after the mixer has stopped insert the rheometer vertically into the container.
4. The static growth test was conducted to find the static yield stress.

5. The flow curve test was conducted to find the dynamic yield stress and plastic viscosity.
6. The material was then placed back into the concrete mixer and mixed for 30 s.
7. Steps 2 through 6 were repeated two more times until 3 samples of each test was collected.

Figure 2-8: The ICAR rheometer measuring the rheology of the concrete mixture

2.2.5 Developing a Performance Scale for the Application

Four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table 2.8 was developed to represent flowable concrete workability performances. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Performance Scale	**Slump Test** (in)	**Visual Observation**	**ICAR Rheometer**			**Float Test** (passes)	
			Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Remove Hole	Remove Texture
Excellent (1)	8 to 6	A or 1	<1000	<250	<10	1 to 2	1 to 2
Good (2)	6 to 4	B or 2	1000-1500	250-500	10 to 15	3 to 4	3 to 4
Moderate (3)	4 to 2	C or 3	1500-2000	500-1000	15 to 20	5 to 6	5 to 6
Poor (4)	2 to 0	D or 4	>2000	>1000	>25	7 to 8	7 to 8
Unusable (5)	0	F or 5	Too stiff	Too Stiff	Too Stiff	>8	>8

Table 2-8: Individual Workability Scale

2.2.5.1 Quantifying Workability Assessments

The seven different measurements in Table 2.8 were determined for each mixture. Depending on their performance each test was given a numerical value. The average numerical value was calculated and used to classify the workability of the mixture. For example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would be 1.43 and be classified as a good overall workability.

2.3 EXPERIMENTAL METHODS

2.3.1 Materials and Mixture Design

To properly validate the different workability tests, mixtures were designed to have various workability characteristics with excellent through unusable workability as shown in Table 2-9. This required mixtures to be designed with a different water to cementitious (w/cm) ratios, paste volumes, water reducer dosages, and aggregate proportions. All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C150. A 20% class C fly ash replacement was used as per ASTM C618. Also, some mixtures used a lignosulfonate mid-range water reducer (WR) with a type A/F classification according to ASTM C494. Two different quarries supplied a coarse and intermediate gradation. Also two different natural sand source were used that met the requirements of ASTM C 33 for fine aggregate. More information on the aggregate characteristics can be found in other work (Cook et al. 2013).

Table 2-9: Mixture designs for variability of the workability tests

Mix*	Coarse (lbs/cy)	Int. (lbs/cy)	Sand (lbs/cy)	Cement (lbs/cy)	Fly Ash (lbs/cy)	Water (lbs/cy)	W/CM	WR (oz/cwt)
1	1940	0	1250	414	103	233	0.45	3
2	1900	0	1220	414	103	310	0.60	0
3	1930	0	1090	451	113	282	0.50	0
4	1830	0	1030	451	113	338	0.60	0
5	2030	0	1140	451	113	226	0.40	3
6	2010	0	1070	489	122	244	0.40	0
7	990	800	1190	451	113	254	0.45	3
8	1620	20	1200	451	113	254	0.45	6
9	1780	0	1210	451	113	254	0.45	0
10	1390	260	1340	451	113	254	0.45	3
11	1160	160	1680	451	113	254	0.45	6
12	1390	400	1200	451	113	254	0.45	3

2.3.2 Mixing and Testing Procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 73°F for at least 24 h before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken to determine the moisture content and adjust the mixture proportions. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included ICAR Rheometer, Slump Test, the Float Test, and visual observations. Figure 2.9 provides an overview of the testing.

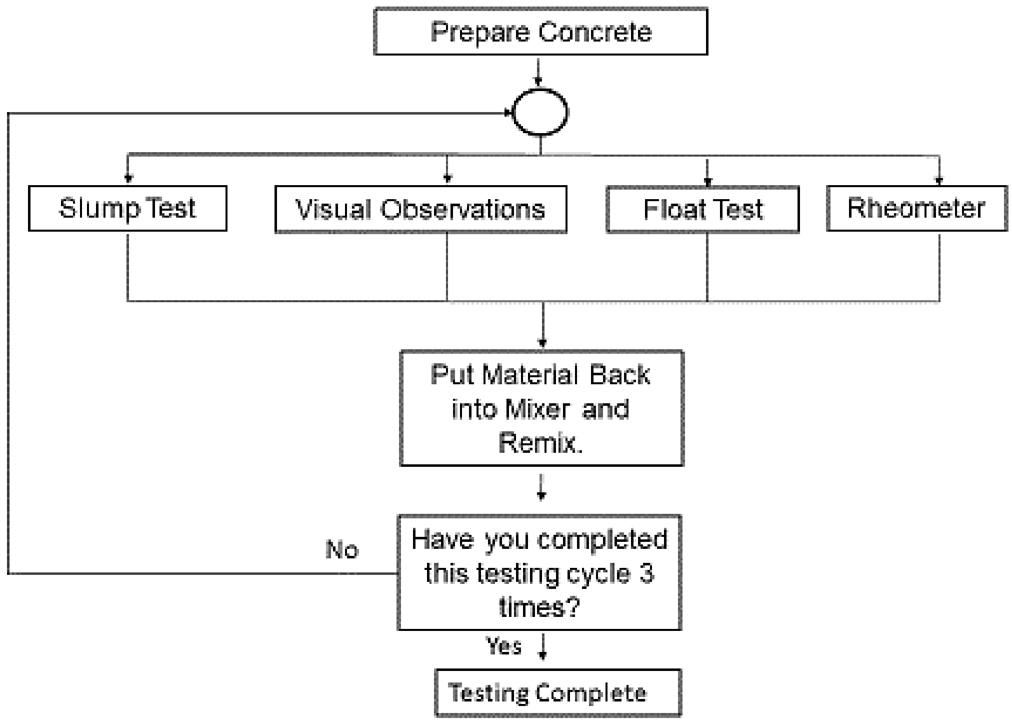


Figure 2-9: Testing steps for each mixture

2.4 RESULTS AND DISCUSSION

Twelve different mixtures were investigated with the Slump Test, Float Test, ICAR Rheometer, and visual observations. Each test was measured multiple times by a single operator to investigate the repeatability of the test. For six mixtures two operators independently completed the tests and the results are compared. The following section will show results, repeatability, suggested improvements, and practical applications of each test.

2.4.1 Single Operator Repeatability

2.4.1.1 Slump Test

To evaluate the repeatability of the Slump Test by three different users, twelve different mixtures were tested and the results are shown in Table 2-10. The Slump values ranged from 1.75 in. to 8.5 in. depending on the mixture. For the mixtures investigated the average coefficient of variation of the Slump Test was 5.4%. The maximum standard deviation was 0.38 in. and a maximum difference is 0.75 in. This is within the acceptable range of ASTM C 143.

Table 2-10: Slump Test and Visual Observations

Mix	Slump (in)			Visual Observations		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	3	2.75	3	3	3	3
2	8.5	8	8.25	3	3	3
3	8.25	8	8	3	4	3
4	5.5	5.5	6	3	3	3
5	3.25	3	3	4	4	4
6	1.75	2	1.75	3	3	4
7	3.25	3.75	3.5	3	3	3
8	5	4.75	5	2	2	2
9	3.5	3.25	2.75	3	3	3
10	5.5	5	5	2	2	2
11	3.75	4	4.25	2	3	2
12	4.75	4.5	4.75	3	3	3

2.4.1.2 Visual Observations

Table 2-9 also shows three repeat visual observation rankings of the same mixture. A letter grade and equivalent numerical ranking was given for each. These rankings are explained in Table 2-8 and section 2.2.2.

The average coefficient for a single operator in this test is 9.1%. This is one of the largest variances of all of the tests investigated. This is expected since the results are based on observation.

2.4.1.3 The Float Test

The Float test was conducted on twelve different mixtures as shown in Table 2-11. The test was conducted twice for each mixture, which counted the number of passes required to fill the holes and also the number of passes required to remove the texture. The results found mixtures required anywhere from 3 passes to more than 12 passes to fill in the holes and also to smooth the surface. The average coefficient of variation of the measurements to fill the hole (5.5%) is lower than removing the surface texture of the concrete (10%). This seems reasonable as the removal of the surface texture requires the operator to observe a much larger area then measuring the size of the hole.

Table 2-11: Slump Test and the Float Test

	Slump (in)			Float Test 1 (passes)		Float Test 2 (passes)	
Mix	1	2	3	Hole	Texture	Hole	Texture
1	3	2.75	3	12+	12+	12+	12+
2	8.5	8	8.25	12+	12+	12+	12+
3	8.25	8	8	10	10	11	10
4	5.5	5.5	6	12+	12+	12+	12+
5	3.25	3	3	12+	12+	12+	12+
6	1.75	2	1.75	12+	12+	12+	12+
7	3.25	3.75	3.5	10	12	9	11
8	5	4.75	5	6	6	6	8
9	3.5	3.25	2.75	8	9	9	10
10	5.5	5	5	4	4	4	4
11	3.75	4	4.25	4	5	5	4
12	4.75	4.5	4.75	4	3	4	4

2.4.1.4 Rheometer Repeatability

The ICAR rheometer measurements are given in Table 2-12. The ICAR rheometer was shown to have good repeatability. The average coefficient of variation of these same measurements were: static yield stress – 7.4%, dynamic yield stress – 4.2%, and plastic viscosity – 5.3%. These variations are low and shows that this is an acceptable and repeatable measurement method.

Table 2-12: Rheological measurements of the ICAR rheometer

	Test 1			Test 2			Test 3		
Mix	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)
1	4160	469	38	4540	577	27	4440	426	44
2	618	191	19	580	206	18	621	195	18
3	1450	210	19	1240	210	18	1410	202	20
4	417	205	27	298	192	27	334	210	26
5	Too Stiff	Too Stiff	Too Stiff	Too Stiff	Too Stiff	Too Stiff	Too Stiff	Too Stiff	Too Stiff
6	4600	Too Stiff	Too Stiff	4695	Too Stiff	Too Stiff	4680	Too Stiff	Too Stiff
7	2230	731	27	2340	675	28	2000	706	27
8	1640	400	18	1410	410	19	1550	400	18
9	1170	339	20	1020	354	21	1070	324	21
10	1210	621	13	1300	648	13	1390	622	13
11	1760	686	11	1700	709	9.8	1590	723	9.7
12	1410	634	17	1580	624	18	1470	634	17

2.4.1.5 Repeatability Comparison

To further summarize repeatability of each test, Table 2-13 shows each test parameter.

Table 2-13: Single Operator Repeatability

Workability Test		Average Coefficient of Variation
Slump Test		5.4%
Visual Observations		9.1%
Float Test	Filling Hole	5.5%
	Removing Texture	10%
ICAR Rheometer	Static Yield Stress	7.4%
	Dynamic Yield Stress	4.2%
	Plastic Viscosity	5.3%

2.4.2 Multiple Operator Comparison

Multiple operator comparisons were conducted on each test and the average of each is shown in Table 2-14. Six different mixtures were conducted with two different operators. For the ICAR rheometer test two or three tests were completed and the average and one standard deviation is shown. The proceeding subsections further discuss each of the multiple operator repeatability.

Table 2-14: Multiple Operators

Mix	Operator	Visual Observation	Slump (in.)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Float Test (passes)	
							Fill Hole	Smooth
7	A	4	3.75	2040±170	459±1	28±2.0	9	12
	B	3	3.5	2190±170	704±28	27±0.6	10	12
8	A	2	5.5	1560±80	461±27	20±0.8	4	6
	B	2	5	1530±120	403±6	19±0.6	6	7
9	A	4	4	1010±80	261±32	18±1.3	12	12
	B	3	3.25	1090±80	339±15	21±0.6	9	10
10	A	1	5.75	1340±58	559±34	7.8±0.3	2	5
	B	2	5.25	1300±15	630±15	13±0.2	4	4
11	A	3	4.5	1340±60	611±8	7.9±0.8	4	4
	B	2	4	1680±82	706±19	10±0.4	4	4
12	A	2	4.75	1200±81	413±2	15±0.5	4	4
	B	3	4.75	1490±82	630±6	17.5±0.4	4	3

2.4.2.1 Repeatability Comparison of Two Operators

The average difference between the two comparisons is given in Table 2-15. Each operator completed the testing independently. The average difference between these six comparisons was small. This suggests these tests are repeatable between two operators.

Table 2-15: Multiple Operator Repeatability

Workability Test		Average Difference
Slump Test		0.17 in.
Visual Observations		0.42
Float Test	Filling Hole	.33 pass
	Removing Texture	0.50 pass
ICAR Rheometer	Static Yield Stress	132 Pa
	Dynamic Yield Stress	108 Pa
	Plastic Viscosity	1.8 Pa/sec

2.4.3 Practical Implications

These tests were developed and validated for flowable concrete. In a laboratory setting each of these can be very useful for understanding and measuring the different workability behaviors of fresh concrete. Unfortunately, the ICAR Rheometer and the Float Test may not be practical to use in the field, but they provide useful information during mixture evaluation. Furthermore, the Slump Test is continuously used in the field and will likely continue to be used to evaluate the consistency of a concrete mixture even if it does not provide as much insight into the workability as other tests. Finally, visual observations have been and will continue to be a useful method to evaluate the workability of a concrete mixture. It would be helpful if in the future more standardized methods of visual observation could be used to evaluate concrete mixtures.

2.5 SUMMARY

Four different workability tests were introduced to evaluate flowable concrete applications. These four tests can evaluate the concrete in eleven different ways. The following can be stated about the different workability tests.

- The Slump test has been the most commonly specified workability test, but it cannot measure the wide range workability performance required of concrete.
- Visual observations is used most often in the field.
- The ICAR Rheometer can measure the rheology parameters of static yield stress, dynamic yield stress, and plastic viscosity reliably with reasonable variations.
- The Float Test measures the ability of a concrete mixture to be adequately surface finished.

CHAPTER 3 - LABORATORY EVALUATIONS OF COARSE AGGREGATE GRADATION FOR OPTIMIZED GRADED CONCRETE BRIDGE DECKS

3.1 INTRODUCTION

A concrete mixture is commonly composed of only a single coarse aggregate and fine aggregate (Taylor et. al 2007, ACI 211 1991, Kosmatka et. al 2011, Neville 2012, Methta and Monteiro 2006, Powers 1968, Richardson 2005, and NSSGA 2013). While these aggregate gradations typically meet the standards of ASTM C 33, the gradations standards were established to most economically produce crushed aggregate and not necessarily the best performance in a concrete mixture (Lamond and Pielert 2006). Furthermore, many different approaches and aggregate concepts have been used to guide the design of the proportion and gradation aggregates (Kosmatka 2011, Neville 2012, NSSGA 2013, ASTM C 33, Powers 1968). Some of these include numerical packing methods (Goltermann et. al 1997, Jones et. al 2002, ASTM C 29, Dewar 1999, de Larrard 1999), surface area estimations (Richardson 2005, Powers 1968, Edwards 1918, Day 2006), and graphical combined gradation techniques based on practical experience (Taylor et. al 2007, Richardson 2005, Shilstone 1990).

When a concrete mixture was poorly proportioned or obtains a poor gradation, the workability performance of the concrete can be negatively impacted (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, Methta and Monteiro 2006, Powers 1968, Richardson 2005, and NSSGA 2013). In some cases adjustments of larger admixture dosages or a higher volume of paste (water and binder) can achieve the desired workability (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, Methta and Monteiro 2006, Powers 1968, Richardson 2005, Cook et. al. 2014, and NSSGA 2013). Higher volumes of paste can cause greater overall cost, decrease in durability, and lower sustainability of the produced structure (Kosmatka 2011, Mehta and Monteiro 2006, Shilstone 1990, Shilstone 1991, Cook et. al. 2013). Unfortunately, very little published work has systematically quantified this relationship (Richardson 2005, Powers 1968, Anson-Cartwright 2011, Obla and Kim 2008, Koehler and Fowler 2007, Goldbeck and Grey 1968).

In Chapters 3, 4, and 5 of this work the impact of the aggregate gradation has been used to quantitatively compare mixtures using various aggregate concepts and proportioning techniques and the workability for flowable concrete. In past work, the combined gradation with the Individual Percent Retained (IPR) chart best predicted the impact of the aggregate gradation and proportioning for the workability of concrete in slip formed pavements. This will serve as a starting point for this research.

3.1.1 Significance of Work

This work aims to build on the previous work and establish limits for the aggregate gradations for the IPR chart that provide insight into the impact on concrete workability for flowable applications, especially those where the concrete has to be pumped. These gradation recommendations will help practitioners choose one or more locally available aggregates that can be blended to produce aggregate gradations that improve the workability of concrete for slip formed pavements. With this improved workability then improvements can be made in economy, sustainability, and durability of these mixtures.

3.2 EXPERIMENTAL METHODS

3.2.1 Materials

All the concrete mixtures described in this paper 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, 564 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 32.2% for the mixture volume. A constant water reducer (WR) of 6 oz. /cwt was used in every mixture to achieve the high flowability properties of each mixture. This WR was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

The aggregate gradations and proportions were change to evaluate the impacts of the workability. Table 3-1 shows the seventy-five different mixture proportions used in this study. Many of the mixtures use a coarse, intermediate, and fine aggregate to proportion the combed gradation. Three crushed limestone sources and three natural sand sources were used to evaluate and validate the aggregate proportioning limits. One coarse aggregate source and one natural sand source were used to evaluate gradation limits, but two different coarse aggregate sources and two different natural sand sources were used to validate these results. Many of the gradations were sieved to evaluate the different gradation limits and cannot be classified according to any standard gradation system.

Table 3-1: Batch Weights

Mix	**Quarry Source**	**Sand Source**	**Coarse** (lbs.)	**Int.** (lbs.)	**Sand** (lbs.)
1	A	A	1762	636	705
2	A	A	1639	588	871
3	A	A	1516	539	1037
4	A	A	1393	490	1204
5	A	A	1269	442	1370
6	A	A	1146	393	1536
7	A	A	1979	0	1115
8	A	A	1023	344	1702
9	A	A	900	296	1869
10	A	A	1598	443	1188
11	A	A	1649	0	1433
12	A	A	1476	201	1404
13	A	A	1063	682	1335
14	A	A	856	922	1301
15	A	A	650	1163	1266
16	A	A	443	1403	1232
17	A	A	1115	847	1124
18	A	A	925	1036	1124
19	A	A	542	1414	1126
20	A	A	1050	911	1125
21	A	A	508	1875	710
22	A	A	807	778	1489
23	A	A	987	951	1147
24	A	A	1166	1124	806
25	A	A	1346	1297	464
26	A	A	807	778	1489
27	A	A	987	951	1147
28	A	A	1166	1124	806
29	A	A	1346	1297	464
30	A	A	1306	482	1296
31	A	A	1543	569	981
32	A	A	1781	657	667
33	A	A	987	951	1147
34	A	A	1166	1124	806
35	A	A	807	778	1489
36	A	A	987	951	1147
37	A	A	1166	1124	806
38	A	A	1346	1297	464
39	A	A	1971	0	1122
40	A	A	1971	0	1122
41	A	A	1971	0	1122

Mix	Quarry Source	Sand Source	**Coarse** (lbs.)	**Int.** (lbs.)	**Sand** (lbs.)
42	A	A	1971	0	1122
43	A	A	1971	0	1122
44	A	A	1971	0	1122
45	A	A	1971	0	1122
46	A	A	1971	0	1122
47	A	A	1971	0	1122
48	A	A	1971	0	1122
49	A	A	1971	0	1122
50	A	A	1971	0	1122
51	A	A	1971	0	1122
52	A	A	1971	0	1122
53	B	B	1172	408	1455
54	B	B	1292	284	1457
55	B	B	1413	161	1459
56	B	B	1533	37	1461
57	B	B	1052	531	1453
58	B	B	931	655	1452
59	B	B	1062	176	1784
60	B	B	1523	393	1131
61	B	B	832	67	2111
62	B	B	1753	502	804
63	B	B	811	778	1450
64	B	B	690	902	1448
65	B	B	1609	0	1471
66	C	C	1009	818	1151
67	C	C	1174	650	1156
68	C	C	1409	412	1163
69	C	C	1644	173	1170
70	C	C	1806	8	1175
71	C	C	1517	472	994
72	C	C	1301	351	1333
73	C	C	1192	290	1503
74	C	C	1084	229	1673
75	C	C	976	169	1842

3.2.2 Sieve Procedure for Creating a Gradation

To investigate different aggregate gradations, sieving was used to create the majority of the gradations investigated. Aggregates were oven dried, sieved into individual sizes, and combined into a single gradation. This process was tedious, but effective for closely controlling the gradation of a mixture.

3.2.3 Mixing and Testing Procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24 h 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 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 initial testing of the mixture included Slump Test, visual observations, ICAR rheometer, and the Float Test. These Test can be further explained in Chapter 2 of this report.

3.2.4 Using the Workability Tests to Evaluate Structural Concrete

Four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table 3-2 was developed to represent flowable concrete workability performance. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Workability Performance Scale for Each Test	**Slump Test** (in)	**Visual Observation**	**ICAR Rheometer**			**Float Test** (passes)	
			Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Remove Hole	Remove Texture
Excellent (1)	8 to 6	A or 1	< 1000	<250	<10	1 to 2	1 to 2
Good (2)	6 to 4	B or 2	1000-1500	250-500	10 to 15	3 to 4	3 to 4
Moderate (3)	4 to 2	C or 3	1500-2000	500-1000	15 to 20	5 to 6	5 to 6
Poor (4)	2 to 0	D or 4	>2000	>1000	>25	7 to 8	7 to 8
Unusable (5)	0	F or 5	Too stiff	Too Stiff	Too Stiff	+9	+9

Table 3-2: Workability Performance Rating System

3.2.5 Quantifying Workability Assessments

After analyzing the data and comparing each workability test for flowable concrete, the quantity of measurements needed to be simplified into a practical manner. In other words, these seven different measurements were quantified into a single overall workability performance rating for a given mixture. This was completed by taking the average workability performance of each measurement as classified in Table 2-2. After the average numerical value was calculated, it was converted back into the following workability scale range: excellent (1), good (2), moderate (3), poor (4), and unusable (5). For an example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would mathematically be 1.43 and be classified as a good overall workability.

3.3 RESULTS AND DISCUSSION

Table 3-3: Workability Results

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
1	Unusable	Unusable	4400	Too Stiff	Too Stiff	7.25	12+	12+
2	poor	poor	1467	272±13	36±2.4	6.25	8	9
3	moderate	moderate	1045±20	327±12	16±0.6	5	5	6
4	good	good	948±92	315±33	10.2±0.7	6.5	4	4
5	good	excellent	1140±142	299±19	12.5±3.0	7	2	2
6	good	good	1139±84	1142±64	10.2±1.5	4	3	3
7	poor	poor	2811±150	720±45	14.4±1.4	2	12+	12+
8	poor	poor	2811±150	720±45	14.4±1.4	2.25	12+	12+
9	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	1.5	5	3
10	moderate	poor	1379±195	393±21	15±1.2	8	12+	12+
11	Moderate	moderate	943±23	428±1	11.9±1.7	6	5	5
12	good	excellent	796±9	341±48	10.8±1.3	7	3	3
13	good	excellent	1193±6	469±16	11.9±1.3	6.5	6	5
14	moderate	good	1755±354	642±12	9.9±1.0	4	10	10
15	poor	moderate	1974±54	647±3	13.1±1.5	4.25	9	9
16	poor	poor	2457±394	751±8	15.4±0.6	2.5	12+	12+
17	good	excellent	791±66	339±21	10.9±1.6	7.5	4	4
18	good	good	773±46	288±14	11.9±0.6	6.5	5	5
19	good	excellent	797±54	415±31	11.8±0.6	5.5	5	4
20	good	excellent	1077±67	378±11	8.3±0.9	7.5	2	2
21	Moderate	good	833±70	390±33	11.8±1.0	6.5	10	8
22	Unusable	poor	Too Stiff	Too Stiff	Too Stiff	2.75	11	8
23	good	good	1131±41	509±9	13±0.3	6	4	3
24	good	good	970±53	296±11	7.7±0.8	7.5	6	8
25	Unusable	poor	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
26	poor	poor	1519±38	450±21	10.7±0.1	3	8	8
27	moderate	good	945±34	318±29	10.6±1.2	7.5	10	10
28	moderate	moderate	882±66	211±15	19.1±1.3	8	5	6
29	Unusable	poor	Too Stiff	Too Stiff	Too Stiff	8.5	12+	12+
30	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
31	poor	poor	2453±179	679±33	27.0±3.0	4.5	6	4
32	Unusable	poor	2119±142	426±100	52.1±6.0	6	12+	12+

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
33	moderate	moderate	2178±226	818±21	12.8±0.4	4	4	4
34	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	7.5	12+	12+
35	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
36	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	1.25	12+	12+
37	poor	poor	1275±25	133±48	35±14	8.25	6	12
38	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
39	poor	poor	936±68	295±11	14.5±0.7	6.75	12+	12+
40	poor	poor	1762±70	538±33	13.9±0.7	3.5	12+	12+
41	moderate	moderate	1876±144	759±35	6.5±0.4	3.5	4	12
42	good	good	1427±37	423±43	10.1±1.1	4.75	4	4
43	moderate	good	1293±71	389±33	15.2±1.9	5.25	6	8
44	good	good	1375±121	457±19	9.1±0.5	5.25	2	3
45	good	good	1437±28	505±61	12.8±0.9	5.25	4	4
46	good	good	1137±137	513±24	6.5±0.3	5.5	5	6
47	moderate	moderate	1681±51	532±22	9.3±1.6	4	8	8
48	poor	poor	1705±70	497±4	9.8±1.1	4	8	8
49	moderate	moderate	865±57	283±13	10.7±1.2	7.75	4	12
50	good	good	846±62	290±6	12.6±0.9	6.75	4	4
51	good	good	1160±4.5	325±12	12.5±1.1	7.5	4	4
52	moderate	poor	1241±27	422±5	9.9±1.3	5.25	4	12
53	good	excellent	1048±93	383±8	8.9±0.4	6.75	3	4
54	good	excellent	1100±195	327±9	10.3±0.3	6.25	4	4
55	good	excellent	975±115	297±28	7.4±0.4	8	5	5
56	good	excellent	1557±175	557±40	11.1±0.1	5.75	3	2
57	good	excellent	1394±99	512±32	7.3±0.7	5.5	6	4
58	moderate	good	1221±111	444±11	9.6±0.4	5.25	7	6
59	poor	moderate	Too Stiff	Too Stiff	Too Stiff	2.75	4	4
60	good	good	1341±106	397±16	14.9±0.6	6	4	5
61	Unusable	poor	Too Stiff	Too Stiff	Too Stiff	0.5	2	1
62	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	7	12+	12+
63	moderate	moderate	1147±118	519±33	8.0±0.4	5.5	6	6

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
64	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	2.75	12+	12+
65	poor	poor	1840±154	599±22	18.6±0.8	3.75	8	8
66	moderate	poor	2036±168	459±1	23.3±2.0	3.75	4	12
67	moderate	moderate	1474±77	422±34	14.3±0.9	6.25	3	12
68	good	good	1203±81	413±2	14.5±0.5	4.75	4	4
69	moderate	good	1562±80	461±27	13.1±0.8	5.5	4	6
70	poor	poor	1013±80	261±32	18.2±1.3	8	12	12
71	Unusable	poor	Too Stiff	Too Stiff	Too Stiff	3.5	12	12
72	good	excellent	1339±58	559±34	7.8±0.3	5.75	2	5
73	good	good	1341±9	578±5	9.8±0.5	5	3	3
74	moderate	moderate	1343±60	611±8	7.9±0.8	4.5	4	4
75	poor	poor	Too Stiff	Too Stiff	Too Stiff	1.5	5	4

3.3.1 Coarse Aggregate

To begin investigating the minimum and maximum gradation limits, Figure 3-1 shows gradations with almost constant sand, but varying coarse to intermediate aggregate volumes with the overall workability performance. The four middle gradations have an overall good workability for flowable concrete. However, when the amount of coarse or intermediate for a given aggregate became excessive on a single sieve or multiple sieves then the workability drastically decreases. This intense amount of intermediate and large coarse aggregate can be further shown visually in Figure 3-2 and also the Slump Test in Figure 3-3. The data suggests the coarse aggregate sieve sizes (#4 through ¾”) becomes excessive at 20% retained on a sieve size. This will be a continuous trend throughout this investigation and a maximum limit of 20% should be set at this value.

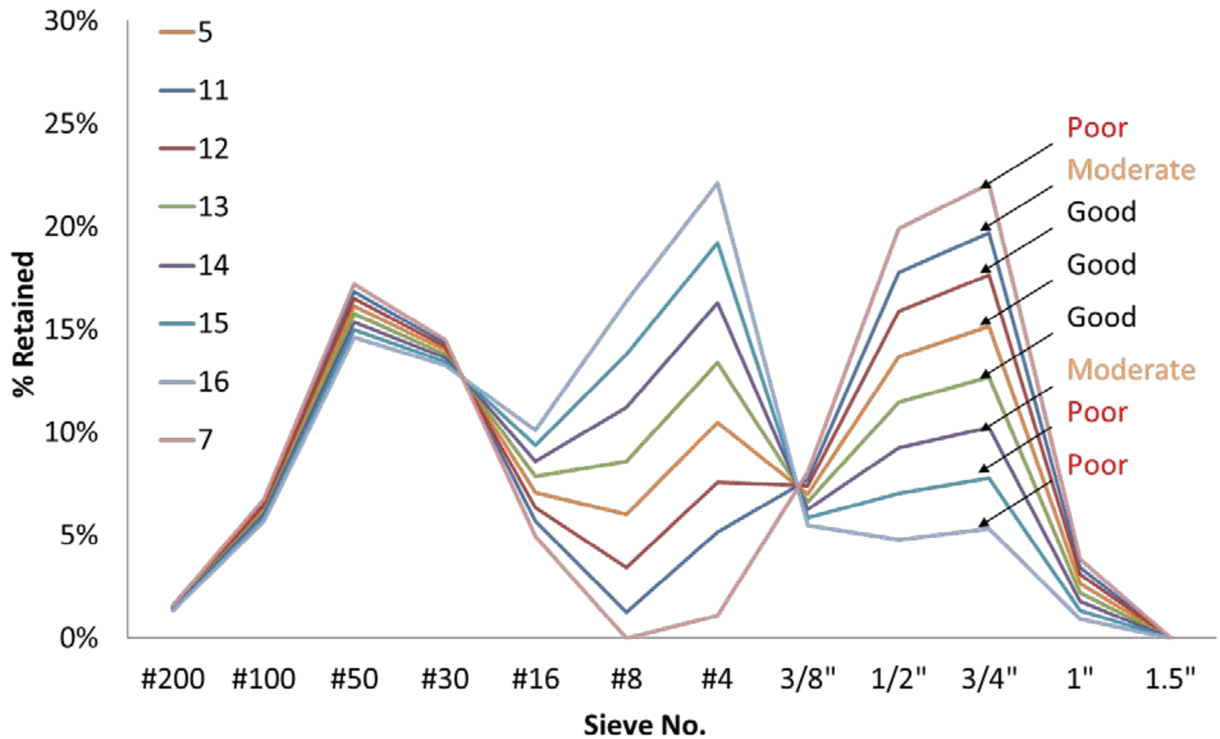


Figure 3-1: Comparison of the overall workability with the different proportions of coarse and intermediate of limestone A

Figure 3-2: Examples of excessive amounts of coarse and intermediate sieve sizes

Figure 3-3: The Slump Test with excessive amounts of coarse and intermediate sieve sizes

3.3.1.1 Using other Aggregate Sources

One coarse aggregate source and one sand source was used to investigate many of the gradation concepts. Two more crushed limestone sources and two more natural sand sources were selected to further validate the findings. Figure 3-4 uses limestone B and sand B and Figure 3-5 plots limestone C and sand C.

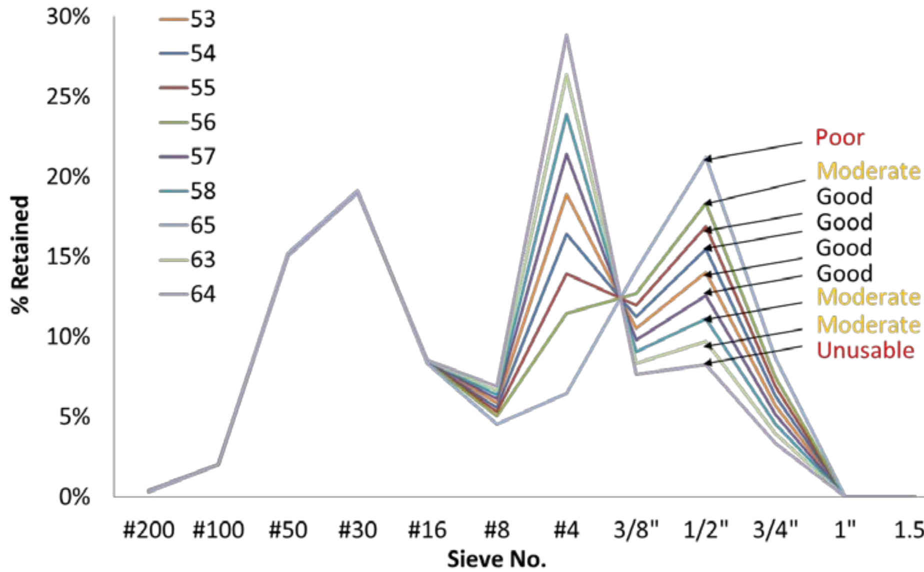


Figure 3-4: The overall workability of Limestone B as the gradation of the coarse aggregate was changed.

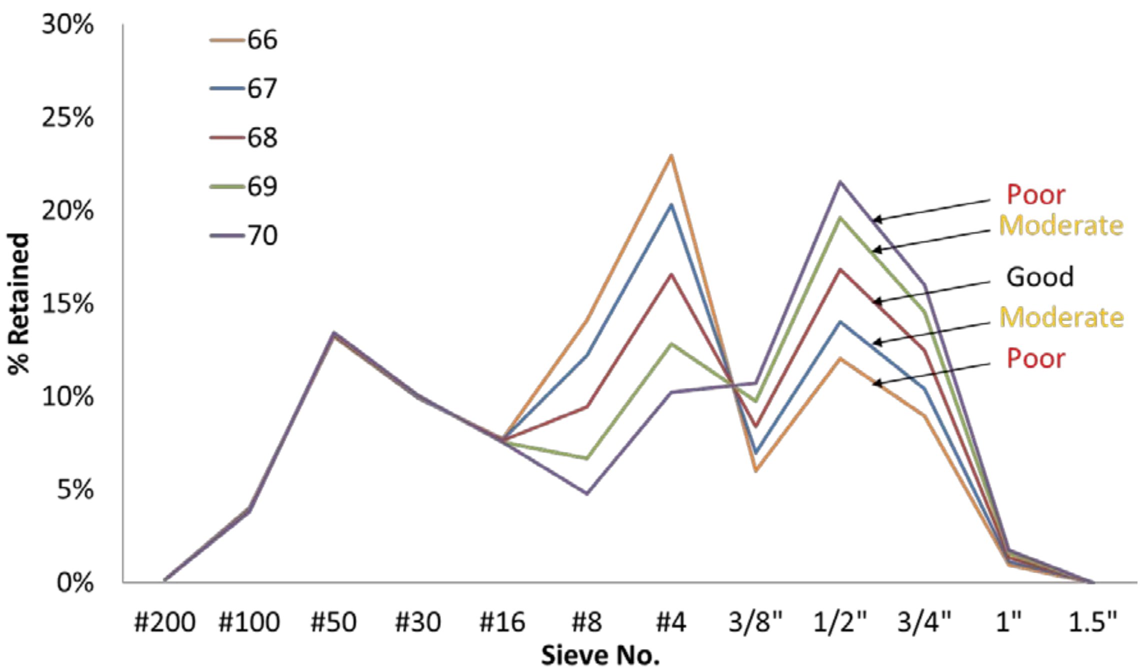


Figure 3-5: The overall workability of Limestone C as the coarse aggregate gradation was changed.

3.3.2 Maximum Boundary Limit

Due to excessive amounts on a single sieve size creating workability problems, maximum sieve size limits from the field have been proposed and range from 15 to 22 % for each sieve size. The results of this work showed excessive amounts can create workability issues. Even though the maximum limits did slightly vary, a simple gradation limit of 20% could be set for a single sieve size ranging from #4 to 0.75 in. The 20% retained on the #4 to 0.75 in. sieve size range will be a reoccurring trend throughout these results and serve as a key finding of this work. These results also match the recommendations made for slip formed pavements in another publication (Cook et. al. 2013).

3.3.3 Theoretical Bell-Shaped Curve

As discussed previously it has been suggested that an ideal packing of aggregates should be obtained with a bell shaped curve on the percent retained chart. This ideal bell shaped curve fits within the 8-18 limits of the Individual Percent Retained Chart. Figure 3-6 compares the ideal bell shaped curve and a practical gradation curve that was obtained by combining two aggregates locally available in Oklahoma. Compared to the practical gradation, the bell shaped curve did not increase the workability of the mixture. In fact, this bell shaped curve reduced the finishability properties of the mixture due to the high amounts of #8 and #16 as shown in Figure 3-7. More investigations have been conducted on these two sieve sizes in the coarse sand section.

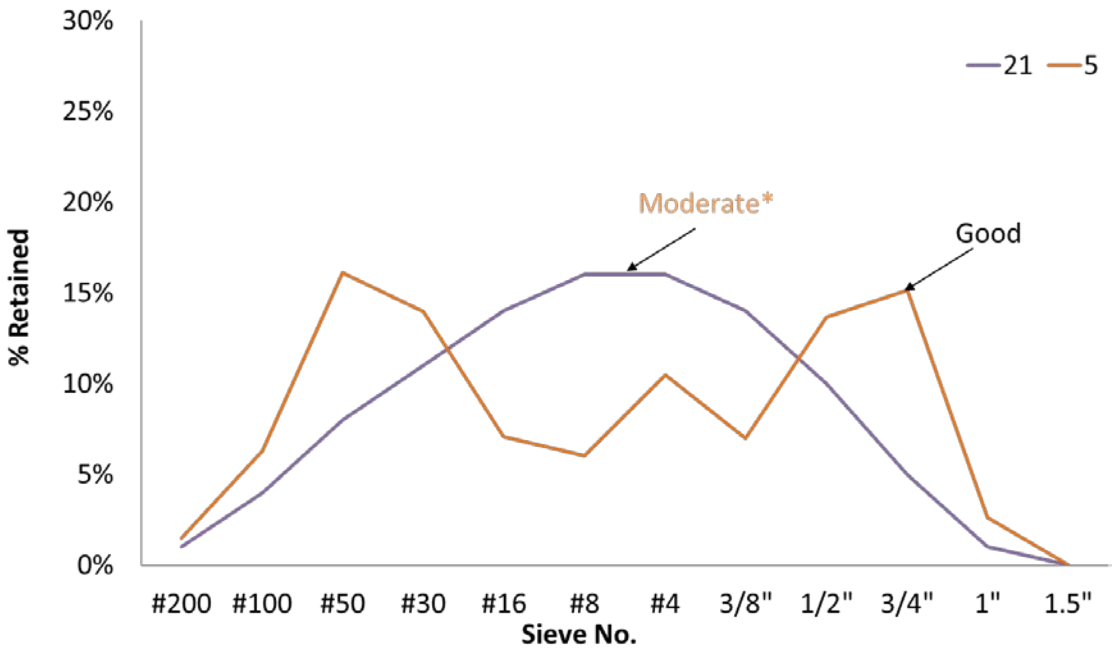


Figure 3-6: The overall workability of the theoretical bell shaped curve is compared with a practical gradation. ***note: this mixture had surface finishability issues**

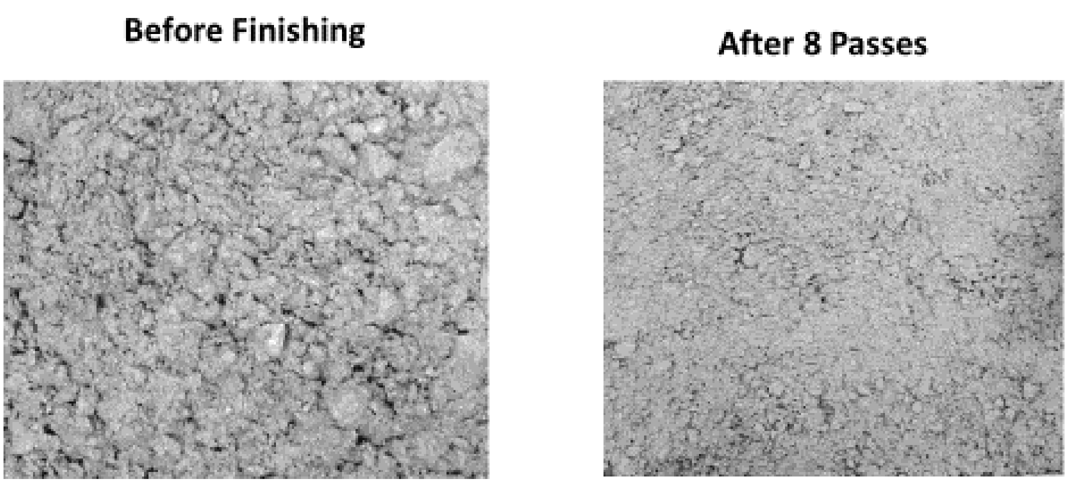


Figure 3-7: A visual comparison of the bell shaped curve and a practical gradation.

3.3.4 Minimum Boundary Limit

Several of the gradations in this research have contained "low" values of certain aggregate sizes. These low spots in the gradation have been called "valleys" and are commonly thought to reduce the workability of the mixture and should be avoided. To investigate the impacts of valleys on gradation curves, Figure 3-8 shows combined gradations containing a valley, a double valley, and a gradation used in the field. The workability performance of the mixture did not drastically change if gradation had a single or a double valley. It should be noted that while changing the gradation of this mixture no single sieve size was greater than 20%.

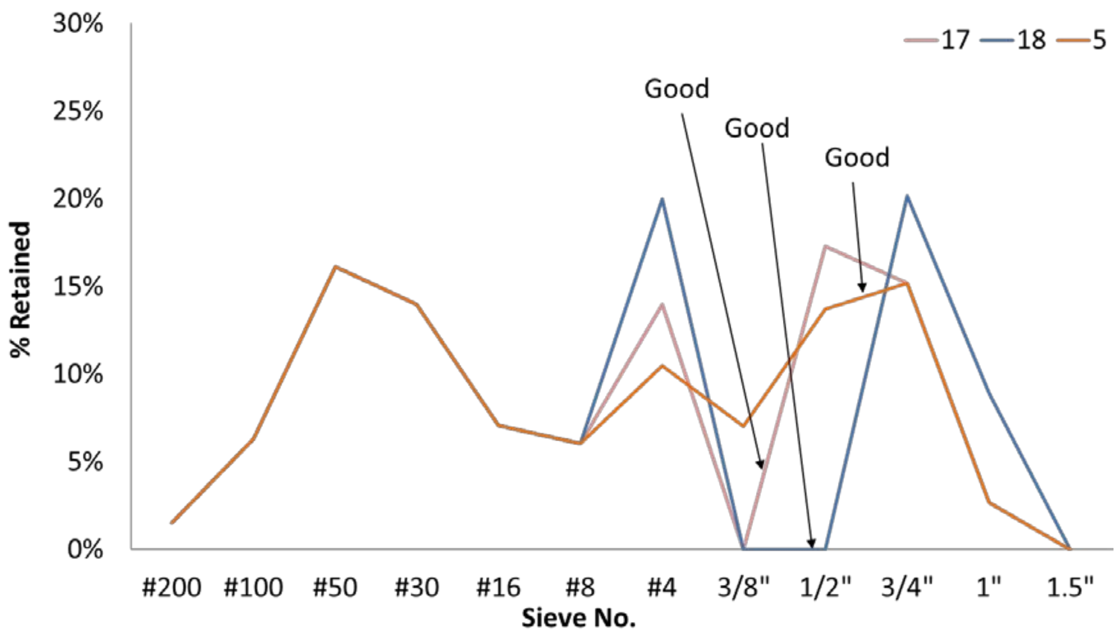


Figure 3-8: The overall workability from a single and double valley in the gradation.

3.3.4.1 Developing a Minimum Boundary

Even though maximum limits of 20% retained on the #4 to 0.75 in. sieve size range could be a reoccurring trend, the results of this work didn't consistently show deficient amounts of coarse aggregate sieve sizes (#4 to 0.75 in.) effecting the workability of concrete. Deficient sieve size amounts can indirectly effect the workability by actually forcing other sieve sizes to exceed a maximum boundary limit of 20%. It should also be stated that fine aggregate sieve sizes have yet to be investigated for effects of the minimum boundary limits.

3.3.5 Nominal Maximum Coarse Aggregate Size

Multiple mixture design methods and publications claim the maximum size of the coarse aggregate affects the workability of the concrete (Taylor et. al. 2007, Kosmatka et. al. 2011, Neville 2012, Mehta and Monteiro 2006, ACI 211). To determine the validity of these claims, 0.5 in, 0.75 in., and 1 in. maximum size gradations were evaluated in Figure 3-9. Each gradation was designed to have similar sand contents and no sieve size above 20%. The results show gradations with various maximum sizes can produce satisfactory mixtures with no significant differences in workability. This data suggests that the guidance of only increasing the aggregate size by itself does not lead to an improvement in the workability of a mixture. However, using a larger maximum aggregate size is beneficial because it more easily produces an aggregate gradation that does not have an excessive amount of material on a single sieve size. In other words, it gives the producer a larger number of sieves to distribute their gradation without creating an excessive amount on a single sieve size.

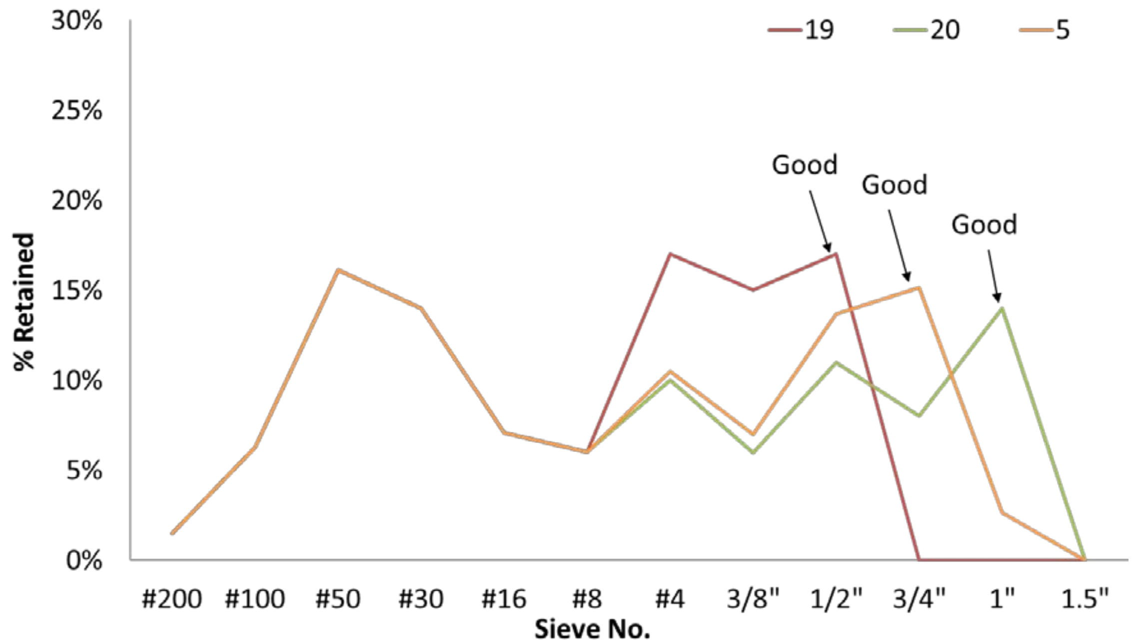


Figure 3-9: A comparison of the overall workability of the different maximum sieve sizes with closely consistent sand amounts.

3.3.6 Recommended boundary limits

Throughout this research, a common trend of coarse aggregate sieve sizes (#4 and larger) retaining over 20% could have a decrease in workability. However, a gradation with low amounts on one or two sieve sizes does not necessarily affect the performance of the concrete. Yet, it becomes difficult to stay within the maximum boundary limits if a gradation missing or having a small amount on an adjacent sieve sizes.

3.3.7 Well-Graded versus Gap-Graded

Even though well and gap-graded definitions are broad, Figure 3-1 shows that more well-graded and gap-graded mixtures could both perform well as long as the gradations did not increase above 20%. The three gradations that were concentrated in the middle of the chart had similar WR even though the degree of gaps were drastically different. Even in Figure 3-6, an idea bell shape curve and many other practical gradations had similar workability. This shows a combined gradation does not have to be well-graded or gap-graded. Multiple varieties of gradations will all perform similar.

3.3.8 Practical Applications

This work was able to develop some basic and simple guidelines for proportioning the coarse aggregate sieve sizes in a combined gradation. These gradation guidelines can be extremely beneficial to improve the construction specifications and practices. Furthermore, the guidelines give the ability of a mixture to reduce the total cementitious material content and thus decreasing the cost of the mixture, improving durability of the concrete, and reducing CO_2 emissions (Taylor et. al. 2007, Kosmatka et. al. 2011, Cook et. al. 2013).

3.4 SUMMARY

The aggregate proportioning methods were investigated for the workability of flowable concrete applications. Based on the data collected, the following have been found:

- If a single sieve size of the coarse aggregate (#4 and larger) retained more than 20%, the workability performance of the concrete would tend to decrease.
- Unless a sieve size retains more than 20%, a large range of gradations can be used without drastically affecting the workability of the concrete.
- Deficient amounts of a single sieve size or consecutively adjacent sieve sieves did not affect the workability of the concrete until a sieve size retained above 20%.
- Ideal bell shaped curve created surface finishability issues and is not recommended in practice.
- The maximum aggregate size did not have a major effect on the workability. However, the maximum aggregate size can help reduce the high amounts on a single sieve size by increasing the number of sieves used.

The gradation and proportioning of fine aggregate is essential to understanding and developing concrete mixtures with the ability to be placed, consolidated, and surface finished. Understanding the gradation limits of an individual percent retained chart is a fundamental step into adequately proportioning aggregates. This will allow for a better approach to predict workability and reduce the paste content of a mixture.

CHAPTER 4 - LABORATORY EVALUATIONS OF FINE AGGREGATE GRADATION FOR OPTIMIZED GRADED CONCRETE BRIDGE DECKS

4.1 INTRODUCTION

One of the most important properties of concrete is workability, which has been commonly described as the ability of a concrete mixture to be mixed, placed, consolidated, and surface finished in desirable manner (Taylor et. al 2007, Kosmatka et. al 2011, Neville 2012, Mehta and Monteiro 2006, Powers 1968, Power 1932). One contributor to this property is fine aggregate (Neville 2012, Mehta and Monteiro 2006, Powers 1968, Powers 1932, NSSGA 2013). A concrete mixture should be proportioned with an adequate volume and gradation consistency of fine aggregate. For surface finishing of concrete, fine aggregate plays an important role in the surface finish of concrete (Neville 2012, Mehta and Monteiro 2006, Powers 1968, Power 1932, NSSGA 2013) and also to be cohesive (Taylor et. al. 2007, Neville 2012). People have used the phrases “fine sand” and “coarse sand” to describe the consistency for the particle distribution of the fine aggregate gradation and the relationship to the workability properties of concrete (Neville 2012, Richardson 2005, Abrams 1918). These two phrases have given powerful meanings. While fine sand helps contribute to the smooth surface finishability and consolidation of the concrete (Kosmatka 2011, Neville 2012), coarse sand helps to “stiffen up” the concrete mixture to prevent segregation (Taylor 2007, ACI 302, Harrison 2004). A variety of fine aggregate gradations can be used to adequately proportion a concrete mixture (Neville 2012, Mehta and Monteiro 2006), but this gradation should not get “too coarse of sand or “too” fine of sand. Unfortunately, very little published work has systematically quantified this relationship (Powers 1968, Abrams 1918, Anson-Cartwright 2011, Obla and Kim 2008, Koehler and Fowler 2007, Goldbeck and Grey 1968).

In another report by the authors (Cook et. al 2013) it was shown that aggregate gradation concepts and proportioning techniques have a significant impact on the workability of concrete for slip formed pavements. The findings suggest a combined gradation based on the Individual Percent Retained (IPR) chart best predicted the impact of the aggregate gradation and proportioning for the workability of concrete for slip formed pavements.

4.1.1 Objectives

This work aims to build on the previous work and establish limits for the fine aggregate gradations for the IPR chart that provide insight into the impact on concrete workability for flowable applications, especially those where concrete should be pumped. These gradation recommendations will help practitioners choose one or more locally available aggregates that can be blended to produce aggregate gradations that improve the workability of concrete for slip formed pavements. With this improved workability then improvements can be made in economy, sustainability, and durability of these mixtures.

4.2 MATERIALS AND METHODS

4.2.1 Materials

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, 564 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 32.2% for the mixture volume. A constant water reducer (WR) of 6 oz. /cwt was used in every mixture to achieve flowable concrete. This WR was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C494. However, the aggregate proportions were changed. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

4.2.2 Mixture Design

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, a paste content of 32.2% of the mixture volume, and 20% class C fly ash replacement. However, the aggregate proportions were changed. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

Table 4-1 shows the batch weights for seventy-five different concrete mixtures used in this study. Many of the mixtures use a coarse, intermediate, and fine aggregate to proportion the combed gradation. Three crushed limestone sources and three natural sand sources were used to evaluate and validate the aggregate proportioning limits. One coarse aggregate source and one natural sand source were used to evaluate gradation limits, but two different coarse aggregate sources and two different natural sand sources were used to validate these results. Many of the gradations were sieved to evaluate the different gradation limits and cannot be classified according to any standard gradation system.

Table 4-1: Batch Weights

Mix	Quarry Source	Sand Source	Coarse (lbs.)	Int. (lbs.)	Sand (lbs.)
1	A	A	1762	636	705
2	A	A	1639	588	871
3	A	A	1516	539	1037
4	A	A	1393	490	1204
5	A	A	1269	442	1370
6	A	A	1146	393	1536
7	A	A	1979	0	1115
8	A	A	1023	344	1702
9	A	A	900	296	1869
10	A	A	1598	443	1188
11	A	A	1649	0	1433
12	A	A	1476	201	1404
13	A	A	1063	682	1335
14	A	A	856	922	1301
15	A	A	650	1163	1266
16	A	A	443	1403	1232
17	A	A	1115	847	1124
18	A	A	925	1036	1124
19	A	A	542	1414	1126
20	A	A	1050	911	1125
21	A	A	508	1875	710
22	A	A	807	778	1489
23	A	A	987	951	1147
24	A	A	1166	1124	806
25	A	A	1346	1297	464
26	A	A	807	778	1489
27	A	A	987	951	1147
28	A	A	1166	1124	806
29	A	A	1346	1297	464
30	A	A	1306	482	1296
31	A	A	1543	569	981
32	A	A	1781	657	667
33	A	A	987	951	1147
34	A	A	1166	1124	806
35	A	A	807	778	1489

36	A	A	987	951	1147
37	A	A	1166	1124	806
38	A	A	1346	1297	464
39	A	A	1971	0	1122
40	A	A	1971	0	1122
41	A	A	1971	0	1122
Mix	**Quarry Source**	**Sand Source**	**Coarse** (lbs.)	**Int.** (lbs.)	**Sand** (lbs.)
42	A	A	1971	0	1122
43	A	A	1971	0	1122
44	A	A	1971	0	1122
45	A	A	1971	0	1122
46	A	A	1971	0	1122
47	A	A	1971	0	1122
48	A	A	1971	0	1122
49	A	A	1971	0	1122
50	A	A	1971	0	1122
51	A	A	1971	0	1122
52	A	A	1971	0	1122
53	B	B	1172	408	1455
54	B	B	1292	284	1457
55	B	B	1413	161	1459
56	B	B	1533	37	1461
57	B	B	1052	531	1453
58	B	B	931	655	1452
59	B	B	1062	176	1784
60	B	B	1523	393	1131
61	B	B	832	67	2111
62	B	B	1753	502	804
63	B	B	811	778	1450
64	B	B	690	902	1448
65	B	B	1609	0	1471
66	C	C	1009	818	1151
67	C	C	1174	650	1156
68	C	C	1409	412	1163
69	C	C	1644	173	1170
70	C	C	1806	8	1175
71	C	C	1517	472	994
72	C	C	1301	351	1333
73	C	C	1192	290	1503
74	C	C	1084	229	1673
75	C	C	976	169	1842

4.2.3 Sieve Procedure for Creating a Gradation

To investigate different aggregate gradations using a single source, sieving was used to create the vast majority of the gradations described. Aggregates were oven dried, sieved into individual sizes, and combined into a single gradation. This process was tedious, but effective for closely controlling the gradation of a mixture.

4.2.4 Mixing and Testing Procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24 h 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 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 initial testing of the mixture included Slump Test [20], visual observations, ICAR rheometer, and the Float Test. These Test can be further explained in Chapter 2 of this report

4.2.5 Using Workability Tests to Evaluate Flowable Concrete

The four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table 4-2 was developed to represent flowable concrete workability performances. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Table 4-2: Workability Performance Rating System

Workability Performance Scale for Each Test	**Slump Test** (in)	**Visual Observation**	**ICAR Rheometer**			**Float Test** (passes)	
			Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Remove Hole	Remove Texture
Excellent (1)	8 to 6	A or 1	<1000	<250	<10	1 to 2	1 to 2
Good (2)	6 to 4	B or 2	1000-1500	250-500	10 to 15	3 to 4	3 to 4
Moderate (3)	4 to 2	C or 3	1500-2000	500-1000	15 to 20	5 to 6	5 to 6
Poor (4)	2 to 0	D or 4	>2000	>1000	>25	7 to 8	7 to 8
Unusable (5)	0	F or 5	Too stiff	Too Stiff	Too Stiff	+9	+9

4.2.6 Quantifying Workability Assessments

After analyzing the data and comparing each workability test for flowable concrete applications, the quantity of measurements needed to be simplified into a practical manner. In other words, these seven different measurements were quantified into a single overall workability performance rating for a given mixture. This was completed by taking the average workability performance of each measurement as classified in Table 4-2. After the average numerical value was calculated, it was converted back into the following workability scale range: excellent (1), good (2), moderate (3), poor (4), and unusable (5). For an example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would mathematically be 1.43 and be classified as a good overall workability.

4.3. RESULTS AND DISCUSSION

The purpose of the research was to develop fine aggregate sieve sizes (#8 and less) limits for a combined gradation in order to better control the workability of a concrete mixture design. To achieve this, the workability of 75 mixtures were evaluated as shown in Table 4-3. This table was color coated with black representing good or excellent workability performance, yellow representing moderate workability performance, and red representing poor or unusable workability performance. Also through the results, the combined gradation of each mixture will be plotted using the individual percent retained chart with the overall workability rating. The sieve ranges that make-up coarse sand and fine sand and the volumes required to achieve the preferred workability were each developed. Unless otherwise stated, crushed limestone A and river sand A were used as the aggregate sources for developing the individual sieve limits. Other aggregate sources were utilized to validate the limits.

Table 4-3: Workability Performance Rating System

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
1	Unusable	Unusable	4400	Too Stiff	Too Stiff	7.25	12+	12+
2	poor	Poor	1467	272±13	36±2.4	6.25	8	9
3	moderate	Moderate	1045±20	327±12	16±0.6	5	5	6
4	good	Good	948±92	315±33	10.2±0.7	6.5	4	4
5	good	Excellent	1140±142	299±19	12.5±3.0	7	2	2
6	good	Good	1139±84	1142±64	10.2±1.5	4	3	3
7	poor	Poor	2811±150	720±45	14.4±1.4	2	12+	12+
8	poor	Poor	2811±150	720±45	14.4±1.4	2.25	12+	12+
9	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	1.5	5	3
10	moderate	Poor	1379±195	393±21	15±1.2	8	12+	12+
11	Moderate	Moderate	943±23	428±1	11.9±1.7	6	5	5
12	good	Excellent	796±9	341±48	10.8±1.3	7	3	3
13	good	Excellent	1193±6	469±16	11.9±1.3	6.5	6	5
14	moderate	Good	1755±354	642±12	9.9±1.0	4	10	10
15	poor	Moderate	1974±54	647±3	13.1±1.5	4.25	9	9
16	poor	Poor	2457±394	751±8	15.4±0.6	2.5	12+	12+
17	good	Excellent	791±66	339±21	10.9±1.6	7.5	4	4
18	good	Good	773±46	288±14	11.9±0.6	6.5	5	5
19	good	Excellent	797±54	415±31	11.8±0.6	5.5	5	4
20	good	Excellent	1077±67	378±11	8.3±0.9	7.5	2	2
21	Moderate	Good	833±70	390±33	11.8±1.0	6.5	10	8
22	Unusable	Poor	Too Stiff	Too Stiff	Too Stiff	2.75	11	8
23	good	Good	1131±41	509±9	13±0.3	6	4	3
24	good	Good	970±53	296±11	7.7±0.8	7.5	6	8
25	Unusable	Poor	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
26	poor	Poor	1519±38	450±21	10.7±0.1	3	8	8
27	moderate	Good	945±34	318±29	10.6±1.2	7.5	10	10
28	moderate	Moderate	882±66	211±15	19.1±1.3	8	5	6
29	Unusable	Poor	Too Stiff	Too Stiff	Too Stiff	8.5	12+	12+
30	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
31	poor	Poor	2453±179	679±33	27.0±3.0	4.5	6	4
32	Unusable	Poor	2119±142	426±100	52.1±6.0	6	12+	12+
33	moderate	Moderate	2178±226	818±21	12.8±0.4	4	4	4
34	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	7.5	12+	12+
35	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
36	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	1.25	12+	12+

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
37	poor	Poor	1275±25	133±48	35±14	8.25	6	12
38	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	0	12+	12+
39	poor	Poor	936±68	295±11	14.5±0.7	6.75	12+	12+
40	poor	Poor	1762±70	538±33	13.9±0.7	3.5	12+	12+
41	moderate	Moderate	1876±144	759±35	6.5±0.4	3.5	4	12
42	good	Good	1427±37	423±43	10.1±1.1	4.75	4	4
43	moderate	Good	1293±71	389±33	15.2±1.9	5.25	6	8
44	good	Good	1375±121	457±19	9.1±0.5	5.25	2	3
45	good	Good	1437±28	505±61	12.8±0.9	5.25	4	4
46	good	Good	1137±137	513±24	6.5±0.3	5.5	5	6
47	moderate	Moderate	1681±51	532±22	9.3±1.6	4	8	8
48	poor	Poor	1705±70	497±4	9.8±1.1	4	8	8
49	moderate	Moderate	865±57	283±13	10.7±1.2	7.75	4	12
50	good	Good	846±62	290±6	12.6±0.9	6.75	4	4
51	good	Good	1160±4.5	325±12	12.5±1.1	7.5	4	4
52	moderate	Poor	1241±27	422±5	9.9±1.3	5.25	4	12
53	good	Excellent	1048±93	383±8	8.9±0.4	6.75	3	4
54	good	Excellent	1100±195	327±9	10.3±0.3	6.25	4	4
55	good	Excellent	975±115	297±28	7.4±0.4	8	5	5
56	good	Excellent	1557±175	557±40	11.1±0.1	5.75	3	2
57	good	Excellent	1394±99	512±32	7.3±0.7	5.5	6	4
58	moderate	Good	1221±111	444±11	9.6±0.4	5.25	7	6
59	poor	Moderate	Too Stiff	Too Stiff	Too Stiff	2.75	4	4
60	good	Good	1341±106	397±16	14.9±0.6	6	4	5
61	Unusable	Poor	Too Stiff	Too Stiff	Too Stiff	0.5	2	1
62	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	7	12+	12+
63	moderate	Moderate	1147±118	519±33	8.0±0.4	5.5	6	6

Mix	Overall Workability	Visual Observation	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (in)	Float Test (passes)	
							Hole	Texture
64	Unusable	Unusable	Too Stiff	Too Stiff	Too Stiff	2.75	12+	12+
65	poor	Poor	1840±154	599±22	18.6±0.8	3.75	8	8
66	moderate	Poor	2036±168	459±1	23.3±2.0	3.75	4	12
67	moderate	Moderate	1474±77	422±34	14.3±0.9	6.25	3	12
68	good	Good	1203±81	413±2	14.5±0.5	4.75	4	4
69	moderate	Good	1562±80	461±27	13.1±0.8	5.5	4	6
70	poor	Poor	1013±80	261±32	18.2±1.3	8	12	12
71	Unusable	Poor	Too Stiff	Too Stiff	Too Stiff	3.5	12	12
72	good	Excellent	1339±58	559±34	7.8±0.3	5.75	2	5
73	good	Good	1341±9	578±5	9.8±0.5	5	3	3
74	moderate	Moderate	1343±60	611±8	7.9±0.8	4.5	4	4
75	poor	Poor	Too Stiff	Too Stiff	Too Stiff	1.5	5	4

4.3.1 Proportioning Fine Sand

Traditionally fine aggregate has been defined as the material retained on the #8-200 sieve sizes (Neville 2012). A concrete mixture must contain a certain amount of fine aggregate to accomplish placement, consolidation, and surface finishing for the desired application. This fine aggregate behavior has been further broken down into coarse sand and fine sand to better understand this behavior. Based on previous work from the authors (Cook et. al. 2013), the fine sand sieves were found to be #30 through #200 and the coarse sand sieves were from #8 through #30. Figure 4-1 shows varying amounts of sand with a constant ratio of the coarse to intermediate aggregate. Without exceeding the developed sieve size limits shown later in the results section, various combined gradations will be investigated to determine adequate volume proportioning ranges for fine aggregate.

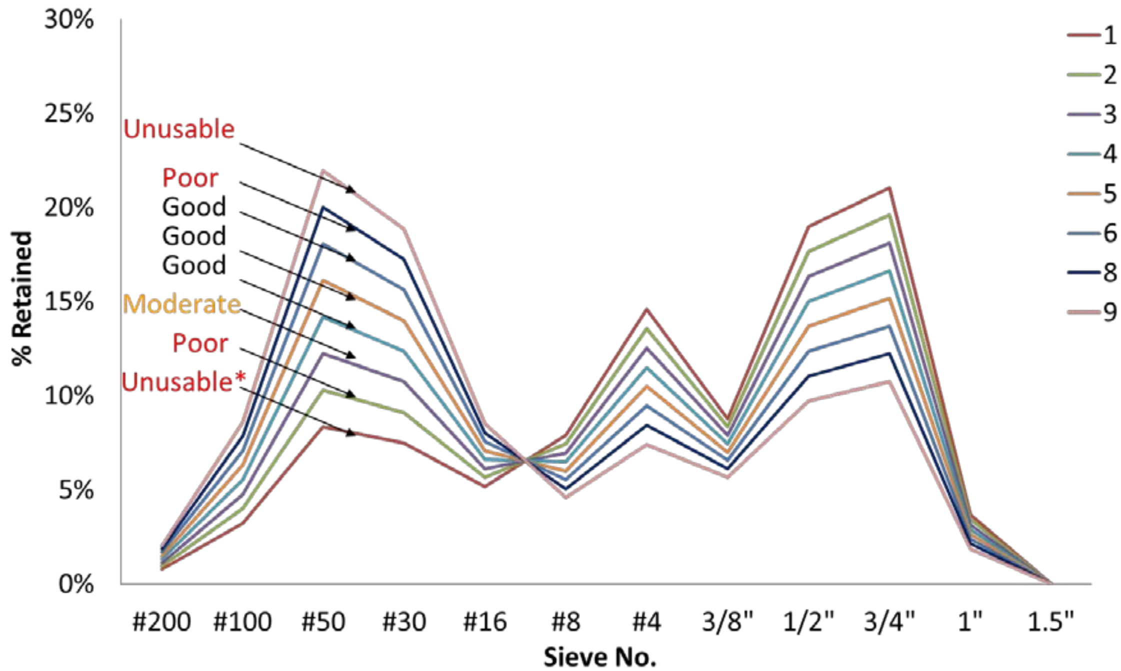


Figure 4-1: The overall workability with different amounts of sand and fixed ratio of coarse to intermediate aggregate. *note: this mixture had surface finishability or cohesion issues

Figure 4-1 shows the trends of workability and fine sand volume. If the gradation was proportioned with inadequate volume amounts of “too much” or “too little” fine sand, the workability was poor. Figure 4-2 shows the pictures of low, sufficient, and high amounts of fine sand. Also in Figure 4-3, a picture of the low, sufficient, and high amounts of fine sand mixtures in the Slump Test. When the volume of fine sand was low in the mixture, the mixture looked like coarse aggregates coated with a small film of paste as shown in Figure 4-2 and Figure 4-3. This low sand volume mixture visually flowed like a coarse aggregate stockpile. Also the low sand mixture was discharged from the mixing and into a wheel barrow. Figure 4-4 was a picture shows the poor exhibited poor cohesion properties as shown in Figure 4-3. When excessive volumes of fine sand were used, the mixture became “sandy”, which created a very stiff and poor flowability properties.

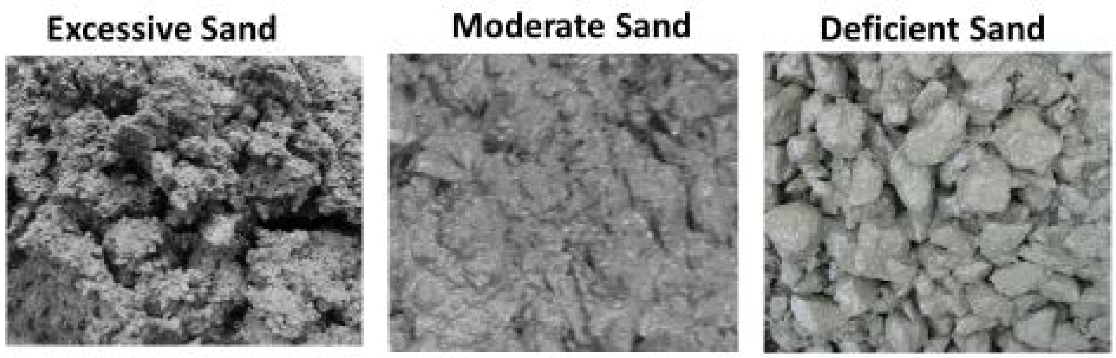


Figure 4-2: Images showing the visual observation with excessive and deficient amounts of sand

Figure 4-3: Images showing the Slump Test measuring the excessive and deficient amounts of sand.

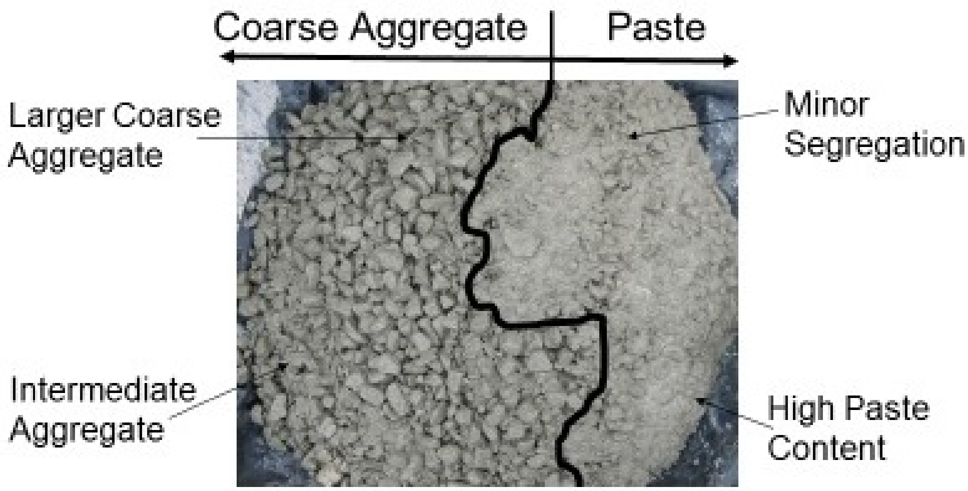


Figure 4-4: Visual observation of the deficient amounts of sand and the resulting segregation.

4.3.1.1 Developing Proportioning Limits for Fine Sand

Other sources were needed to help develop fine sand volume proportioning limits. Figure 4-5 and Figure 4-6 both different aggregate sources with varying amounts of sand with a constant ratio of the coarse to intermediate aggregate. These fine sand volume limits cannot be easily displayed on an individual percent retained chart. Figure 4-7 plots the mixtures from Figure 4-4 through 4-6 using the fine sand volume and overall workability performance. A distinct upward parabola trend can be shown and recommended limits were set between 25% to 40% fine sand volume.

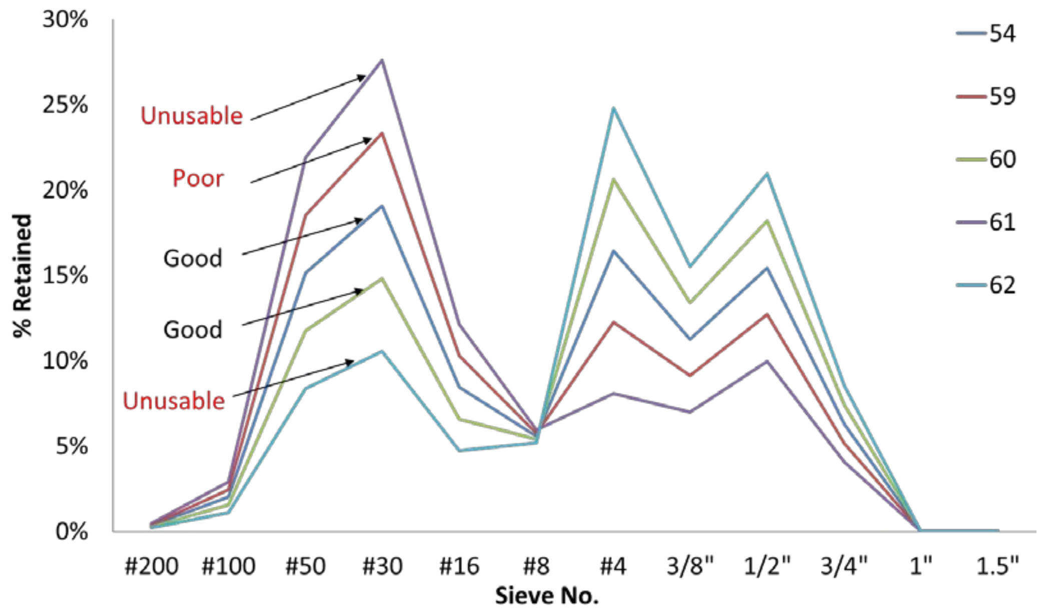


Figure 4-5: The sand proportions for overall workability of limestone B and sand B.

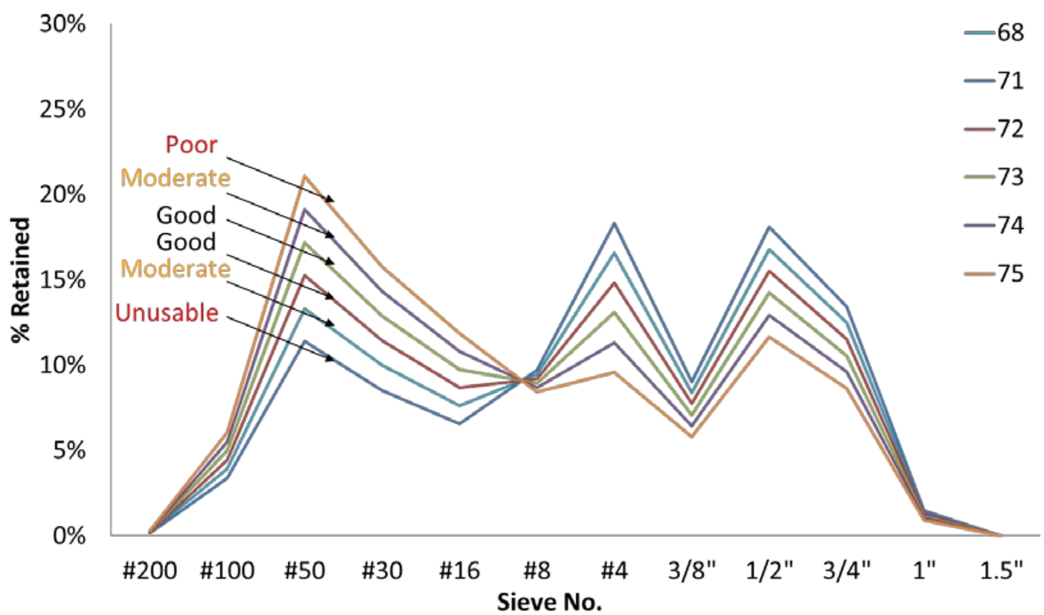


Figure 4-6: The sand proportions for overall workability of limestone C and sand C

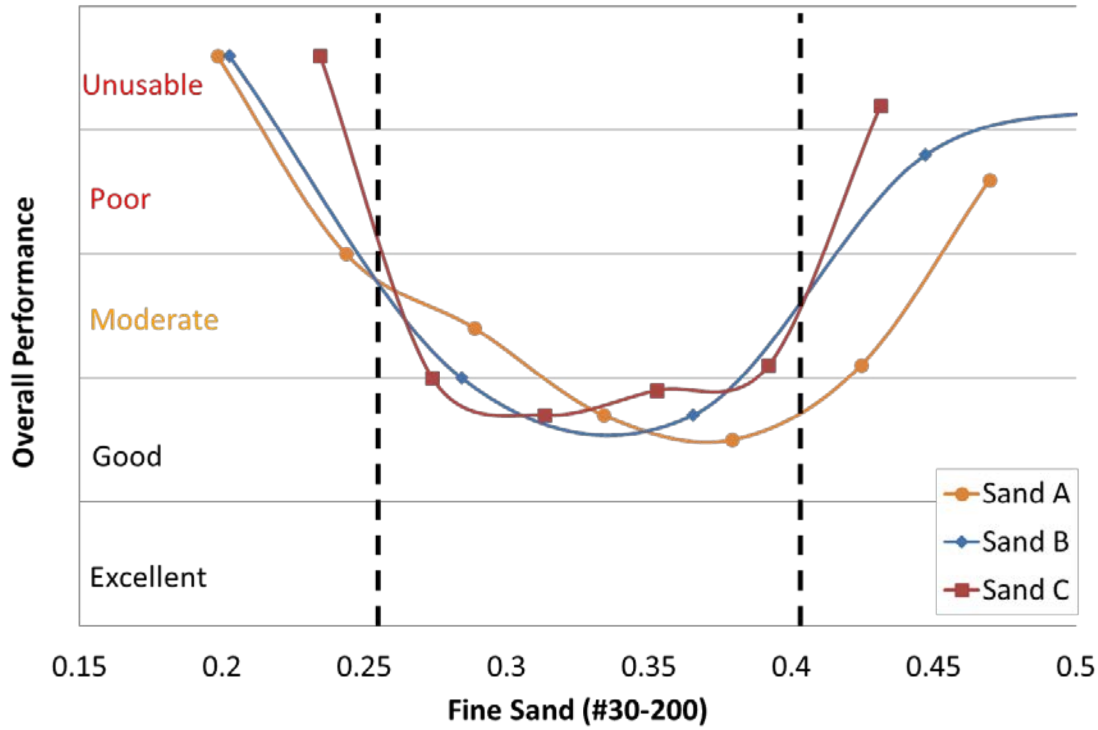


Figure 4-7: The overall workability and different fine sand volumes

4.3.1.2 Fine Sand Distribution

Past investigations (Cook et. al. 2013) presented similar workability behaviors with a variety of fine sand distributions. Figure 4-8 shows distributions of fine sand for flowable applications. The combined gradation stayed constant from #16 and larger with the exception of one very ultra-fine gradation. The purpose of the figure was to compare the workability behaviors of different distributions of #30 through #200.

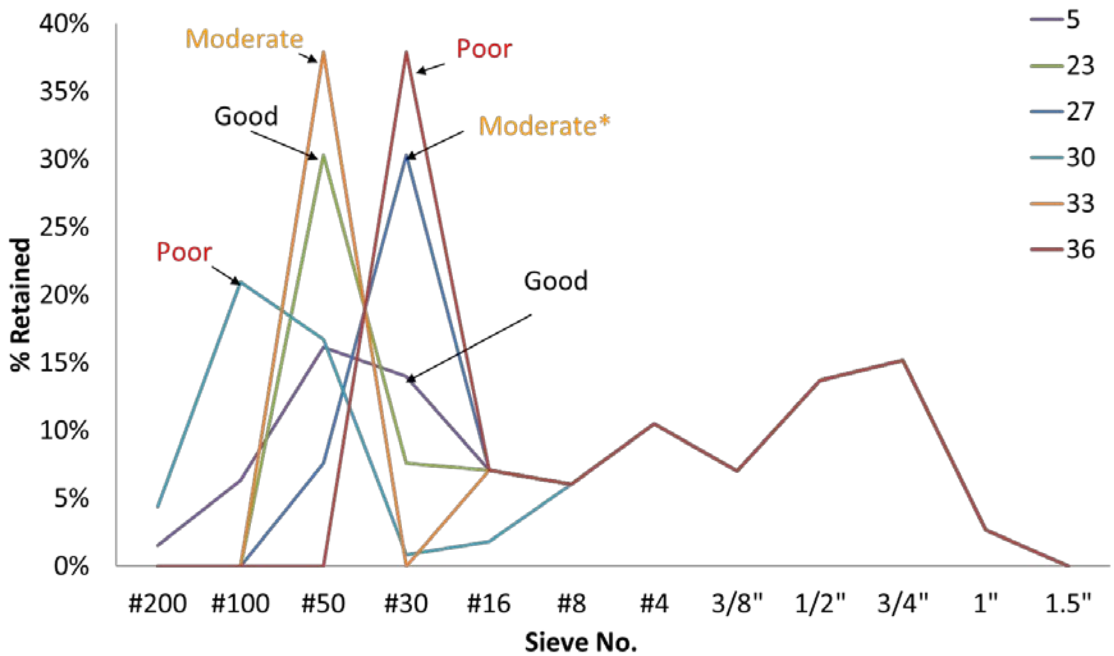


Figure 4-8: Various fine sand distributions and the overall workability. *note: this mixture had surface finishability issues

4.3.1.2.1 Effects of #30

Mixture 27 had a gradation close to 30% on the #30 sieve and also had issues with surface finishing as shown in Figure 4-9. The large amount of #30 created a very poor finishability and could be described as gritty. This is not a desirable for mixtures requiring a surface finish, especially with a hard trowel. In another report (Cook et. al. 2013) has found the same behavior with high amounts of #30 with a boundary limit of 20%. A practical boundary limit of 20% on the #30 was also concluded for the flowable concrete research.

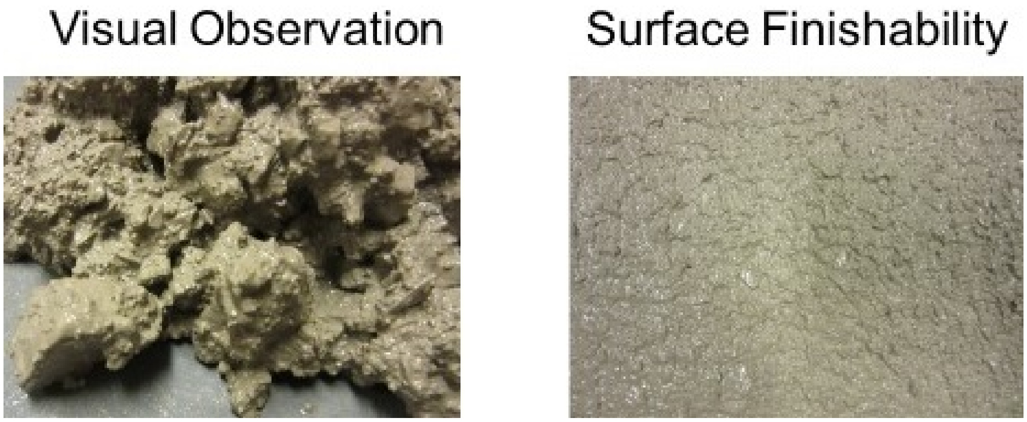


Figure 4-9: Pictures of mixtures with excessive amounts of #30 in mixture 27

4.3.1.2.2 Effects of #50

Also, the gradation with 30% retained on the #50 was shown to create a very smooth surface finish. While this mixture was being mixed, the sides of the drum finished the mixture as shown Figure 4-10. In other words, this was a very easy mixture to finish.

Figure 4-10: Pictures of the 30% of #50 in mixture 23.

4.3.1.2.3 Effects of #100 and #200

Mixture 30 in Figure 4-8 had very poor workability performance. Figure 4-11 shows the visual observations of the mixture. The amounts of #100 and #200 sieve sizes created a mixture with sand and paste around the coarse aggregate particles. Obviously, this gradation is not desirable. A similar limit for concrete to be used for slip formed pavements was established in another report (Cook et. al. 2013). For this work a limit of 10% on the #100 is recommended. More research needs to be conducted into understanding the behavior of #100 and #200.

Figure 4-11: Pictures of mixtures with excessive amounts of #100 and #200 in mixture 30.

4.3.2 Coarse Sand

Throughout these investigations, it was very clear to see the coarse sand gives a fresh concrete mixture stiffness and cohesive properties. The importance of coarse sand property has pushed the creation rules of thumb from the field. These rules of thumb try to ensure a mixture will have enough coarse sand to help prevent edge slumping and segregation in pavements and slab on grade (ACI 302, Harrison 11, Richardson 2005). However, the sieve sizes creating these properties have never been clearly defined and therefore could not be adequately proportioned. Another publication (Cook et. al. 2013) shows the #8, #16, and #30 sieve sizes form the coarse sand. Below are subsections into the investigations of these coarse sand sieve sizes.

4.3.2.1 Investigating #8

To investigate the #8 sieve size, gradations were created with the 0% of #16 sieve size and 0% to 20% of #8 as shown in Figure 4-12. Gradations containing low amounts (0% and 4%) of #8 had poor cohesion. Figure 4-13 was a picture of the mixture 39 being discharged into a wheel barrow. The segregation of the mixture can be observed through the lack of bonding between the coarse aggregate and the rest of the mixture. Also, the gradation of mixture 52 contained 20% of #8 sieve size and had poor finishability as shown in Figure 4-14. A maximum sieve limit could be recommended at 20%.

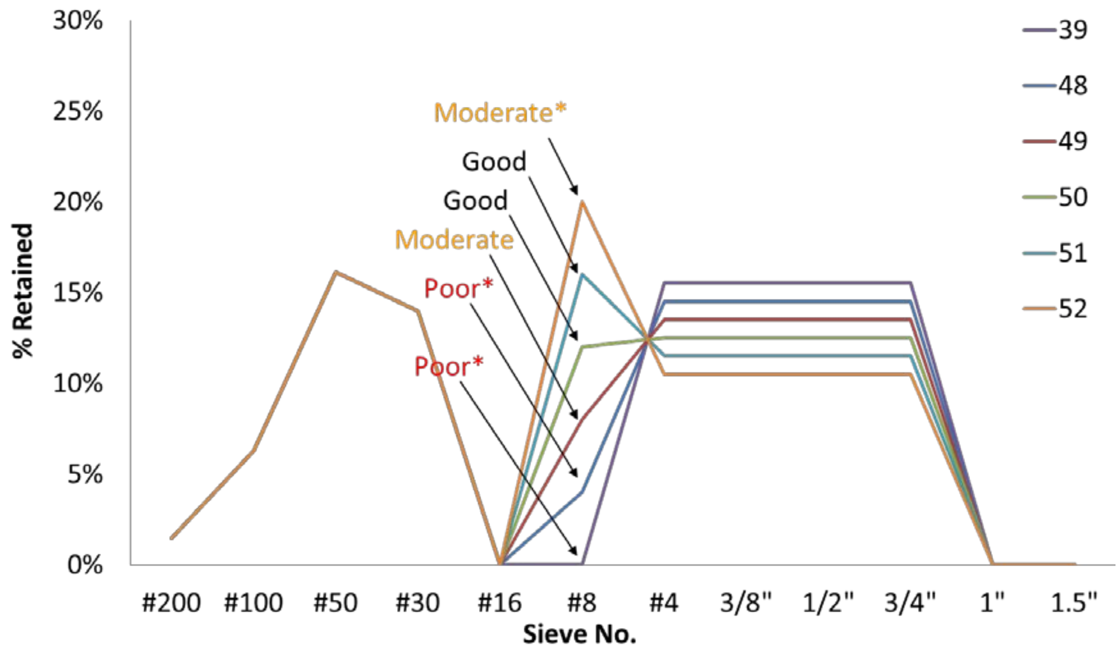


Figure 4-12: The overall workability of mixtures with various amounts of #8. *note: this mixture had surface finishability or cohesion issues.

Figure 4-13: Mixture with poor cohesion of mixture 39 without #8 and #16.

Figure 4-14: Mixture with poor finishability of mixture 52 with high amounts of #8.

4.3.2.2 Investigating #16

To investigate the #16 sieve size, the #8 sieve size was removed and various amounts of #16 were varied from 0% to 16% as shown in Figure 4-15. Like previously discussed, mixture 39 with 0% of #16 had poor cohesion as shown in Figure 4-13. However, adding 4% of #16 allowed the mixture to have good workability. When the gradation of mixture 47 had 16% of #16, it created poor finishability as shown in Figure 4-16. This was a picture after 30 passes. A maximum sieve limit could be recommended at 16%.

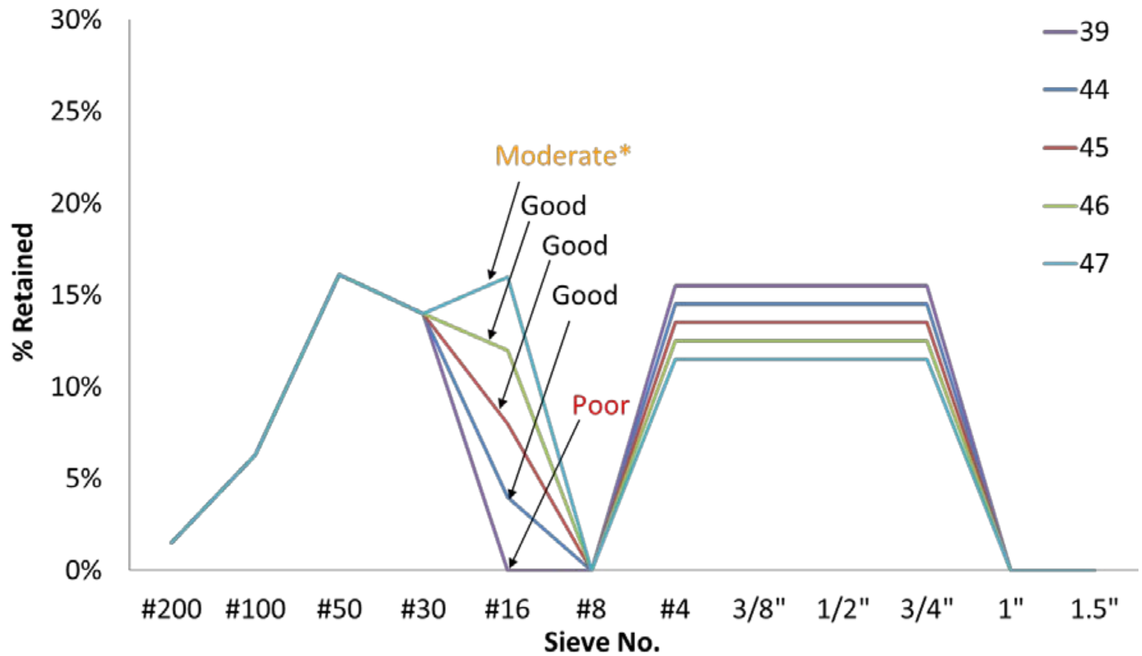


Figure 4-15: The overall workability of mixtures with various amounts of #16.

***note: this mixture had surface finishability or cohesion issues**

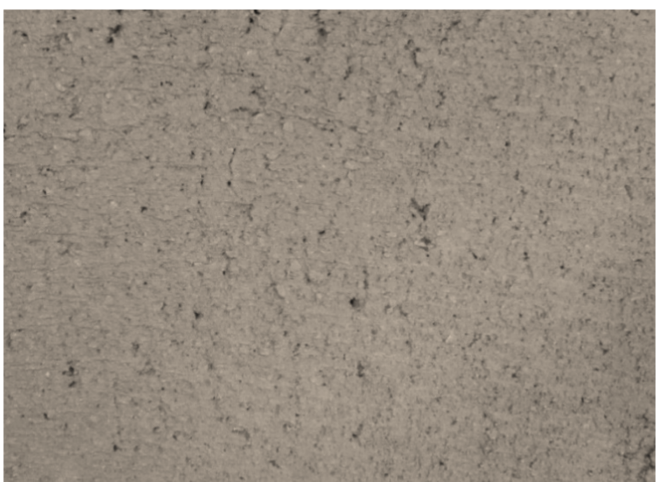


Figure 4-16: Mixture 47 shows poor finishability with high amounts of #16.

4.3.2.3 Investigating the Combination of #8 and #16

To investigate the #8 and #16 sieve size, these sieves were removed from the gradation and various amounts of both sieve sizes were slowly added from 0% to 14% as shown in Figure 4-17. Like previously discussed, mixture 39 with 0% of #8 and #16 had poor cohesion as shown in Figure 4-13. However, adding 2% of #8 and #16 allowed the mixture to improve the workability. Poor finishability was created with a gradation using 14% of #8 and #16. Even after 30 passes, the surface could not be adequately floated. A lower maximum sieve limit amount of 12% should be recommended. This recommendation also matches the slip formed pavement recommendations in another report (Cook et. al. 2013).

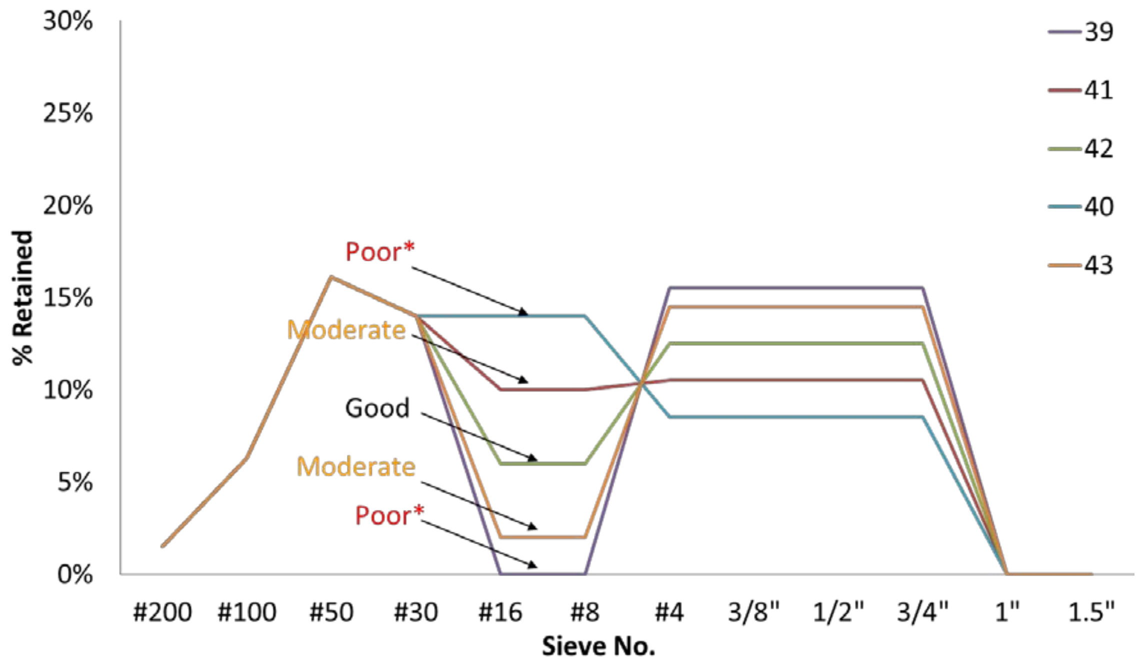


Figure 4-17: The overall workability with various amounts of #8 and #16. *note: this mixture had surface finishability or cohesion issues.

4.3.3 Recommended Combined Gradation Limits

Throughout this research, a common trend of coarse aggregate sieve sizes retaining over 20% could have a decrease in workability. However, a gradation with low amounts on one or two sieve sizes does not necessarily affect the performance of the concrete. Yet, it becomes difficult to stay within the maximum boundary limits if a gradation was missing or having a small amount on an adjacent sieve sizes. Figure 4-18 shows the recommended individual sieve size and proportioning limits of a combined gradation.

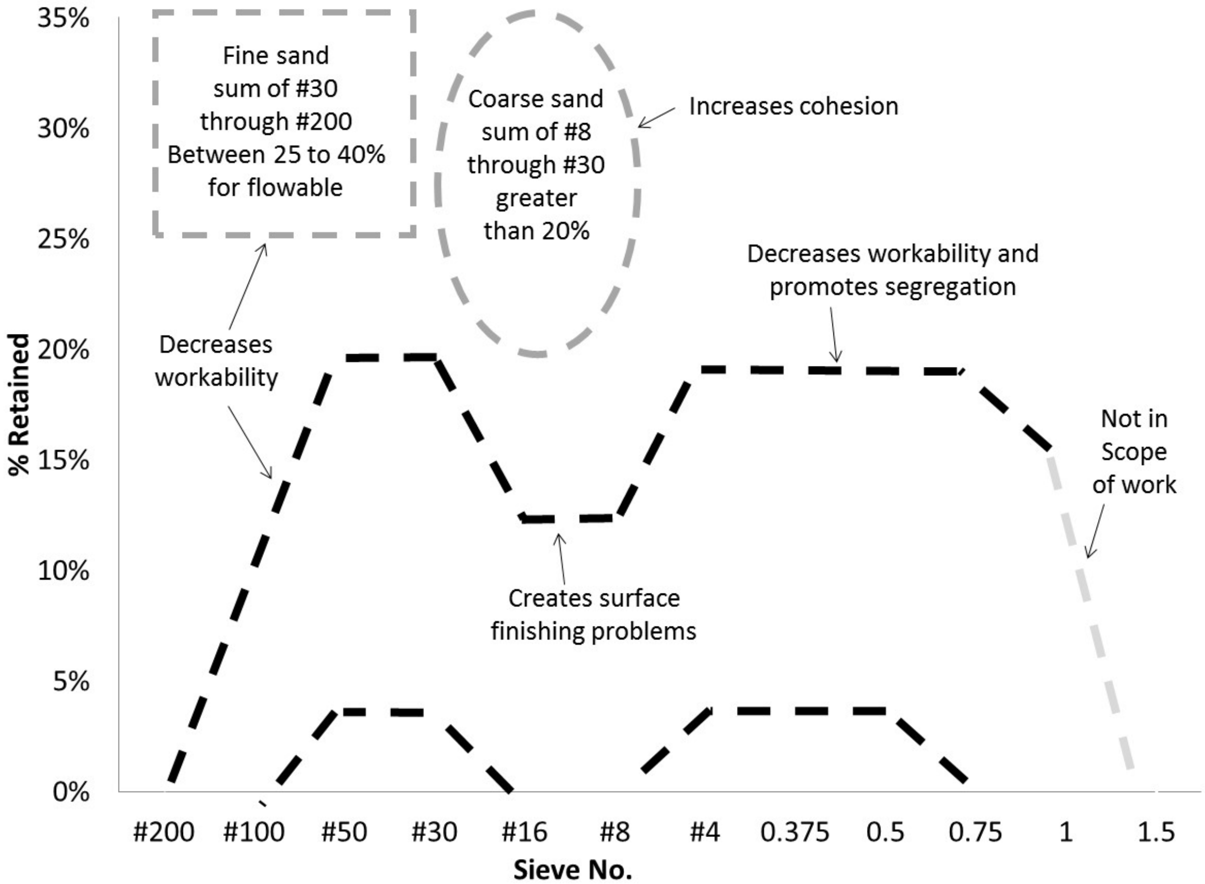


Figure 4-18: Developed limits with coarse sand and fine sand ranges

4.3.3.1 Coarse Sand Limits

Coarse sand was proven to effect the cohesion and surface finishability of the mixture. These workability issues can be very problematic. A minimum volume of coarse sand and individual sieve sizes limits were developed to help prevent these issues.

4.3.3.1.1 Surface Finishability Issues

If the mixture was high on a coarse sand sieve size, surface finishability issues occurred. Finishability issues were created at 20% of #8, 16% of #16, and 12% of both #8 and #16. Since #8 and #16 commonly have similar percentage amounts retained, a conservative maximum sieve size boundary at 12% for the #8 and #16. Also, a maximum limit of 20% was set for the #30 sieve size.

4.3.3.1.2 Cohesion

If low amounts of coarse sand (#8 to #30) were present, the mixture tended to segregate. Similar findings were found in the slip formed pavement report (Cook et. al. 2013) and also other publications (Richardson 2005, ACI 302, Harrison 2004). For this investigation, minimal amounts of coarse sand could create adequate cohesion from the following: 4% on the #16 with 15% of #30, 12% on the #8 with 15% of #30, or 2% on the #8 and #16 with 15% of #30. A reasonable minimal volume limit of 20% was recommended for coarse sand value using a natural sand.

4.3.3.2 Fine Sand Limits

Fine sand proportioning was shown to be fairly consistent in Figure 4-7. The practical volume ranges of fine sand (#30 to #200) for flowable concrete was recommended from 25% to 40%. These proportioning trends of fine sand (#30 to #200) from 24% to 34% were similar to the proportioning trends in the slip formed pavement report (Cook et. al. 2013). This wider range for the flowable concrete could be from either the increased paste content or broader workability range of flowable concrete.

4.3.4 Practical Applications

This work was able to develop some basic and simple guidelines for proportioning the coarse aggregate sieve sizes in a combined gradation. These gradation guidelines can be extremely beneficial to improve the construction specifications and practices. Furthermore, the guidelines give the ability of a mixture to reduce the total cementitious material content and thus decreasing the cost of the mixture, improving durability of the concrete, and reducing CO_2 emissions (Shilstone 1990).

4.4 SUMMARY

Various fine aggregate concepts were investigated for a better understanding of the workability of flowable concrete. The research showed gradations significantly impacted the workability of concrete mixtures. Also, proportioning of aggregate can be a very complex issues, but could be simplified using coarse sand and fine sand volume ranges. Based on the data collected using these specific aggregate sources, the following have been found:

- Coarse sand (#8 through #30) impact the cohesion of the mixture.
- A minimum value of 20% was suggested to be retained on the coarse sand (#8 through #30).
- Surface finishability issues could be created with gradations retaining over 12% on the #16 and #8 and also 20% of #30.
- Fine sand (#30 through #200) volume was recommend to range from 25% to 40% of the combined gradation.

These recommendations are helpful to trouble shoot and help design flowable concrete mixtures for a wide range of materials and applications.

CHAPTER 5 – LABORATORY EVALUATIONS OF PUMPING CONCRETE MIXTURES

5.0 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 (Collins et. al. 2006 and The Contractor's Guide 2005).

In the last two chapters extensive testing was conducted into the effects of gradation on the workability of flowable concrete. The objective of this chapter is to further investigate these developed gradation limits using a concrete pump. 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.

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. 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.

5.1.1.2 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 sand used in the grout mixture also came from Sand A.

5.1.2 Equipment

5.1.2.1 Concrete Pump and Pipe Network

A Putzmeister TK50 concrete pump was used for this research and is shown in Figure 5-1. 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 5-1: The concrete pump used in this work (Putzmeister TK 50).

An instrumented 52.5 ft. pipe network with three 90^o 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 5-2. 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 90º 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 90º 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.

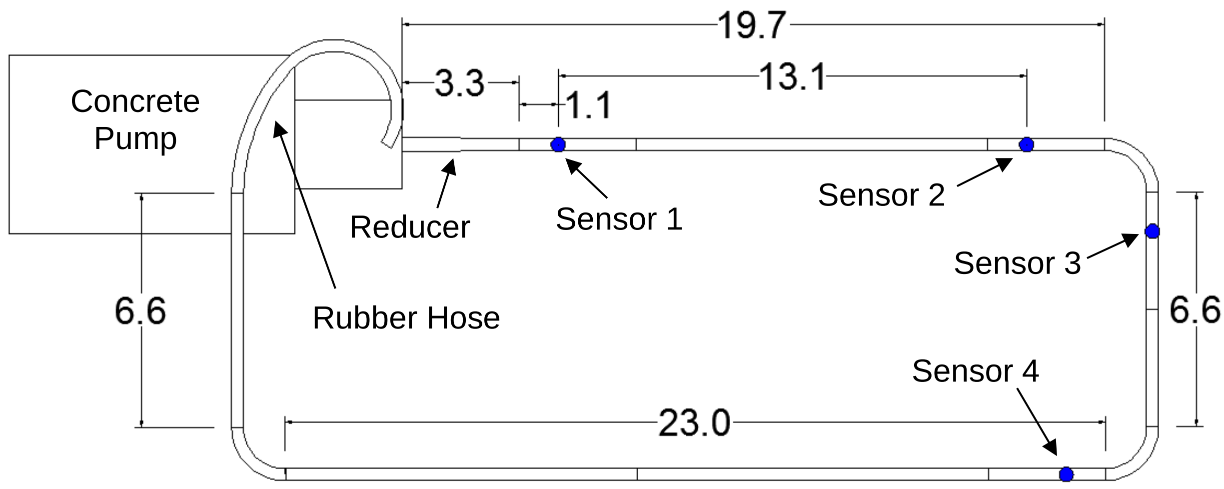


Figure 5-2: Plan view of the pump layout (units in feet).

The TK 50 pump has two major pump 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^o, 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.

5.1.2.2 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 5-3.

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.

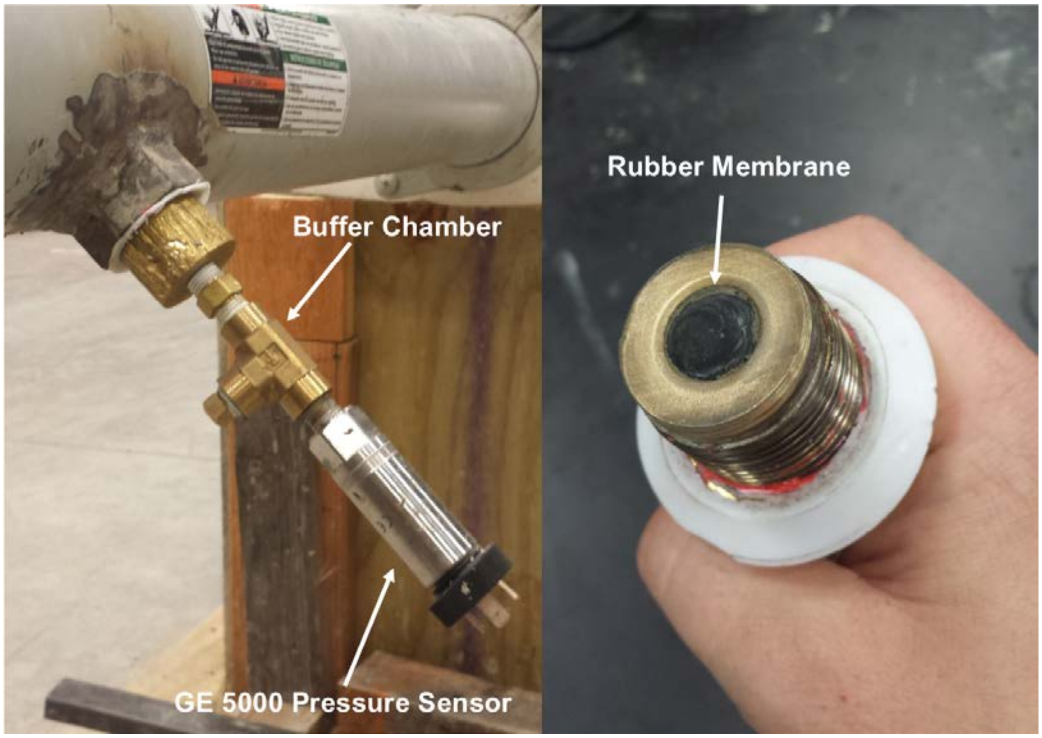


Figure 5-3: An overview of the pressure sensor is shown. Oil fills the buffer chamber and as the rubber membrane moves the pressure can be read by the pressure sensor.

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^{o} 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 0.05 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 5-4.

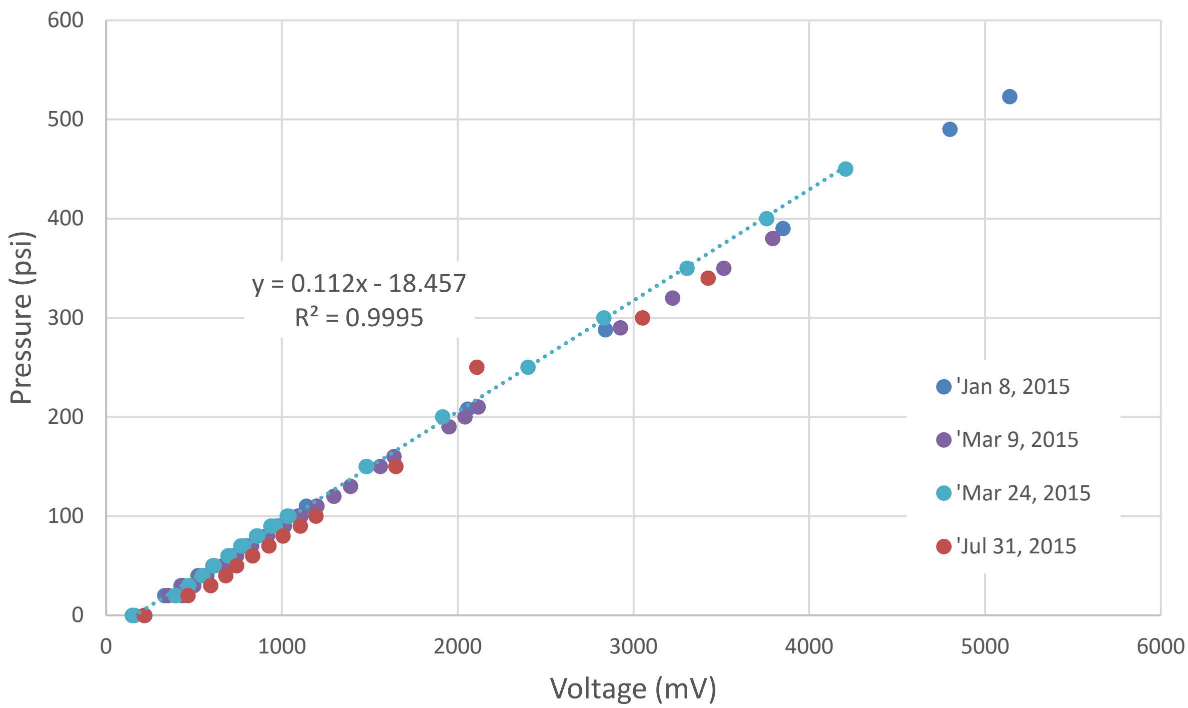


Figure 5-4:The sensors were calibrated using a pressure chamber filled with water and then calculating a best fit line.

It should be noted the y-intercepts 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 first filling the pipe network with concrete and turning the pump off. The sensor values were recorded while the concrete filled the line but did not move. This gauge reading was set equal to the zero pressure value. This ensured all four sensors only recorded the pressures caused by the movement of the concrete and not the weight of the concrete or any drift in the calibration of the sensor. 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.

5.1.3 Testing Methods

5.1.3.1 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 5-1.

Table 5-1 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

5.1.3.2 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.

5.1.3.3 Data Collection

In order to sample concrete from the pump line, the concrete 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 up the bucket 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. intervals to allow for this. 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 ran 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 5-5 for the pumping testing procedure over time.

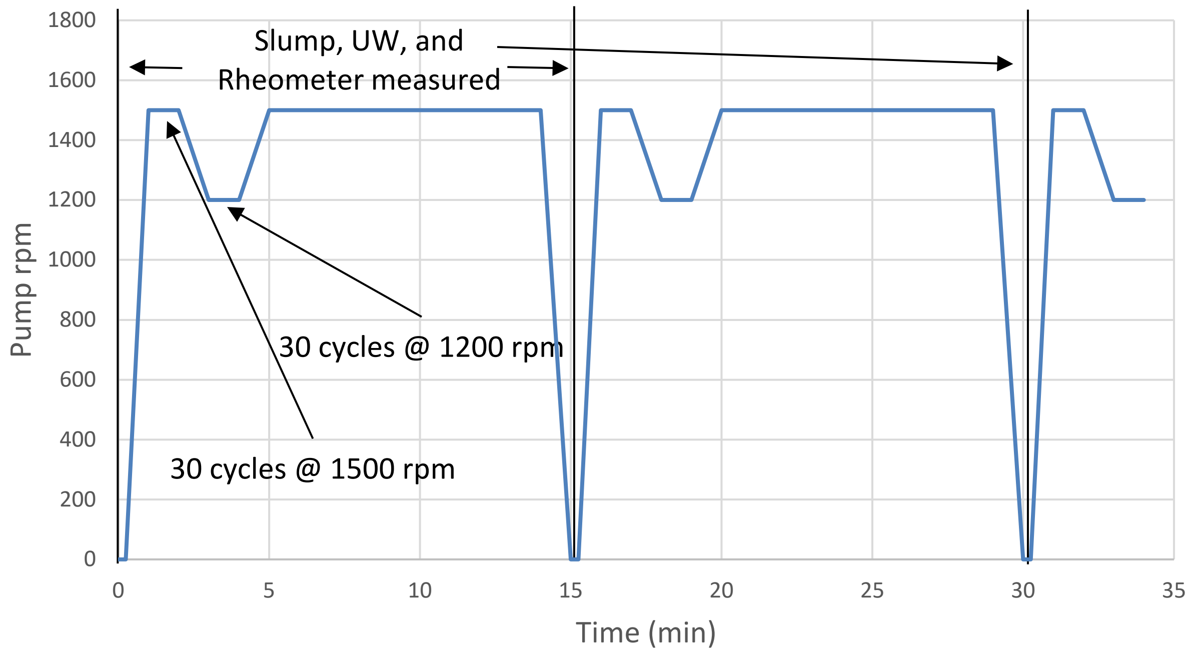


Figure 5-5: A typical pump cycle over time and the tests completed at different intervals.

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.

5.1.3.4 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 5-6.

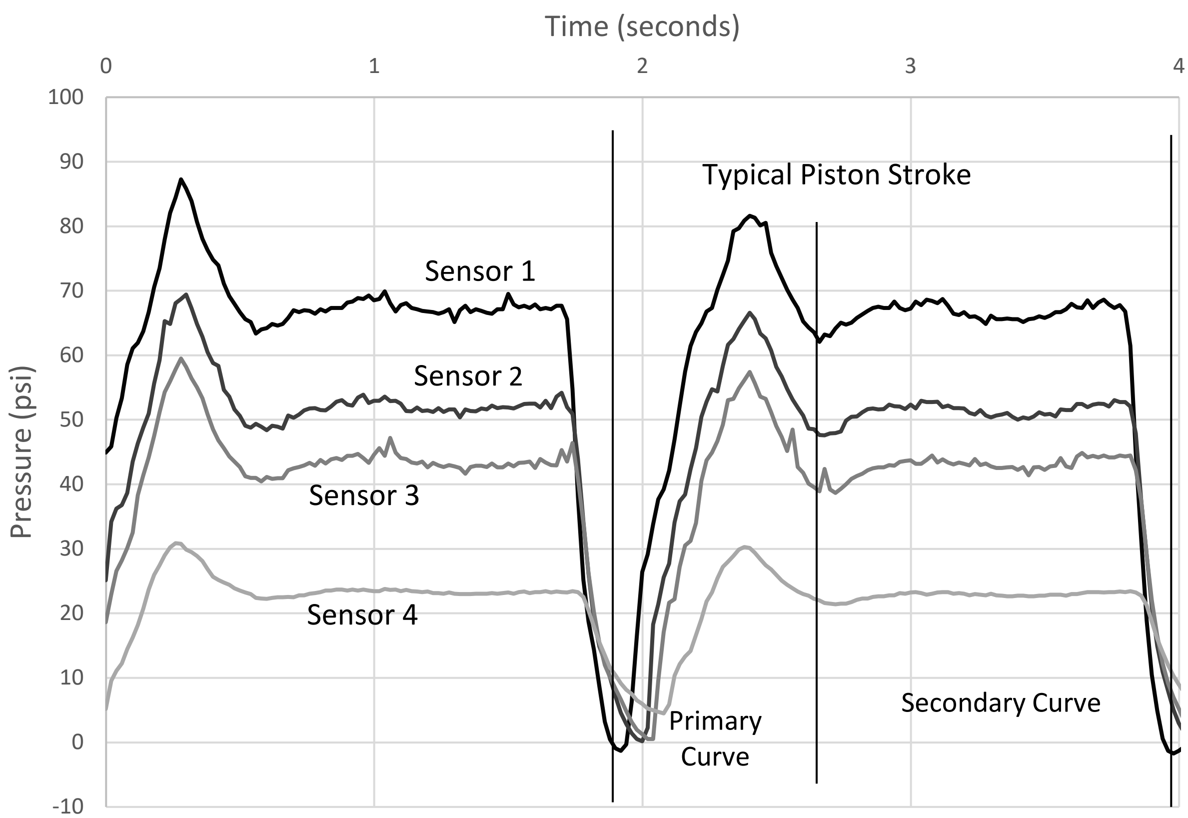


Figure 5-6: A typical pumping pressure curve has a primary and secondary curve.

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.

5.2 RESULTS AND DISCUSSION

In all cases the pressure in the line decreased with distance away from the pump. 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 air gaps, segregation, or concrete that was too stiff, then the pressure curves looked erratic. Figure 5-7 shows examples of erratic curves from different observed phenomenon.

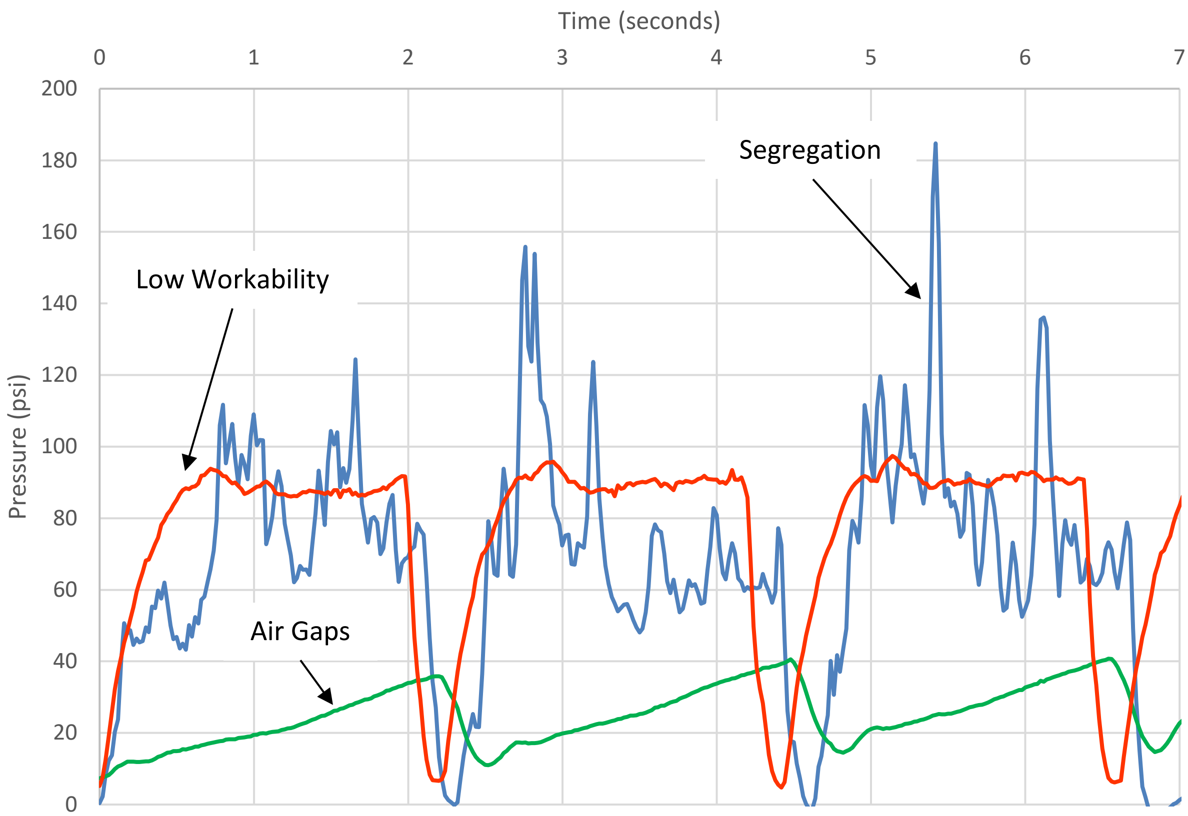


Figure 5-7: Air gaps, low workability and segregation can be seen on the pump curves.

5.2.1.1 Mixture Repeatability

One mixture was repeated three times. Their secondary pressure curves were tabulated in Table 5-2 to analyze the pressure variability for a single mixture.

Table 5-2 Sensor 1 values at 1500 rpm taken over three tests of the same mixture.

	C-01_01 1 min	**C-01_02** 0.1 min	**C-01_04** 1.5 min	**Total**
	41.0	50.5	45.5	
	41.5	50.0	45.5	
	41.5	50.0	46.0	
	41.5	49.0	42.0	
	42.0	49.5	45.5	
	46.0	48.5	44.5	
	42.0	49.5	45.0	
	41.0	49.5	43.5	
	39.0	49.0	44.5	
	41.0	49.5	45.5	
	42.0	50.5	44.5	
	41.0	50.0	43.0	
	40.0	51.5	45.5	
		51.0	45.5	
AVG	41.5	49.9	44.7	45.4
ST. DEV	1.59	0.82	1.16	4.22
c_v	3.8%	1.6%	2.6%	9.3%

Only a section of the secondary curve is averaged to ensure that only the part where concrete is steadily flowing is analyzed. These results show that within a given measurement of a mixture that the variance is very small with the largest coefficient of variation of 3.8%. However, between measurements the coefficient variation was larger at 9.3%. 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 8.5 psi (this is twice the standard deviation between the three mixtures) and the performance can be considered similar.

5.2.1.2 Average Pressure of the Secondary Curves

The pressure curves were variable depending on the concrete mixture but in most of the concrete mixtures a primary and secondary curve could be identified. To analyze these curves, the average pressures were evaluated between 40% and 90% of the secondary curve interval. An example of the pump curve section that was averaged can be seen on Figure 5-8. This section of the secondary curve was the most consistent in all cases and represents where the concrete is moving through the pipe. Here, the pressure line is flat. Typically, this was done over 15 to 20 pressure curves depending on the quality of the curves being analyzed. On occasion, when the concrete mixture was exhibiting low workability and thus less desirable pressure curves, analysis was done on as low as five consecutive curves because each curve had to be analyzed manually to find the proper interval to average. Also, at very low workability it became extremely difficult to locate consecutive curves that were able to be analyzed. In all cases, these measurements were typically made at 0, 15, and 30 minutes after pumping began. The averages of the individual pump curves were then averaged together and the total value was recorded as the required pressure to move concrete through the pump. The coefficient of variation was never greater than 4% in a pressure average. Table 5-3 shows the recorded pressure data at 1500 rpm for each mixture at each time interval.

When all results were compiled, 65 psi was a conservative estimate for when a concrete mixture became undesirable to pump. This is about a 20% 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 65 psi for Sensor 1 are highlighted. Events that caused the mixture to become unusable are highlighted in red to signify an unacceptable mixture.

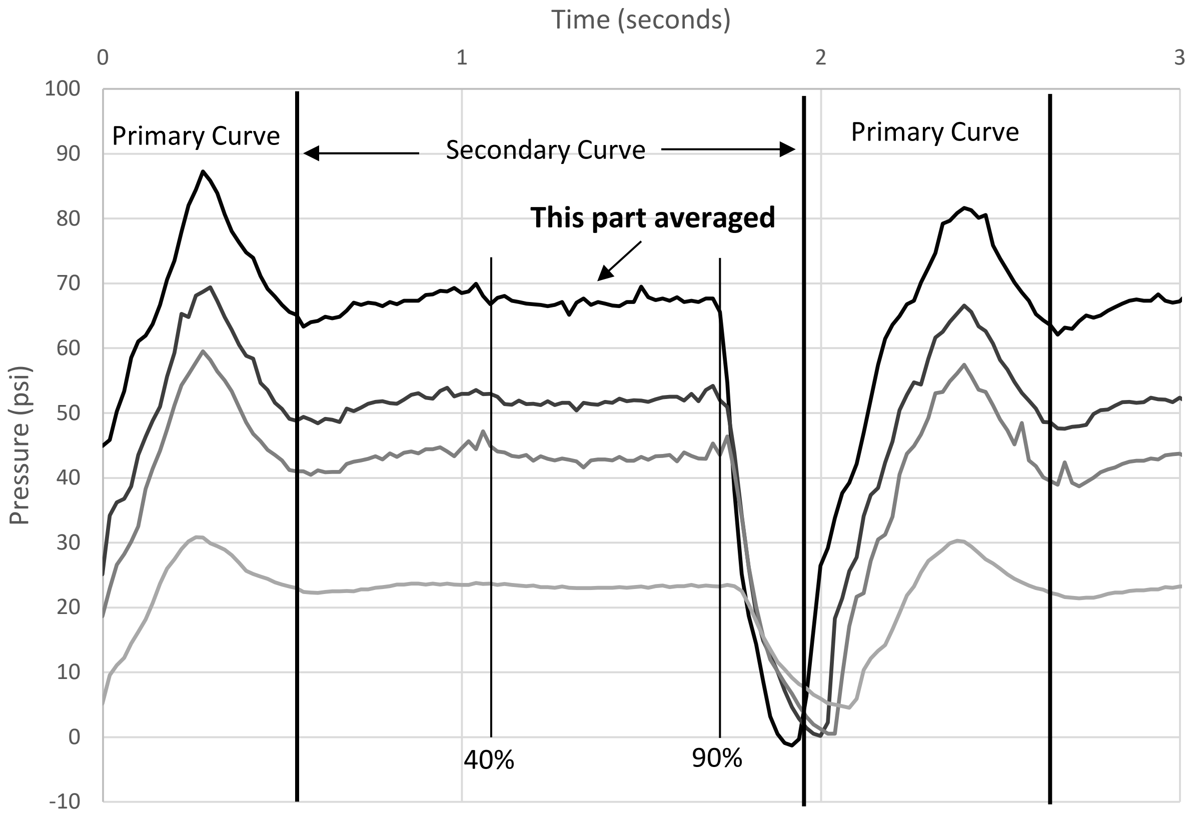


Figure 5-8: The average pressure was taken between 40% and 90% of the secondary curve.

Table 5-3 Sensor values at 1500 rpm. Mixture is undesirable if above 65 psi and is marked in orange. Events that entirely stopped pumping are marked in red.

		Time (min)	Sensor 1 (psi)	Sensor 2 (psi)	Sensor 3 (psi)	Sensor 4 (psi)	Comments
Coarse Agg Bounds	1/2" - 15.7%	0	45.0	39.5	26.5	23.0	
		35	57.0	51.5	37.0	31.5	
		45	64.5	56.5	42.0	35.5	
	1/2" = 20%	0	55.5	39.0	38.0	32.0	
		15	75.5	59.5	53.5	45.5	
	1/2" = 22%	0	52.5	43.5	35.5	30.5	
		15	74.0	62.0	53.0	45.5	Air Gaps
	1/2" = 25%	0	37.5	30.0	24.0	13.0	Segregation
		15	39.0	32.0	25.0	9.0	
		30	51.0	43.0	33.5	16.0	
		40	64.0	55.0	43.0	23.0	
Int Agg Bounds	#4 = 15.6%	0	45.0	39.5	26.5	23.0	
		35	57.0	51.5	37.0	31.5	
		45	64.5	56.5	42.0	35.5	
	#4 = 20%	0	58.0	45.5	38.5	30.5	
		15	71.5	56.5	49.0	33.5	
	#4 = 22%	0	48.0	38.0	31.5	24.5	
		15	65.5	53.0	45.5	36.0	Air Gaps
	#4 = 25%	0	51.0	41.5	33.0	18.5	
		15	51.5	43.5	34.0	19.0	
		30	73.5	62.5	49.0	30.5	
		40	92.0	80.0	65.0	43.5	
Fine Sand Bounds	FS = 24%	0	**Pipe Jam**				
	FS = 28%	0	59.0	46.5	38.0	23.5	
		15	66.5	52.5	43.5	27.0	
		30	82.0	68.5	59.0	37.0	
	FS = 32.5%	0	67.5	53.5	45.0	24.0	
		15	73.5	58.5	50.5	28.5	
		30	86.0	70.5	62.0	36.5	
	FS = 36.1%	0	**Sensor Error**	41.5	35.0	16.0	
		15		47.10	40.5	19.5	
		30		59.0	51.0	26.0	
	FS = 39.8%	0	45.0	39.5	26.5	23.0	
		35	57.0	51.5	37.0	31.5	
		45	64.5	56.5	42.0	35.5	
	FS = 44.6%	0	**Sensor Error**	54.5	49.0	27.0	
		10		52.5	45.0	24.5	
	FS = 56.5%	0	86.5	71.5	58.5	48.5	Unworkable

5.2.1.3 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 5-3. When the rpms were increased to 1500 rpm, the air gaps disappeared. It is interesting that both of these occurred when a significant amount of a certain aggregate size was used.

5.2.1.4 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 5-5 with the respective performance ratings in Table 5-4 from the previous chapter, shown below. In Table 5-5 and Table 5-6, an asterisk by a value means less than three measurements were able to be attained. If no acceptable data was able to be collected, n/c will be reported in the table.

Table 5-4 Classification of the workability of mixtures based on various tests in this report.

Workability Performance Scale for Each Test	Slump Test (in)	Visual Observation	ICAR Rheometer		
			Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)
Excellent (1)	8 to 6	A or 1	<1000	<250	<10
Good (2)	6 to 4	B or 2	1000-1500	250-500	10 to 15
Moderate (3)	4 to 2	C or 3	1500-2000	500-1000	15 to 20
Poor (4)	2 to 0	D or 4	>2000	>1000	>25
Unusable (5)	0	F or 5	Too stiff	Too Stiff	Too Stiff

Table 5-5 A summary of the rheometer, slump and pump rating for the mixtures investigated. The workability rating based on table 5-4 is also given.

	Time (min)	Static (Pa)		Dynamic (Pa)		Plastic Viscosity (Pa/s)		Slump (in.)	Pump Rating
1/2" = 15.7%	0	1210	B	382	B	12	B	7.25	
	35	1270	B	529	C	6	A	6.75	
	45	1500	C	701	C	4	A	4.25	
1/2" = 20%	0	2410	D	53.6	A	20	C	5.50	
	15	4250	D	484	B	38	D	2.50	
1/2" = 22%	0	880	A	177	A	16	C	8.00	
	15	1610	C	518	C	16	C	6.50	Air Gaps
1/2" = 25%	0	455	A	144	A	14	B	9.00	Segregation
	15	515	A	186	A	12	B	8.50	
	30	1070	B	408	C	9	A	6.50	
#4 = 15.6%	0	1206	B	382	B	12	B	7.25	
	35	1270	B	529	C	6	A	6.75	
	45	1500	C	702	C	4	A	4.25	
#4 = 20%	0	1200	B	229	A	28	D	5.50	
	15	3120	D					2.50	
#4 = 22%	0	1180	B	241	A	23	D	7.25	
	15	1640	C	551	C	14	B	4.50	Air Gaps
#4 = 25%	0	795	A	237	A	16	C	7.50	
	15	1100	B	369	B	11	B	4.00	
	30	4350	D	1070	D	9*	A	2.50	
FS = 24%	0	830	A	157	A	15	B	8.50	Segregation
FS = 28%	0	716	A	407	B	24	D	5.00	
	15	2850	D	734	C	15	B	3.75	
	30	4500	D					2.00	
FS = 32.5%	0	2750	D	485	B	33	D	4.50	
	15	3140	D	839	C	17*	C	3.50	
	30	4240	D	1130	D	25*	D	1.50	
FS = 36.1%	0	834	A	258	B	21	D	5.00	
	15	1420	B	540	C	15	C	4.50	
	30	3270	D	836	C	8*	A	2.50	
FS = 39.8%	0	1210	B	382	B	12	B	7.25	
	35	1270	B	529	C	6	A	6.75	
	45	1500	C	702	C	4	A	4.25	
FS = 44.6%	0	2440	D	628	C	21	D	4.00	
	10	3270	D	935	C	24*	D	2.00	
FS = 56.5%	0	4120	D	684	C	20	C	1.50	Unworkable
Times where pressure exceeded 65 psi are highlighted in orange. Events that stopped pumping are highlighted in red.									

Table 5-6: A summary of the rheometer, slump and pump rating for the different sack contents using a gradation well within the bounds of the tarantula curve.

	Time (min)	Static (Pa)		Dynamic (Pa)		Plastic Viscosity (Pa/s)		Slump (in.)	Pump Rating
6.5 Sacks	0	384	A	148	A	15	C	8.75	
	15	772	A	215	A	14	B	9.00	
	30	1120	B	404	B	9	A	6.50	
	45	2703	D	878	C	11	B	2.50	
6.0 Sacks	0	1482	B	363	B	25	D	5.25	
	15	1804	C	563	C	19	C	4.75	
	30	4308	D	1111	D	18	C	2.00	
5.5 Sacks	0	2279	D	389	B	68	D	3.00	Unworkable
Times where pressure exceeded 65 psi are highlighted in orange. Events that stopped pumping are highlighted in red.									

The 6.5 sack concrete mixtures produced acceptable values during pumping. This matches the paste content as the other mixtures in this report. A 6 sack concrete mixture of the same gradation also able to be pumped for about 15 minutes. The 5.5 sack mixture failed immediately.

In practice it seems feasible that a 6 sack mixture could be used as long as the gradation is within the bounds specified in the Tarantula Curve. In fact, there are many tools that could be used improve the pumping time of the mixture. These include: increasing the rpm of the pump, increasing the water reducer dosage, increasing the fly ash content. A 6 sack mixture is the lowest paste content recommended in the previous chapters based on the other workability tests. The pumping work confirmed this finding. It should be noted that when more paste is added to the concrete mixture then this would provide more room for error with gradation as well as increase pumping times. Ideally the performances of concrete mixtures with low paste contents that must be pumped would be evaluated in the field.

5.2.2 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 5-9.

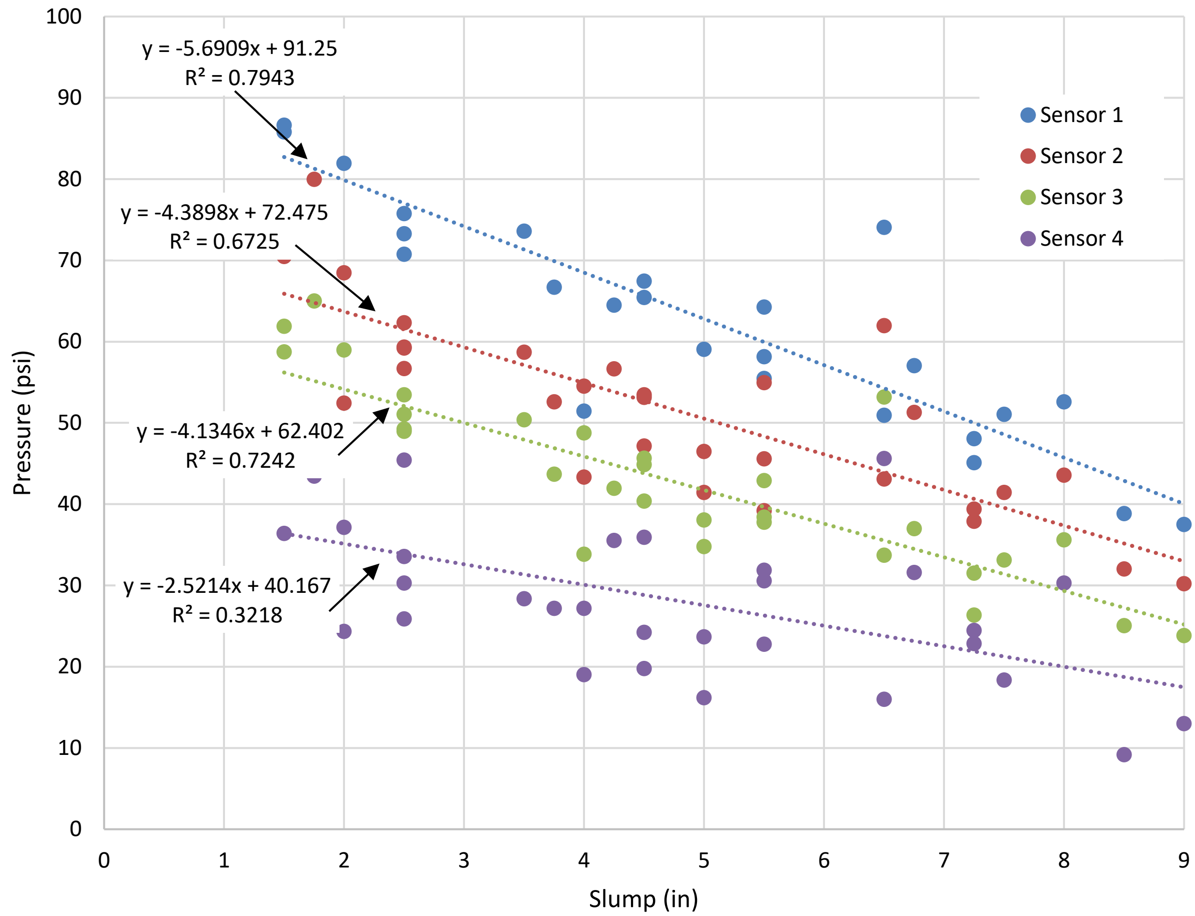


Figure 5-9: Pumping pressure versus slump.

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 90º, 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.

5.2.2 Pressure versus Rheometer Data

Figure 5-10, 5-11, 5-12, and 5-13 show the rheometer values for both static and dynamic stresses plotted against the pressure in each sensor along with lines of best fit.

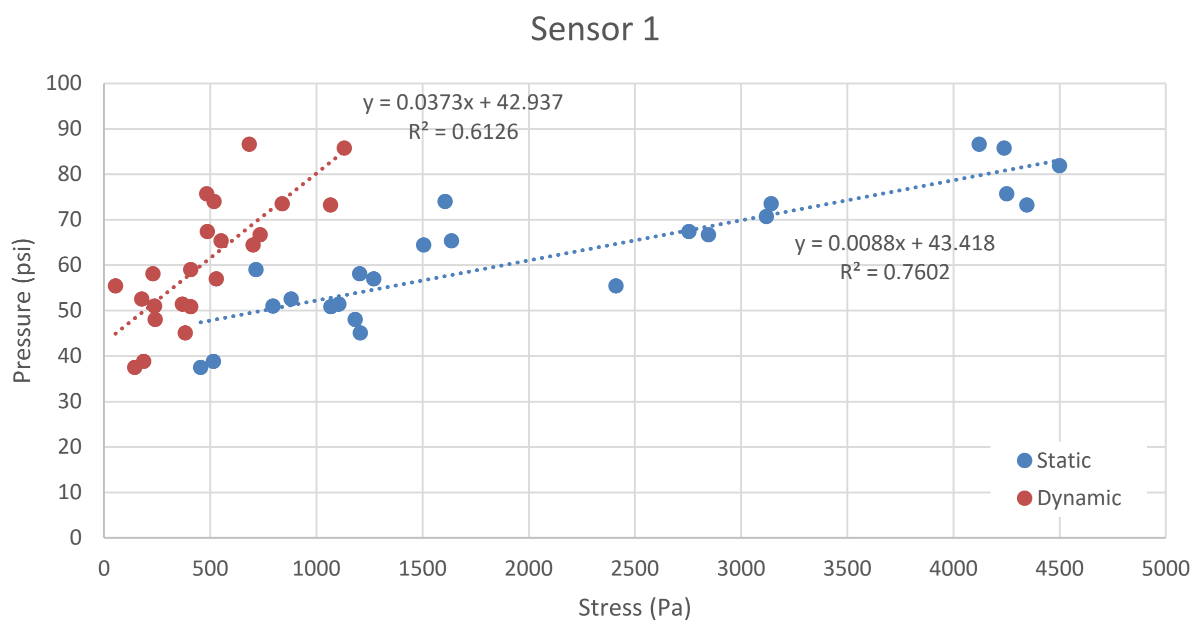


Figure 5-10: Pressure from Sensor 1 at 1500 rpm versus yield stress.

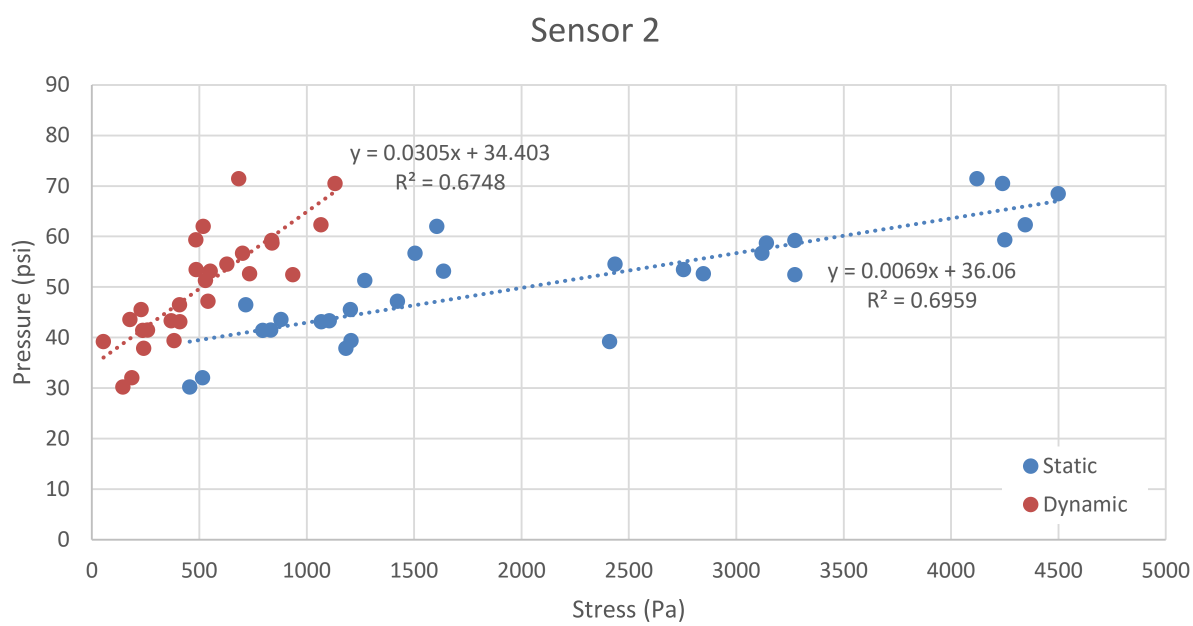


Figure 5-11: Pressure from Sensor 2 at 1500 rpm versus yield stress.

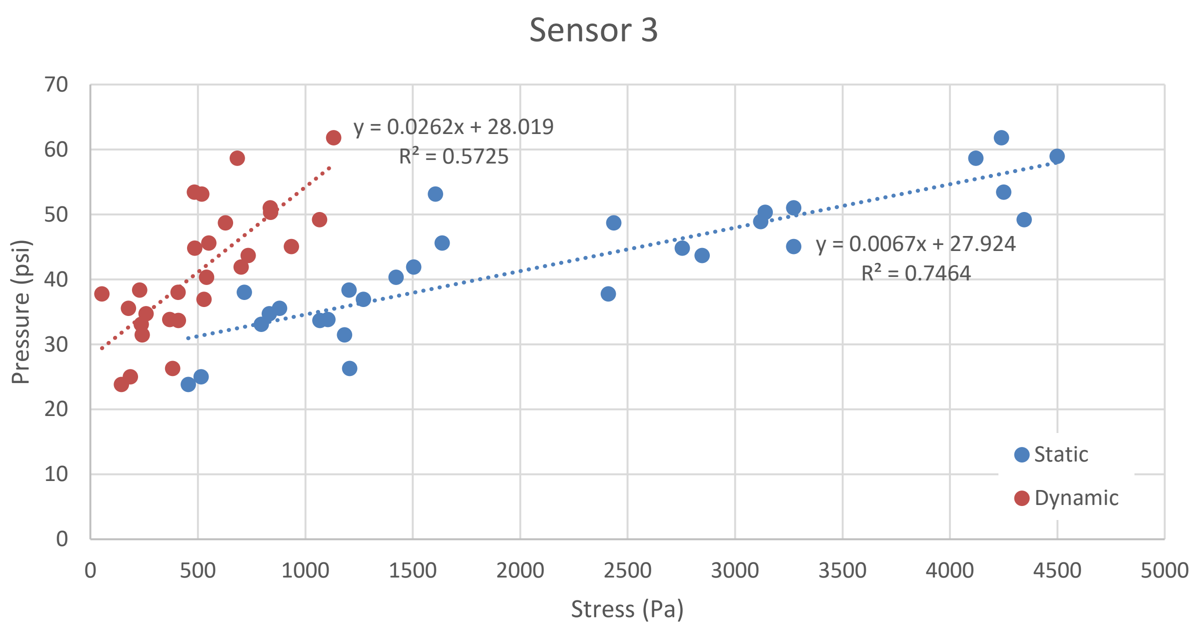


Figure 5-12: Pressure from Sensor 3 at 1500 rpm versus yield stress

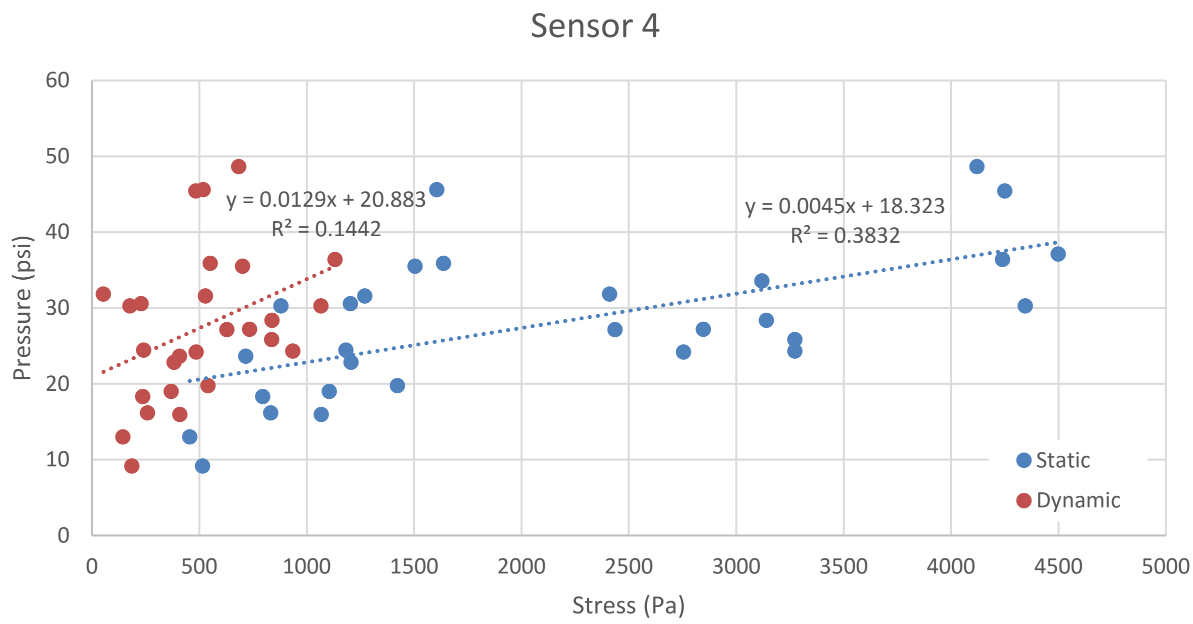


Figure 5-13: Pressure from Sensor 4 at 1500 rpm versus yield stress.

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 a good 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.

5.2.3 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.

Table 5-3 shows the Sensor 2 data for each mixture at 0 minutes and 1500 rpm with the corresponding percent retained curves. As shown in Figures 5-10, 5-11, 5-12, and 5-13, Both Sensors 1 and 2 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 sections: Coarse Aggregate, Intermediate Aggregate, and Fine Sands. The mixtures are separated like this to highlight the portion of the gradation that is being varied. Unacceptable performance are shown in red, mixtures with undesirable performance are shown in yellow, and mixtures with acceptable performance are shown in black.

5.2.3.1 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 5-14 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.

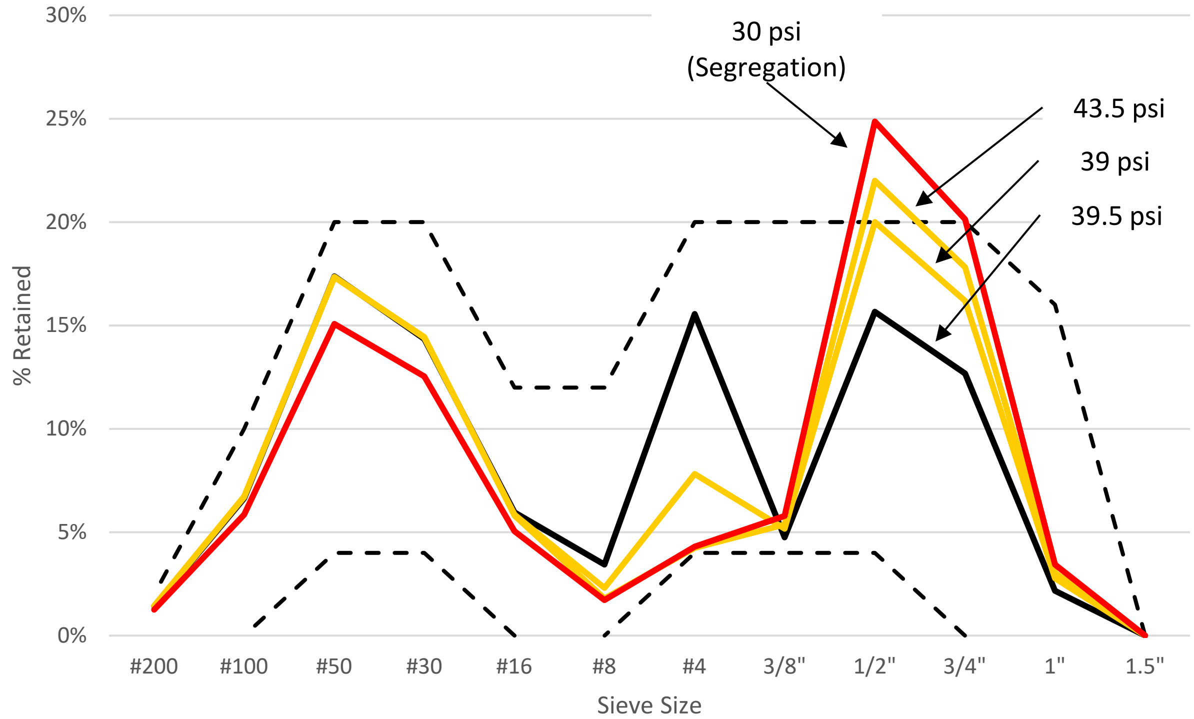


Figure 5-14 Sensor 2 pressures at 1500 rpm at 0 minutes per coarse gradation. Desirable gradations are in black, undesirable are in yellow, and unacceptable are in red.

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 5-14. An image of the mixture segregating is shown in Figure 5-15. 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. This observation of segregation matches those in previous chapters for this limit of the Tarantula Curve.

Figure 5-15 Coarse aggregate exiting the pipeline and showing segregation.

5.2.3.2 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 5-16 as well as their respective average pressure values from Sensor 2 at 0 minutes at 1500 rpm.

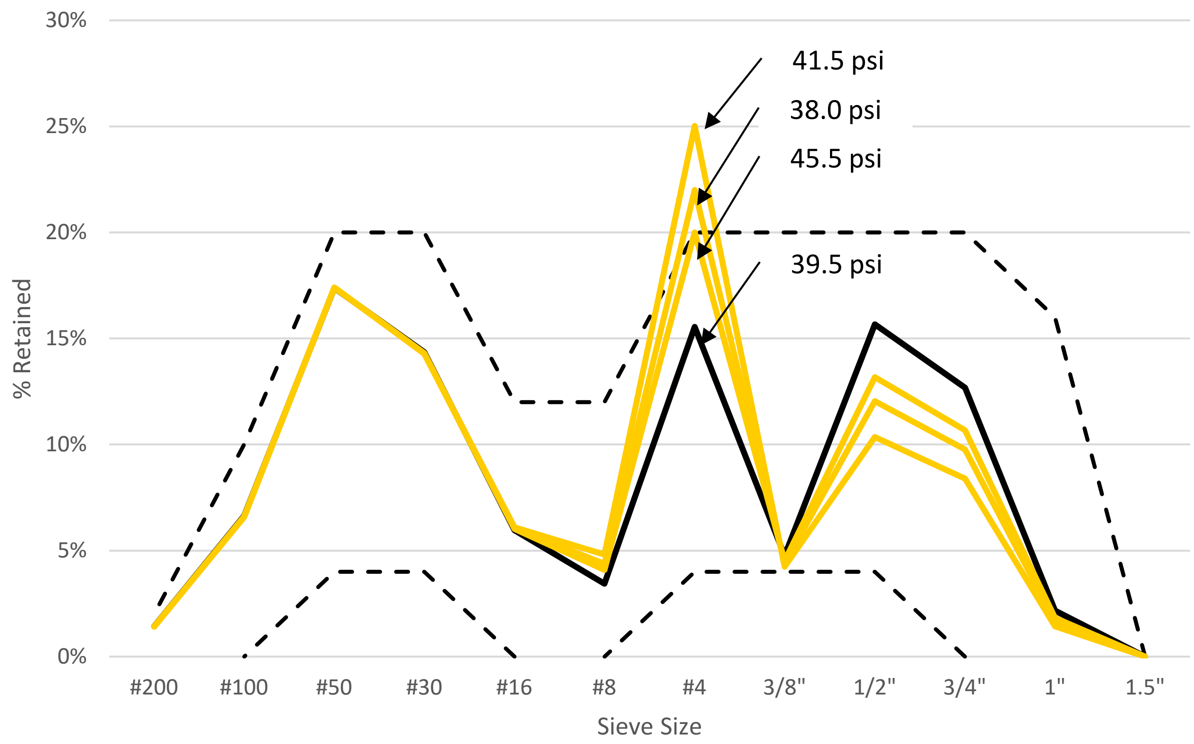


Figure 5-16 Sensor 2 pressures at 1500 rpm at 0 minutes per intermediate gradation. Desirable gradations are in black, undesirable are in yellow, and unacceptable are in red.

The greatest difference in pressure is 7.5 psi between the higher pressure at 20% of #4 and the lower pressure gradation at 22% of #4. This difference is very close-to 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.

5.2.3.3 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%. 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 5-17 below.

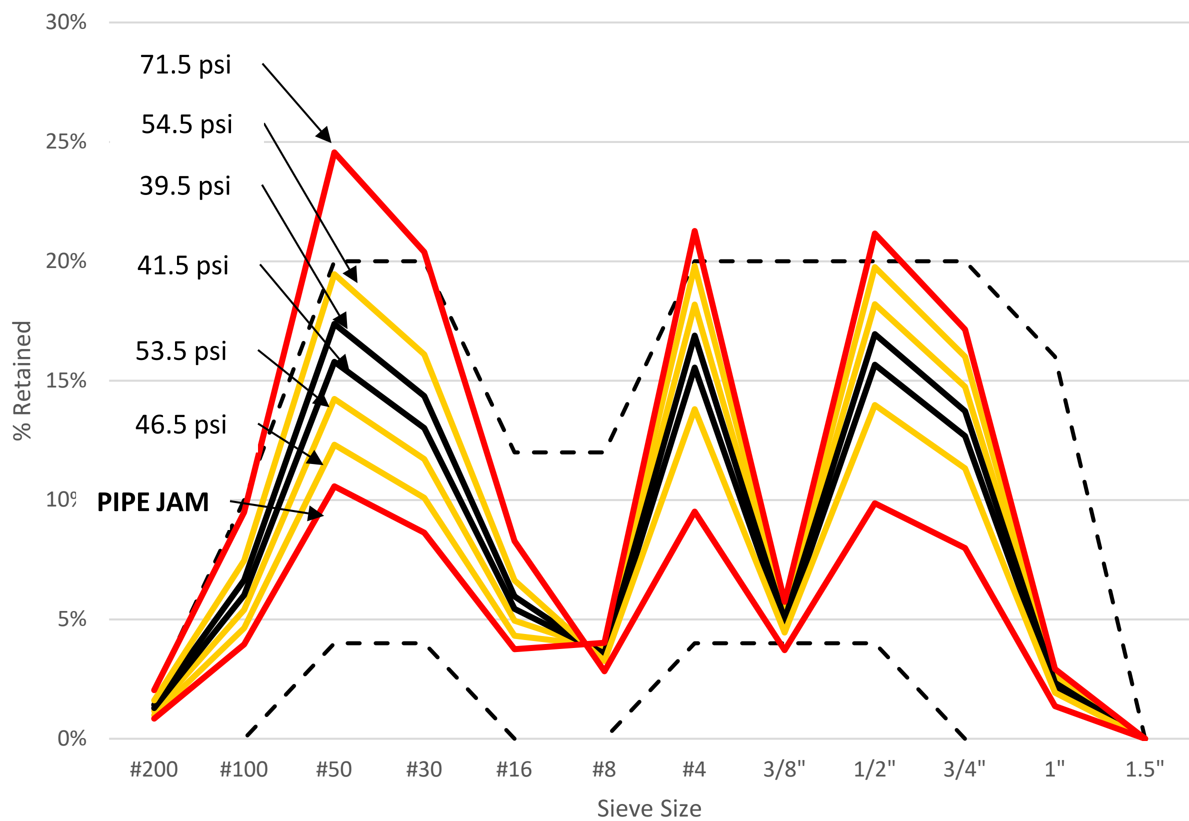


Figure 5-17 Sensor 2 pressures at 1500 rpm at 0 minutes per fine sand gradation. Desirable gradations are in black, undesirable are in yellow, and unacceptable are in red.

Two concrete mixtures are of major importance in these figures. The first is the 24% Fine Sand mixture. 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 cannot be pumped for long, only 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 81% higher than the mix that has a 39.5 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. Both the static and dynamic yield stresses received unacceptable values immediately after the pumping started

5.2.3.3.1 24% Fine Sand Mixture Design

In Table 5-5, 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 5-19 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 some aggregate fell out but the majority of the jamming rock remained until it was manually cleared out. See Figure 5-20 to see the jam in the pipeline.

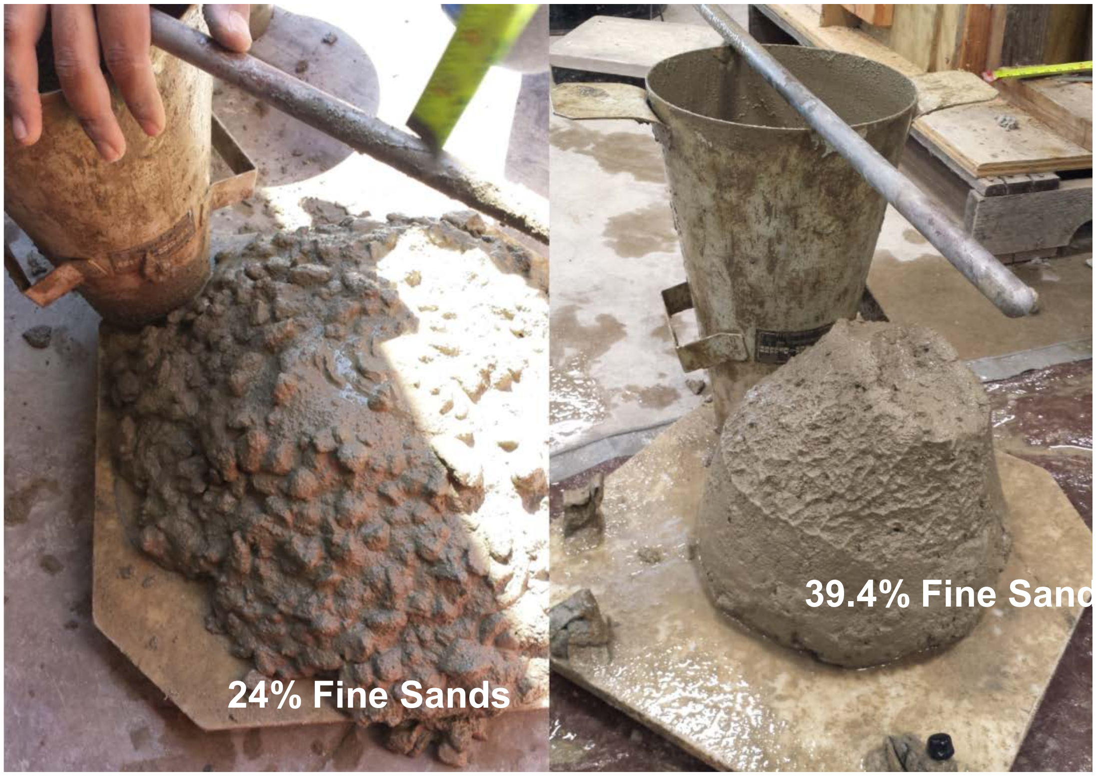


Figure 5-18 Concrete with 24% fine sands breaks apart when the Slump Test is conducted.

Figure 5-19: Concrete with 24% fine sands has insufficient mortar to move the aggregate, thus jamming the reducer.

After 14 piston cycles the rock had backed up all the way to the pistons, seizing the pump. See Figure 5-20 for an example of the pressure data while segregation occurred.

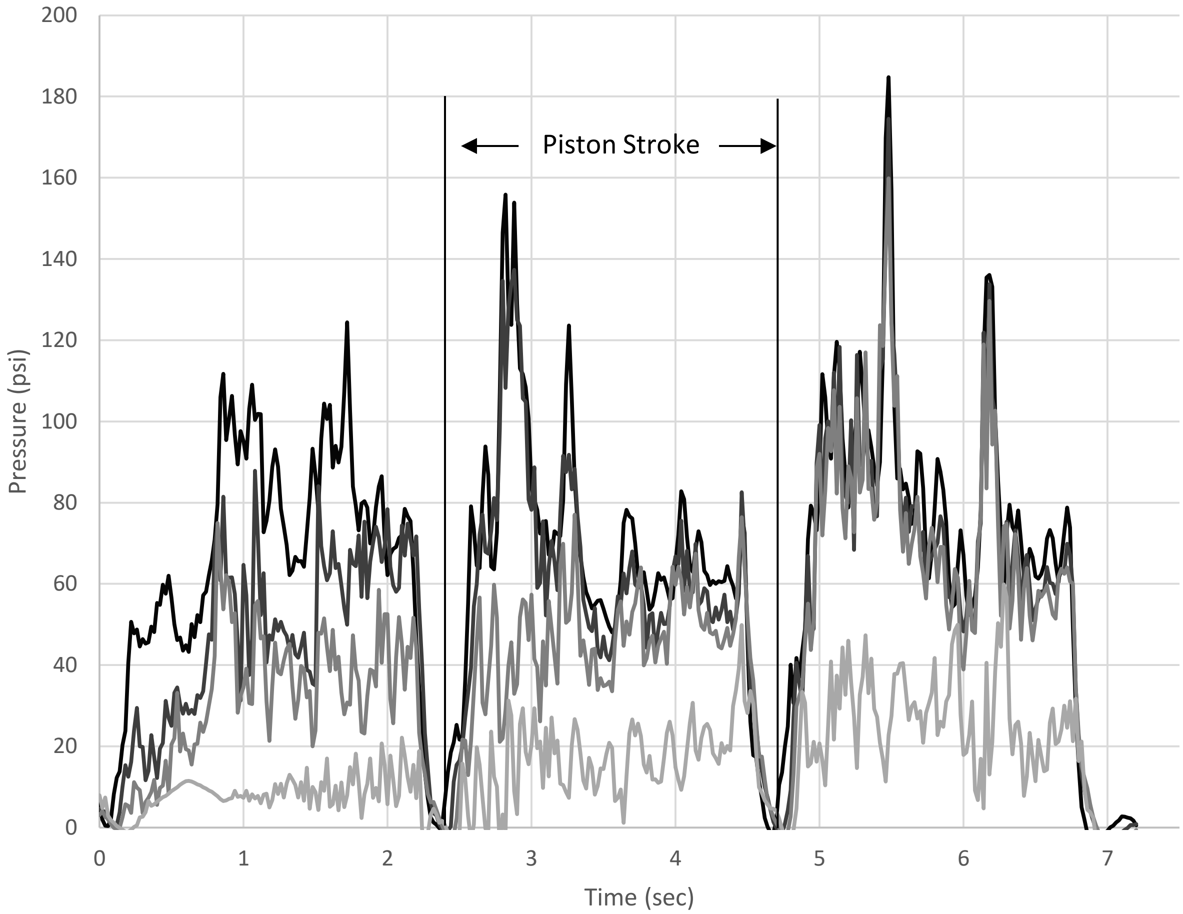


Figure 5-20: Segregation in the line causes erratic, unpredictable pressure curves.

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.

5.2.4 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 5-17 and

Figure 5-17, 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 plotted on Figures 5-21, 5-22, 5-23, and 5-24. 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.

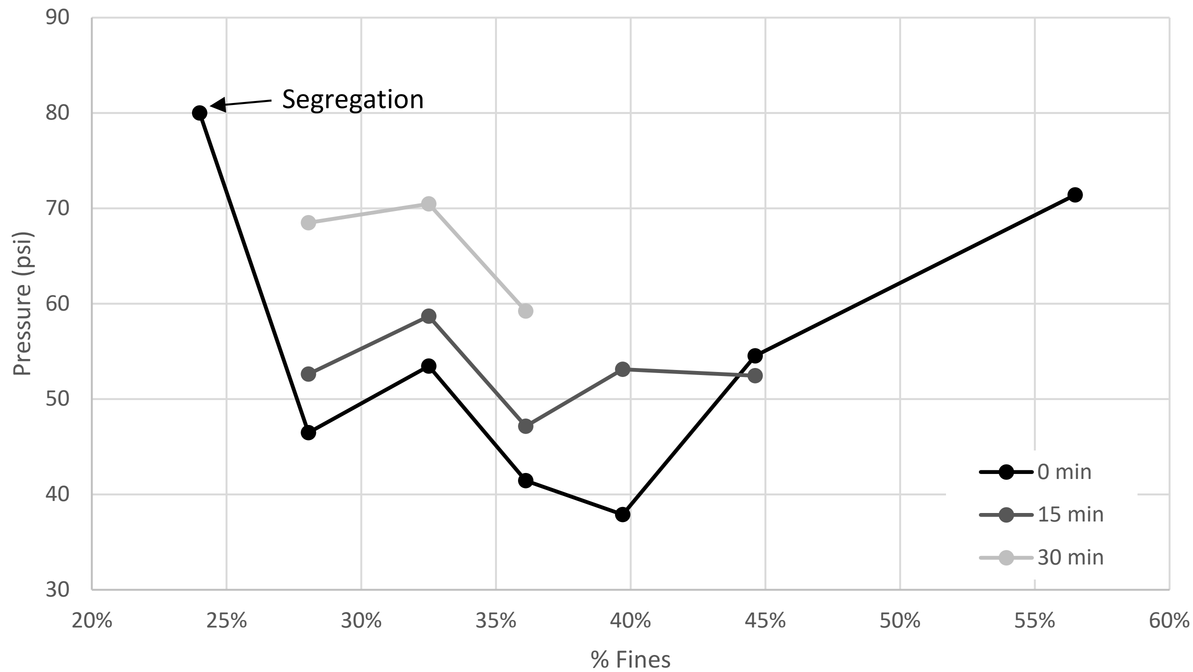


Figure 5-21 Pressure from Sensor 2 over time at 1500 rpm.

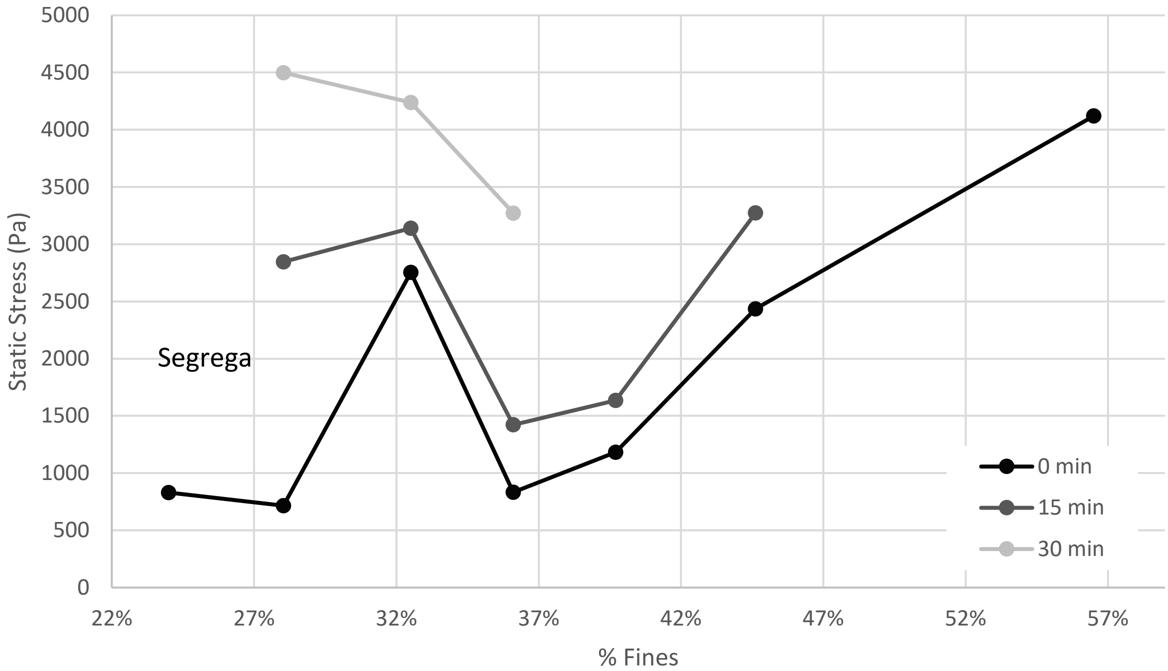


Figure 5-22 Static yield stress change over time at 1500 rpm.

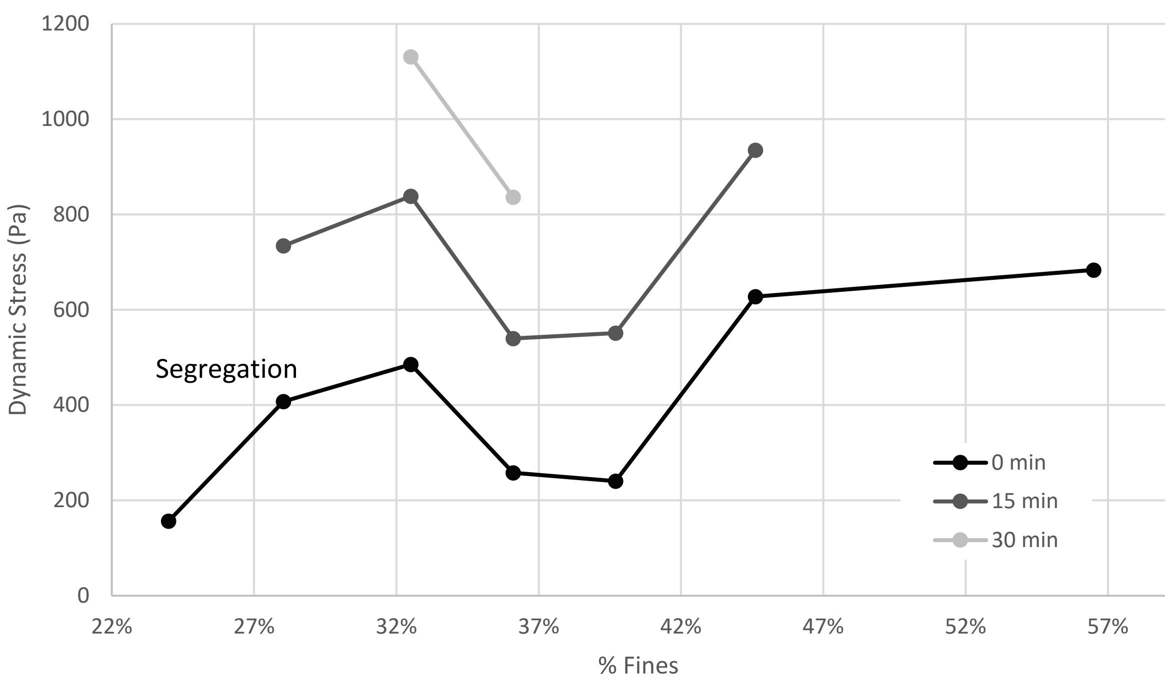


Figure 5-23 Dynamic yield stress change over time at 1500 rpm.

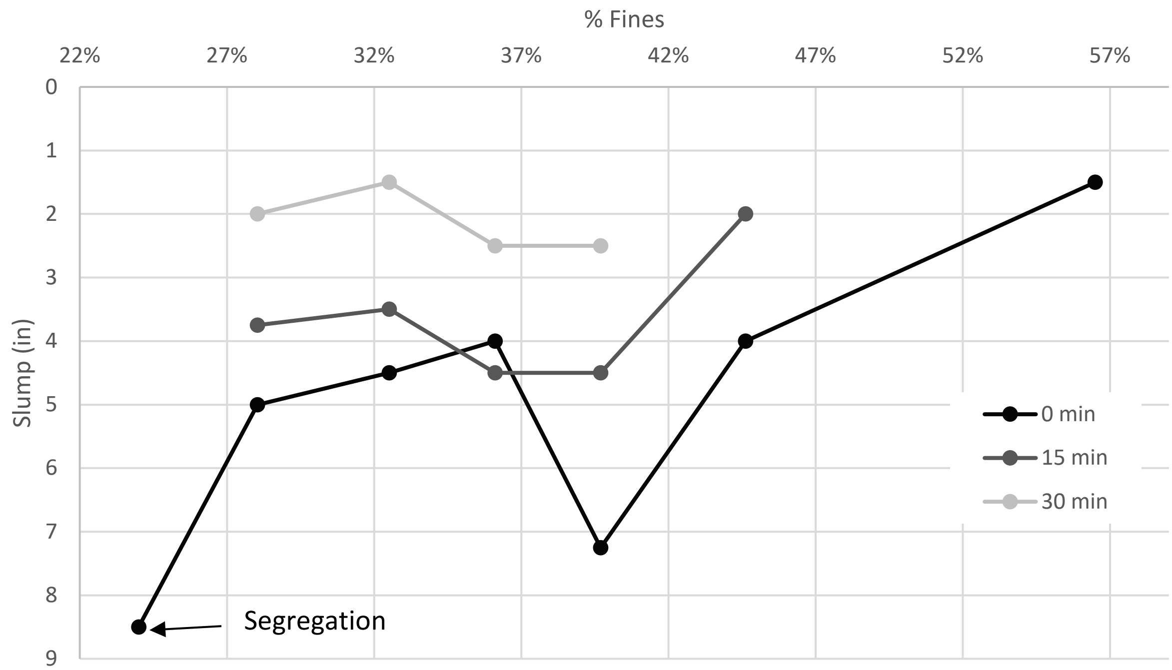


Figure 5-24 Slump decreases over time at 1500 rpm.

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.

5.2.4.1 Discussion of Fine Sand Range

Figure 5-25 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.

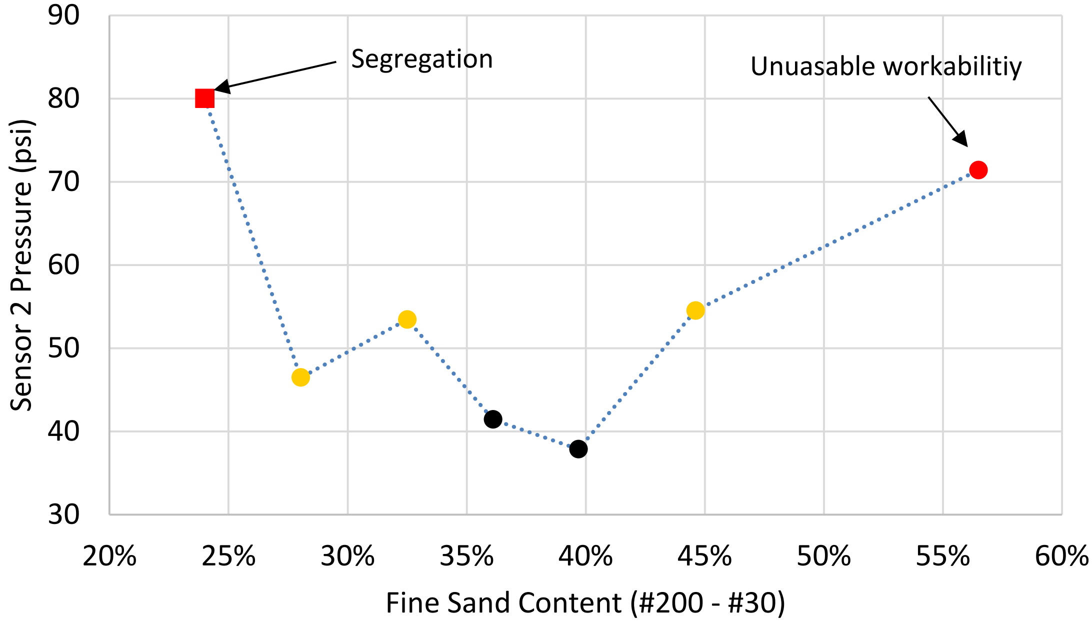


Figure 5-25: Sensor 2 pressures at 1500 rpm at 0 minutes with fine sand content show a range of pumpability. Desirable contents are in black, undesirable are in yellow, and unacceptable are in red.

Note that this curve looks extremely similar to Figure 4-7 in the previous chapter and has been shown again below in Figure 5-26. 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 5-25, the percent of Fine Sand content marked undesirable in yellow follows closely with Moderate Overall Performance shown in figure 5-26. This remains true for those mixes deemed unacceptable, both from segregation and poor workability. Those percent Fine Sand content, 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 used 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.

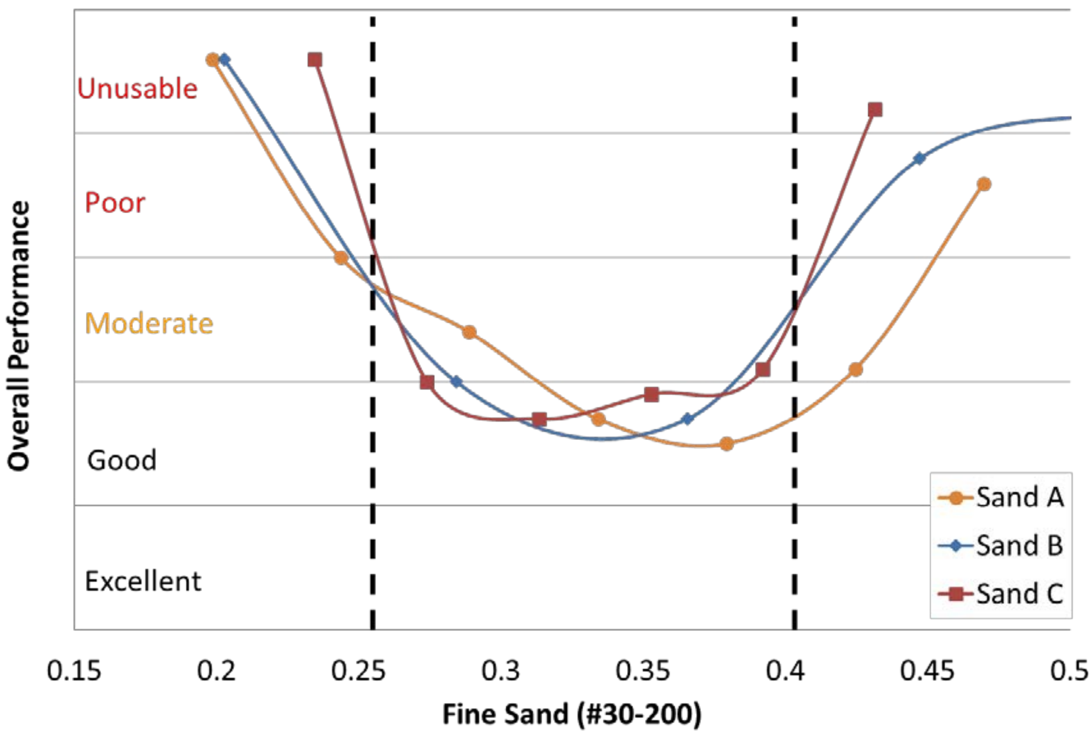


Figure 5-26: The Overall Performance of concrete mixtures with three different sands versus the amount of fine sand in the mixture. Sand A is slightly shifted to the right. The results from Sand in the pumping test gives a similar result.

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 discussed earlier. The reader should be reminded that the sack content for each mixture is 6.5 sacks, not 6 sacks as was previously used in other parts of this document. But with the 6.5 sack content similar limits were 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 causing the mixture to become too stiff. Mixes with total fine sands less than 28% may have lower yield stresses and pressures but segregation within the concrete make it not usable.

5.3 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 aggregate together so it is not left behind in 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 still 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 90º bend.
- The pumping pressures after the second 90º bend (sensor 4) 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 6 – RECOMMENDED AGGREGATE GRADATIONS FOR FLOWABLE CONCRETE

By using a combination of performance during pumping, rheometer measurements, visual observations, finishability tests, and Slump the desirable gradations for flowable concrete was determined for the materials and mixtures investigated. The culmination of these efforts suggest that the bounds of the Tarantula Curve provide a practical range for coarse, and intermediate aggregates and coarse and fine sand create a flowable concrete that is also pumpable. This is summarized in Figure 6-1.

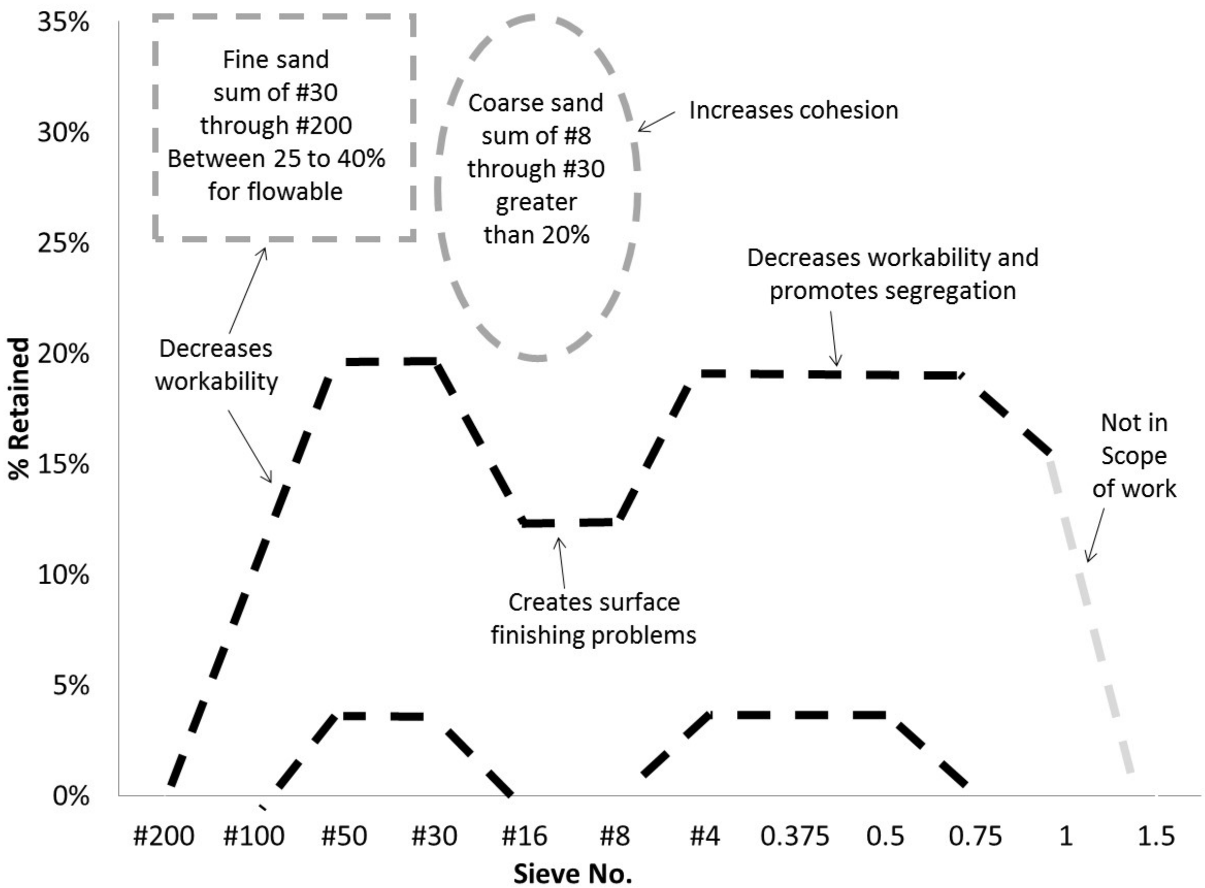


Figure 6-1: An overview of the recommended aggregate gradation limits known as the Tarantula Curve.

In addition to the gradation, it is recommended that the slump of the concrete mixture should be at least 4 in. The authors feel that it is necessary to propose these gradation limits because the workability tests were not able to examine all important aspects of the performance of the mixture design. For example, the Slump Test does not measure the surface finishability of the mixture, or the amount of segregation that occurs. While tests and measurement methods were found in this study that can observe these phenomenon, they are not practical to regularly run in the field.

It also should be noted that as these proposed boundaries are met or broken, the potential for either an undesirable or failing concrete mixture greatly increases. The Tarantula Curve and the fine sand and coarse sand limits provide a conservative range for proportioning the aggregate for flowable concrete. By using these criteria then it can allow reductions in cement, water, admixtures, or all three of these in a mixture. This will help improve sustainability, economy, and long term durability of flowable concrete.

It should be noted, that three different sand sources were investigated in this study and Sand A had a different performance than the other two. This could be caused by the shape or texture of the sand. However, the suggested bounds were chosen to still provide a safe recommendation regardless of the aggregate sources investigated.

The researchers suggest that ODOT consider dropping the total cementitious content of concrete mixtures for structural concrete to 6 sacks. In cases where the concrete does not need to be pumped then it may be further dropped to 5.5 sacks. These changes have the ability to create significant savings. Personal communications from ODOT suggest that approximately based on a three year average that 676,000 CY of structural concrete is placed in each year. If a 0.5 sack of cement is reduced for each of these mixtures, then the savings would be $1.5 million each year. Additional cost savings will also be realized through reduced maintenance and longer performance of these structures. In addition there will be significant energy savings from the reduction in cement usage. The estimated energy savings each year is 59 billion BTUs each year. This is enough to power approximately 440 homes in Oklahoma each year.

CHAPTER 7 – CONCLUSION

This report has provided a summary of the work completed to date on ODOT project 2160 “Investigation of Optimize Graded Concrete for Oklahoma Phase II”. Based on the data collected using four different workability evaluation techniques, the following have been found:

- If a single sieve size of the coarse aggregate (#4 and larger) retained more than 20%, the workability performance of the concrete would tend to decrease and segregation would increase.
- Unless a sieve size retains more than 20%, a large range of gradations can be used without drastically impacting the workability of the concrete.
- Deficient amounts of a single sieve size or consecutively adjacent sieve sieves did not affect the workability of the concrete until a sieve size retained above 20%.
- Ideal bell shaped curve created surface finishability issues and is not recommended in practice.
- The maximum aggregate size did not have a major effect on the workability. However, the maximum aggregate size can help reduce the high amounts on a single sieve size by increasing the number of sieves used.
- Coarse sand (#8 through #30) was shown to impact the cohesion of the mixture.
- A minimum value of 20% was suggested to be retained on the coarse sand (#8 through #30).
- Surface finishability issues could be created with gradations retaining over 12% on the #16 and #8 and also 20% of #30.

- Fine sand (#30 through #200) volume was recommend to range from 25% to 40% of the combined gradation.
- 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 correlation 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 90º bend.
- 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 mixture that would be too stiff to pump, especially for long periods of time.
- Implementing the recommendations in this report has the potential to save the state of Oklahoma over $1.5 million and enough energy to power 440 Oklahoma homes each year that it is implemented.

REFERENCES

Abrams, D. (1918). “Design of Concrete Mixtures.” *Structural Materials Research Laboratory*, Bulletin 1. Lewis Institute. Chicago, IL.

Abrams, D. (1922). “Proportioning Concrete Mixtures.” ACI Journal Proceedings. (18) 2., 174-181.

ACI (American Concrete Institute). (1991). “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.” *ACI 211-91*. American Concrete Institute. Farmington Hills, MI.

ACI (American Concrete Institute). (2004). “Guide for Concrete Floor and Slab Construction.” *ACI 302.1R-04*. American Concrete Institute. Farmington Hills, MI.

Anson-Cartwright, M. (2011). “Optimization of Aggregate Gradation Combinations to Improve Concrete Sustainability.” Thesis in Civil Engineering, University of Toronto.

ASTM (American Standard Testing Method). (2010). “Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate.” *ASTM D4791.* West Conshohocken, PA.

ASTM (American Standard Testing Method). (2012). “Standard Test Method for Slump of Hydraulic Cement Concrete.” *ASTM C143.* West Conshohocken, PA.

ASTM (American Standard Testing Method). (2012). “Standard Specification for Portland Cement.” *ASTM C 150.* West Conshohocken, PA.

ASTM (American Standard Testing Method). (2005). “Standard Specification for Chemical Admixtures for Concrete.” *ASTM C 494*. West Conshohocken, PA.

ASTM (American Standard Testing Method). (2013). “Standard Specification for Concrete Aggregates.” *ASTM C 33.* West Conshohocken, PA.

ASTM (American Standard Testing Methods). (2009). “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate.” ASTM C 29. West Conshohocken, PA.

Barnes, HA. (2000) “A Handbook of Elementary Rheology.” University of Wales. Institute of Non-Newtonian Fluid Mechanics. Aberystwyth, Wales.

Collins, TC, Panarese, WC, Bradley, BJ. (2006) “Concrete Finisher’s Guide.” Portland Cement Association. Skokie, Illinois.

Cook, M. (2013). “Optimized Graded Concrete for Slip Formed Paving.” Thesis in Civil and Environmental Engineering, Oklahoma State University. Stillwater, OK.

Cook, D., Ghaeezadah, A., Ley, T. (2013). “Investigation of Optimized Graded Concrete for Oklahoma.” OTCREOS11.1-39. Oklahoma Transportation Center. Midwest City, OK.

Cook, D., Ghaeezadah, A., Ley, T, Russell, B. (2013). “Investigation of Optimized Graded Concrete for Oklahoma- Phase 1.” Oklahoma Department of Transportation. Oklahoma City, OK.

Cook, D., and Ley, T. <http://www.optimizedgraded.com/> (July 30, 2015).
Cook, D., Ghaeezadah, A., Ley, T. (2014). “A Workability Test for Slip Formed Concrete Pavements.” *Construction and Building* Materials. 68. Elsevier. 376-383.

Day, K. (2006). “Concrete Mix Design, Quality Control and Specifications." 3rd ed. E & FN Spon. London, UK.

de Larrard, F. (1999). “Concrete Mixture Proportioning: A Scientific Approach.” E & FN Spon. London, UK.

Dewar, J. (1999). “Computer Modeling of Concrete Mixtures.” E & FN Spon. London, UK.

Edwards, L. (1918). “Proportioning of Mortars and Concretes by Surface Area of Aggregates.” ASTM Proceedings. ASTM. 235-283.

Fuller, W., and Thompson, S. (1907). “The Laws of Proportioning Concrete.” Transactions of ASCE. New York, NY.

Ghaeezadeh, A. (2014). “Aggregate Assessment and Durability Evaluation of Optimized Graded Concrete in the State of Oklahoma.” Thesis in Civil and Environmental Engineering, Oklahoma State University. Stillwater, OK.

Goldbeck, A., and Grey, J. (1968). “Method for Proportioning Concrete for Compressive, Strength, Durability, and Workability.” Bulletin 11. *National Crushed Stone Association.* Washington, DC.

Goltermann, P., Johansen, V., Palbol, L. (1997). “Packing of Aggregates: An Alternative Tool to Determine the Optimal Aggregate Mix.” *ACI Materials Journal.* 94 (5). Farmington Hills, MI. 435-443.

Harrison, P. (2004). “For the Ideal Slab-on-Gradation Mixture.” *Concrete International*. ACI Farmington Hills, MI. 49-55.

Jones, M., Zheng, L., Newlands, M. (2002). “Comparison of Particle Packing Models for Proportioning Concrete Constituents for Minimum Void Ratio.” *Materials and Structures,* 35 (249). 301-309.

Koehler, E. and Fowler, D. (2007). "Aggregates in Self-Consolidating Concrete." Report 108-2F. International Center of Aggregate Research. Austin, TX.

Kosmatka, S., and Wilson, M. (2011). "Design and Control of Concrete Mixtures." 15th ed. Portland Cement Association. Stokie, Illinois.

Ley, M.T., Cook, D., Fick, G. (2012). "Concrete Pavement Mixture Design and Analysis (MDA): Effect of Aggregate Systems on Concrete Mixture Properties." National Concrete Pavement Technology Center. Iowa.

Mehta, P., and Monteiro, P. (2006). "Concrete Microstructure, Properties, and Materials." 3rd ed. McGraw-Hill. New York, NY.

National Stone, Sand, and Gravel Association. (2013). "The Aggregates Handbook." 2nd ed. Sheridan Books, Inc. Alexandria, Virginia.

Neville, A. (2012). "Properties of Concrete." 5th ed. Prentice Hall. San Francisco, CA.

Obla, K., and Kim, H. (2008). "On Aggregate Grading." *Concrete International*. ACI. Farmington Hills, MI. 45-50.

Powers, T.C. (1932). "Studies of Workability of Concrete." *Journal of American Concrete Institute Proceeding*. 28. ACI, 418-448.

Powers, T.C. (1968). "The Properties of Fresh Concrete." John Wiley & Sons, Inc. New York, NY.

Shilstone, J. (1990). "Concrete Mixture Optimization." *Concrete International*. 12 (6). ACI Farmington Hills, MI. 33-39.

Shilstone, J. (1989). "A Hard Look at Concrete." *Civil Engineering*, 59(1). 47-49.

Shilstone, J. (1991). "Performance Specifications for Concrete Pavements." *Concrete International*. 13 (12). ACI. Farmington Hills, MI. 28-34.

Richardson, D. (2005). "Aggregate Gradation Optimization- Literature Search." RDT 05-001. Missouri Department of Transport. Jefferson, Missouri.

Rached, M., Moya, M., Fowler D. (2007). "Utilizing Aggregates Characteristics to Minimize Cement Content in Portland Cement Concrete." Report 401. International Center of Aggregate Research. Austin, TX.

Roussel, N. (2012) "Understanding the Rheology of Concrete." Woodhead Publishing. Cambridge, England.

Talbot, A., and Richart, F. (1923). "The Strength of Concrete, Its Relation to the Cement Aggregates and Water." Engineering Experiment Station. Bulletin 137. University of Illinois. Urbana, IL.

Taylor, P., Hosmatka, S., Voigt, G., Brink, M., Harrington, D., Grove, J, et al. (2007). "Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual", 2nd reprint. FHWA-HIF-07-004. FHWA. Washington, DC.

The Contractor's Guide to Quality Concrete Construction. (2005) 3rd edition. American Concrete Institute. Farmington Hills, MI.

The Transtec Group, Inc. (2004). "Concrete Mixture Performance Analysis System." (Computer software). Version 1.00.0022. Austin, TX.

Wong, S., Alexander, M., Haskins, R., Pool, T., Maloone, P., Wakeley, L. (2001). "Portland-Cement Concrete Rheology and Workability: Final Report." FHWA-RD-00-025. FHWA. Washington, DC.

APPENDIX

PROPOSED OKLAHOMA DEPARTMENT OF TRANSPORTATION SPECIAL PROVISIONS FOR OPTIMIZED GRADED CONCRETE IN STRUCTURAL APPLICATIONS

MIX DESIGN AND PROPORTIONING

If the contractor provides a concrete mixture meeting the specifications of optimized graded concrete for structural applications (OGCSA) such as a bridge deck, the minimum cementitious content may be reduced to 564 lbs./yd^3 [335 kg/m^3].

Specification

To meet the optimized graded concrete pavement provision criteria, the batch weights, individual aggregate sieve analysis, SSD specific gravities of the aggregates, and other material information will be inputted into the OGCSA spreadsheet. This spreadsheet can be found here. The OGCSA spreadsheet will evaluate the following requirements:

- The combined gradation must be within the boundary limits for each sieve size.
- The total volume of fine sand (#30-200) must be within 25% and 40% of the aggregate content used.
- The total volume of coarse sand (#8-#30) must be 20% or greater.
- Limit the flat or elongated coarse aggregate to 15% or less at a ratio of 1:3 according to ASTM D4791.

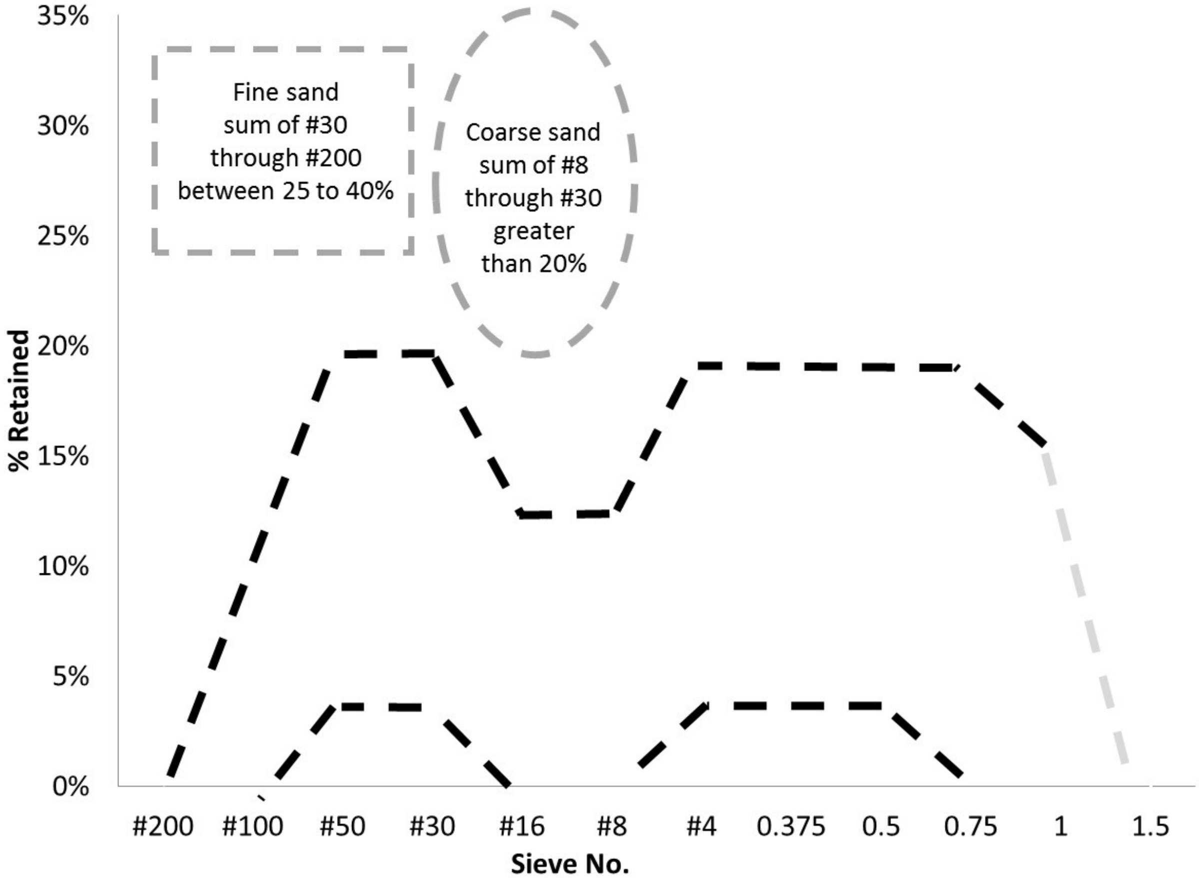


Figure A1 The limits for the minimum and maximum boundary limits.

Gradation Tolerance

Make necessary adjustments to individual aggregate stockpile proportions during the concrete production to ensure the gradation stays within ODOT requirements. If this is not possible then the minimum cementitious content in the mixture shall be increased to 611 lbs./yd^3 (363 kg/m^3).