INVESTIGATION OF OPTIMIZE GRADED CONCRETE FOR OKLAHOMA - PHASE 1

FINAL REPORT-FHWA-OK-13-12
ODOT SP&R ITEM NUMBER 2160

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October, 2013

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. **FHWA-OK-13-12**	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT=S CATALOG NO.
4. TITLE AND SUBTITLE **Investigation of Optimized Graded Concrete for Oklahoma- Phase 1**		5. REPORT DATE **October 2013** 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) **Marllon D. Cook, Ashkan Ghaeezadeh, 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 2160**
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 2011 – October 2013** 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Optimized Graded Concrete has been a subject widely discussed through the history of concrete. Since aggregates make up over 70% of the volume in a mixture, gradation is critical to the strength, workability, and durability of concrete. In practice only a small quantitative guidance can be 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 the impracticality. 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 have been able to provide quantitative data about the workability of concrete. This work focused on creating a practical test method and using it to better understand the aggregate gradation impacts on the workability of concrete.

In this report a new workability test for concrete was developed to investigate mixtures for slip formed pavements. This was done by creating a test called the “Box Test” in Chapter 2. The Box Test was then used to evaluate several existing optimized graded design methods in Chapter 3. After finding some shortcomings in the current methods, Chapter 4 develops a new set of design recommendations and specifications. Finally, Chapter 5 investigates the durability of the optimized graded mixtures in freeze thaw and shrinkage testing.

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 2013 production this design method has the potential to save the state of Oklahoma over $4 million per year and long term costs through reduced maintenance from durability issues and the reduced amount of cement paste needed to make satisfactory mixtures.

17. KEY WORDS **Optimized Graded Concrete, Aggregate Gradation**	18. DISTRIBUTION STATEMENT **No restrictions. This publication is available from the Planning & Research Division, Oklahoma DOT.**		
19. SECURITY CLASSIF. (OF THIS REPORT) **Unclassified**	20. SECURITY CLASSIF. (OF THIS PAGE) **Unclassified**	21. NO. OF PAGES	22. PRICE **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)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
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)

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CHAPTER 1 - INTRODUCTION

Optimized Graded Concrete is a subject that has been widely discussed throughout the history of concrete. It has been realized by many that the aggregate volume and gradation is critical to the strength, workability, and durability of concrete as it makes up over 70% of the mixture. However, there is little quantitative guidance to practitioners on how the aggregates in mixtures should be proportioned to obtain the desired performance. In fact the ACI 201 Mixture Design Procedure, the most widely taught mixture design method, is not widely used in practice because the method does not provide practical recommendations. The method only contains a handful of aggregate parameters and many argue about their validity. One reason that more progress has not been made is that there are few test methods that are able to provide quantitative data about the workability of concrete. This work focused on creating such a method and then using it to better understand how aggregate gradation impacts concrete workability.

In this report a new workability test for concrete is developed to investigate mixtures for slip formed pavements. This was done by creating a test called the “Box Test” in Chapter 2. This test is then used to evaluate several existing optimized graded design methods in Chapter 3. After finding some shortcomings in the current methods, a new set of design recommendations and specifications are presented in Chapter 4. Finally, in Chapter 5 the durability of these mixtures in freeze thaw and shrinkage testing is investigated.

The ultimate product of this work is a new specification in the state of Oklahoma for mixtures with a greater durability at reduced cost and with improved sustainability.

This work has the potential to save the state of Oklahoma over $4 million based on 2013 pavement concrete volume and prices. Furthermore, there will be substantial long term costs through reduced maintenance from durability issues and the reduced amount of cement paste needed to make satisfactory mixtures.

CHAPTER 2 - THE BOX TEST

2.1 INTRODUCTION

The current practice for a concrete mixture is to require relevant strength and durability specifications, while also providing sufficient workability for the desired application. Producing a concrete mixture that meets all of these requirements can be elusive and highly iterative (ACI 309, 2008). Although tests exist to evaluate the strength and durability of a mixture, only a few reliable tests can evaluate the workability.

The workability of a mixture is a combination of the paste volume and yield stress, aggregate characteristics, and aggregate gradation. While each of these variables is known to be important, no tool exists that allows a quantitative impact of these variables for concrete pavements. When mixtures do not possess sufficient workability, it is common to increase the cement and water content of the mixture. This can increase cost and decrease the sustainability and durability of the concrete (Taylor et al. 2007).

A concrete mixture for a slip formed pavement must be stiff enough to hold an edge after leaving the paver, but workable enough to be consolidated. To fulfill the need in the concrete pavement industry for a reliable slip formed pavement workability test, this chapter presents a simple and economical test method that attempts to evaluate the vibratory response of a concrete mixture and subsequently hold a vertical edge under its weight.

2.1.1 CURRENT LABORATORY TESTS FOR THE WORKABILITY OF CONCRETE

Historically, the workability of a concrete mixture was determined by experience. Multiple laboratory tests have been created to measure workability (Taylor et al. 2007, Powers 1968, Wong et al. 2001, Fulton 1961, ASTM C143 2012, ASTM C1621 2009) but none are applicable for slip formed paving. The goal of a workability test should be to provide a standard measurement that evaluates the performance of a mixture in the desired application.

While the Slump Test (ASTM C143) has been widely used as a specification to evaluate workability, it is not useful for mixtures with low flowability (Taylor et al. 2007, Powers 1968). 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). The Remolding Test (Powers 1968), Vebe Apparatus Test (Wong et al. 2001) and other similar vibratory tests (Wong et al. 2001) measure the ability of a mixture to change shapes under vibration. Transformation of a concrete mixture into a shape may measure the consolidation of a mixture, but can promote mixtures that are too flowable to hold an edge. Finally, the vibrating slope apparatus measures the rate of free flow on an angled chute subjected to vibration. While the test was designed to measure the yield stress and plastic viscosity of low slump concrete, it was found to be highly variable and not recommended (Wong et al. 2001). The common denominator for these workability tests is their inability to evaluate the ability of a mixture to be consolidated by vibration, but also possess enough stiffness to hold a vertical edge as it leaves a paver.

2.1.2 OBJECTIVES

First, a straight forward and inexpensive test is needed to evaluate the ability of a mixture to be placed with a slip form paver. Once this test is developed, it can be used with a simple procedure to provide useful tools in quantifying the impacts of many workability variables. It is important to realize not all processes of a slip formed paver can be or should be mimicked for expense and complexity. Instead, the focus of this work is to simulate the important components of the paving process. Secondly, this novel workability test can be used to evaluate different proportioning methods and aggregate gradation.

2.2 EXPERIMENTAL METHODS

2.2.1 Materials

The concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C150. All mixtures contained 20% by mass of an ASTM C618 Class C fly ash. The water reducer (WR) was a lignosulfonate mid-range with manufacturer maximum recommended dosage of 12 ounces per hundred pounds of cementitious weight (oz./cwt). Three crushed limestones, which were labeled A, B, & C and two river sand sources, which were labeled A & B were from Oklahoma. From Colorado river gravel was label D. The different crushed limestones and river gravel each had a ¾" coarse and 3/8" intermediate. Visually, the crushed limestones are angular while the river rock is smooth. Also, crushed limestone B is visually flatter than crushed limestones A & C. More detailed descriptions of the materials and a sieve analysis can be found in Chapter 3 and other publications (Cook et al. 2013).

2.2.2 Mixture Design

A slip formed pavement mixture should contain enough paste to consolidate the concrete, but still keep a stiff edge. Since the aggregate characteristics and gradation can affect the workability, the cementitious content varied from 4.5 to 5 sacks (423 to 470 lbs) with 20% fly ash replacement and a constant w/cm at 0.45. In order to reduce the number of testing variables, air entraining admixtures were not employed. Table 2-1 shows the twenty-eight different mixture designs used in this research.

TABLE 2-1 Summary of the Mixture Designs

Mix	Quarry	Sand Source	3/4" Coarse	3/8"Int.	Sand	Cement	Fly Ash	Water
1	A	A	1550	507	1265	376	94	212
2	A	A	1680	552	1093	376	94	212
3	A	A	2003	0	1303	376	94	212
4	B	A	1645	411	1211	376	94	212
5	B	A	1243	764	1263	376	94	212
6	A	B	2003	0	1313	376	94	212
7	A	B	1606	406	1289	376	94	212
8	C	A	1247	958	1303	338.4	84.6	190
9	C	A	1351	1042	1124	338.4	84.6	190
10	C	A	2137	0	1317	338.4	84.6	190
11	C	A	1497	902	1127	338.4	84.6	190
12	C	A	1643	762	1129	338.4	84.6	190
13	C	A	1457	851	1209	338.4	84.6	190
14	D	A	952	1115	1275	338.4	84.6	190
15	D	A	1031	1223	1083	338.4	84.6	190
16	D	A	1111	1331	892	338.4	84.6	190
17	C	A	2170	287	1105	338.4	84.6	190
18	C	A	2024	446	1085	338.4	84.6	190
19	C	A	1874	605	1063	338.4	84.6	190
20	C	A	1727	765	1043	338.4	84.6	190
21	C	A	1579	926	1023	338.4	84.6	190
22	C	A	1430	1088	1003	338.4	84.6	190
23	C	A	1283	1252	984	338.4	84.6	190
24	C	A	1133	1415	963	338.4	84.6	190
25	C	A	2016	656	883	338.4	84.6	190
26	C	A	1733	554	1247	338.4	84.6	190
27	C	A	1587	502	1429	338.4	84.6	190
28	C	A	1444	450	1615	338.4	84.6	190

2.2.3 Mixing and Testing Procedure

Aggregates are collected from outside storage piles, and brought into a temperature-controlled laboratory 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 for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed.

Next, the cement 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 and a novel test method to examine the response to vibration called the Box Test.

2.2.3.1 The Box Test

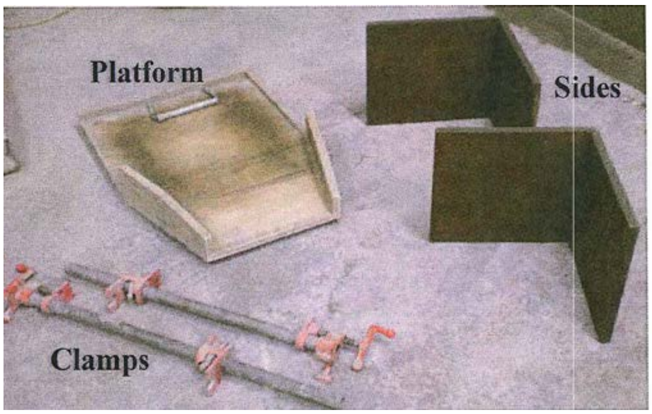
2.2.3.1.1 Development of the Box Test

A common issue for a poor performing concrete mixture with slip formed paving is the unresponsiveness of mixture to consolidation (Haung 2003). However, with the variety of different makes and models of slip formed paving machines and various operating procedures, to design a slip formed pavement laboratory test method could be very complex and expensive. A useful test should quickly and easily evaluate the ability of a mixture to be consolidated and subsequently hold an edge. Of all the slip formed pavement components, the vibrator contributes the majority of the energy applied to consolidate concrete. The ability to consolidate fresh concrete is dependent on the speed and power of the vibrator, the dimensions of section being consolidated, and the workability of a mixture (Kosmatka et al. 2011). In order to closely mimic the consolidation of a slip formed paver, a laboratory test was developed to evaluate a mixture's performance to a standard amount of vibration and to hold an edge.

A slip formed paver uses a hydraulic vibrator to produce high amplitude, low frequency vibration to consolidate concrete (Kosmatka et al. 2011). In order to minimize the impact on the air content, it is recommended that a vibrator on a slip formed paver have a frequency range of 5,000 to 8,000 vibrations per minute with a speed less than three feet per minute (ACI 309 2008, Huang 2003). These vibrator heads are typically 2.25" in diameter with an average spacing of 12 to 16 inches, and they are typically placed towards the top surface of concrete.

However, it was not possible to use a hydraulic vibrator and make this test easy to implement. Instead, an electric vibrator, which is commonly used in portable consolidation applications, was used. Calculations were utilized to find the energy of a concrete paver imparts to a concrete section when traveling at three feet per minute at 16" spacing. The concrete dimensions, vibrator frequency, head size, and time of vibration were adjusted to have comparable energy of a hydraulic vibrator on a paver. Also, the test uses a two directional vertical consolidation instead of the one directional horizontal consolidation for a paver.

As shown in Figure 2-1 (a) and (b), the Box Test used ½" plywood with a length, width, and height of 12" with 2" L-brackets in two corners. Two 1.5' pipe clamps were used to hold the other two corners together. Each step of the Box Test process is given in Figure 2-2. Placed on the base, a 1 ft^3 wooden formed box was constructed and held together by clamps as shown in Figure 1 (b). Concrete was uniformly hand scooped into the box up to a height of 9.5”. A 1” square head vibrator at 12,500 vibrations per minute was used to consolidate the concrete by inserting it at the center of the box. The vibrator was lowered for three seconds to the bottom of the box and then raised upward for three seconds. The clamps were removed from the side of the box and the side walls were removed.



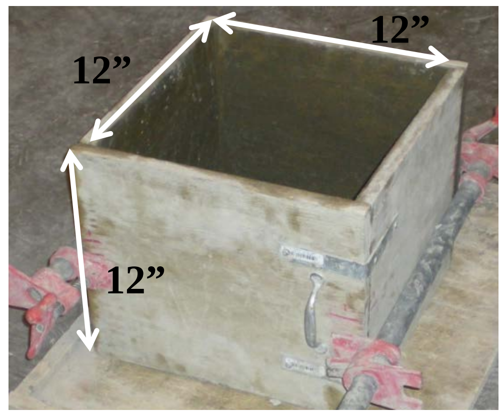


FIGURE 2-1 Left picture shows each component of the Box Test and picture on the right shows constructed components and inside dimensions.

	
Step 1	**Step 2**
Construct box and place clamps tightly around box. Hand scoop mixture into box until the concrete height is 9.5”.	Vibrate downward for 3 seconds and upward for 3 seconds.
	
Step 3	**Step 4**
Remove vibrator.	After removing clamps and the forms, inspect the sides for surface voids and edge slumping.

FIGURE 2-2 displays the four steps of the Box Test.

The response of a mixture to vibration can be assessed by the surface voids observed on the sides of the box using Figure 2-3. If a mixture responded well to vibration, the overall surface voids should be minimal because the mortar was able to flow and fill these voids. However, if the sides of the box had large amounts of surface voids, a mixture did not respond well to vibration. The average surface voids for each of the four sides were estimated with a number ranking using Figure 2-3 and an overall average visual ranking was given to each test. The average of four sides with 10-30% surface voids, or a ranking of 2 for a mixture was deemed a good vibration response and an acceptable amount of voids. In other words, concrete mixtures that had a visual ranking of “3” or “4” in the box test are not considered suitable for slip form paving.

Finally, top or bottom edge slumping can be measured to the nearest ¼” by placing a straightedge at a corner and horizontally using a tape measure to find the length of the highest extruding point.

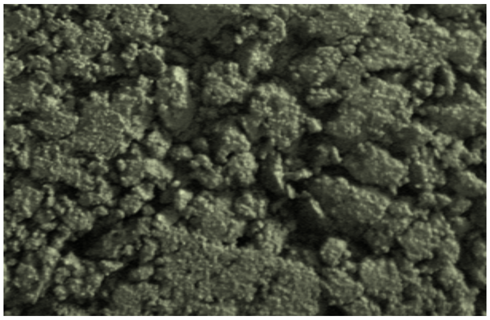
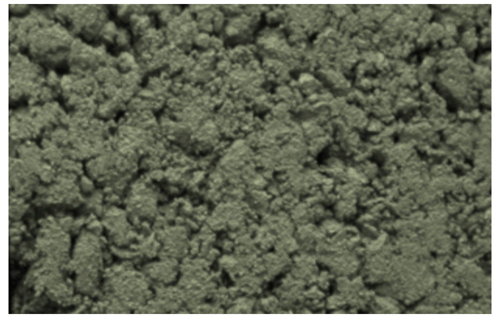
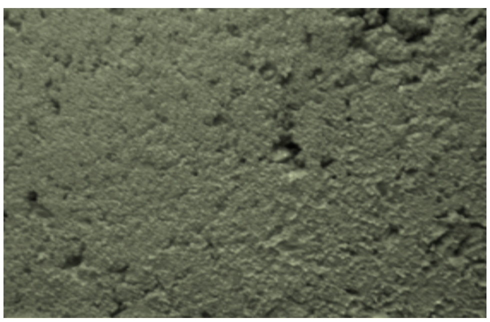
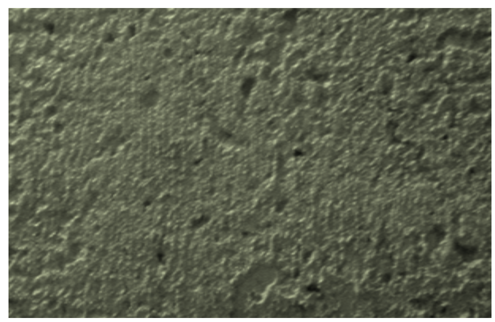
	
4	**3**
Over 50% overall surface voids.	30-50% overall surface voids.
	
2	**1**
10-30% overall surface voids.	Less than 10% overall surface voids.

FIGURE 2-3 shows the visual and numerical surface void values used to rank mixtures in the Box Test.

2.2.3.1.2 The Box Test Procedure

The Box Test provides a useful way to compare the performance of slip formed paving mixtures. When a mixture recieves a ranking of 3 or 4, the response to vibration was poor. As dicussed previously, the addition of paste or WR can reduce the yield stress of a mixture and improve the response to vibration. The yield stress can be measured by the amount of energy it takes to move the concrete.

If the paste volume and w/cm are held constant while changing other properties of a mixture, such as gradation or aggregate characteristics, the response of the mixture to vibration can be quantified by comparing the amount of WR needed to pass the Box Test. This was achieved by making a concrete mixture and conducting the Box Test. If the mixture did not pass the Box Test, WR was added and remixed until the mixture passed the Box Test. Mixtures that needed smaller amounts of WR performed better than mixtures that needed larger amounts of WR to pass the Box Test. A more detailed description of the Box Test procedure is given below.

After a mixture was prepared, the Slump and the Box Test were conducted. If the Box Test failed, the material from the slump and Box Test were placed back into the mixture. While the mixer was being remixed, a discrete amount of WR was added. After the three minutes of mixing, the Slump and Box Test was conducted a second time. If the Box Test failed again, the process of adding WR continued until the Box Test passed. Tyically, 2 oz/cwt WR dosage increment was used though the dosage value varried depending on the amount of voids observed. For example, if the Box Test was conducted and found the mixture to have close to 50% overall surface voids, the operator may need to add 4 oz/cwt before testing again. In Figure 2-4, a flow chart shows the Box Test evaulation procedure. All mixtures were evaluated over a one hour period in a 72°F room. If the test was not complete within one hour, the sample was discarded to ensure intial set did not affect the results.

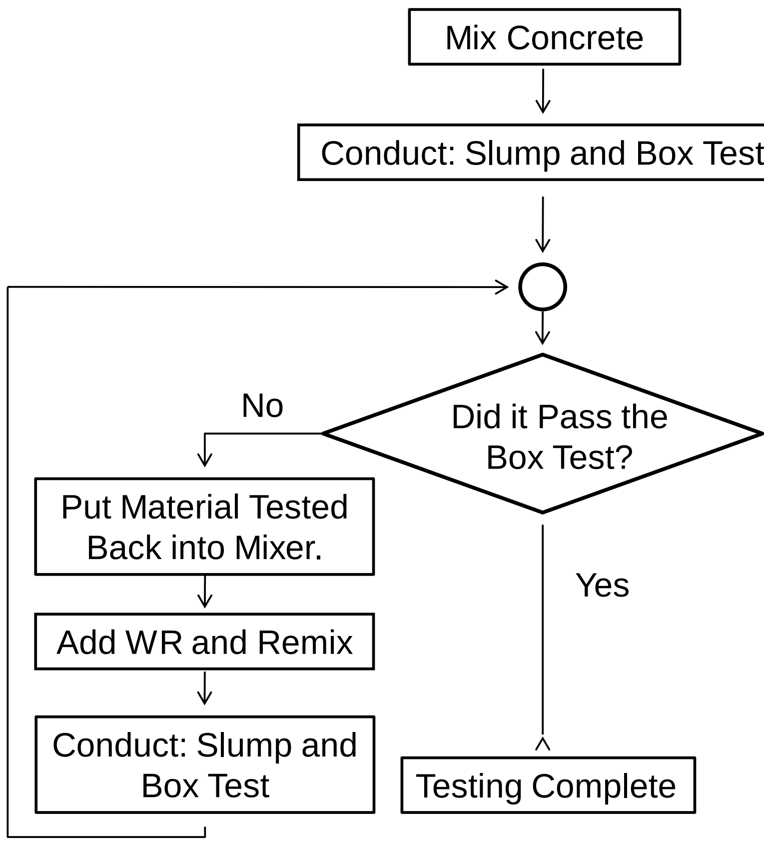


FIGURE 2-4 displays the flow chart of the Box Test procedure.

2.3 RESULTS

A number of variables were investigated to validate the Box Test. These included: dosage method, repeatability of a mixture by single and multiple operators, and comparison of visual rankings from multiple operators. A number of mixtures were investigated with a constant visual ranking of 2 because mixtures responding poorly to vibration can have the sides collapse. A limited number of tests were also completed in the field with side by side comparison to a slip formed paver.

2.3.1 Effects of Sequential Dosage

To investigate the impacts of the time and sequential dosage of the test procedure, a series of nine replicate tests were completed where a single dosage of WR was added during mixing instead of the sequential dosages. The results are shown in Table 2-2.

TABLE 2-2 Comparison of Single and Multiple Dosages

Mix	WR (oz./cwt)	Multiple Dosage		Single Dosage	
		Rank	Slump(in)	Rank	Slump(in)
1	8.3	2	1.5	2	1.5
6	18.1	2	2	2	2
4	13.4	2	2	2	2
8	5.5	2	0.5	2	0.5
9	5.8	2	1.25	2	0.5
10	14.5	2	1.25	2	1.25
11	3.4	2	1	2	0.5
12	6.2	2	0.5	2	0.5
13	13.5	2	2	2	2

2.3.2 Repeatability of a Mixture by Single and Multiple Operators

The result for the repeatability of WR dosage for a single operator is shown in Table 2-3. Ten mixtures were blindly replicated to compare the fresh properties. For each mixture, the WR dosage added was enough to recieve a 2 ranking. In Table 2-4, five different mxitures were evaluated with three different operators. This allows ten different comparrisons to be made. Each operator added enough WR for a mixture to have a two visual ranking. The WR dosage statistics are also listed. For each mixture, the absolute difference and average value is given. The percent difference is the absolute difference divided by the average WR expressed in percent. The data show that the average absolute difference was 1.2 oz. and that the average percent difference was 16.1 percent. The standard deviation on the percent difference statistic was 13.5 percent.

TABLE 2-3 Single Operator Repeatability

Mix	Operator	WR (oz/cwt)	Slump (in)	Average WR (oz/cwt)	Absolute Difference*	Percent Difference (%)	
1	A	8.3	1.5	8.9	1.2	13.5	
		9.5	1.25				
2	A	14.5	2	14	1	7.1	
		13.5	1.5				
3	A	7	2	5.8	2.5	43.5	
		4.5	2				
4	A	15	1.5	14.9	0.2	1.3	
		14.8	1.5				
5	A	17.5	2	16.7	1.7	10.2	
		15.8	2				
8	A	5.5	0.5	6.7	2.4	35.8	
		7.9	0.5				
9	A	5.8	1.25	6.4	1.1	17.3	
		6.9	1				
10	A	14.5	1.25	14.9	0.7	4.7	
		15.2	1				
11	A	7.3	0.5	6.8	1.1	16.3	
		6.2	0.5				
12	A	3.8	1	3.6	0.4	11.1	
		3.4	0.5				
					1.2	16.1	Average
					0.8	13.5	Standard Deviation

For multiple operators, the replications were treated as blind trials so the operator was not aware of the specific concrete mixture. For each mixture, the WR was added until the dosage was sufficient to achieve a visual ranking of 2 using the Box Test. Table 2-4 results are reported from five different mxitures evaluated with three different operators. The table reports the absolute difference and the percent difference between the paired operator trials. The data show that the average absolute difference was 1.7 oz. and that the average percent difference was 27.2 percent. The standard deviation on the percent difference statistic was 20.8 percent.

TABLE 2-4 Multiple Operator Repeatability

Mix	Operator	WR (oz/cwt)	Slump (in)	Average WR (oz/cwt)	Absolute Difference	Percent Difference (%)	
3	A	7	2	5.3	3.5	66.7	
	B	3.5	2				
3	A	7	2	6.1	1.9	31.4	
	C	5.1	2				
8	A	7.9	0.5	6.7	2.4	35.8	
	B	5.5	1				
8	A	7.9	0.5	6.5	2.8	43.1	
	C	5.1	1				
9	A	6.9	1	5.8	2.2	37.9	
	B	4.7	1.25				
9	A	6.9	1	7.1	0.3	4.3	
	C	7.2	1.25				
10	A	15.2	1	15.5	0.5	3.2	
	B	15.7	1				
10	A	15.2	1	15.2	0	0.0	
	C	15.2	1				
11	A	7.3	0.5	6.4	1.8	28.1	
	B	5.5	0.5				
11	A	7.3	0.5	8.2	1.8	22.0	
	C	9.1	0.5				
					1.7	27.2	Average
					1.1	20.8	Standard Deviation

2.3.3 Estimating the Void Range using Multiple Evaluators

Three different evaluators used the visual ranking scale to evaluate the void range amount of eleven different mixtures. Ten out of eleven evaluations had the same average ranking from the three evaluators. In the non-uniformed ranking mixture, a three ranking was given by two of the evaluators while the other evaluator gave it a two ranking. This suggests the values were close.

2.3.4 Comparison to a Slip Formed Paver

Comparisons between the Box Test and a slip formed paver were completed to determine if there was a similar performance. The Box Test was conducted on a highway and a city street jobsite, where they were using a slip formed paver. On both jobsites, the Box Test was conducted on three different truck loads and found to have satisfactory visual ranking of a two and no edge slumping.

2.3.5 Evaluating Gradations Using the Box Test

With the w/cm and paste content held constant, the Box Test was used on a variety of mixtures to show the ability of the Box Test to make quantitative comparisons between different gradations. The combined gradations were plotted on the individual percent retained chart. In Figure 2-5 (a) the sand volume is constant and the amounts of coarse to intermediate aggregate is varied. In Figure 2-5 (b) the coarse to intermediate ratio is held constant and volume of sand is varied. In each figure, the WR dosage required to pass the Box Test is give in the legend.

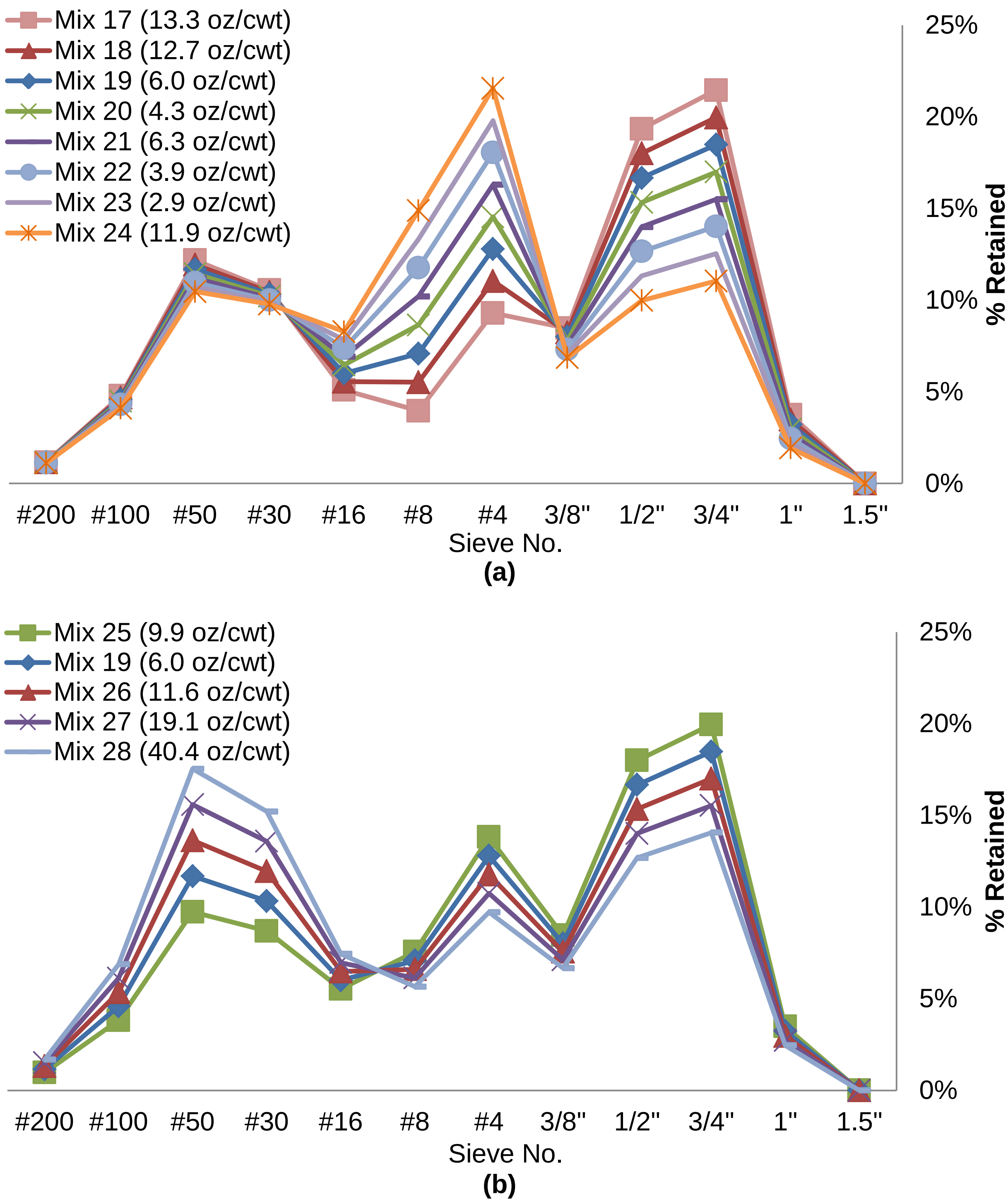


FIGURE 2-5 (a) shows the impacts of the Box Test measuring the gradation changes of intermediate to coarse aggregate with a constant sand amount and (b) shows the impacts of The Box Test measuring the gradation changes of sand to coarse aggregate.

2.4 DISCUSSION

The Box Test proved to be a useful tool to evaluate the response of the concrete to vibration and simultaneously holding an edge. It is important to note all mixtures investiaged had less than ¼" edge slump and therefore this was not reported. It seems that the visual ranking scale was a useful indication to how the concrete responded to vibration. Validations were conducted to determine how different variables impacted the surface voids of the Box Test. Dosage method and repeatability of single and multiple operators were the primary variables investigated and are discussed in the following sections. Also, it should be noted that a consistent slump measurement did not correspond to a passing Box Test value. This will be discussed in more detail later, but this is a significant observation that is prevalent in all results.

2.4.1 Effects of Sequential Dosage

Nine different mixtures were investigated to compare the response difference in multiple and single dosages. Whether a single or multiple dosage of WR was used, the slump value varied on a few mixtures while the Box Test value stayed consistent.

2.4.2 Repeatability of a Mixture by Single and Multiple Operators

As shown in Table 2-3, ten different mixtures were blindly replicated by a single operator. From those mixtures it was found that the largest difference in WR to pass the Box Test was 2.5 oz/cwt with an average absolute difference of 1.2 oz/cwt and a standard deviation of 0.77 oz/cwt. Low repeatability suggests that the Box Test can be repeated accurately by a single user to 2.74 oz/cwt with a 95% confidence interval.

The repeatability of multiple operators is shown in Table 2-3. The maximum difference in WR dosage was 3.6 oz/cwt with an average value of 1.7 oz/cwt and a standard deviation of 1 oz/cwt. These values are higher than what was obtained from a single operator. This is expected because there is some variance in replicating the same concrete mixture, subjectivity in the dosage of WR, and the visual ranking. However, these values are not extreme and still provide a useful comparison method between mixtures and their response to vibration. Two tests from multiple operators should be repeatable to 3.9 oz/cwt. The slump of each replicated mixture varied by 0.5" or less.

2.4.3 Multiple Evaluators

When multiple evaluators assessed similar surfaces, only one out of 11 evaluations had a different visual ranking. This suggests the visual ranking between users is consistent over 90% of the time.

2.4.4 Applying the Box Test

Both Figure 2-6 (a) and (b) use the WR dosage from the Box Test to compare the performance of aggregate gradations with a fixed paste content. The gradations requiring a higher dosage of WR are less desirable than a gradation requiring a lower WR dosage. Both figures have a range of gradations requiring a low amount of WR that would be expected to perform well. Gradations outside of this zone seemed to require significantly higher amounts of WR with only small changes in gradation. While the amount of coarse and intermediate aggregate varied largely with only small differences in WR dosage, a change in the amount of sand had a greater impact on the workability of the mixture. This data is useful as these comparisons were not possible with previous testing methods and will be discussed further in future publications.

2.4.5 Slump and Box Test Measurement

When a mixture passed the Box Test, the slump value was within a typical range for a concrete pavement mixture (ranging between 0” to 2”) (ACI 309 2008). Although the slump values were consistent between all repeated mixtures, a single slump value did not correspond with a passing performance in the Box Test. This is a critical observation that supports the idea that the Slump Test does not provide a consistent measuring tool for concrete used in slip formed paving and suggests the Box Test is more sensitive to these mixtures.

2.4.6 Improvements to the Box Test

While the Box Test is a useful test to evaluate the workability of a mixture for a slip formed pavement, improvements can be made. The primary variability of the test comes from the dosage of WR added by the operator. If a more systematic WR dosage procedure was used then this may reduce the variability between users. However, the variability of the test was still found to be within acceptable ranges to make comparisons between mixtures. This is especially true for single operators.

Although the visual ranking scale was found to be very consistent, it could still be improved if a systematic point count method was used to quantify the amount of voids on the surface similar to the hardened air void analysis. An image analysis technique or a simple transparent overlay could be placed on the concrete and individual points could be counted and compared to the total area, which is the same technique used in ASTM C 457 and other work (Bentz 1987).

Additional work could be done to determine how sensitive the test is to different mixing and consolidation procedures. Further evaluation with field concrete and the Box Test would also be beneficial.

2.4.7 Practical Implications

It is important to realize the Box Test was only designed to evaluate a response of a mixture to vibration and not necessarily to correlate with the exact performance of a slip formed paver. This means the WR dosage required in the Box Test may be higher than what is required in the field. However, as previously discussed, the field evaluations completed with the Box Test showed a satisfactory comparison. One of the more valuable attributes of the Box Test is the actual simplistic approach of the test. The equipment of the Box Test is inexpensive and commonly available to those in the concrete industry. Conducting and evaluating a mixture using the Box Test is quick and easy to perform and provides a useful way to compare data.

2.5 CONCLUSION

An outline for the Box Test procedure was given and the data was presented over the variability of the test. The results show the Box Test is a useful and repeatable tool for evaluating different mixtures for slip formed paving. The following points were made in this work:

- In two different field comparisons, the Box Test performed comparably the same as a slip formed paving machine.

- There was no difference between mixtures evaluated with single or multiple dosages of water reducer for the Box Test and minor variation in the slump.
- The repeatability of a single operator adding WR dosage had an average absolute difference of 1.2 oz/cwt with a standard deviation of 0.8 oz/cwt.
- Multiple operators adding WR dosage had an average absolute difference of 1.7 oz/cwt with a standard deviation of 1.1 oz/cwt.
- The visual ranking of multiple evaluators showed agreement over 90% of the time.
- The Box Test was able to provide a quantitative comparison on the impact of the ratio of coarse to intermediate aggregate with a fixed sand content and the ratio of fine to a fixed coarse and intermediate ratio on the response to vibration. The results clearly showed a satisfactory range in performance for these materials.
- The Box Test proved to be a more sensitive tool than the Slump Test to evaluate a concrete mixture for the application of slip formed pavements.
- This work shows the Box Test provides a simple and qualitative tool to evaluate the impact of different mixture variables for slip formed pavement mixtures.

CHAPTER 3 - LABORATORY EVALUATIONS OF DIFFERENT AGGREGATE PROPORTIONING TECHNIQUES FOR OPTIMIZED GRADED CONCRETE PAVEMENTS

3.1 INTRODUCTION

When Duff Abrams wrote *Design of Concrete Mixtures* in 1918, it outlined the basic fundamental concepts of a concrete mixture design that people still use today. These basic concepts stemmed from his testing experience of well over 100,000 mixtures. However, a method of proportioning aggregates and paste for a predictable workability could not be developed. Instead, mixtures are designed to meet certain specifications such as water to cementitious material (w/cm) ratio, compressive strength, durability, sustainability, permeability, and workability. While the w/cm ratio and compressive strength can help account for the durability, sustainability, and permeability, the workability criteria can be a very elusive specification to meet (Mehta and Monteriro 2006). The workability of the concrete can be changed by parameters such as the yield stress, paste content, aggregate characteristics, and gradation. To compensate for mixtures with low workability, it is common in practice to increase the cement, water, or both in a mixture. This can cause an increase in the cost, decrease in durability, and sustainability of the concrete.

Many different gradation techniques have been used over the years with success to create optimized graded concrete. However, construction companies move from jobsite to jobsite using the materials available in that specific area to design and produce concrete. Other than field experience, a very limited amount of useful data has been presented on the subject of aggregate proportioning for concrete mixtures. This research investigates some of the more popular aggregate proportioning methods previously discussed and compares the workability performance of each mixture. The workability application will focus on slip formed pavement application, which will be measured with the Slump Test and the Box Test. For more information about the Box Test, refer to chapter 2 of the report.

3.1.1 Gradation Techniques

Three different mixture design techniques have been used to proportion a concrete mixture. The Shilstone chart, the percent retained chart, and the power 45 chart have each been used as a different function to compare a gradation.

3.1.1.1 Shilstone Chart

From his experiences, Shilstone constructed a graphical method to force an aggregate blend to a certain gradation. The Shilstone chart impacts the combined percentage ratio volume for fine, intermediate, and coarse aggregates. Shown in Figure 3-1 are the different zones that divide the Shilstone chart. The different zones supposedly divide the different extreme volumes. Zone I is gap graded with very little amounts of intermediate; zone II is well-graded and the optimal gradation for a concrete mixture design. Zone III has a large majority of intermediate and very little coarse aggregate. Zone IV and zone V correlate with extreme sandiness and rockiness.

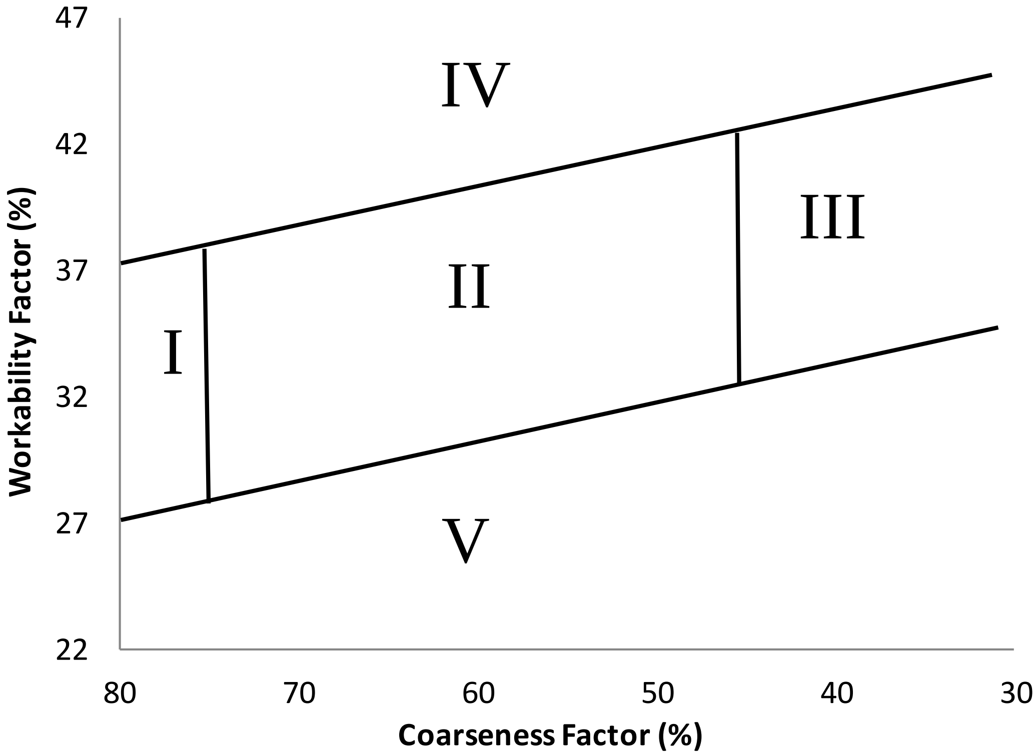


Figure 3-1 shows the Shilstone chart with the 5 different zones.

The Shilstone chart is made up of the coarseness factor and the workability factor. The two parameter equations control the percentage of sand, intermediate, and coarse aggregates. Shown in equation 3.1, the workability factor changes the percentage of sand in the mixture. The ratio of large to intermediate aggregate for a given sand content is controlled by the coarseness factor shown by equation 3.2.

Equation 3.1

Workability Factor (WF) = W + (2.5(C-564)/94)

W= cumulative % passing the no. 8 sieve
C= cementitious material content (lbs/yd^3)

Equation 3.2

Coarseness Factor (CF) = (Q/R)*100

Q= cumulative % retained on the 3/8 sieve
R= cumulative % retained on the no. 8 sieve

3.1.1.2 Percent Retained on Individual Sieve

Many different techniques can be used to explain the gradation of aggregates. Gradations can be graphs using the cumulative percent passing, the cumulative percent retained, and the individual percent retained on each sieve size. While the cumulative percent passing has been the most widely used graphical representation of a gradation, it tends to hide the amount on a sieve size and only show general trends of multiple adjacent sieve sizes. Shown in Figure 3-2, an intermediate gradation, a coarse gradation, and fine gradation are each graphed in percent individually retained on each sieve size. However, when the combined aggregate gradation for a mixture is graphed on the individual percent retained, it makes individual aggregate size distribution more clear.

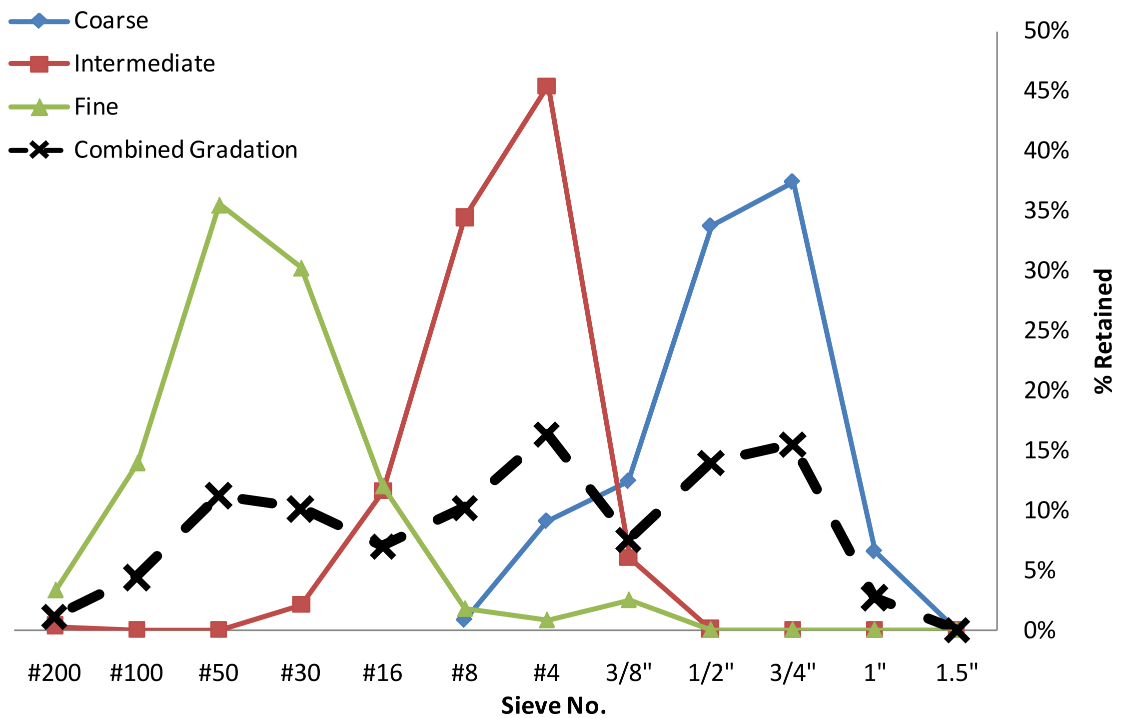


Figure 3-2 shows the individual gradation being integrated as a single combined gradation.

The individual percent retained has been identified as being valuable to many people (Shilstone 1990, Taylor et al. 2007). From experiences, people have specified a maximum boundary of 18 % retained and a minimum retained of 8 % as shown in Figure 3-3. But a very limited amount of research has been conducted to justify the limits.

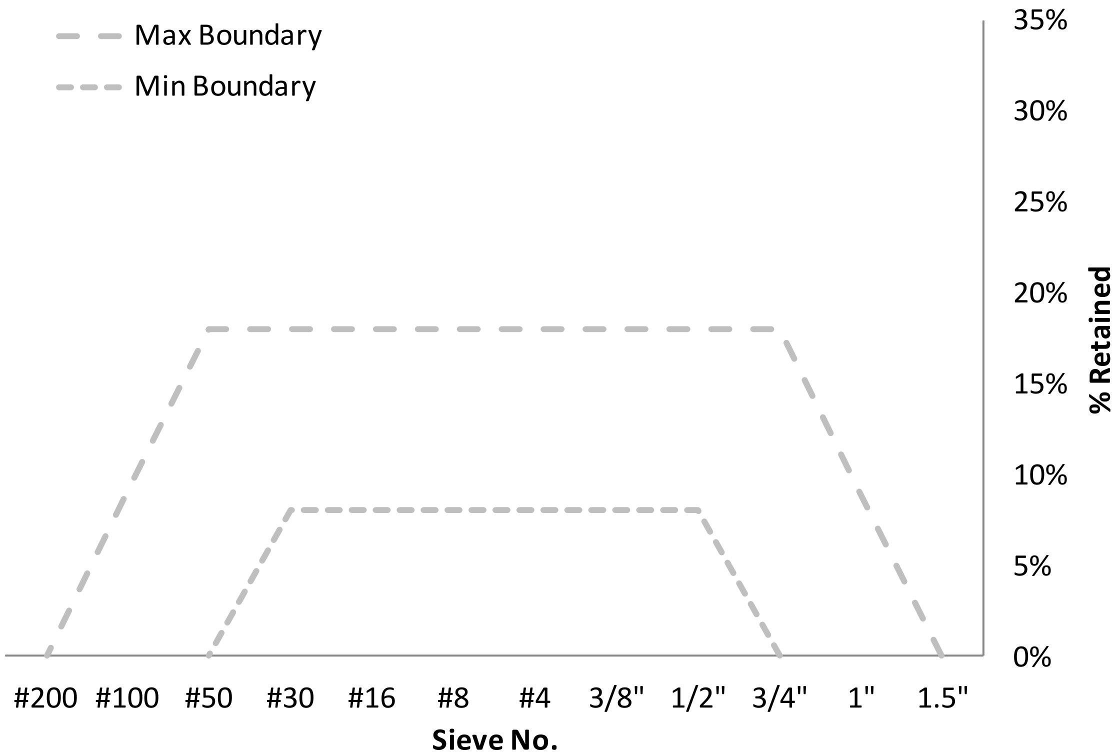


Figure 3-3 is the individual percent retained on each sieve number.

3.1.1.3 Power 45 Curve

Developed by the concrete industry in 1907 and now used by the asphalt industry, the power 45 curve uses a combined gradation to best-fit to a straight line on the cumulative percent passing chart (Fuller and Thompson 1907). As shown in Figure 3-4 the straight line from the origin to the nominal maximum size was thought to be the maximum density of a combined gradation, which supposedly creates the maximum density and the minimum amount of voids in a mixture. However, from previous research our team conducted, we found using a best fit curve produced a poor workability and was not the best way to proportion aggregates for a slip formed pavement mixture (Ley et al. 2012).

In addition, others have used the straight line from origin through nominal maximum size to visually evaluate the overall distribution of the mixture. The technique was used on many mixture designs throughout the report. However, it was not found to be useful and will not be further discussed in this report.

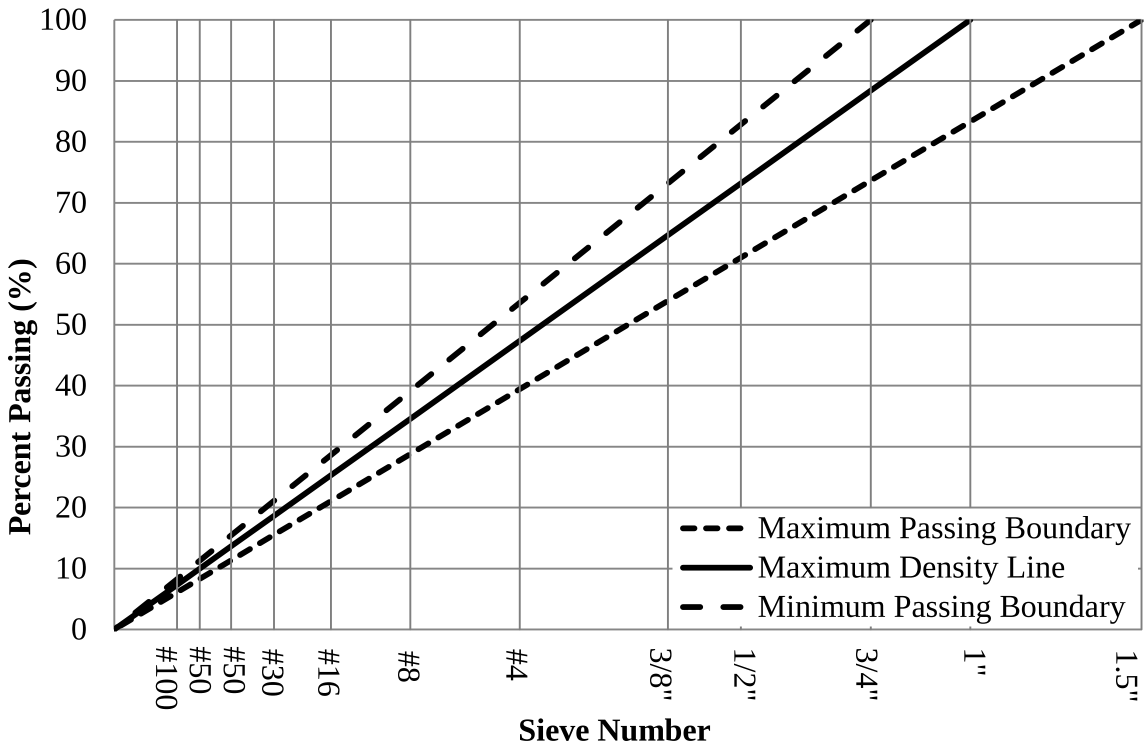


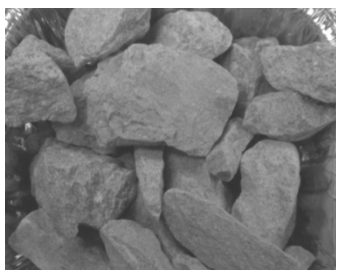
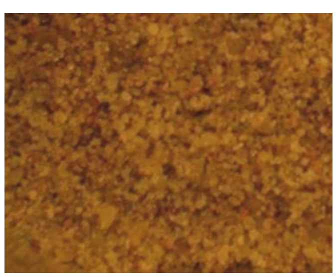
Figure 3-4 shows the Power 45 Curve with typical limits.

3.2 LABORATORY INVESTIGATIONS

3.2.1 Materials

Aggregates were attained from various quarries in Oklahoma. Three different coarse aggregates and two different fine aggregates were used. Each aggregate type was tested to find the gradation (ASTM C136), absorption, and specific gravity (ASTM C127 and ASTM C128). The aggregates were ODOT approved for concrete and gradations were plotted in Figure 3-5. A visual picture and description of the shape and surface characteristics of each aggregate is shown in Table 3-1. For more information on the shape and surface characteristics of the aggregate refer to other publications (Cook et al. 2013).

Table 3-1. Aggregate Description

Aggregate	Photo of Aggregate	Description
Limestone A		An angular and mid spherical crushed limestone.
Limestone B		An angular and mid spherical crushed limestone.
Limestone C		An angular and mid spherical crushed limestone.
River Sand A		A river sand.
River Sand B		A river sand.

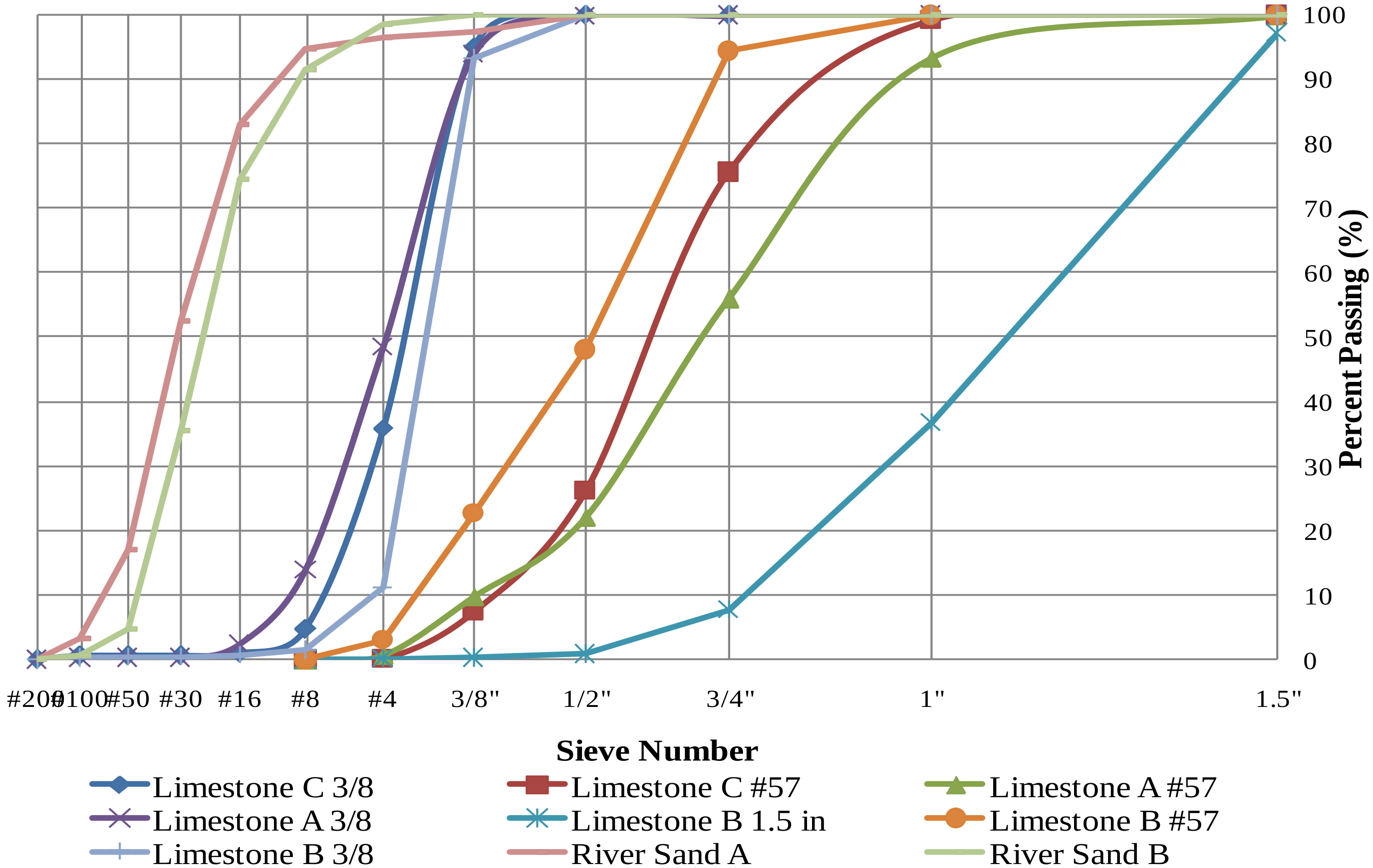


Figure 3-5 plots on the percent passing sieve analysis.

Each mixture used both cement and fly ash. The cement conformed to ASTM C150 Type I cement. The oxide analysis and phase concentrations are shown below in Table 3-2. Fly Ash conforming to ASTM C618 Class C was used in every mixture produced for this project. Each mixture had a 20% fly ash replacement by weight. Total cementitious content varied from 4.5 sacks to 5.5 sacks. The water reducer used is a lignosulfonate mid-range water reducer classified by ASTM C494.

Table 3-2 Oxide Analysis of the Cement

Chemical Test Results	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
	21.1%	4.7%	2.6%	62.1%	2.4%	3.2%	0.2%	0.3%
Phase Concentration	C_3S	C_2S	C_3A	C_4AF				
	56.7%	17.8%	8.2%	7.8%				

3.2.2 Mixture Proportions

The mixture proportions were based on the different points of the Shilstone Chart and a typical mixture design of 60% coarse aggregate and 40% fine aggregate by volume. Different places in zone II of the Shilstone chart were picked to help give a clear evaluation of the Shilstone chart, as shown in Figure 3-6. A description of each mixture proportion is given in Table 3-3.

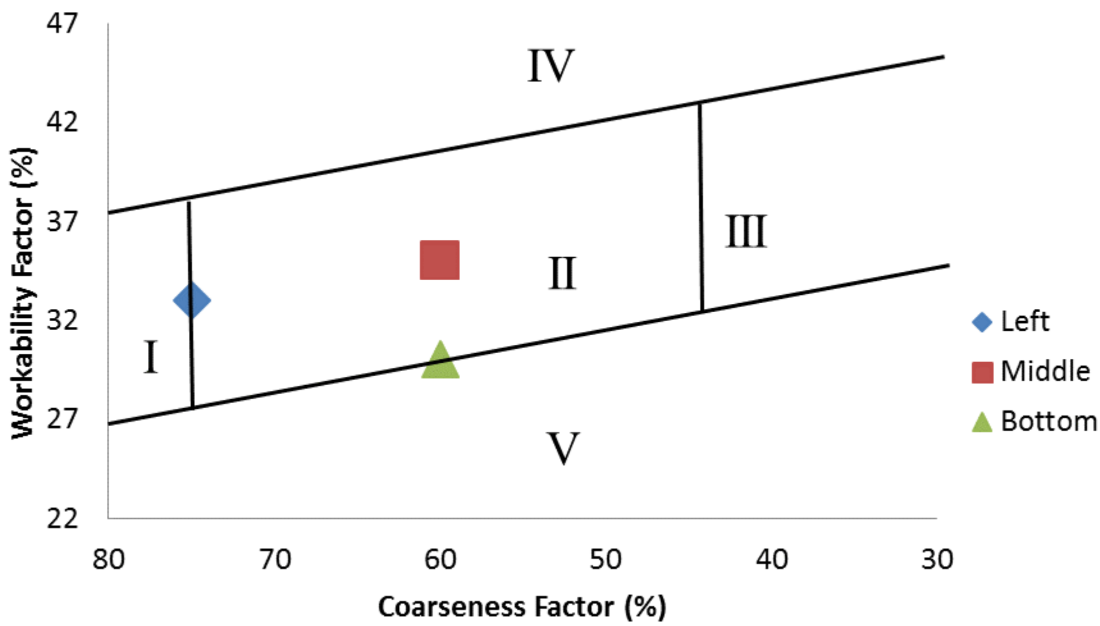


Figure 3-6 plots the different proportions on the Shilstone Chart.

Table 3-3 Description and location of mixture proportion on the Shilstone Chart

Mixture Proportion	Description
Middle	Supposed to have overall best mixture design. Located in the middle of zone II. CF 60 & WF 35
Bottom	Contains the largest amount of intermediate proportion compared to the other mixture proportions. Located on the bottom border of zone II. CF 60 & WF 30
Left	A very small amount of intermediate. Located on the left border of zone II. CF 75 & WF 33
60/40	Typical concrete mixture. Located somewhere in zone I, IV, or II.

3.2.3 Mixing Procedures

The aggregate blend was charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Then cement and fly ash were loaded into the mixer, followed by the remaining mixing water. The mixer was turned on for an additional three minutes. Once this mixing period was complete, the buildup of material along the walls was removed. Next, the mixer was started and the mixture was mixed for three minutes. The initial testing of the mixture included air content (ASTM C 231), slump (ASTM C 143), unit weight (ASTM C 138), and the box test. For a further description of the Box Test, refer to Chapter 2.

If the box test failed, the material from the slump and box test were placed back into the mixture. The air content was discarded. The mixer was turned on and a discrete amount of WR was added. After the three minutes of mixing, the slump, unit weight, and box test were conducted. If the box test failed again, the process of adding WR continued until the box test passed. Then cylinders were made for compressive strength (ASTM C39) and electrical resistance testing. In Figure 3-7, a flow chart visually shows the box test evaulation procedure. If the w/cm and paste volume are held constant. the box test evaluation procedure can determine the performance of different gradations by comparing the amount of WR needed to pass the box test.

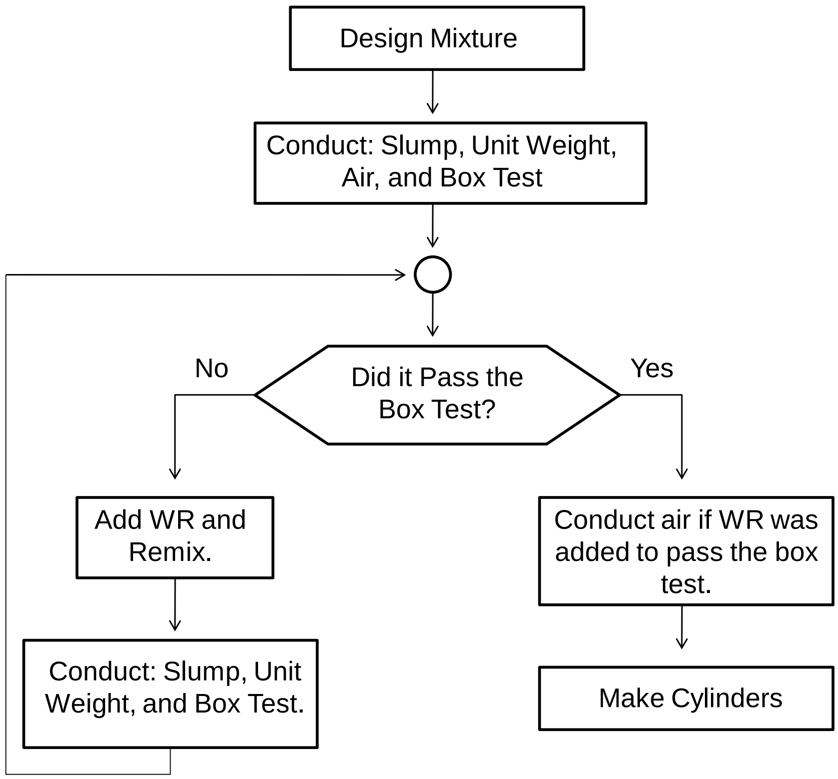


Figure 3-7 visually shows the flow chart for the box test evaluation procedure.

3.3 RESULTS

3.3.1 Evaluation Results for the Different Gradations

In Tables 3-4 and 3-5, the fresh properties results and batch weights were combined for determining the performance of the aggregate gradation on the performance of paving mixtures. Before testing the compressive strength of the cylinders, electrical resistivity was conducted using the Wenner Probe, as shown in Table 3-6. Figures 3-8 through 3-21 show the WR amounts for each mixture on the Shilstone chart, or the individual percent retained. For each mixture presented in Figures 12-21, the w/cm was held constant. Figure 3-22 compares the performance of two mixtures using the middle of the Shilstone chart. Then Figure 3-23 shows the results of limestone A and river sand A being sieved to the individual size gradation of the middle of the Shilstone chart for Limestone B and river sand A.

Table 3-4 Aggregate Proportions (PCY), Required Water Reducer (oz/cwt) and Compressive Strengths (psi) for Limestone B

Aggregate Type					Gradation			
					Shilstone Chart			
Coarse	Fine	Sacks	W/CM	Properties	Left	Center	Bottom	60/40
Limestone B #57	River Sand A	5.5	0.38	WR (oz/cwt)	12.5	16.8	11.0	18.2
				Slump (in)	0.75	0.75	0.75	1.5
				7 day f’c	5420	5890	5630	6020
				28 day f’c	7200	7810	7420	7500
				Coarse	2100	1575	1706	2018
				Intermediate	48	516	562	0
				Fine	1169	1229	1057	1296
				CF WF	75 35	60 35	60 30	
Limestone B #57	River Sand A	5.5	0.45	WR (oz/cwt)	0.0	0.0	2.7	0.0
				Slump (in)	1.50	1.50	0.75	1.5
				7 day f’c	4470	4470	4550	4530
				28 day f’c	5670	6000	6120	6030
				Coarse	2039	1529	1656	1932
				Intermediate	46	501	545	0
				Fine	1135	1193	1026	1284
				CF WF	75 35	60 35	60 30	
Limestone B #57	River Sand A	5	0.45	WR (oz/cwt)	12.7*	8.3	16.1	17.1
				Slump (in)	1.75	1.50	1.50	2
				7 day f’c	4450	5370	4340	5070
				28 day f’c	5480	6200	5900	5900
				Coarse	1963	1553	1684	2015
				Intermediate	41	508	554	0
				Fine	1304	1280	1107	1321
				CF WF	75 35	60 35	60 30	76 40
Limestone B #57	River Sand B	5	0.45	WR (oz/cwt)	20.0	17.5	19.4	18.1
				Slump (in)	2.50	1.25	1.00	2
				7 day f’c	5740	4490	5130	4920
				28 day f’c	7000	5710	6330	5910
				Coarse	2072	1606	1728	2003
				Intermediate	0	406	465	0
				Fine	1227	1289	1113	1313
				CF WF	75 35	60 35	60 30	73 35
Limestone B 1.5"	River Sand A	5	0.45	WR (oz/cwt)	15.77	14.44	15.56	
				Slump (in)	1.75	1.75	1.75	
				7day f’c	5419	5032	5215	
				28 day f’c	6309	6083	6487	
				Coarse	1598	1201	1301	
				Intermediate	557	886	963	
				Fine	1194	1258	1086	
				CF WF	75 33	60 35	60 30	

Note: the coarse, intermediate, and fine are measured in lbs per cubic yard.
*the mixture failed because of edge slumping.

Table 3-5 Aggregate Proportions (PCY), Required Water Reducer (oz/cwt) and Compressive Strengths (psi) for Limestone A and C

Aggregate Type					Gradation			
					Shilstone Chart			
Coarse	Fine	Sacks	W/CM	Properties	Left	Center	Bottom	60/40
Limestone C #57	River Sand A	5	0.45	WR (oz/cwt)	13.4	15.0	14.2	13.0
				Slump (in)	1.50	1.50	1.50	1.75
				7 day fc (psi)	5419	5657	5194	5020
				28 day fc (psi)	7114	7034	6592	6440
				Coarse	1598	1201	1301	1955
				Intermediate	557	886	963	0
				Fine	1194	1258	1086	1293
				CF WF	75 33	60 35	60 30	88 34
Limestone C #57	River Sand B	5	0.45	WR (oz/cwt)	21.2	19.3	18.5	15.6
				Slump (in)	2.25	2.25	1.00	1.5
				7 day fc (psi)	5741	4487	5129	5590
				28 day fc (psi)	6992	5705	6328	6830
				Coarse	1691	1289	1390	1955
				Intermediate	330	681	762	0
				Fine	1228	1280	1101	1293
				CF WF	75 33	60 35	60 30	88 34
Limestone A #57	River Sand A	5	0.45	WR (oz/cwt)	0.86	0.00	0.00	
				Slump (in)	1.50	1.50	1.00	
				7 day fc (psi)		5270	4870	
				28 day fc (psi)		7340	6500	
				Coarse	1909	1449	1562	
				Intermediate	418	847	917	
				Fine	1115	1121	950	
				CF WF	74 33	60 35	60 30	
Limestone A #57	River Sand A	4.5	0.45	WR (oz/cwt)	5.2	9.1	6.4	9.8
				Slump (in)	0.50	0.25	0.00	0.5
				7 day fc (psi)	4000	5530	5400	5010
				28 day fc (psi)	6180	8900	7300	7100
				Coarse	1929	1457	1579	2199
				Intermediate	421	851	926	0
				Fine	1191	1209	1023	1352
				CF WF	75 33	60 35	60 30	88 36

Note: the coarse, intermediate, and fine are measured in lbs per cubic yard.

Table 3-6 Electrical Resistivity Using the Wenner Probe

Aggregate Type					Gradation			
					Shilstone			
Coarse	Fine	Sack	W/CM	Properties	Left	Center	Bottom	60/40
Limestone B #57	**River Sand A**	**5.5**	**0.38**	WR	12.5	16.8	11.0	18.2
				7 day	5.0	4.2	4.9	4.4
				28 day	8.9	7.5	8.1	7.7
Limestone B #57	**River Sand A**	**5.5**	**0.45**	WR	0.0	0.0	2.7	0.0
				7 day	4.4	4.5	4.5	4.1
				28 day	7.7	7.3	7.0	7.6
Limestone B #57	**River Sand A**	**5**	**0.45**	WR	12.7	8.3	16.1	17.1
				7 day	3.6	5.5	3.8	3.2
				28 day	6.7	6.7	7.0	6.0
Limestone B #57	**River Sand B**	**5**	**0.45**	WR	20.0	17.5	19.4	18.1
				7 day		3.9		4.1
				28 day	5.8	7.2	6.4	6.8
Limestone C #57	**River Sand A**	**5**	**0.45**	WR	13.4	15.0	14.2	13.0
				7 day	4.2	4.0		4.5
				28 day	6.6	6.0		6.8
Limestone C #57	**River Sand B**	**5**	**0.45**	WR	21.2	19.3	18.5	15.6
				7 day				4.5
				28 day				7.2
Limestone A #57	**River Sand B**	**4.5**	**0.45**	WR	5.2	9.1	6.4	9.8
				7 day	4.5	3.5	3.4	3.9
				28 day	8.1	7.6	6.9	7.4

Note: The Probe is measured in ohms/cm. “WR” is the water reducer used in oz/cwt.

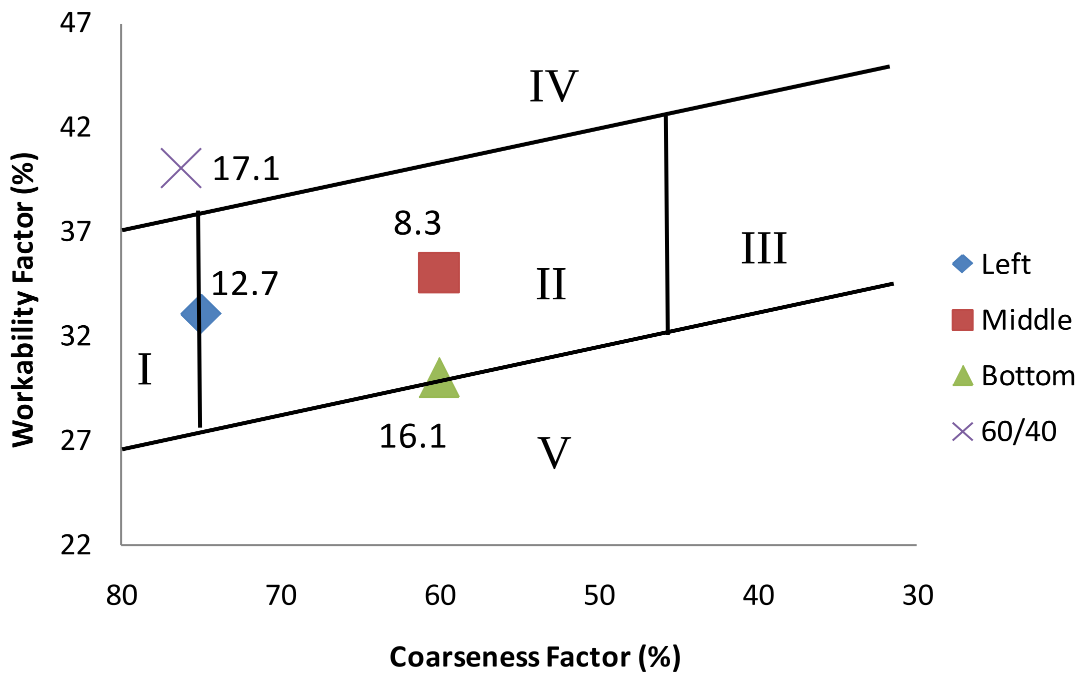


Figure 3-8 is a 5 sack limestone B #57 and river sand A.
Note. Numbers are WR dosage needed to pass the box test.

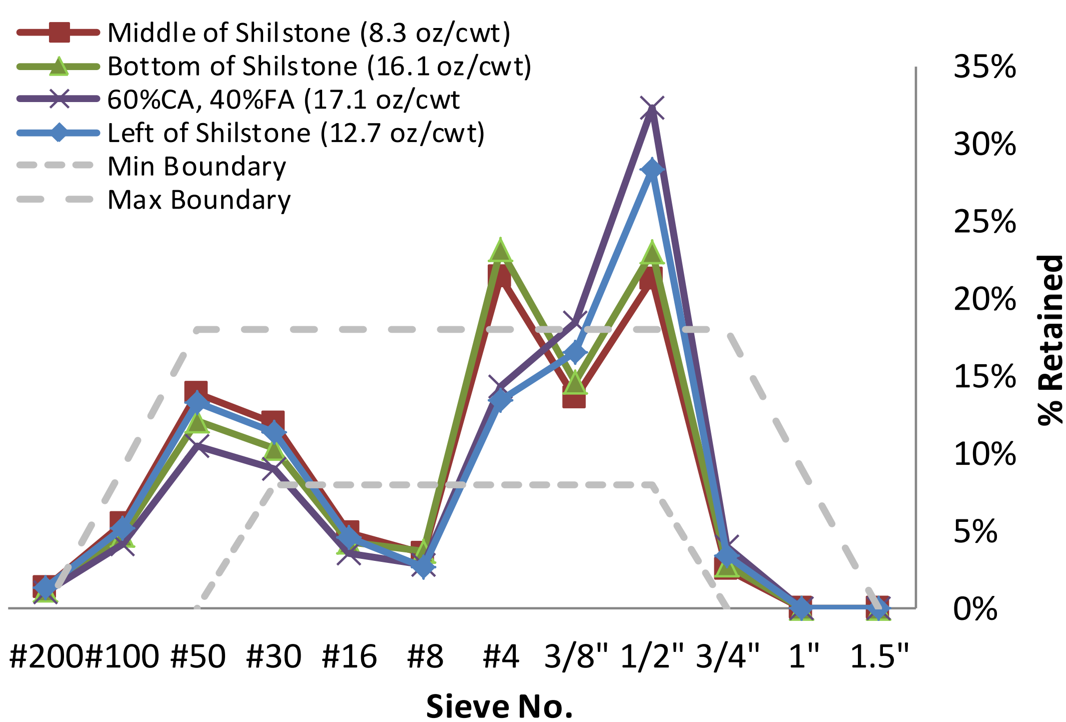


Figure 3-9 shows 5 sack limestone B #57 and river sand A.

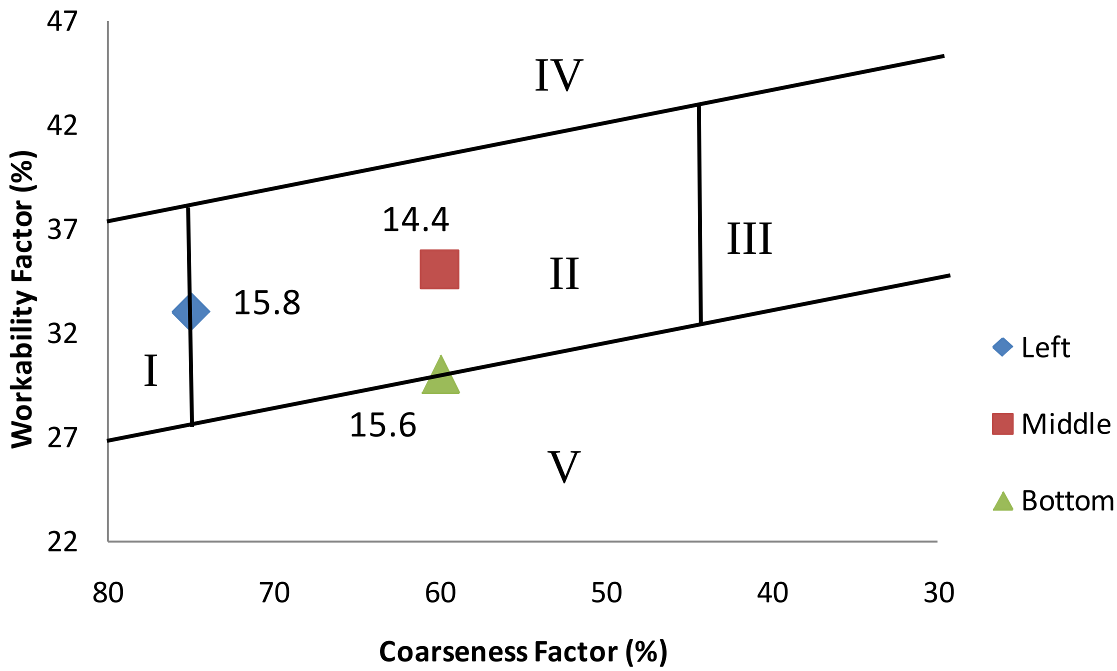


Figure 3-10 plots 5 sack limestone B 1.5” and river sand A.
Note. Numbers are WR dosage needed to pass the box test.

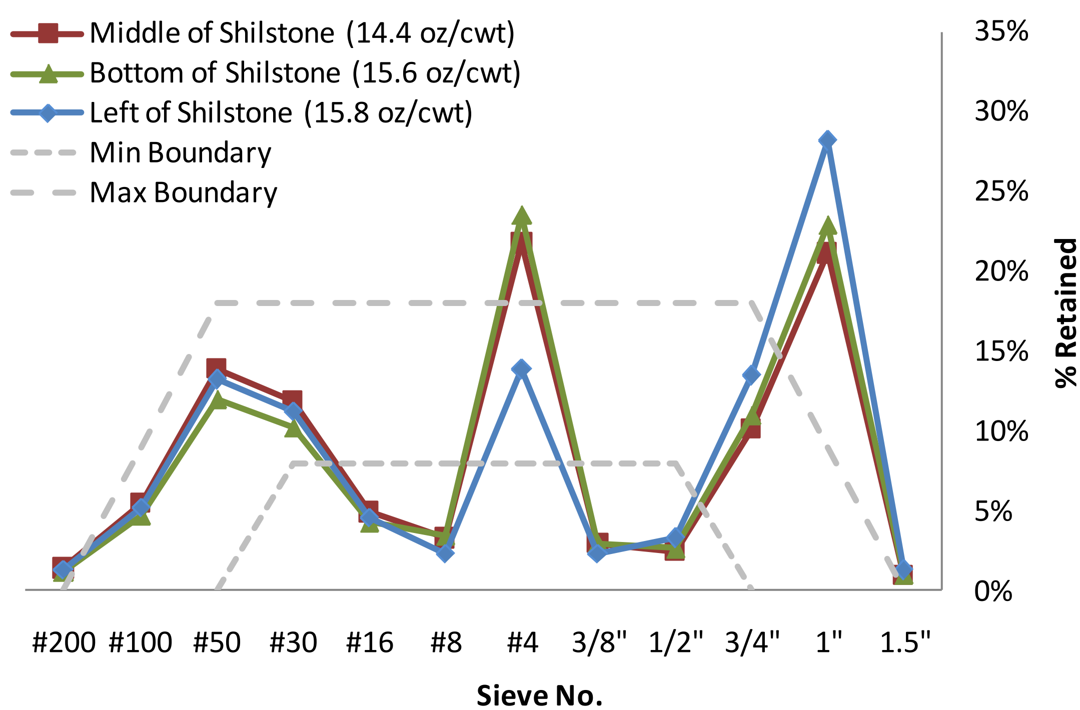


Figure 3-11 graphs 5 sack limestone B 1.5” and river sand A.

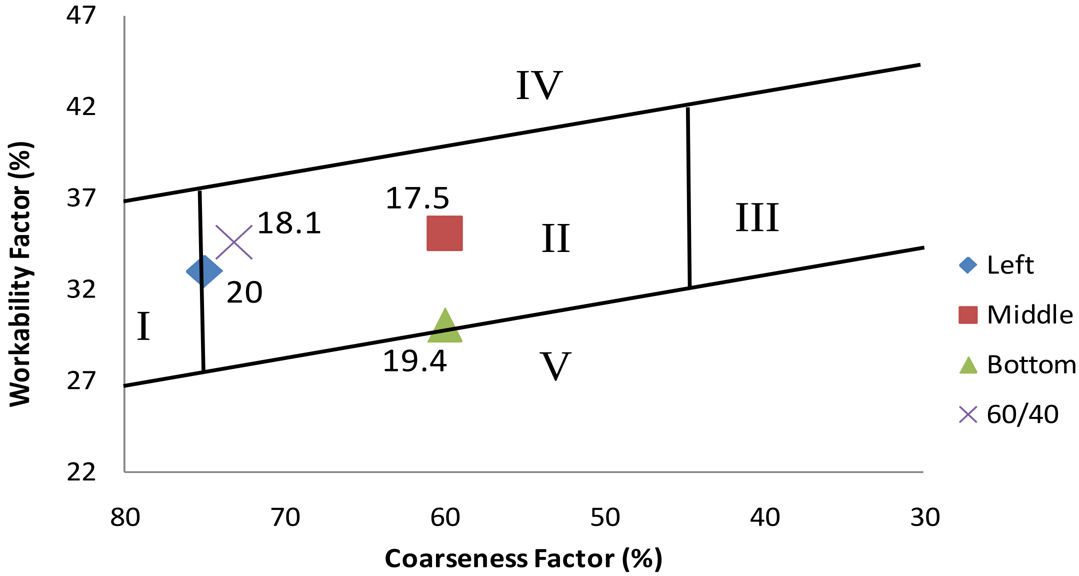


Figure 3-12 plots 5 sack limestone B #57 and river sand B.
Note. Numbers are WR dosage needed to pass the box test.

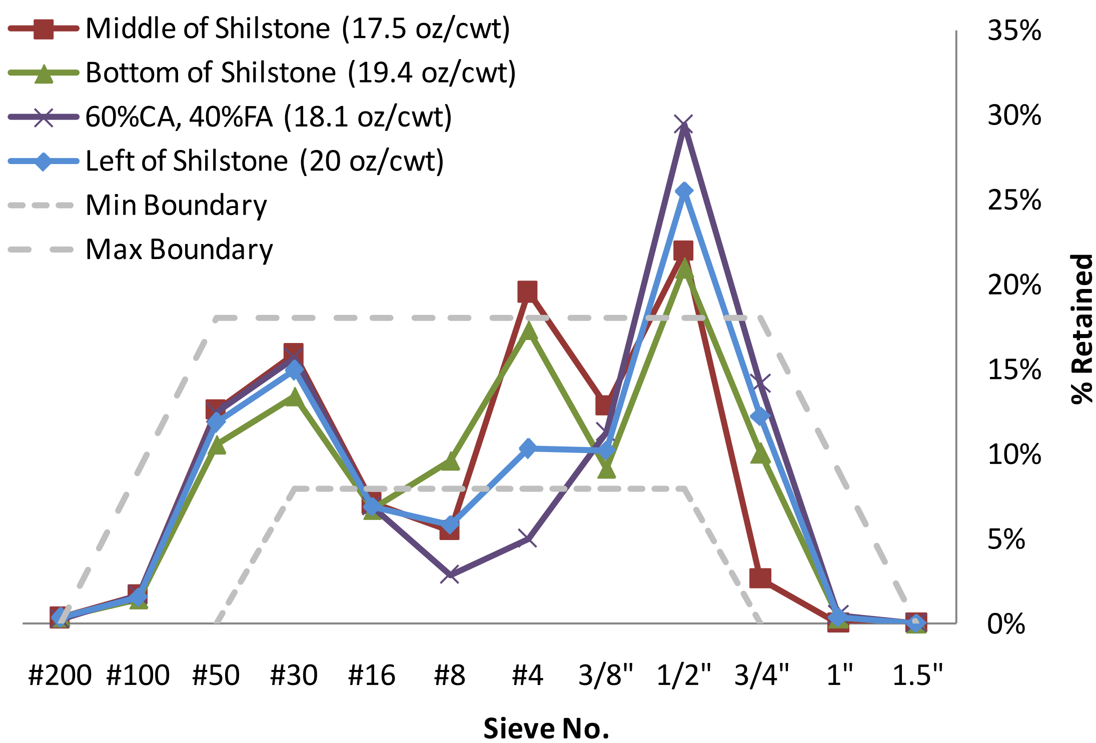


Figure 3-13 graphs 5 sack limestone B #57 and river sand B.

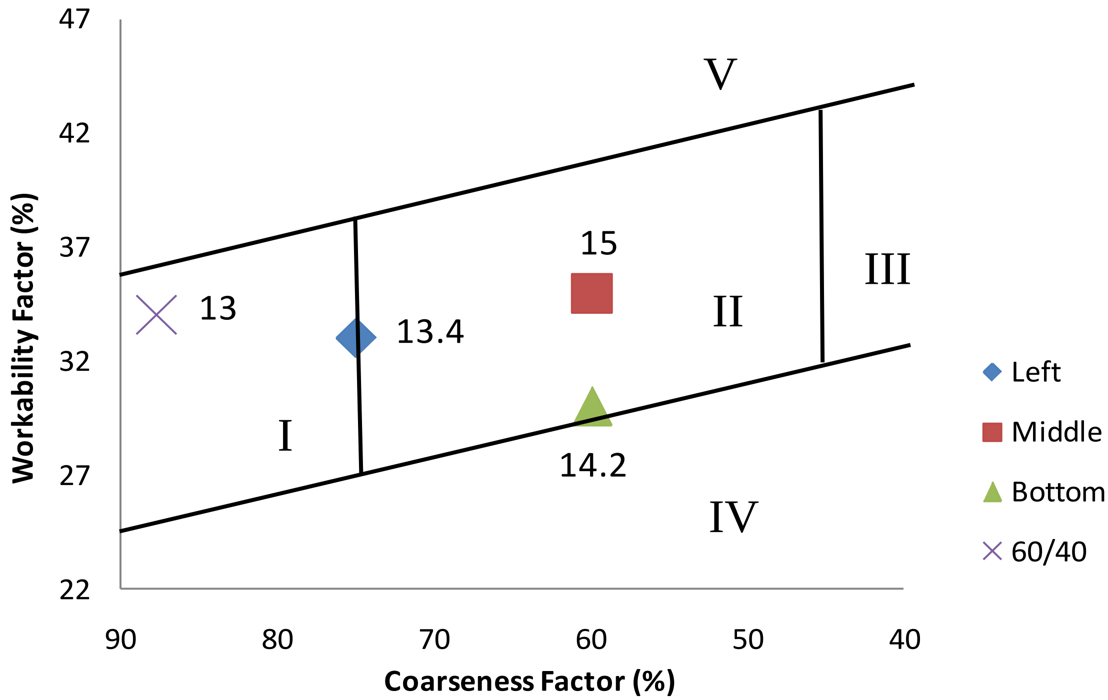


Figure 3-14 plots 5 sack limestone C #57 and river sand A.
Note. Numbers are WR dosage needed to pass the box test.

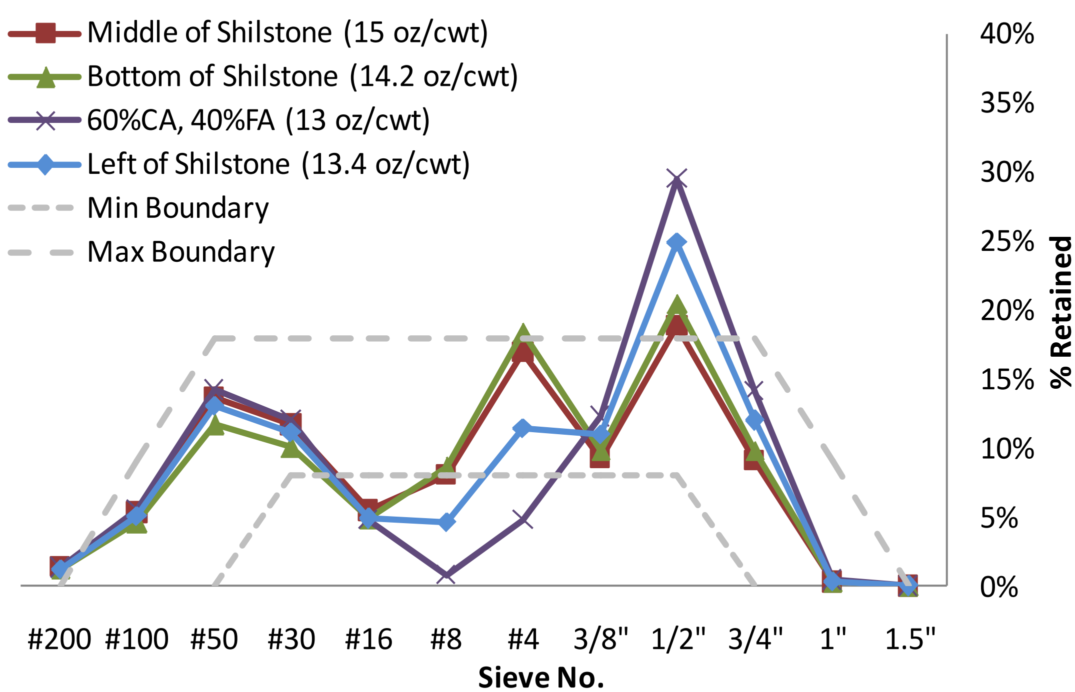


Figure 3-15 shows 5 sack limestone C #57 and river sand A.

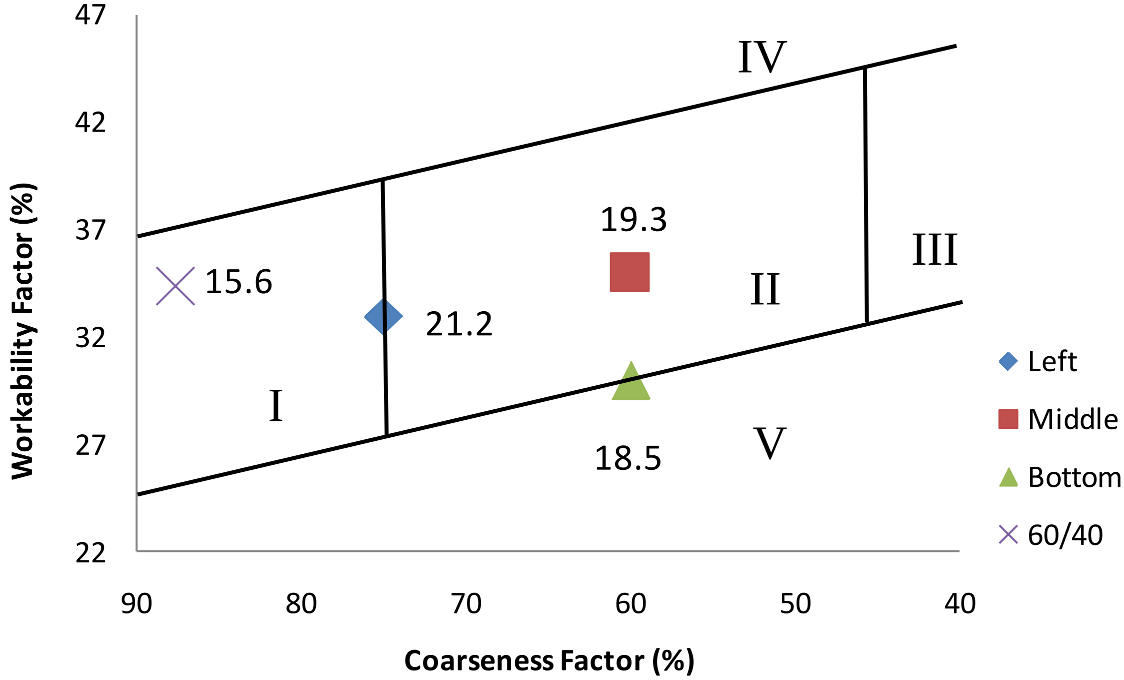


Figure 3-16 is a 5 sack limestone C and river sand B.
Note. Numbers are WR dosage needed to pass the box test.

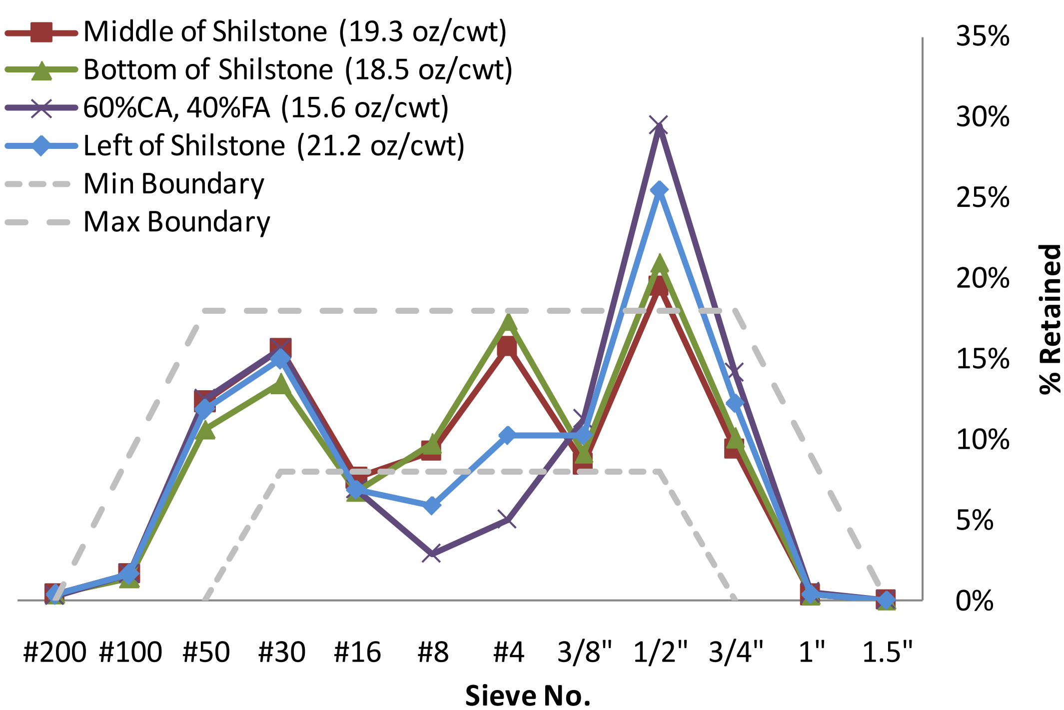


Figure 3-17 is a 5 sack limestone C and river sand B.

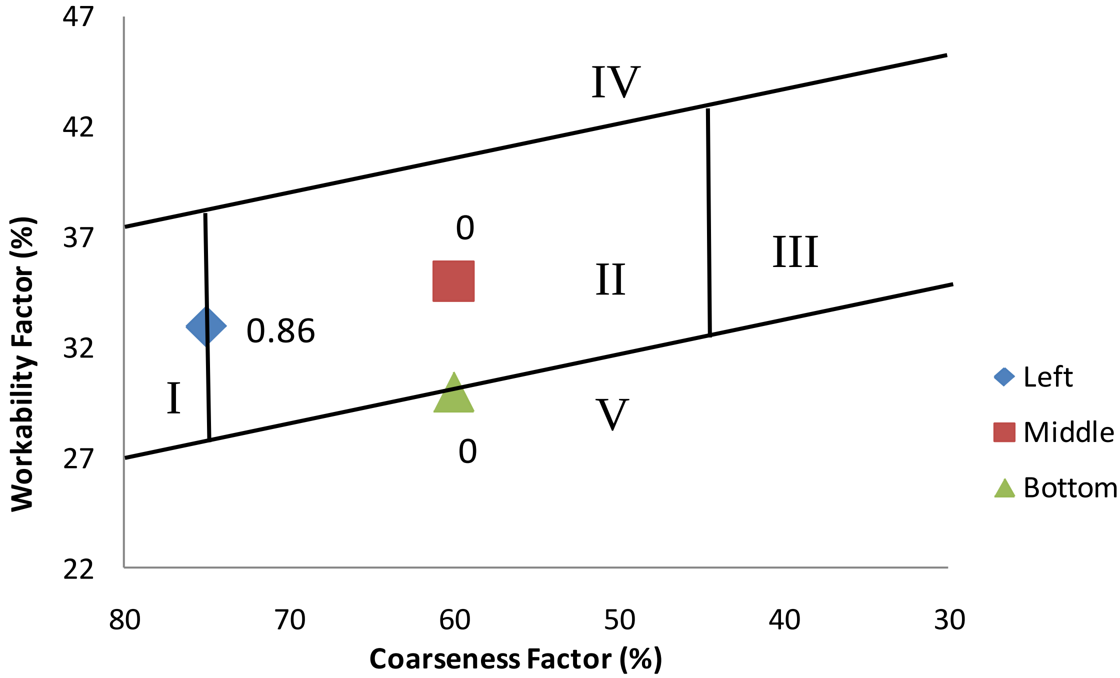


Figure 3-18 graphs 5 sack limestone A #57 and river sand A.
Note. Numbers are WR dosage needed to pass the box test.

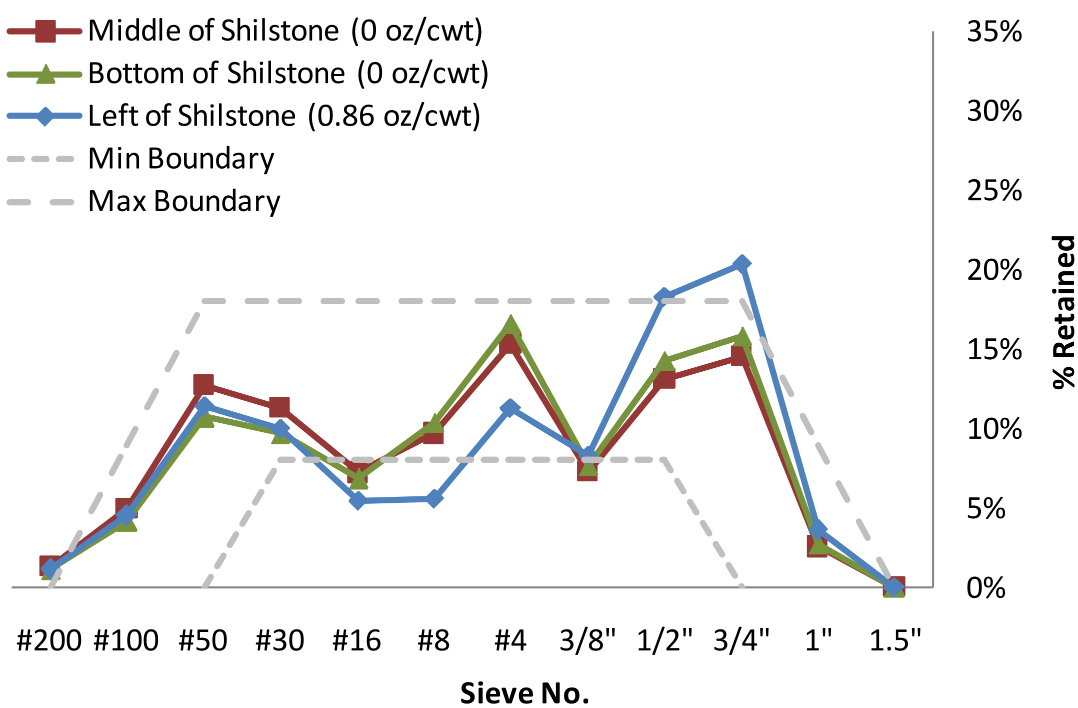


Figure 3-19 graphs 5 sack limestone A #57 and river sand A.

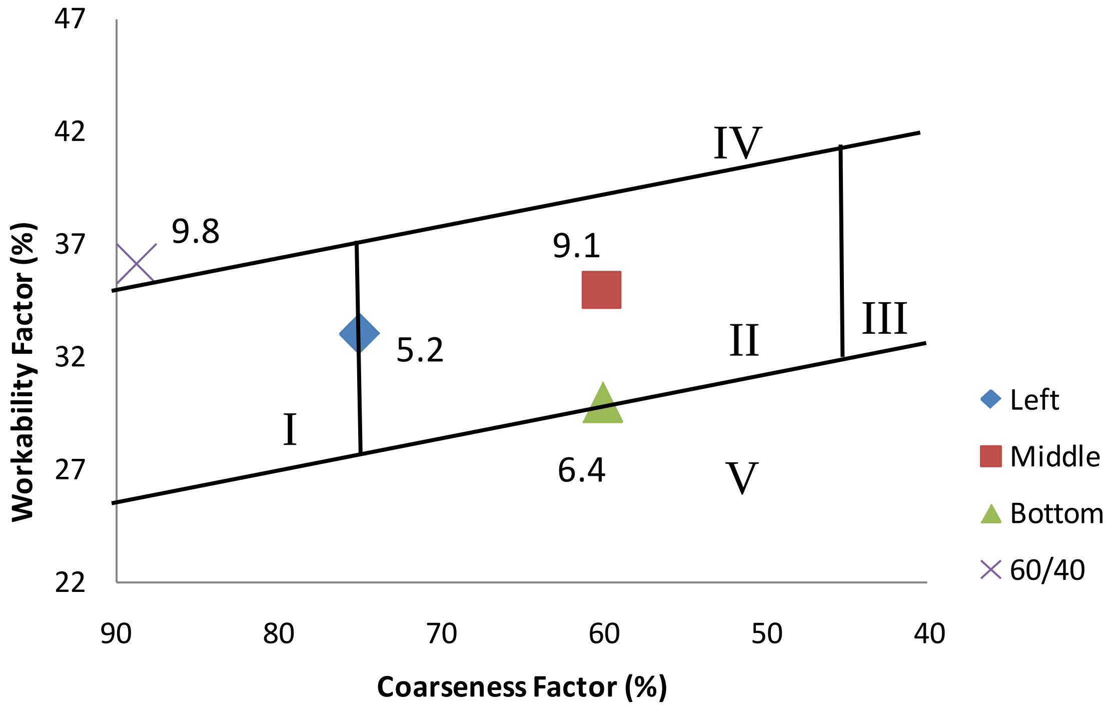


Figure 3-20 is a 4.5 sack limestone A #57 and river sand A.
Note. Numbers are WR dosage needed to pass the box test.

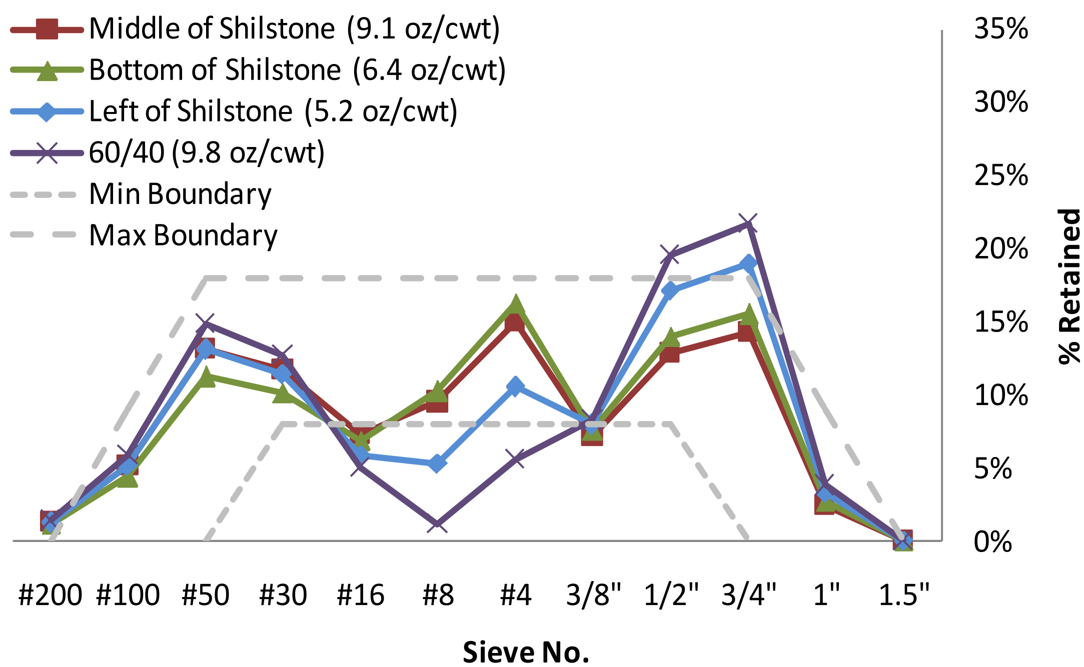


Figure 3-21 plots 4.5 sack limestone A #57 and river sand A.

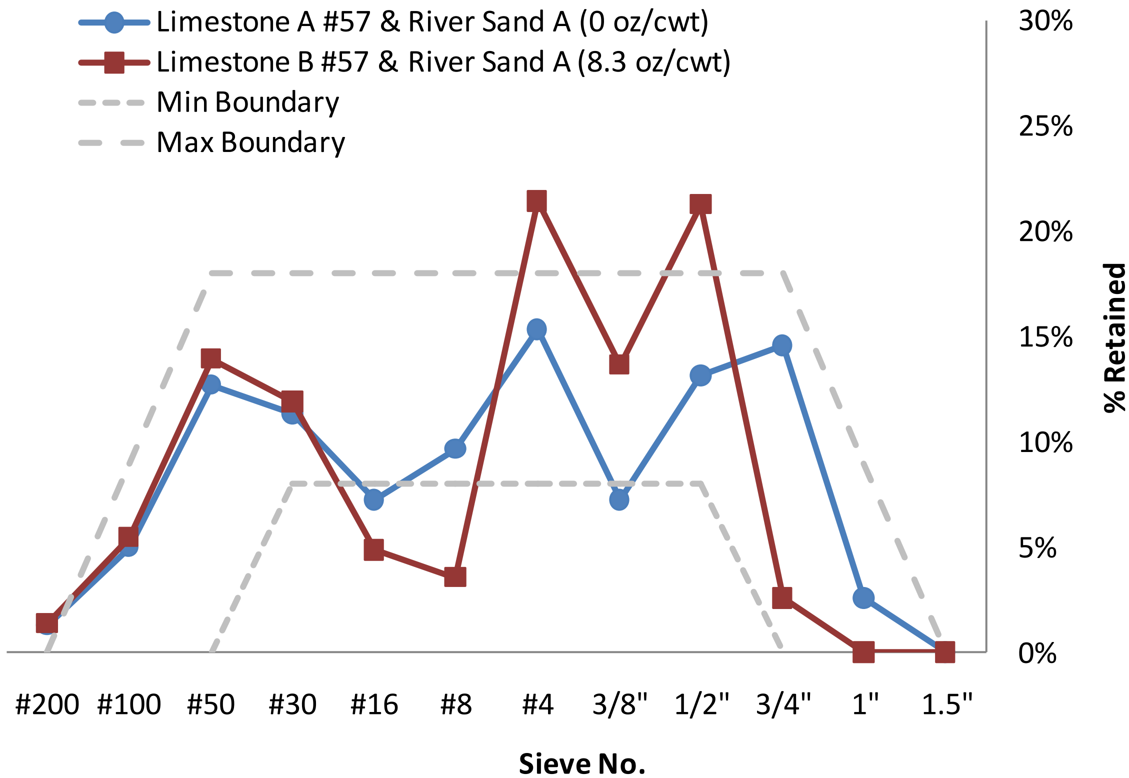


Figure 3-22 graphs middle of the Shilstone chart with a 5 sack mixtures.
Note. Numbers are WR dosage needed to pass the box test.

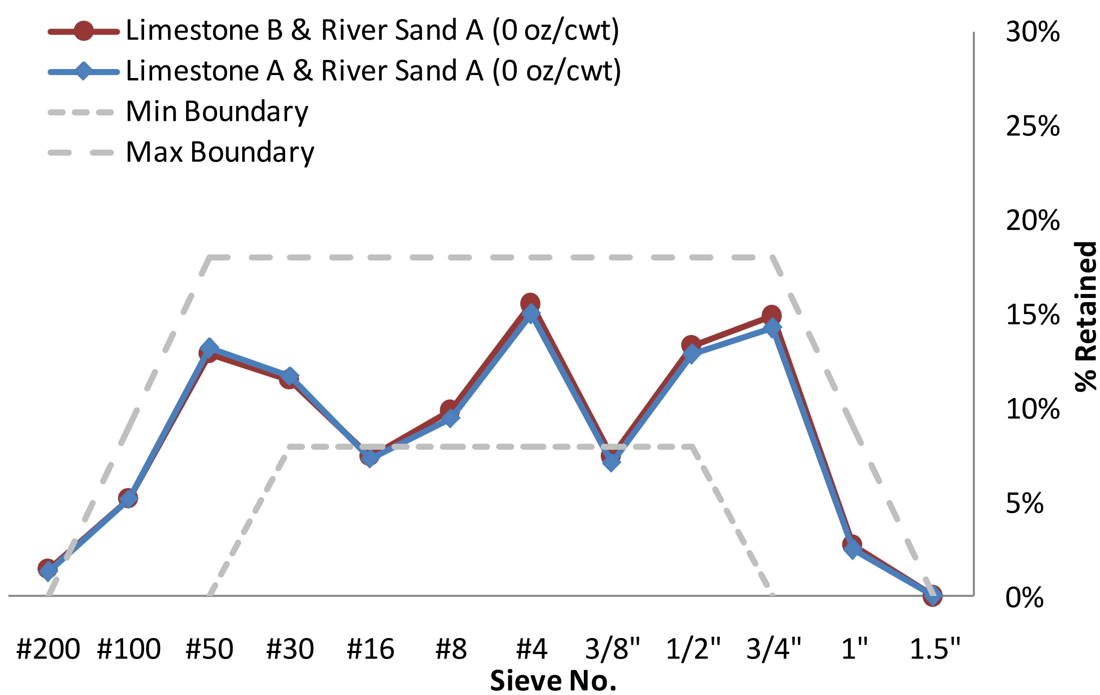


Figure 3-23 is a sieved limestone B to limestone A middle of the Shilstone chart with 5 sack mixture.

3.4 DISCUSSION

The box test evaluation procedure is a good method to evaluate a mixture's response to vibration. Shown in Tables 3-4 and 3-5, when a mixture passed the box test, the slump values of 0" to 2.5" corresponded very well to slump values for mixtures using slip form pavers in the field. Mixtures with larger amounts of intermediates had lower slumps. But the use of intermediates can help or hurt the response to vibration. The majority of the 60/40 mixtures had just as good workability as mixtures with intermediates. However, the 60/40 and left of chart mixtures were more susceptible to edge slumping issues.

The results indicate the Box Test and Slump Test are measuring two different phenomena. While the box test measures the response to vibration, the slump test only measures the downward movement of the concrete caused by its self-weight. The results showed two different mixtures with the same slump can respond to vibration differently, such as 60/40 and middle of the Shilstone using limestone B #57 and river sand A.

The Wenner probe measures the electrical resistivity of concrete. Theoretically, electrical resistivity should change with changes in pore solution chemistry and the connectivity of pores. Looking at Table 3-6, when the w/cm ratio or amount of cement changed, the resistivity did not have a noticeable change. Also, results indicate that gradations did not affect the electrical resistivity. However, as hydration time increased, then the resistivity decreased indicating greater resistance through the pore spaces of the hardened concrete mixtures over time.

If we look at the workability of a mixture and compare the WR dosages, then the lower the WR dosage a mixture requires, the better the mixture performances. Results shown in figures 3-12 to 3-25 suggest that the Shilstone chart is not reliable. Specifying the middle of zone II, or any specific place in zone II will not necessarily provide the best response to vibration. The Shilstone chart is a graphical representation of the percent ranges of the combined aggregates. The different zones give broad boundaries of the different proportions, but the zones are not exact. For example, in Figure 3-16, the 60/40 mixture proportion for 5 sack limestone B #57 and river sand B is located in zone II.

Looking at mixtures with a constant 0.45 w/cm and the same sack content in Table 3-5 and 3-6, the middle of the Shilstone chart, or any place on the Shilstone chart does not necessarily optimize aggregate gradation for the mixture. The Shilstone equations control the combined percent of coarse, intermediate, and fine aggregate, but do not necessarily determine the mixture's performance to vibration. This is likely because the Shilstone chart focuses only on a few sieve sizes. In Figures 3-12 through 25, different aggregates had completely different results because the distribution of aggregates was different.

As shown in Figure 3-27, limestone B #57 and river sand A were sieved to the exact aggregate distribution values of the middle of the Shilstone chart for limestone A #57 and river sand A. The sieved limestone B #57 and river sand A gradation had improved performance because it required less WR dosage to pass the box test; this gives a strong indication that the distribution of aggregate is important in determining how the mixture responds to vibration.

3.5 CONCLUSIONS

Based on the work in this chapter the following has been determined:

- A clear trend was not present for the performance response to vibration of mixtures with fixed paste content and gradations in different areas of the Shilstone box. It should be noted that using the middle of the Shilstone chart does not necessarily produce a concrete mixture that will respond to vibration.
- The distribution of aggregate sizes when plotted with the individual percent retained chart seems to best describe the impact of the aggregate gradation. Work is still needed to better understand the combined gradation of the individual percent retained on each sieve size.
- The box test was again shown to be a simple, quick, and useful test that has allowed significant insight into the workability of concrete mixtures and their response to vibration.

CHAPTER 4 - DEVELOPMENT OF A SPECIFICATION FOR AGGREGATE GRADATION IN SLIP FORMED PAVING

4.1 INTRODUCTION

Concrete mixtures must be proportioned to provide adequate durability, workability, and strength (Mehta and Monteriro 2006). Typically the durability performance of a concrete mixture is based on requiring that quality materials be used and limiting the water to binder ratio in the mixture (ACI 1990, Kosmatka et al. 2011, Mehta and Monteriro 2006, NSSGA 2013). It is common for strength requirements of concrete to be specified and verified in the field. This is critical to ensure that the constructed structure provides a sufficient safety factor for the desired usage. Finally the workability of a concrete mixture is required to be mixed, placed, consolidated, and the surface finished for the application (ACI 1990, Kosmatka et al. 2011, NSSGA 2013). To achieve the required workability, several adjustments can be made to the concrete mixture including the paste volume, plastic viscosity and yield stress, and the volume, shape, and gradation of the aggregates in the mixture. However, the workability of a concrete mixture is largely left to the contractor and material supplier to be determined for the construction equipment and resources available.

While it is possible to manipulate a concrete mixture in a number of ways to achieve the desired performance, the most beneficial way to obtain an economical but still durable and sustainable mixture is to reduce the amount of paste in the mixture and therefore increase the amount of aggregate, which is called optimized graded concrete. Unfortunately, the challenge of optimized graded concrete comes from an inherent loss of workability due to decreasing the paste content and increasing the aggregate volume.

History and experience show that a combined gradation can be designed to increase workability while reducing paste content (Shilstone 1990). However, current mixture design methods such as ACI 211 do not provide sufficient guidance for the aggregate gradation, shape, and other aggregate properties on the workability of a concrete mixture. Further, the workability varies depending on the intended use of the concrete mixture.

Many different concepts have been developed about the consistency of a combined gradation. Typically the concepts pertain to the overall flow of the combined gradation and the amount retained on individual sieve sizes. Over the years the broad terms gap-graded and well-graded have been used to describe the combined gradation. A well-graded mixture is expected to have moderate amounts of material retained on each sieve size, which has been theorized to improve aggregate packing. Some have gone as far as to suggest an ideal bell shaped curve will provide the gradation needed to maximize aggregate packing and therefore reduce paste content (Shilstone 1990, Kosmatka et al. 2011, Taylor et al. 2007). On the other end, a gap-graded mixture, which is typically used in the field, has low amounts on some of the intermediate sieve sizes. Many previous publications suggest if a relatively low amount is retained on a sieve size or sizes, it can cause significant impacts on the workability of the concrete.

Using experience and trial and error, optimized graded mixtures have produced satisfactory workability and multiple recommendations for aggregate gradation that have not been systematically investigated. In addition, many different gradation concepts and techniques have been developed, such as proportioning by volume, dry-rodded unit weights, fineness modulus, Shilstone workability chart, power 45 chart, and the percent retained chart (ACI 1990, Kosmatka et al. 2011, NSSGA 2013). However, the small amounts of research completed on these subjects do not provide useful guidance or understanding that can help the practitioner develop suitable mixtures for optimized graded concrete without extensive trial batching using the intended aggregates for each job.

The development of the aggregate guidelines would be extremely beneficial to improve the construction specifications and practices in Oklahoma, regionally, and even nationally. This report shows optimized graded concrete has the ability to reduce the total cementitious material in a mixture by about a sack, or 94 lbs per cubic yard over current mixture practices in Oklahoma. Not only will this decrease the cost of the mixture but it will also save the energy needed to create the cement and improve the durability of the concrete. The focus of this work has been to develop a straightforward, easy to implement, and predictable performance specification for optimized graded concrete pavements.

As shown in Chapters 2 and 3 of this report and other publications (Ley et al. 2012), work has been done to investigate different techniques to reduce the paste of the concrete but still allow the mixture to achieve the workability requirements. By using a fixed paste content and w/cm, the aggregate gradation and volume was changed according to different aggregate techniques. Then each mixture was measured for workability requirements of slip formed pavements using the Box Test, Slump Test, and observations of surface finishing with a hand float. From the work shown in Chapter 3 and other publications (Ley et al. 2012), the best technique our research team found to predict workability was the percent retained chart. This work will use this chart to develop useful limits to help in the design and specification of concrete for the Oklahoma DOT to be used in concrete pavements.

4.2 EXPERIMENTAL METHODS

4.2.1 Materials & Mixture Design

All of the mixtures investigated were designed with a constant paste volume, fly ash replacement, and w/cm. Each mixture had a constant volume of paste and total aggregate. However, the aggregate distribution and proportions were varied and a mid-range water reducer (WR) was used in a systematic manner to evaluate the impact on the aggregate gradation and volume to be investigated as described in Chapter 2. A 0.45 w/cm was used and the paste was held constant at 24.2% of the mixture volume. Each mixture had the equivalent of 4.5 sacks or 423 lbs of cementitious material per cubic yard of concrete with a 20% ASTM C618 class C fly ash replacement by weight. All the concrete mixtures described in this paper were prepared using an ASTM C150 Type I cement. The water reducer used was a lignosulfonate mid-range water reducer classified by ASTM C494.

The aggregates used in this study conformed to the Oklahoma Department of Transportation specifications. Two different river sand sources were used to evaluate gradation limits. A coarse and intermediate gradation was used from three different sources, which will be labeled crushed limestone A, crushed limestone B, and river gravel. Visually, the crushed limestones are jagged while the river rock is smooth. Also, the coarse aggregate was “cubical” shaped. For more information on the aggregate characteristics, refer to chapter 3 of the report and other work (Cook et al. 2013).

4.2.2 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 in this chapter. 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.

4.2.3 Mixing and Testing Procedure

The aggregates were collected from outside storage piles and brought into a temperature-controlled laboratory room at 73°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that 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 slump (ASTM C143), the Box Test as discussed in Chapter 2 of this report, and observations from surface finishing with a hand float.

A very important property of fresh concrete is the ability to finish the surface. On a slip formed paver, the pan profile is used to achieve the initial surface finish. It is essential that the paver and if required the finishers behind the paver are able to provide the necessary surface finish without significant effort. A simple way to evaluate surface finishability of concrete is to use a magnesium hand float with a consistent angle and constant downward force on the surface and observe the response. As the hand float passes over the top of the concrete, it will smooth the surface. If a large number of passes with a hand float were required, the mixture was deemed difficult to surface finish. This was an important criteria and so was investigated on each mixture.

If the mixture responded poorly to vibration, the material was placed back into the mixer and remixed with an additional WR dosage. This process continued until enough WR was added until the mixture received a ranking of 2. Next, the surface finishability of the mixture was evaluated and cylinders were made. A visual description of the testing procedure can be shown in Figure 4-1.

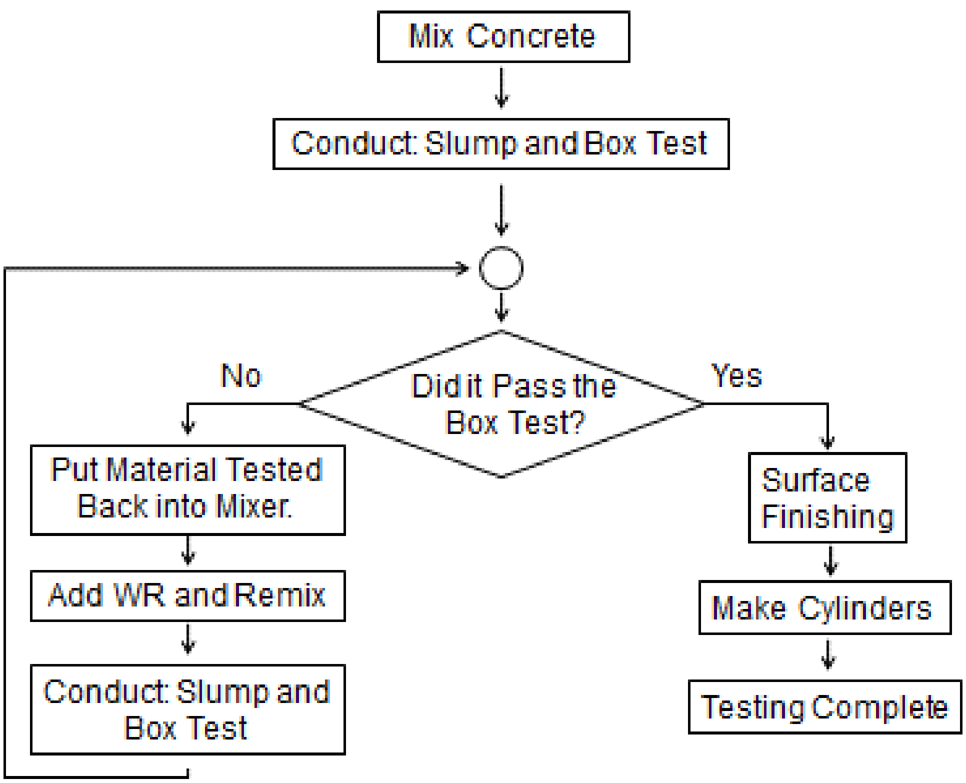


Figure 4-1 shows a flow chart of the testing procedure.

4.3 RESULTS & DISCUSSION

The purpose of the research was to develop guidelines for aggregate gradation and proportioning in order to better control a concrete mixture design for concrete contractors, engineers and suppliers. To develop limits for each sieve size, the combined gradation was plotted in percent retained charts because the research shown in Chapter 3 and previous publications (Cook 2013, Ley et al. 2012) demonstrated that I was a useful way to compare and evaluate the data from various concrete mixtures and aggregate proportions. The area under the curve in the percent retained chart has a total volume of 100%. When the amount of a sieve size is reduced, another sieve size or sizes must increase.

Also, each combined gradation curve on a percent retained chart has an arrow with a number corresponding to the WR dosage that allowed this combined gradation to pass the Box Test. With single operators having a repeatability of 2.74 oz/cwt with a 95% confidence interval, mixtures were compared for efficiency by the amount of water reducer required to achieve a Box Test Rating of 2. In other words, if two different mixtures have a WR dosage within 2.74 oz/cwt of each other, no difference can be determined. For more information on the methodology of the Box Test and the performance ratings for the Box Test, refer to Chapter 2. Gradations requiring high WR dosages are not as desirable as those that require low dosages. The WR dosage in this testing is an indicator of the water demand or workability of the mixture. For this research, any mixture shown to have a WR demand higher than 12 oz/cwt was determined to have poor workability. For these mixtures this suggests that a higher volume of paste is needed in the mixture for satisfactory performance, and this is not desirable as the goal of this work is to minimize paste content. It should be noted that the authors are not suggesting that the indicated WR dosages would match the required WR dosage for the field due to different effectiveness of admixture type, operator techniques, and various slip formed paver equipment. Instead, the WR dosage requirements should be used as a comparison tool for indicating the workability of a mixture at varying gradations.

Unless otherwise stated, crushed limestone A and river sand A were used as the main aggregate sources for developing the individual sieve limits. Other aggregate sources were utilized later to validate the limits.

4.3.1 Coarse Aggregate

Figure 4-2 shows a series of gradations with the weight and gradation of sand was held constant while varying the coarse and intermediate crushed limestone A to investigate the impacts of gradation on the WR dosage required to achieve a Box Test Rating of 2. The five different gradations in the middle of the chart had similar WR amounts, which ranged from 2.9 to 6.3 oz/cwt. However, when the amount of coarse or intermediate for a given aggregate became excessive on a single sieve or multiple sieves then the WR requirement drastically increased. This seems to suggest the coarse aggregate should be limited to 20% and the intermediate sieve sizes to 23% To simplify gradation limits for a single sieve size ranging from #4 to 3/4”, it could be set to 20%. The 20% retained on the #4 to 3/4” sieve size range will be a reoccurring trend throughout these results and serve as a key finding of this work.

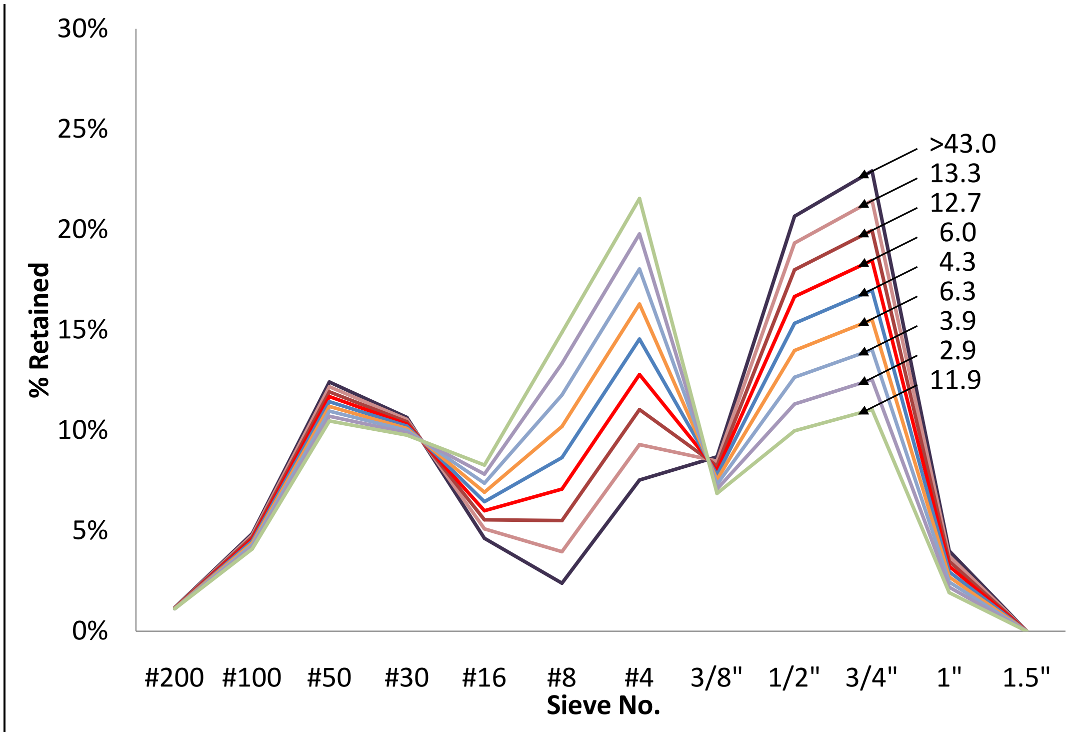


Figure 4-2 compares the WR required to pass the Box Test with a constant volume and gradation of sand and different ratios of coarse to intermediate of limestone A.

Additionally, the gradation with the lowest amount of intermediate and highest amount of coarse aggregate required over 43.0 oz/cwt and had large segregation and edge slumping issues. It is intriguing that the workability of the mixture so suddenly deteriorated due to the change in aggregate gradation. The lack of intermediate coupled with over 20% coarse amounts on adjacent sieve sizes did not allow the mixture to respond to vibration because the gradation created an inability of the mixture to stay together, or what has been suggested as a lack of cohesion. This observation suggests the intermediate sizes in a mixture help provide cohesion. This supports findings by Neville (2011).

4.3.1.1 Impact of Gap-Gradation

The impact of gap-gradation was investigated in further detail using mixtures with a constant volume and gradation of sand and varying amounts of intermediate and coarse aggregate as shown in Figure 4-3. The gradation requiring 4.3 oz/cwt, which is a typical field gradation using #57 and a 3/8" chip, had a minor gap on the 3/8" sieve size. To determine if the minor gap effected the WR required, the gap was removed on the 3/8" sieve and lowered on the #4 sieve. By removing this minor gap, it lowered the WR required to 0 oz/cwt. However, this alteration was on the borderline of requiring a small amount of WR. To investigate gap-gradations further, the intermediate sieve sizes were redistributed to the ¾" and ½" sieve size. The gradation required more than 43 oz/cwt and had segregation and edge slumping issues due to the amounts of aggregate on the ¾" and ½" sieve sizes were above the 20% boundary which was found to be an excessive amount in the previous section.

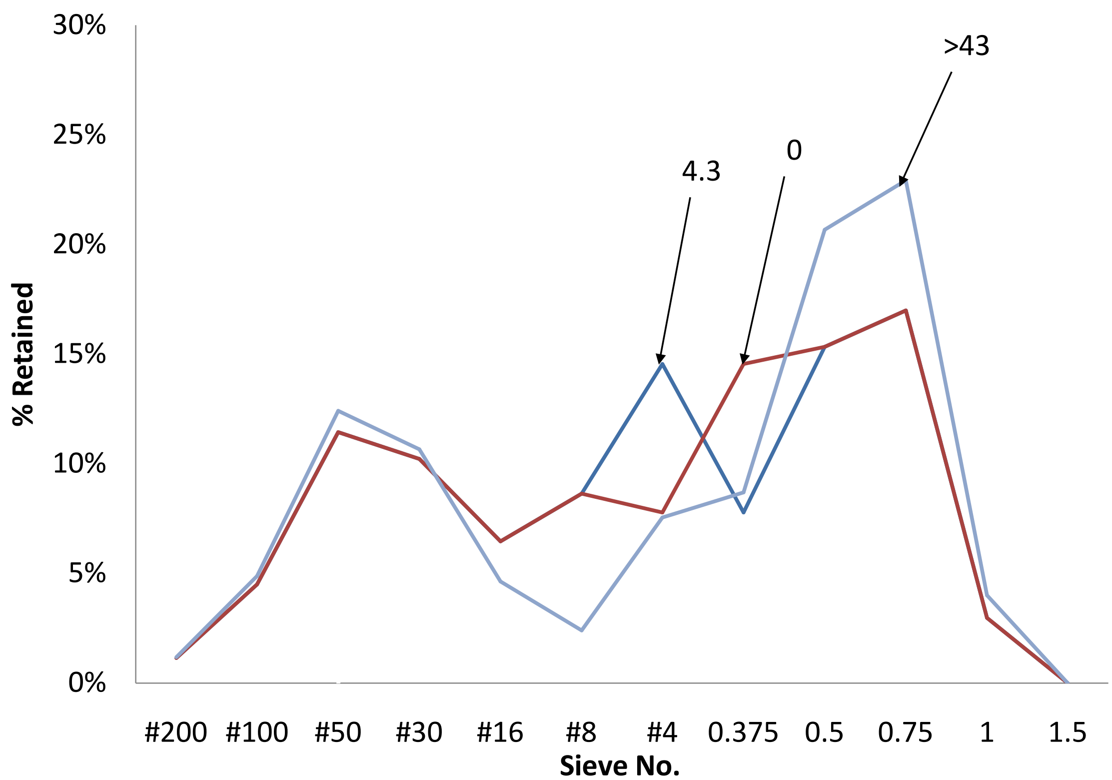


Figure 4-3 shows the performance of different degrees of gap-graded.

4.3.1.2 Impact of Valleys in Gradation Curves

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 4-4 shows gradations containing various amounts on the 3/8" sieve size. The results show a gradation having a single valley or no aggregate retained on the 3/8" sieve does not affect the performance of the mixtures. It should be noted that while changing the gradation of this mixture no single sieve size was greater than 20%.

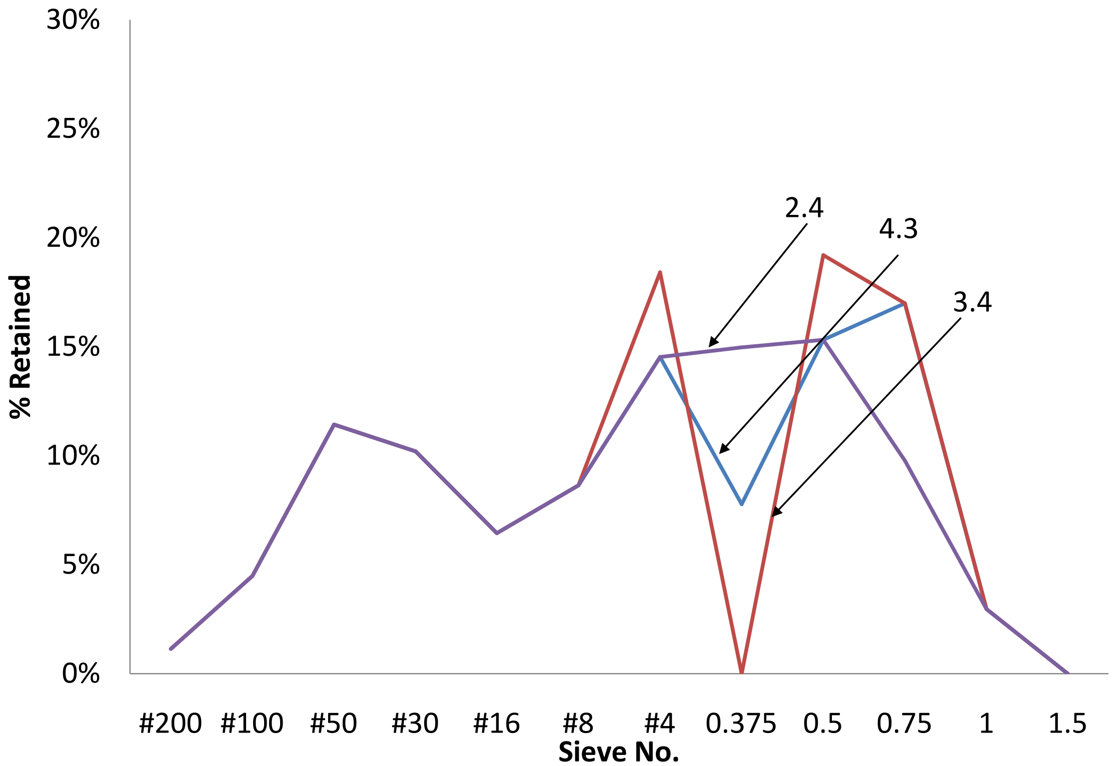


Figure 4-4 compares WR dosage requirements of various aggregate amounts on the 3/8" sieve size.

To further investigate the performance of varying degrees of a valley, the gradations of two adjacent sieve sizes were varied as shown in Figure 4-5. Two of the gradations performed satisfactorily, but the gradation not containing any 0.375" and 0.5" sieve sizes had an increase demand in WR of 4.5 oz/cwt. The mixture contained large amounts of 0.75" and #4 aggregate sizes, which was near the maximum boundary limit of 20% limits of those sieve sizes. This supports the idea that mixtures performed satisfactorily as long as a single aggregate size did not retain too large of an amount.

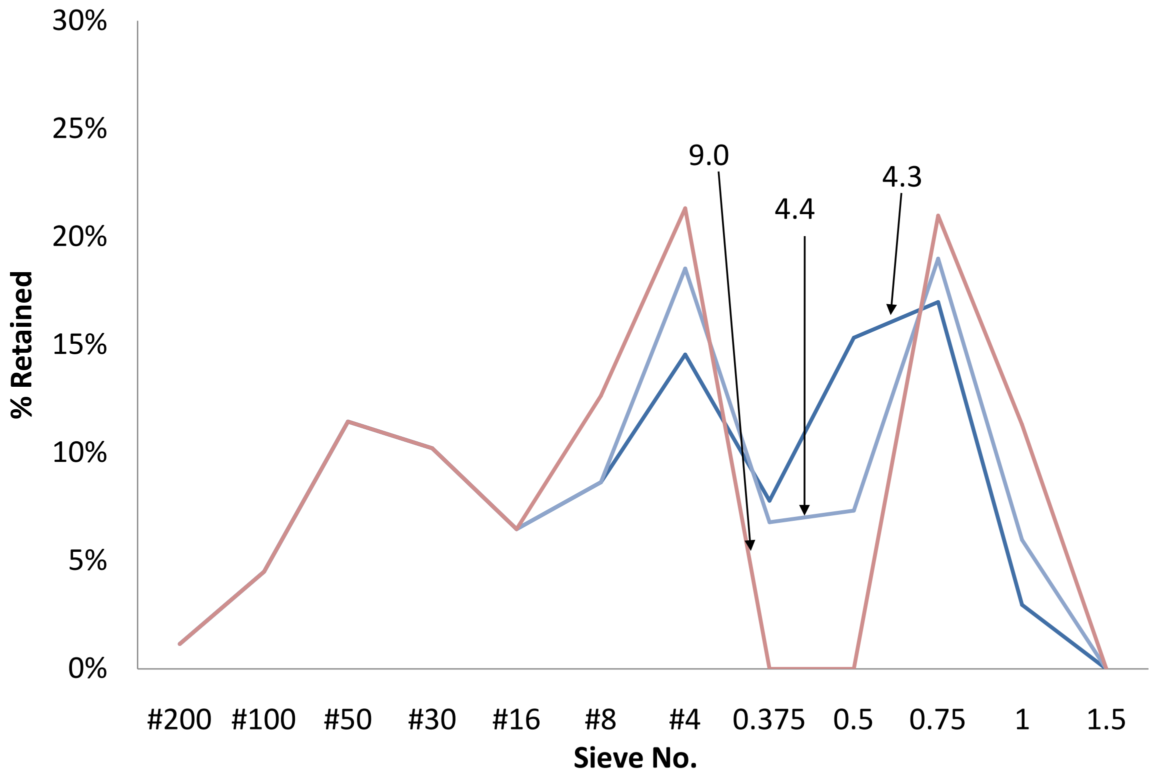


Figure 4-5 compares the WR dosage required for varying amounts on the 3/8" and ½" sieve size.

<u>4.3.1.3 Impact on Maximum Aggregate Size</u>

Multiple mixture design methods and publications claim the maximum size of the coarse aggregate affects the workability of the concrete (ACI 1990, Kosmatka et al. 2011, Mehta and Monteriro 2006, Fookes et al. 2001, Powers 1968). To determine the validity of these claims, ½", ¾", and 1" maximum size gradations were evaluated in Figure 4-6. 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 very little difference in workability. The 1" maximum mixture required the lowest WR dosage to pass the box test but this difference is not significant. 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.

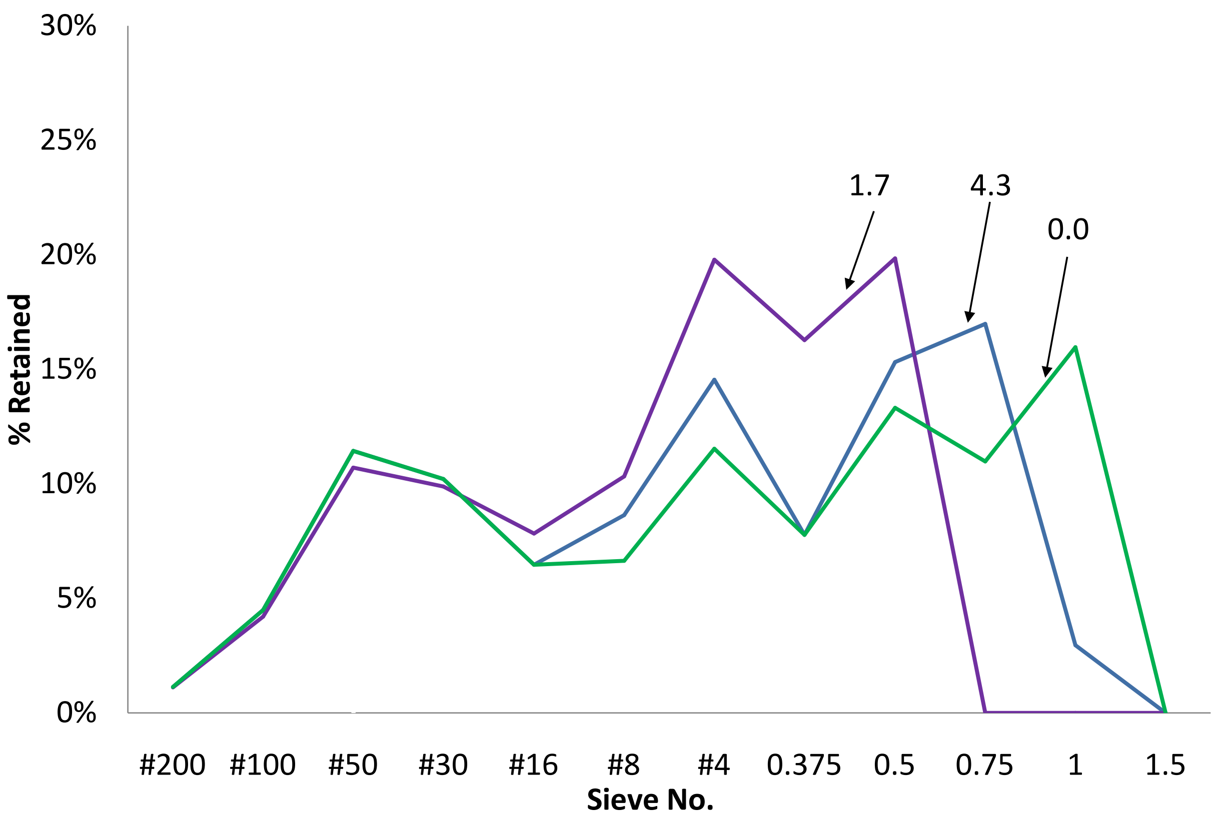


Figure 4-6 compares the WR requirements to the different maximum sieve sizes with closely consistent sand amounts.

4.3.1.4 Ideal Versus Actual Gradations

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. Figure 4-7 compares the ideal bell shaped curve and a practical gradation curve that was obtained by combining two aggregates locally available in Oklahoma. Both gradations required similar amounts of WR dosage. However, a visual observation using a hand float for the surface finish concluded these high amounts of #8 and #16 caused finishing problems in the concrete. After 10 to 15 passes with a hand float, paste came to the surface. When the hand float passed over the surface of the concrete, excessive amounts of #8 and #16 created holes behind the hand float. After 30 to 35 passes it was concluded these high amounts of #8 and #16 could not possibly obtain the necessary surface finish without leaving surface holes. These issues are similar to those reported with manufactured sands in the field. Not only is the ideal bell shape curve not practical, but this data suggests the ideal bell shaped curve produces a mixture with more problems than other practical gradations and is therefore not recommended.

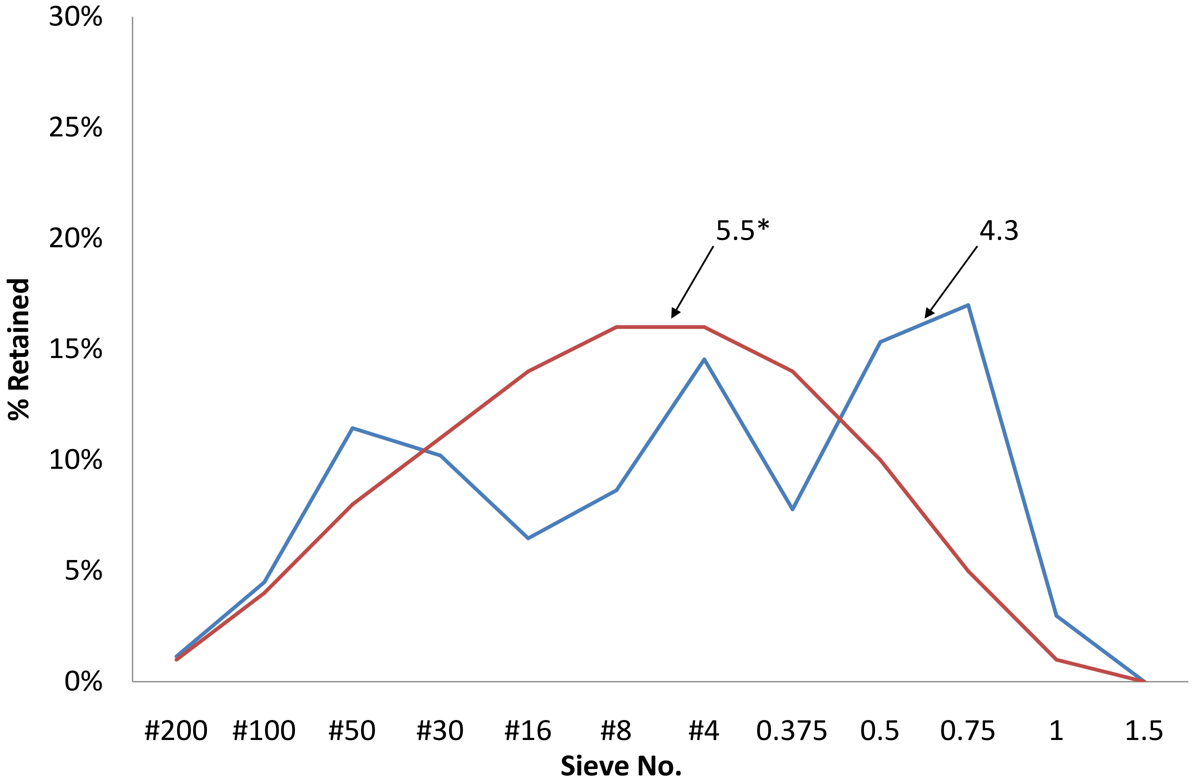


Figure 4-7 compares the performance of the ideal bell shaped curve with a practical gradation. *note: this mixture had surface finishability issues.

4.3.1.5 Using other Aggregates to Investigate Coarse and Intermediate Limits

From many of the previous figures, individual maximum sieve limits for the 1” to #4 sieve sizes were found. Some of the sieve sieves such as ¾” sieve could not exceed 20% while the #4 sieve size should be limited to 22%. To validate these upper limits, mixtures were produced with river gravel and previously used river sand A as shown in Figure 4-8. Figure 4-9 shows results with crushed limestone B and previous river sand A. The previously established gradation limits were found to require high amounts of WR with these aggregates. From the results, the #4 and 3/8” again could exceed 20% by only a few percentage while the 1/2" could not exceed 20% without reducing workability.

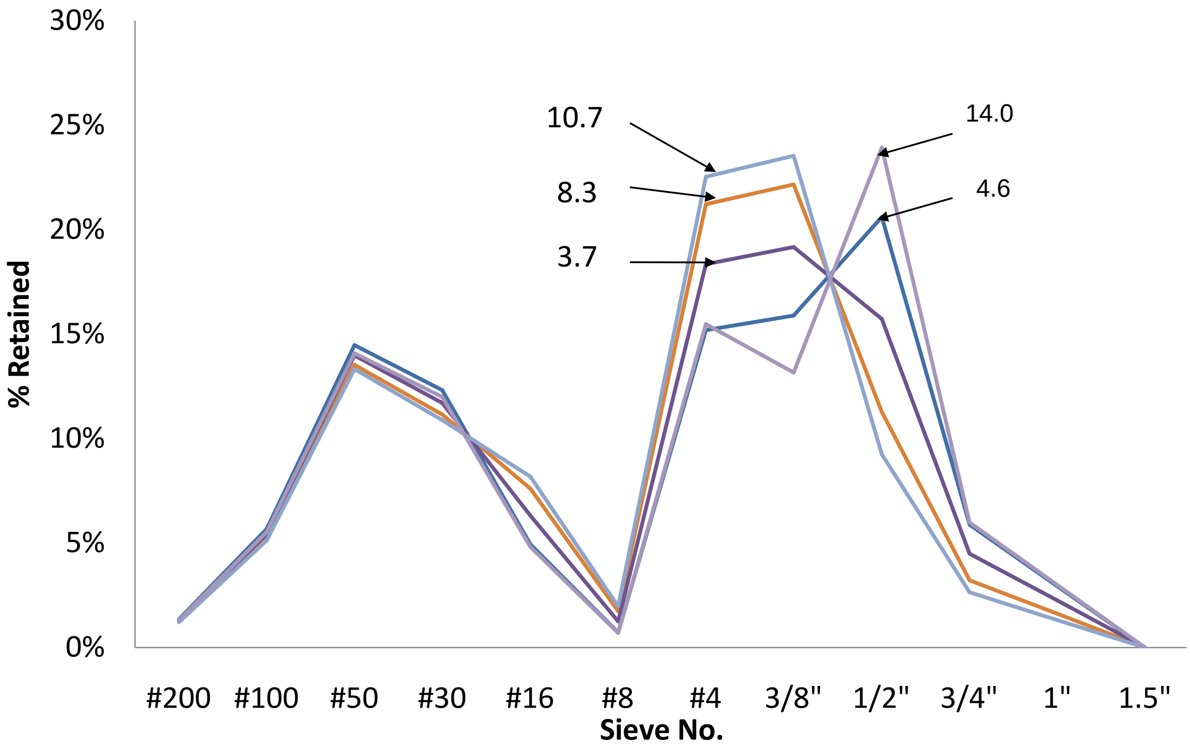


Figure 4-8 compares the WR dosage requirements for various river gravel gradations.

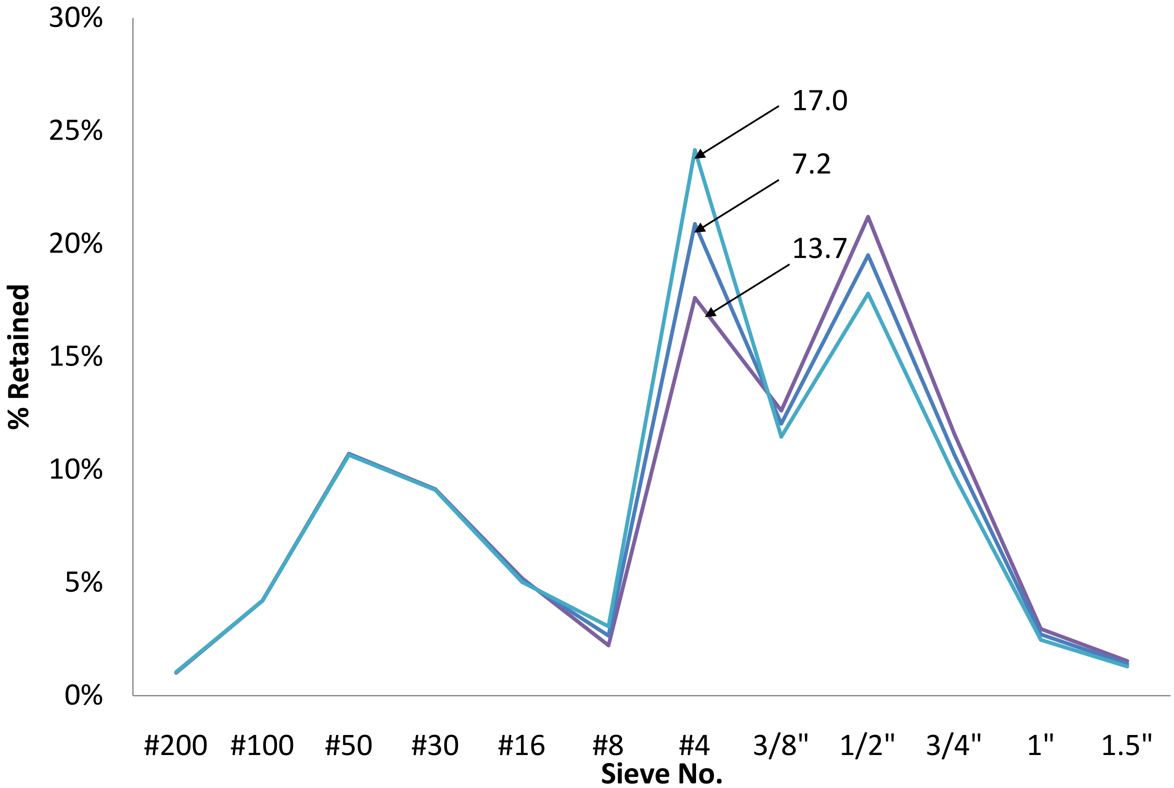


Figure 4-9 compares the performance of crushed limestone B with the required WR.

4.3.2 Fine Aggregate

A concrete mixture must contain a certain amount of sand to accomplish placement, consolidation, and surface finishing in the desirable application. Sand is traditionally defined as the material retained on the #8-200 sieve sizes. Sands have been described as being either fine or coarse. To simplify the succeeding discussions, the volume range of #30 to #200 sieve sizes will be referred to as “fine sand” in the document and #4 through #30 sieve sizes as “coarse sand”. The sand sieve sizes are not well understood and not currently predictable because it is impractical to control the sieve sizes in the field and can vary drastically from location to location. The goal of the investigation into sand is to better understand the distribution and proportions of fine aggregate sieve sizes. To do this, the following variables were investigated: determining the sieve ranges that make-up coarse sand and fine sand and the volumes required to achieve the preferred workability.

4.3.2.1 Proportioning of Sand

To begin understanding the behavior of fine aggregate, Figure 4-10 shows varying amounts of sand with a constant ratio of the coarse to intermediate aggregate.

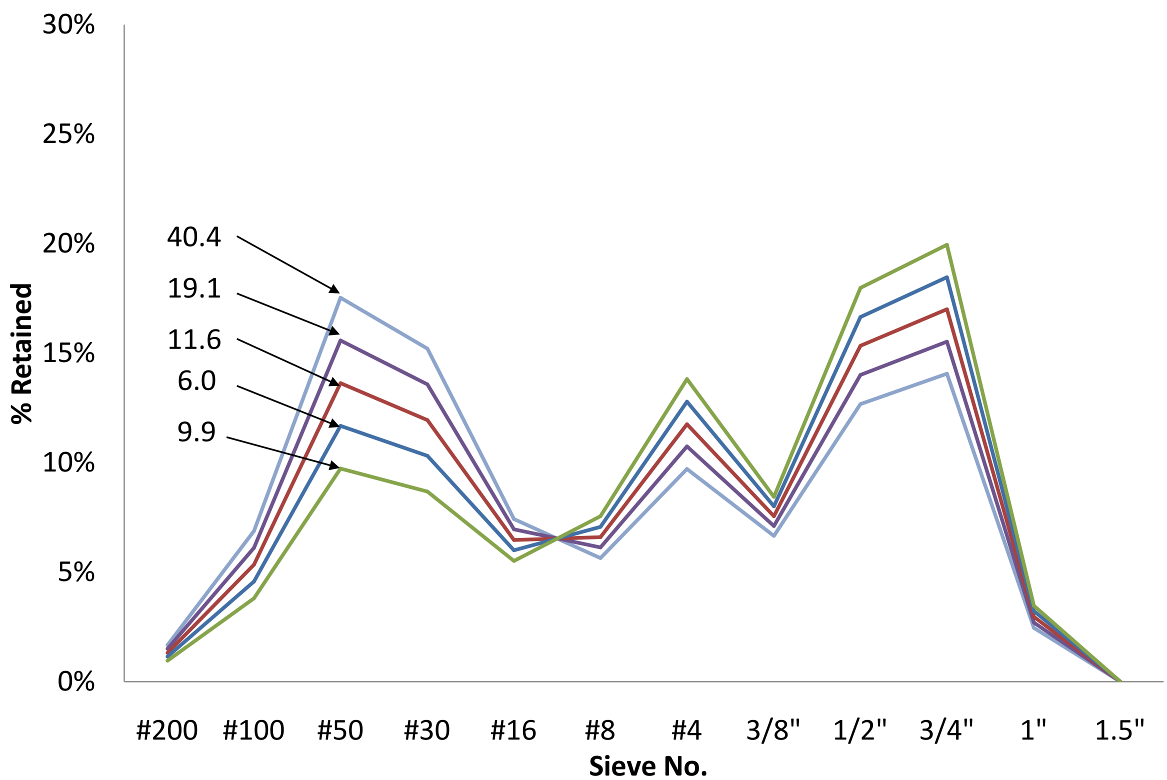
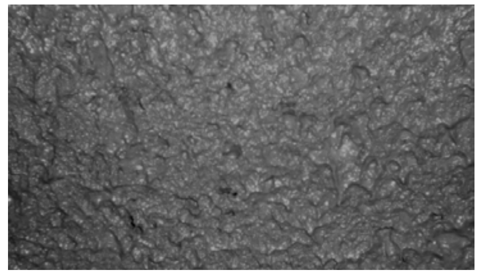
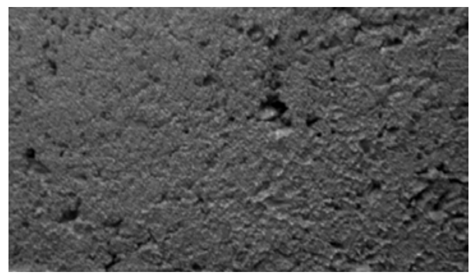
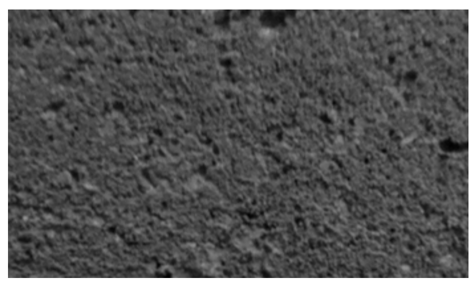


Figure 4-10 compares of mixtures with different amounts of sand and fixed ratio of coarse to intermediate aggregate.

As shown in Figure 10 if too much or too little fine sand is present in the mixture, the workability will be reduced. When the volume of sand was low in the mixture, the mixture looked like aggregates coated with a small film of paste. This mixture was very difficult to consolidate and surface finish. When higher volumes of sand were used, the mixture became stiff, which created difficultly in surface finishing and consolidation. A picture and description of a low, medium, and high amount of sand is presented in Table 4-1.

Table 4-1 Concrete Surface with Different Volumes of Sand

Amount of Sand	Description	Picture
Low	Acting like paste with coarse aggregate, low sand amounts reduce consolidating and surface finishing of the concrete.	
Medium	The mixture will consolidate and finish well.	
High	High sand amounts increase the paste content required to achieve a certain workability and causes finishing problems.	

4.3.1.2 Coarse Sand

To investigate and understand the characteristics of coarse sand, #4 through #30 sieve sizes were evaluated as shown in Figures 4-11 through 4-13. A published rule of thumb for creating the cohesive property associated with a coarse sand has been claimed a mixture requires the sum of #8 and #16 to be lower than 12.5% or edge slumping issues will occur (Richard 2005).

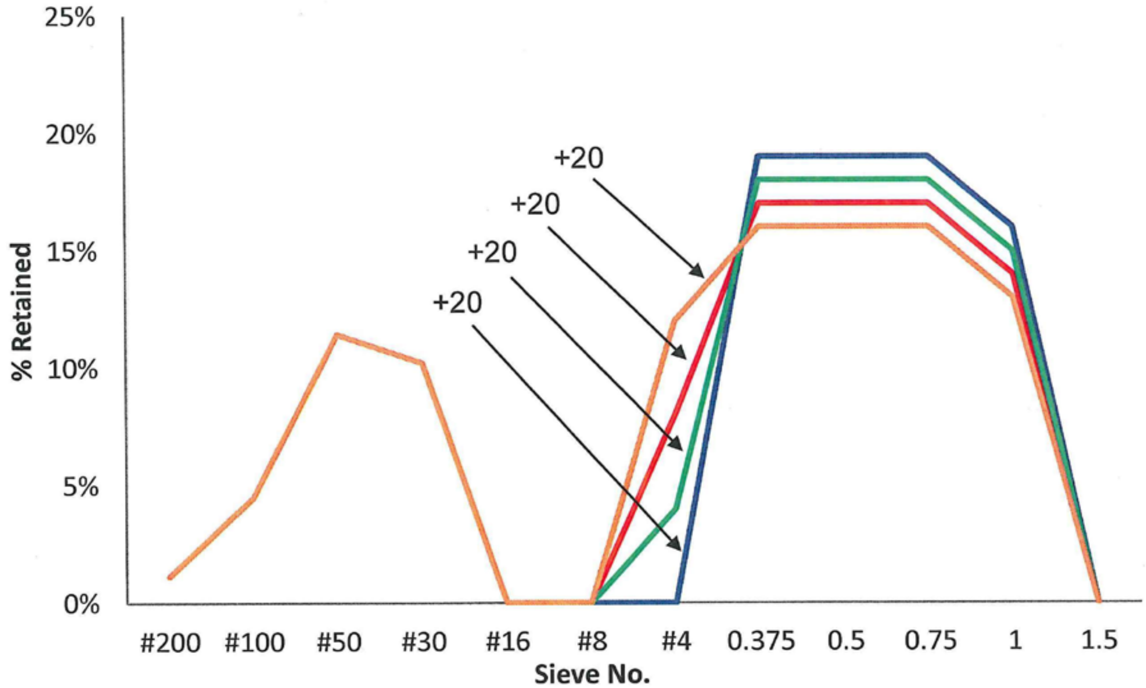


Figure 4-11 compares the performance of different amounts of #4 sieve size.

After removing the amounts retained on the #8 and #16 sieve sizes, the effects of #4 were investigated by varying the amount of #4 from 0% to 12% retained. Each of the gradations preformed similarly and could not respond to vibration even after 20 oz/cwt. From visual observations, each mixture had segregation issues where the coarse aggregate and mortar could not stick together. As more WR was added, it lowered the viscosity of the paste, but actually reduced the ability of the paste to cling to the coarse aggregate and become a single homogenous mixture. Even with 12% of #4, the mortar and coarse aggregate did not act as a single homogenous mixture. Also, the concrete sample from the Box test began to start edge slumping because the mortar did not want to stick to the coarse aggregate. This concludes that #4 does not largely contribute to the properties associated with mortar and perhaps should not be classified as fine aggregate.

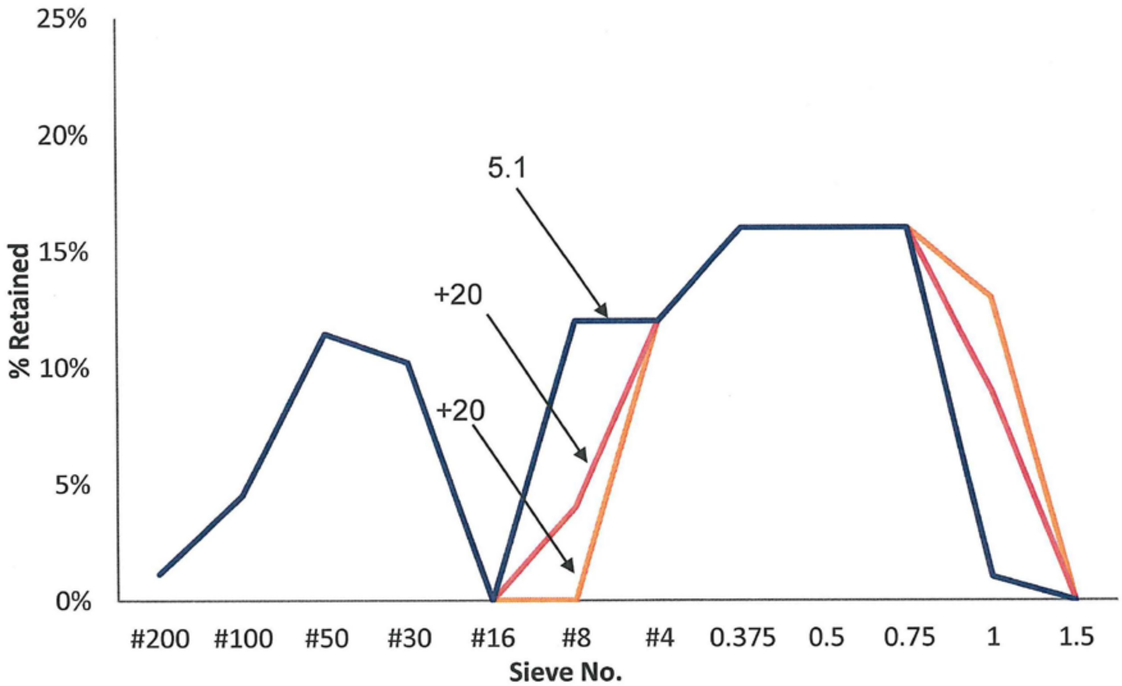


Figure 4-12 compares the performance of different amounts of #8 sieve size.

Next, the effects of #8 were investigated by varying the amount of #8 from 0%, 4%, and 12% retained. From visual observations, the mixture using only 0% and 4% retained on the #8 had minor segregation issues where the coarse aggregate and mortar could not stick together. This is similar to the results in Figure 4-11. However, the 12% retained on the #8 allowed the coarse aggregate and mortar to cling together and had a good surface finishing.

After removing the amounts retained of the #8 and #16 sieve sizes, the effects of #16 were investigated by varying the amount of #16 from 0%, 4%, and 12% retained. The mixture using 4% retained on the #16 came together similarly to mixture with 12% retained on the #8 in Figure 11. The 12% retained on the #16 stayed together and had an adequate surface finishability. This data suggests that the published rule of thumb is conservative (Richardson) and lower values can still produce a cohesive mixture.

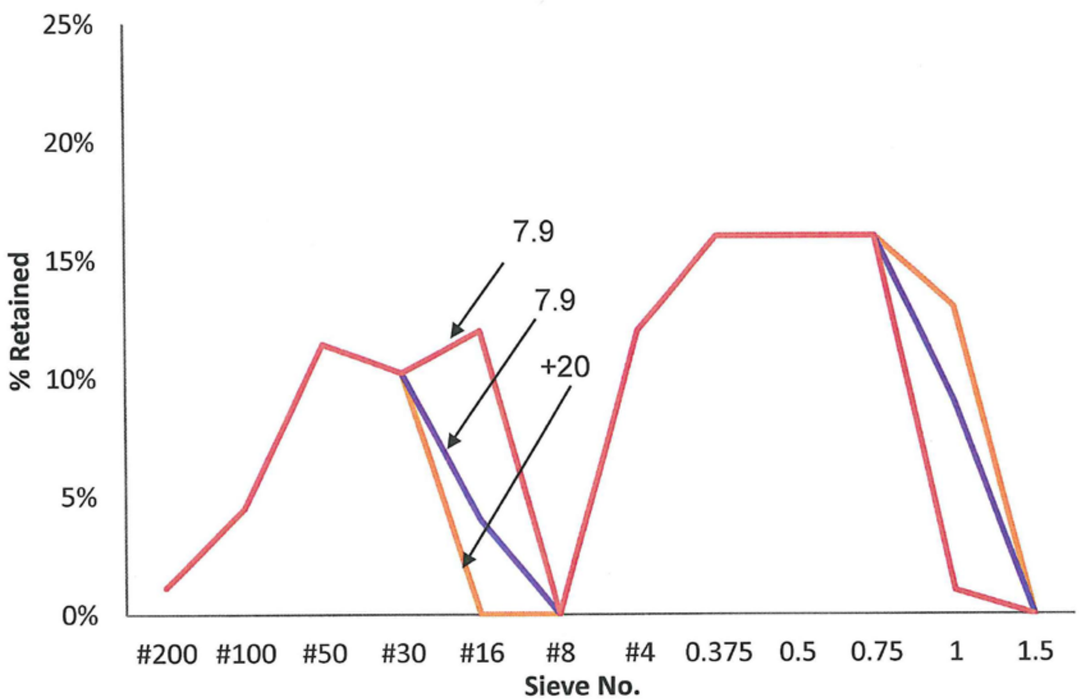


Figure 4-13 compares the performance of different amount #16 sieve size.

The results of Figure 4-7 showed finishability issues were created when both 16% was retained on the #8 sieve and 14% was retained on the #16 sieve. To further investigate surface finishability issues, Figure 4-14 shows one mixture with 12% on both the #8 and #16 sieve size. Also in Figure 4-14, another mixture has 20% retained on the #30 sieve size with 0% retained on the #8 and #16.

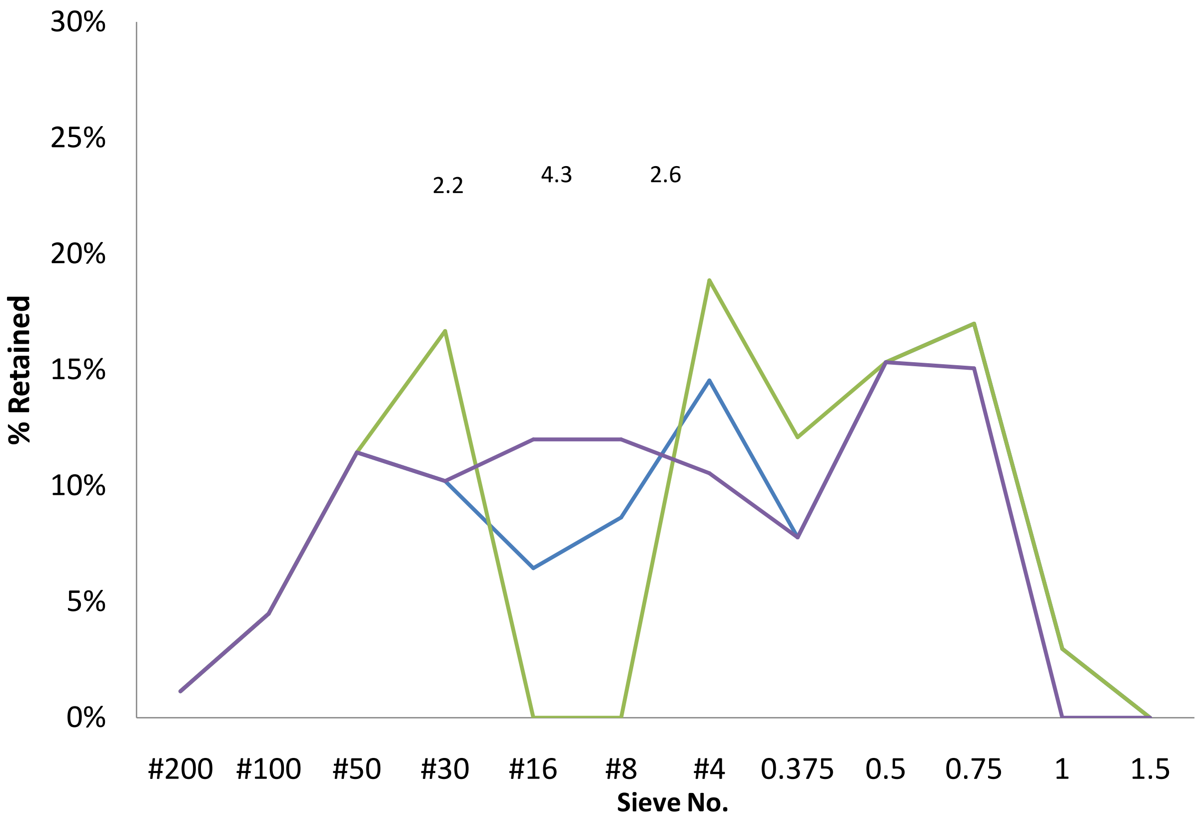


Figure 4-14 compares the surface finishability performance of #8, #16, and #30 sieve sizes.

In Figure 4-14 the gradation with 12% retained on the #8 and #16 sieve sizes did not require large amounts of WR. For hand finishing, 12% on the #8 and #16 was determined to be tolerable and higher amounts especially on the #16 sieve size is not recommended.

Also, #30 sieve size was investigated to determine the influences of cohesion on a mixture. In Figure 4-14, a gradation was used that did not have any #8 and #16, but had 17% #30. The mixture responded favorably to vibration, surface finishing, and ability to hold an edge. From visual observations, #30 created a stiffer mixture that was shown to bring the coarse aggregate and mortar together. The mixture still performed well even when the #8 and #16 sieve sizes were zero. This indicates a mixture does not necessarily need the #8 and #16 sieve sizes for consolidation but higher amounts of

#30 may be necessary. However, more research is needed to understand the interaction of #8, #16, and #30 sieve sizes on the workability of concrete. A recommendation is made that at least 15% of the aggregate should be on the #8 through #30 sieve.

4.3.2.3 Fine Sand

To begin understanding the mortar property of concrete, Figure 4-15 investigates the effects of minor changes in the #30 to 200 sieve sizes on the performance of a mixture. Using a constant gradation on the 1" to #16 sieve sizes, three different gradations were evaluated with a constant volume of #30 to 200 sieve sizes, but small changes in the distribution of those four sieve sizes. The results show small amounts of variation do not drastically change the workability.

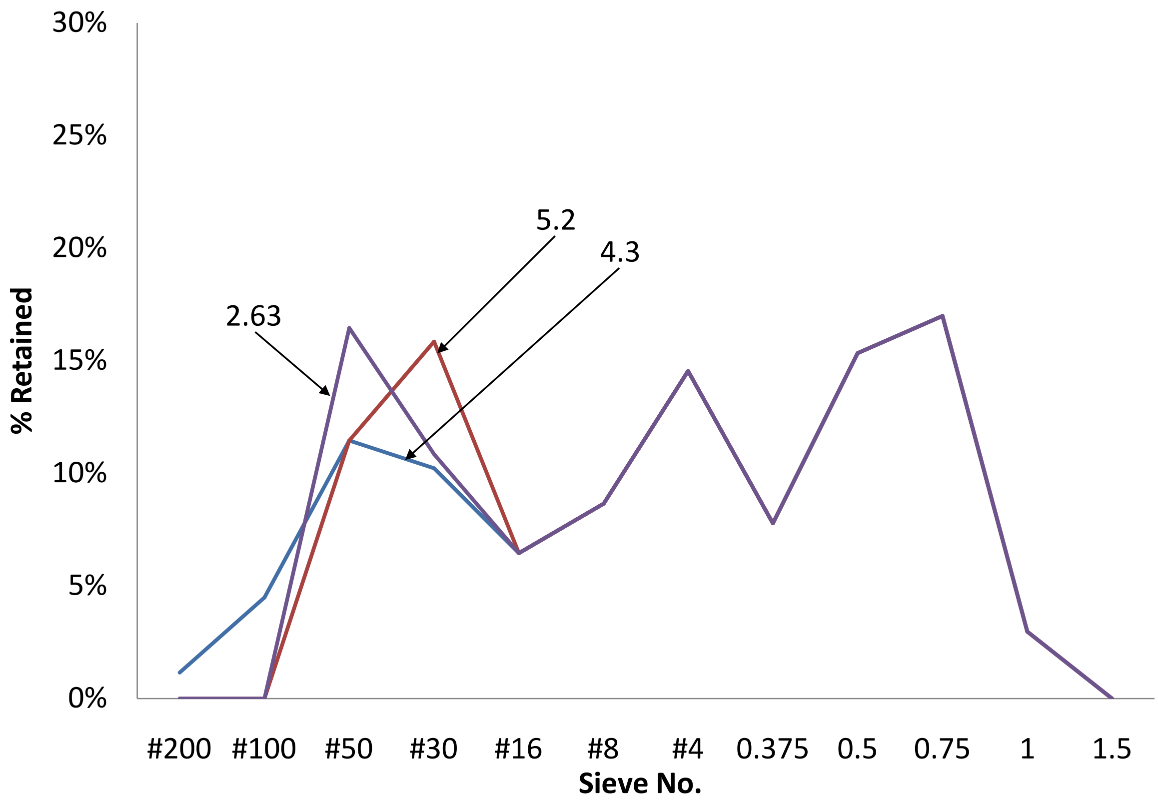


Figure 4-15 compares WR requirements of minor gradation changes on the #30-200 sieve sizes.

4.3.2.3.1 Distribution of #30 Sieve Size

To determine the effects of different amounts retained on the #30 sieve size, the mixtures in Figure 4-16 were designed to have a constant gradation on the 1" to #16 sieve sizes with varying amounts on the #30 sieve. High amounts of WR were required when 27% was retained on the #30 sieve. Also, the gradation close to 20% on the #30 sieve had issues with surface finishing. When a hand float was used on the surface the aggregate retained on the #30 sieve size would create holes on the surface. Furthermore, the gradation requiring 20.4 oz. /cwt not only required high amounts of WR, but it also had poor surface finishing due to the high amounts of #30. Even though a high volume of #30 did not impact the response to vibration, it creates difficulty in surface finishing because the mixture cannot accommodate the large amount of material on a given sieve size. As the material is finished the concrete tries to expel the excess material.

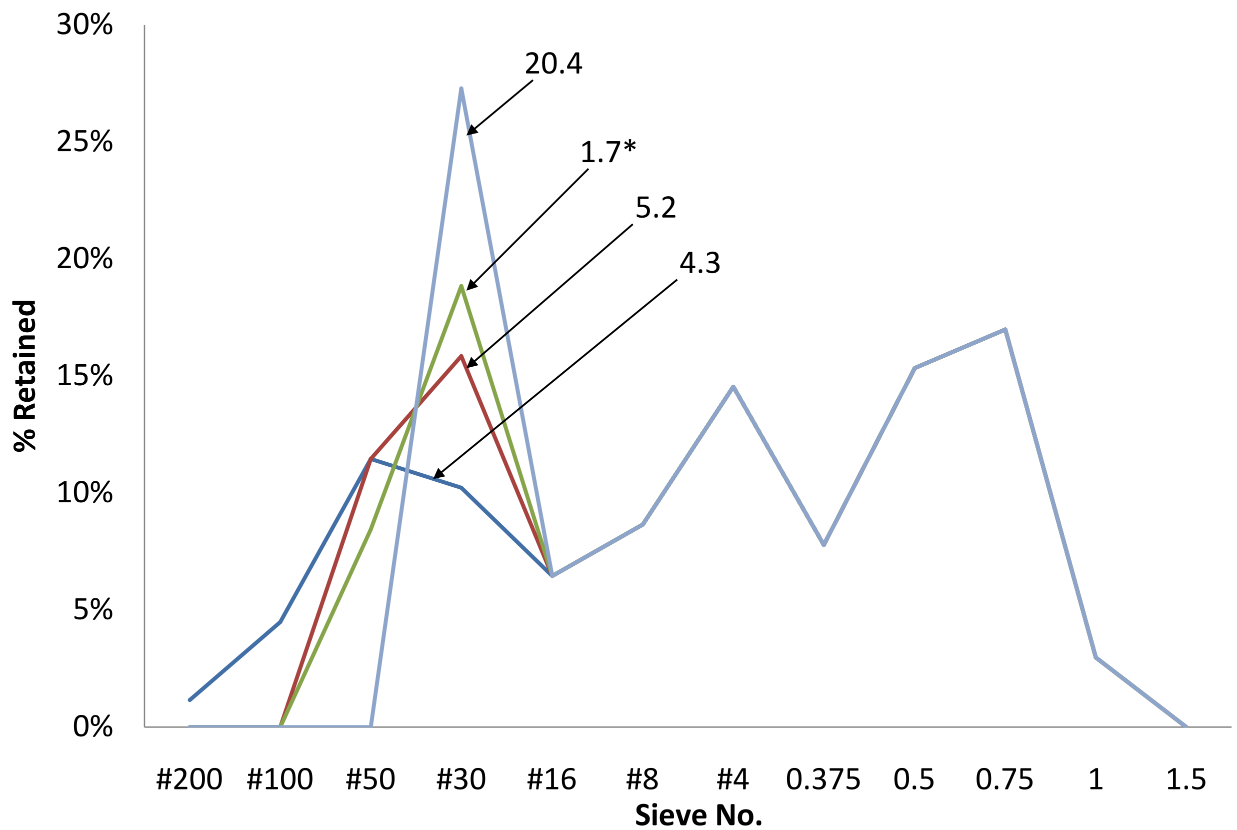


Figure 4-16 varies the distribution of #30 sieve size while keeping 1" through #16 constant. *note: this mixture had surface finishability issues.

4.3.2.3.2 Distribution of #50 Sieve Size

Similar testing parameters such as those for the distribution of #30 sieve size were conducted except the #50 sieve size was evaluated. Figure 4-17 was designed to have a constant gradation on the 1" to #16 sieve sizes with various amounts on the #50 sieve. The graph shows a mixture using only #50 did not require high amounts of WR to pass the box test. Additionally, the gradation with 27% retained on the #50 was shown to create a very smooth surface finish with a hand float. This does not match previous findings for the #30, #16, or #8 sieve sizes. Further work is needed to conclude a maximum limit for the #50 sieve size.

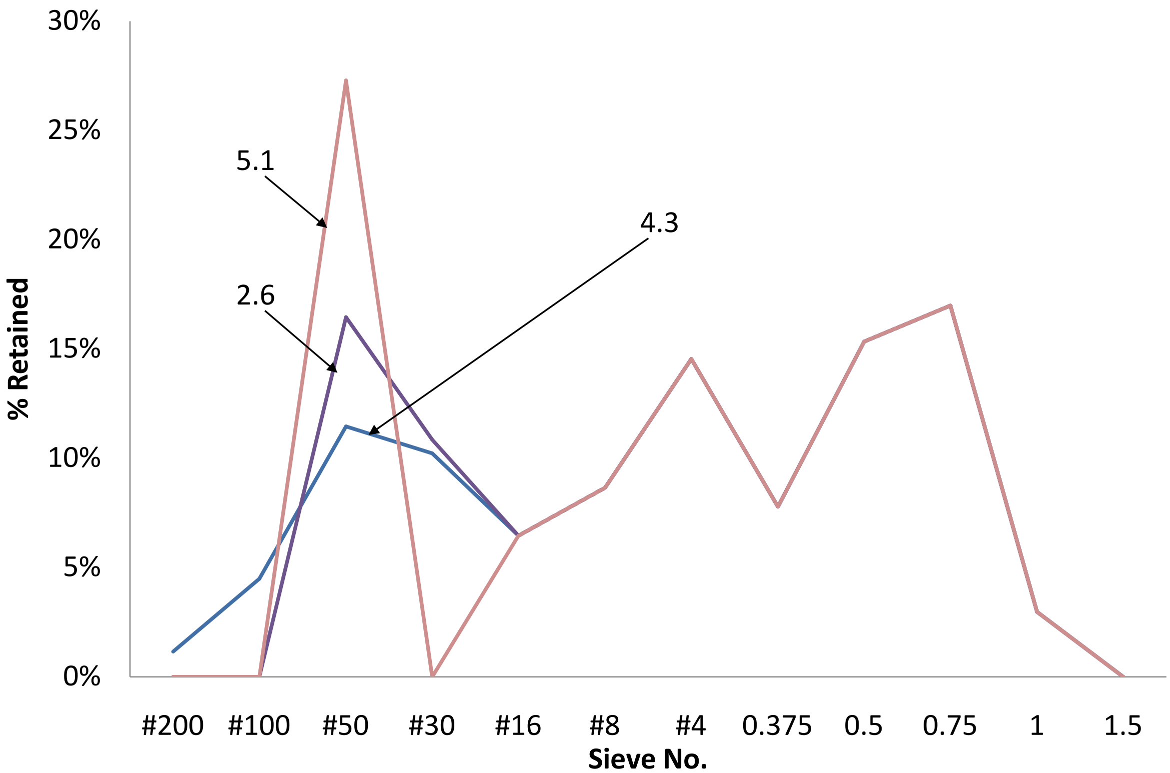


Figure 4-17 compares mixtures with varying distributions of #50 sieve with constant values of 1" to #16 sieve sizes.

<u>4.3.2.3.3 Distribution of #100 and #200 Sieve Sizes</u>

Figure 4-18 shows a distribution of different amounts of sands with higher amounts of #100 and #200 sieve sizes. It was shown amounts of 15% on the #100 sieve and 4% on the #200 sieve required significantly higher WR dosages to pass the box test. However, reducing the amount retained on the #200 and #100 sieve sizes allowed the mixture to require only a small amount of WR to pass the box test. Also, from visual observations the gradations with high amounts of #100 created a very smooth surface finish, but the paste around the coarse aggregate was easily removed with very little paste remaining on the coarse aggregate. The #100 sieve size creates a very smooth surface finishability, which was also observed by others (NSSGA 2013). Only a limited amount of mixtures were investigated due to challenges of obtaining enough material retained on the #100 and #200. Nevertheless, 10% on the #100 and 3% retained on the #200 have been shown to not decrease the workability of the concrete.

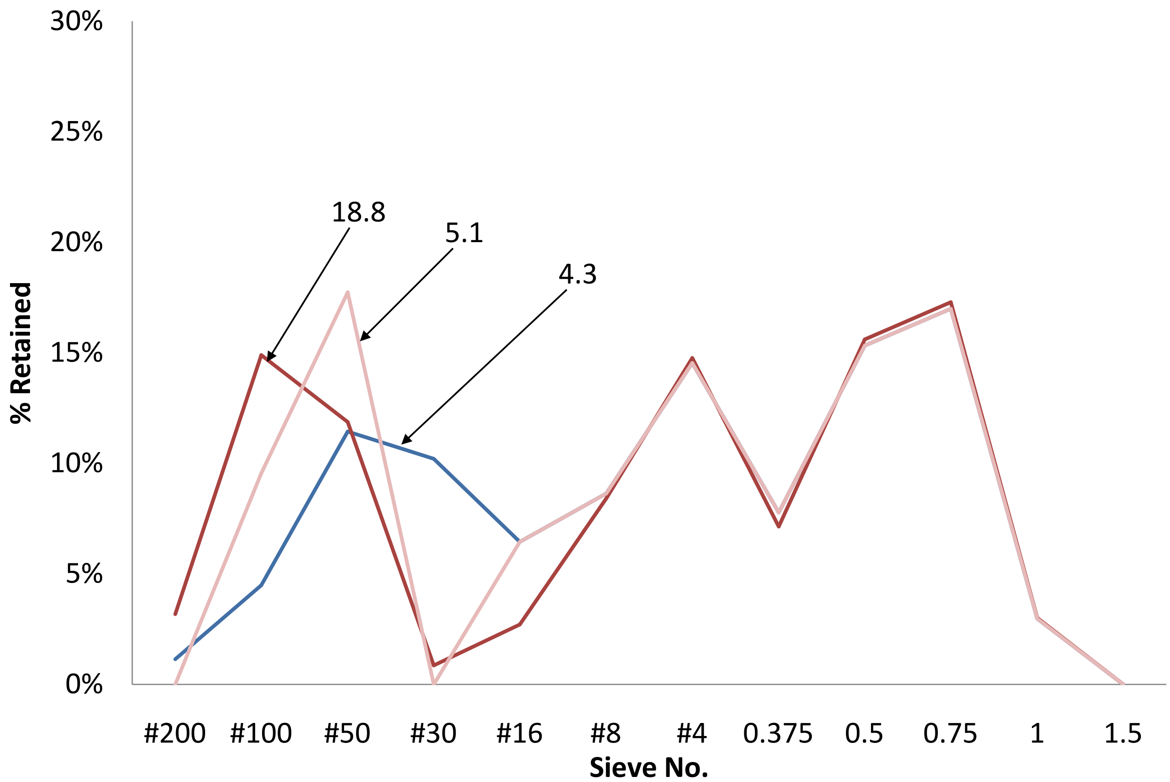


Figure 4-18 compares mixtures with various amounts of #100 and #200 sieve sieves.

4.3.2.3.4 Developing a Fine Sand Range

While Figure 4-10 suggests a certain range of acceptable fine sand volume for the aggregate sources and gradation, the adequate fine sand ranges for different combinations of coarse and sand aggregate sources need to be investigated. Figures 4-19 through 22 show how fine sand impacts with different coarse and sand sources. The gradations were carefully designed so that no sieve size exceeds the maximum limits established previously. Only two coarse aggregate sources and one other sand source were used to determine the fine sand limits.

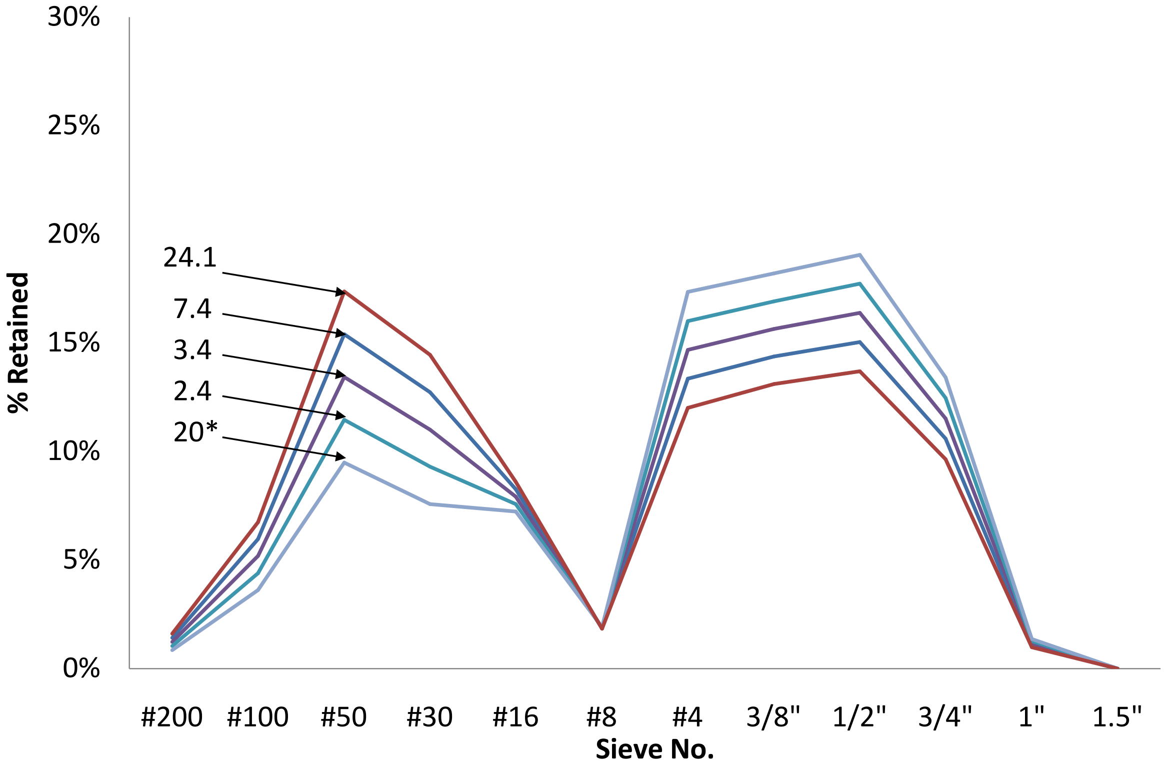


Figure 4-19 shows the performance of river rock A and river sand A.

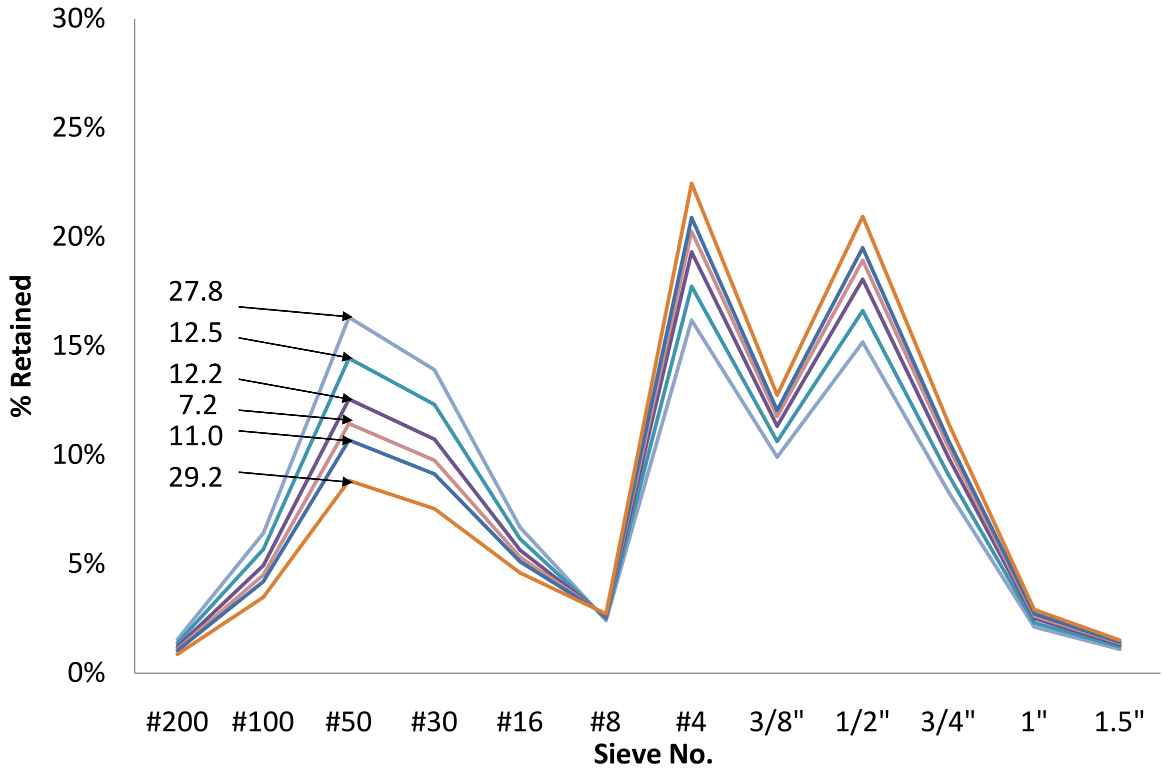


Figure 4-20 shows the performance of limestone B and river sand A.

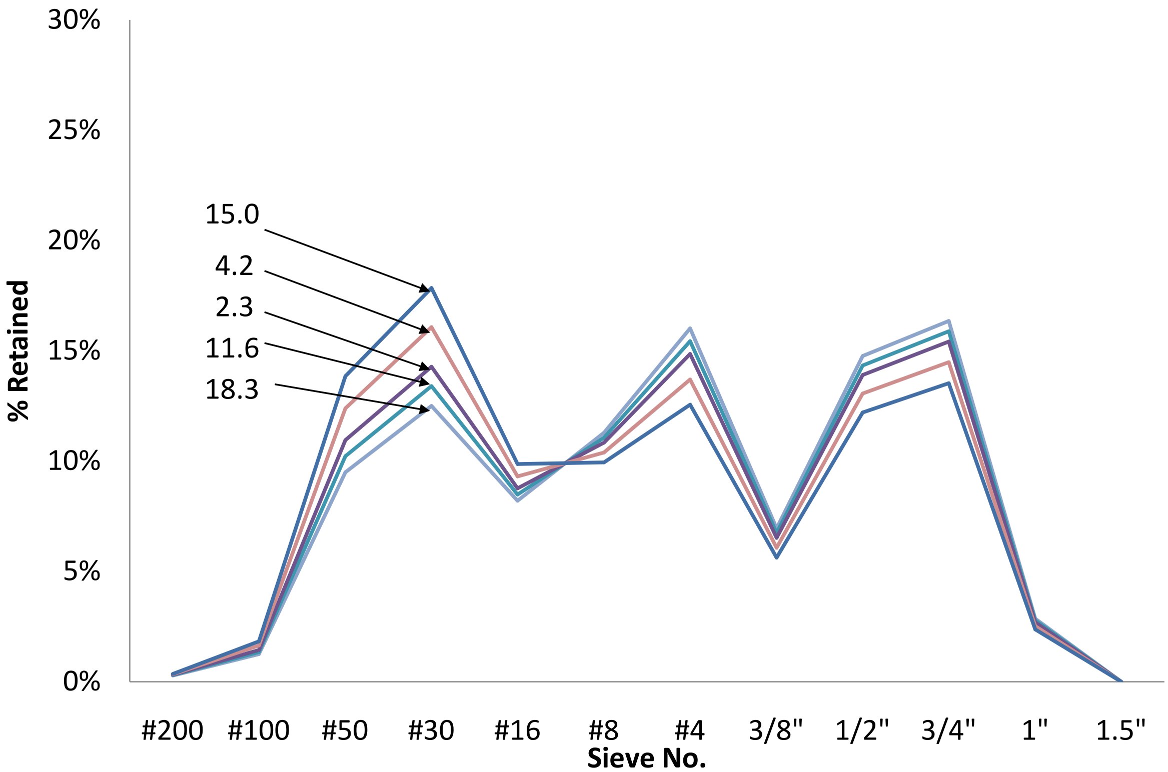


Figure 4-21 shows the performance of limestone A and river sand B.

Another way to compare the data is shown in Figure 4-22 where different volumes of fine sand were compared to the WR dosage required in the Box Test. The performance in the test was an upward slopping parabola. A range of 24% to 34% fine sand was shown to give satisfactory performance in the Box Test. When the fine sand volume in the mixture was not within the range, the WR dosage required increased dramatically.

Also in Figure 4-22, river sand B had a steeper slope than river sand A. The effect is likely caused by the ratio of fine sand sizes on individual sieves. As previously shown, in developing individual sieve limits of sand, it is very possible that changing the distribution of the fine sieve sizes could change the shape of the parabola and, therefore, the necessary volume ranges needed to consolidate and finish the concrete.

However, more research is needed to further investigate this. However, a range between 24% and 34% seems to be satisfactory for the primary sand sources in Oklahoma.

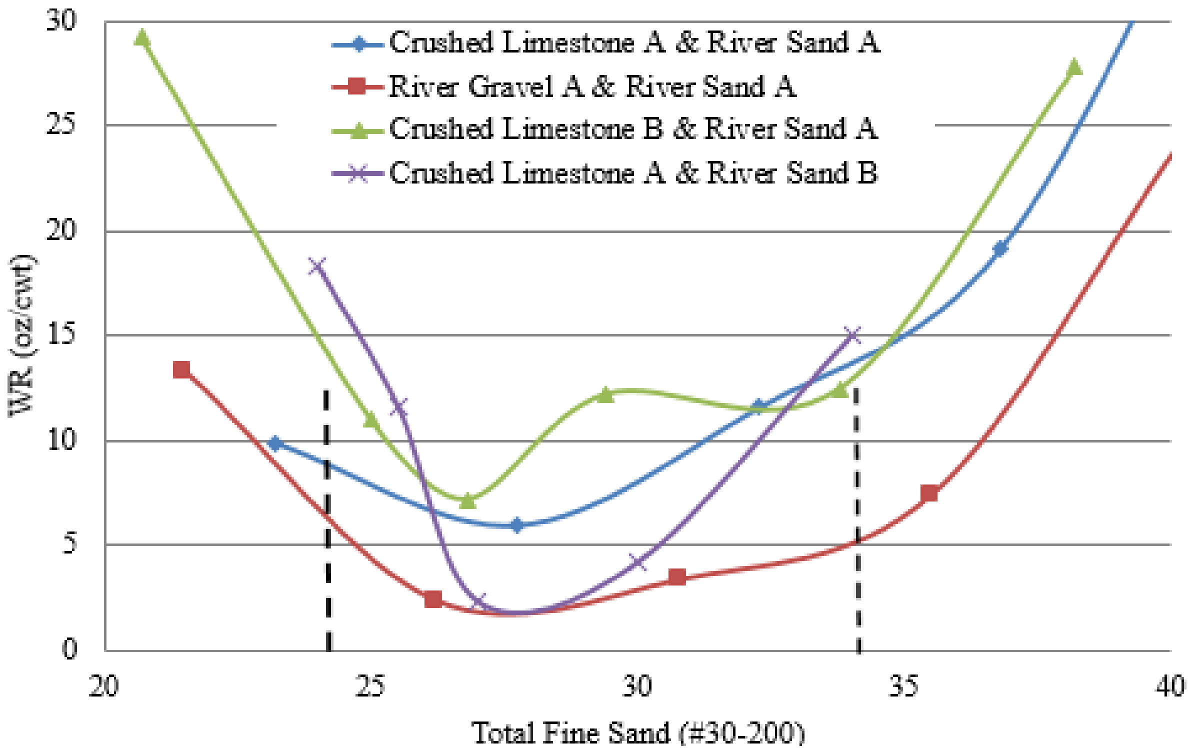


Figure 4-22 plots the WR versus fine sand of different aggregate combinations.

4.4 RECOMMENDATIONS

The previous testing was used to develop limits for individual sieves and determine a range of fine sand volumes that produce concrete with reasonable water demand and satisfactory surface finishing. As shown in Figure 4-23, the gradation limits and fine ranges are recommended in order to complete satisfactory concrete for slip formed pavers. These recommendations are based on over 400 mixture designs with five different coarse and three different sand aggregate sources.

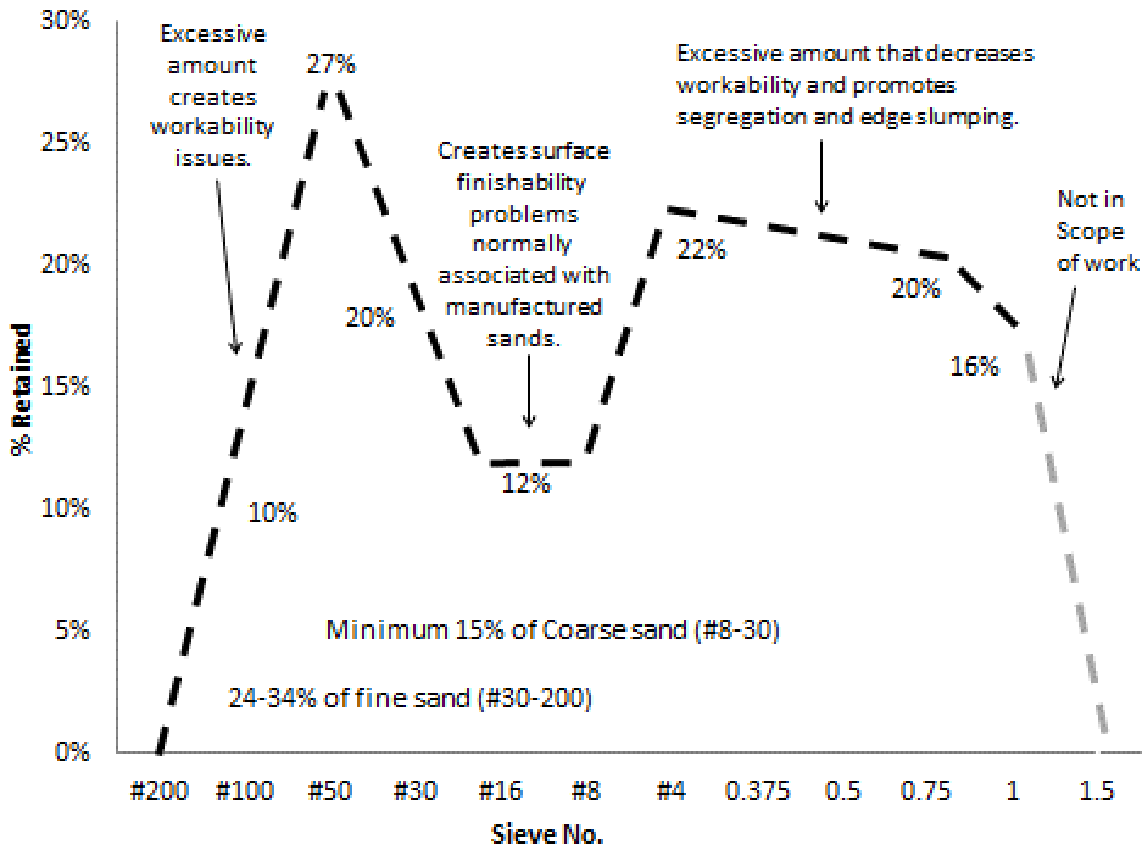


Figure 4-23 is the established research limits.

Throughout discussions with the Oklahoma DOT, the limits were streamlined and minimum sieve limits were added to make the recommendations easier to implement and are shown in Figure 4-24. Also, found in the Appendix, a recommended specification for slip formed pavements has been created to make the process of evaluating a mixture easier and possibly even allow for modification of the mixture in the field if the approved gradation is changed. The limits also have been shared with a number of aggregate producers in Oklahoma, and all of them have agreed the recommended aggregate gradations can be economically produced.

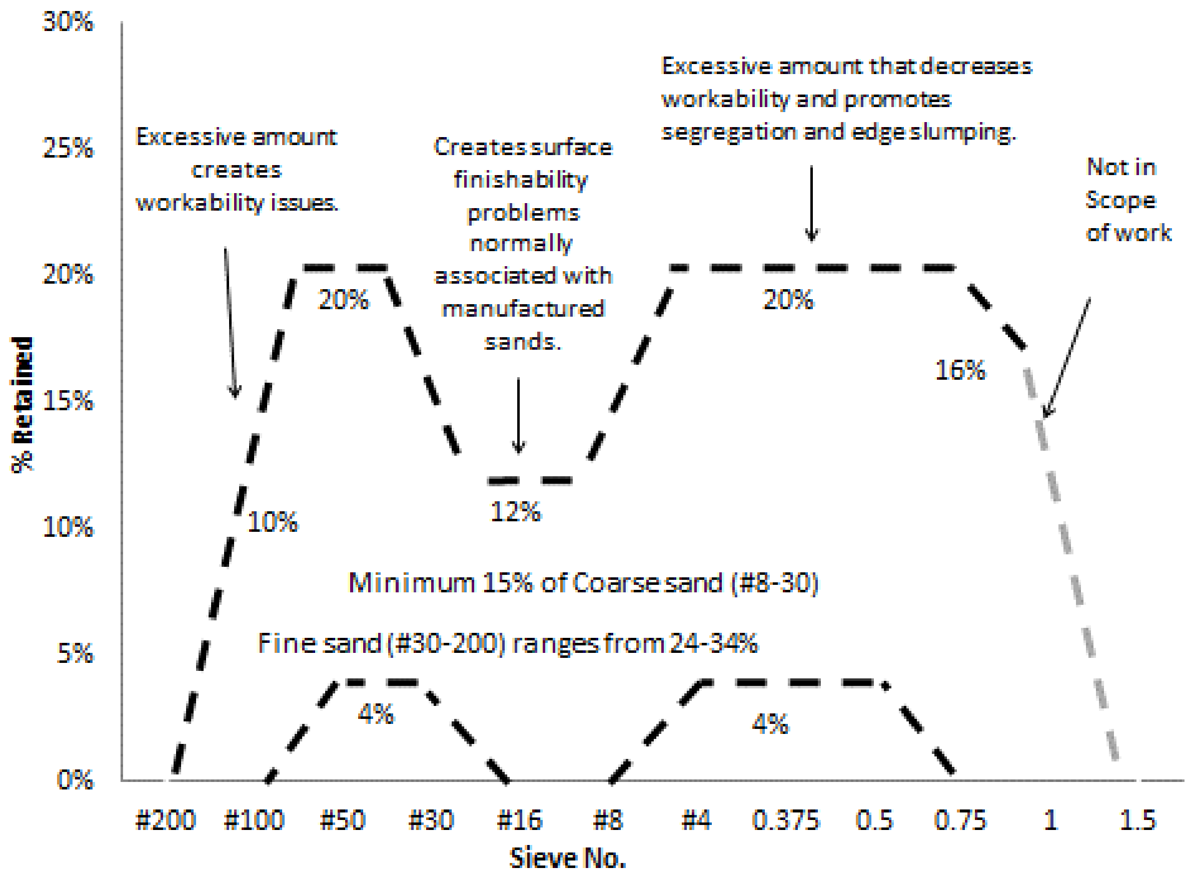


Figure 4-24 shows the recommended specification limits for Oklahoma.

All of the mixtures investigated in this chapter contained a 0.45 w/cm and 4.5 sacks or 423 lbs/CY of total cementitous materials with 20% Class C fly ash replacement by weight. As long as quality control is conducted, the researchers feel this mixture criteria with the specified gradations will consecutively produce satisfactory mixtures that can be consistently placed in the field. It may be beneficial to use a higher cementitious content in the mixtures. This has been found to be more forgiving and mixtures using these techniques were used on the FHWA Highways for Life project in Ft. Worth, Texas, where 12.5 lane miles of continuous reinforced concrete pavement were placed using mixtures that meet these specifications with 4.75 sacks of cementitious materials (446.5 lbs/CY) with 35% class F fly ash replacement. This allowed a 10% cost savings over conventional concrete pavement methods.

The researchers suggest that ODOT consider dropping the total cementitous content of concrete mixtures from 5 to 4.75 sacks for their mainline pavements that meet the suggested specification. This may even be able to be further reduced to 4.5 sacks if performance allows. These changes have the ability to create significant savings. Personal communications from ODOT suggest that approximately 310,000 CY of concrete pavement is placed in 2013 at a cost of $40.5 million. If a cost savings of 10% is obtained on these projects as was experienced with the FHWA Highways for Life project then this will create a savings of over $4 million each year. Additional cost savings will also be realized through reduced maintenance and longer performance. In addition there will be significant energy savings from the reduction in cement usage. If 5 sack mixtures are used instead of 6 sack with 20% fly ash replacement then this will lead to a savings of 54 billion BTUs each year. This is enough to power approximately 400 homes in Oklahoma each year.

4.5 COMPRESSIVE STRENGTH

After each mixture achieves the Box Test workability criteria, cylinders were typically made and tested at 7-days and 28-days according to ASTM C39. Table 4-2 contains the compressive strength of the various coarse gradations mixtures using river sand A, 423 lbs of total cementitious material, and a 0.45 w/cm. When cylinders were broken at 7-days, almost every one achieved the 4,000 psi strength. This means that at

7-days every mixture had satisfied the 28-day strength criteria required by ODOT. At 28-days, the mixtures had an average strength between 6400 and 7450 psi. When compared to the crushed limestones, the river rock had a lower 7-day and 28-day compressive strength values.

Even though the workability of the mixtures was the primary focus of this work, the strength of all of the mixtures produced was found to be satisfactory. Future work will be completed to investigate how different gradations impacted the performance of the mixtures.

Table 4-2 Compressive Strength of Various Coarse Gradations and Sources

	7 Day Strength			28 Day Strength		
Source	Min-Max (psi)	Average (psi)	Standard deviation (psi)	Min-Max (psi)	Average (psi)	Standard deviation (psi)
Limestone A	4000-6320	5180	124	5330-8890	6940	103
Limestone B	4990-5270	5130	405	6220-7940	7450	85
River Rock	3990-4850	4440	28	5760-7050	6410	574

4.6 CONCLUSION

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

- A large range of gradation values can be used without drastically impacting the workability of the concrete. However, practical gradation limitations were found during the testing that would help the workability and strength performance of a concrete pavement.
- Very low amounts on individual coarse sieve size did not impact the workability of a mixture. However, it is not recommended for a gradation to be absent in

multiple coarse sieve sizes because it may increase the amount of other sieve sizes and cause workability issues.

- The maximum aggregate size did not have a major effect on the workability. However, the maximum aggregate size can affect the distribution of the gradation due to the amount allowed on each sieve size.
- Amounts over 20% on 3/4" to #30 sieve sizes was determined to create workability issues for the mixtures investigated.
- Amounts over 12% on the #16 and #8 created surface finishing issues for the mixtures investigated.
- Not only is the ideal bell shaped curve not practical for production purposes, but the high amounts of #8 and #16 in the gradation created surface finishing issues.
- Smaller sieve sizes of #50, #100, and #200 give a smooth surface finish.
- The total volume of fine sand (#30 to #200) is suggested to be between 24% and 34% for the mixtures investigated.
- Coarse sand (#8 through #30) was shown to impact the cohesion of the mixture, which can lead to edge slumping and segregation. A value greater than 15% is suggested to be retained on the coarse sand (#8 through #30).
- The 4.5 sacks of cementitious material mixtures investigated consistently achieved over 4,400 psi strength at 7-days and 6,400 psi at 28-days.
- Gradation limits were produced and suggested to ODOT for implementation as a new specification.

4.7 FURTHER RESEARCH

A further investigation into the aggregate shape needs to be completed. Despite the findings being completed for a wide range of aggregates, none of the work presented had irregular shapes. Without certain shape limits of coarse aggregate, a gradation analysis cannot be fully predictable. Also, a modeling technique is needed to better understand various aggregate gradations and shape packing. This may help to understand the mechanisms behind this work.

CHAPTER 5 - DURABILITY PREFORMANCE OF OPTIMIZED GRADED CONCRETE

5.1 INTRODUCTION

While the previous chapters have outlined a specification to produce a satisfactory optimized graded concrete mixture for workability and strength, the durability of the mixtures has not been discussed and evaluated. Since optimized graded concrete reduces the paste content and increases the amount of aggregate in the mixture, a durability investigation was needed. Many different durability mechanisms could be investigated here. However, drying shrinkage and freeze thaw durability will be the focus of the research due to the primary application of concrete pavements. Drying shrinkage is defined as the contraction of a hardened concrete paste due to the loss of capillary water. A concrete mixture containing a lower paste content and therefore a higher aggregate volume should restrain the mixture and have less drying shrinkage issues. When the pores of the concrete become saturated and exposed to freezing temperatures, the microstructure can be damaged. Over multiple freeze thaw cycles the concrete can be damaged and have widespread cracking. However, air-entrainment agents can be added to create an air void system inside the concrete that can drastically reduce the effects on concrete from freeze-thaw cycles. This air void system is distributed throughout the paste and it actually protects paste from freeze and thaw damage. An optimized graded concrete reduces the paste content and therefore should require less air volume to provide frost durability.

5.2 EXPERIMENTAL METHODS

5.2.1 Materials

For preparing samples type I cement was used according to ASTM C150 with 20% fly ash replacement in accordance with ASTM C618, which classifies the fly ash as type C. Table 5-1 shows the oxide analysis of the cement. To achieve the workability requirements of the Box Test, a lignosulfonate mid-range water reducer classified by ASTM C494 was used. Also, a wood rosin air-entraining agent was used. Two different kinds of crushed limestone and a river sand were used in this research. As shown in Figure 5-1, the combined sieve analysis for the two different kinds of crushed limestone and a river sand had very similar gradations.

Table 5-1. The Oxide Analysis for the Cement Used In the Study

Chemical Test Results	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
	21.1%	4.7%	2.6%	62.1%	2.4%	3.2%	0.2%	0.3%
Bogue	C_3S	C_2S	C_3A	C_4AF				
	56.7%	17.8%	8.2%	7.8%				

5.2.2 Mixture Design

For the mixture design, two mixtures that meet the recommended specification that was discussed in the previous chapter were produced. One single mixture design with three different paste contents was used to produce the specimens. The different aggregate gradation sources of the mixtures were held the same. All the mixtures have w/cm of 0.45 with 20% fly ash replacement. Details on batch weights can be found in Table 5-2 and 5-3.

Table 5-2 Mixture Design for Limestone A

	4.5 sack	4.75 sack	5 sack
Percent Paste	19.7	20.8	21.9
Cement (lbs/cy)	338	357	376
Fly Ash (lbs/cy)	85	89	94
Coarse (lbs/cy)	2034	2023	2012
Intermediate (lbs/cy)	395	393	391
Fine (lbs/cy)	1004	968	932
Water(lbs/cy)	190	201	212
W/C	0.45	0.45	0.45

Table 5-3 Mixture Design for Limestone B

	4.5 sack	4.75 sack	5 sack
Percent Paste	19.7	20.8	21.9
Cement (lbs/cy)	338	357	376
Fly Ash (lbs/cy)	85	89	94
Coarse (lbs/cy)	1505	1497	1488
Intermediate (lbs/cy)	1004	1000	994
Fine (lbs/cy)	1019	983	947
Water(lbs/cy)	190	201	212
W/C	0.45	0.45	0.45

5.2.3 Mixing Procedure

Aggregates are collected from outside storage piles and brought into a temperature-controlled laboratory room at 72°F (22°C) for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken for a moisture correction. Starting the premixing stage, 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 aggregates to approach the saturated surface dry (SSD) condition and ensure that 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 mixer were scraped. After the rest period, the mixer was turned on and mixed for three minutes. During this final mixing period the air entrainment agent was introduced to the mixture.

5.2.4 Sample Preparation

After mixing, the material was tested for slump (ASTM C143), unit weight (ASTM C138), and fresh concrete air content (ASTM C231). Once the fresh properties were determined to be acceptable, samples were prepared for freeze thaw durability testing (ASTM C666), drying shrinkage durability testing ASTM C157/C-04, and hardened air void analysis (ASTM C457).

5.2.4.1 Freeze and Thaw

Each mixture was made with target air contents of 2.5%, 3.5%, and 4.5% air and two ASTM C666 beams and an ASTM C457 sample were created for each mixture. Freeze thaw prisms were cured for one day in steel molds while covered with wet burlap and then in saturated limewater for the remainder of the 14 day curing period, as per ASTM C666. All the mixtures were replicated with two different aggregate sources. Details can be found in Table 5-4.

Next, the freeze thaw beams were placed inside a temperature controlled water bath and brought to 40°F. Once the prisms were at 40°F the length, mass, and dynamic modulus were measured. The soaked prisms were then investigated in the ASTM C666 test for 300 cycles. As per ASTM C666 dynamic modulus, expansion, and mass change were measured every 36 cycles or before. ASTMC 666 does not clearly define freeze thaw failure, however some guidance is given in admixture standards ASTM C260, ASTM C494, and ASTM C1017. These standards recommend the ASTM C666 durability factor of a mixture with and without an admixture should not differ by more than 20%. If this criterion is used to evaluate the performance of a mixture in the ASTM C666 test, then the limiting durability factor would be between 70% and 80% (Ley 2007). For this work a specimen was determined failed if the durability factor decreased below 80% at any point during the testing cycle.

Table 5-4 Fresh Properties, Paste, and Air Values of the Mixtures

Source	Binder/CY	Air %	% Air in the paste	Unit Weight (lb/ft^3)	Slump (Inch)
Limestone A	4.5	2.2 3.1 4.3	10.1 13.6 17.9	152.9 152.2 151.0	- - -
Limestone A	4.75	2.5 3.6 4.6	10.7 14.8 18.1	152.8 150.3 149.9	0.25 0.25 -
Limestone A	5	2 3.6 4	8.4 14.1 15.5	152.4 147.0 149.2	0.5 0.5 0.5
Limestone B	4.5	2.6 3.5 4.05	11.7 15.1 17.1	154.0 152.8 152.0	0.75 0.75 0.25
Limestone B	4.75	2.48 3.05 4.49	10.7 12.8 17.8	154.4 153.5 152.3	0.25 0.75 1.25
Limestone B	5	2.12 3.23 4.54	8.9 12.9 17.2	153.8 152.5 150.4	1 1.5 1.75

5.2.4.2 Shrinkage

For the shrinkage potential of optimized graded mixture for Oklahoma concrete pavement, ASTM C157/C-04 was used as the procedure for testing the samples. After each mixture was tested for air content, three concrete prisms were made and placed in lime water for 28 days. Then each sample was measured using a comparator. Next, the samples were placed in an environmental chamber at 74^{o}F and 40% relative humidity. Length and weight change measurements were taken every month for 150 days.

5.3 RESULTS

5.3.1 Freeze-Thaw

With accordance to ASTM C666, the samples were continuously measured at or before the 36 cycle intervals throughout the three hundred freezing and thawing cycles. The average durability factor of each mixture throughout the three hundred cycles is shown in Figure 5-1. The high and low value is also shown.

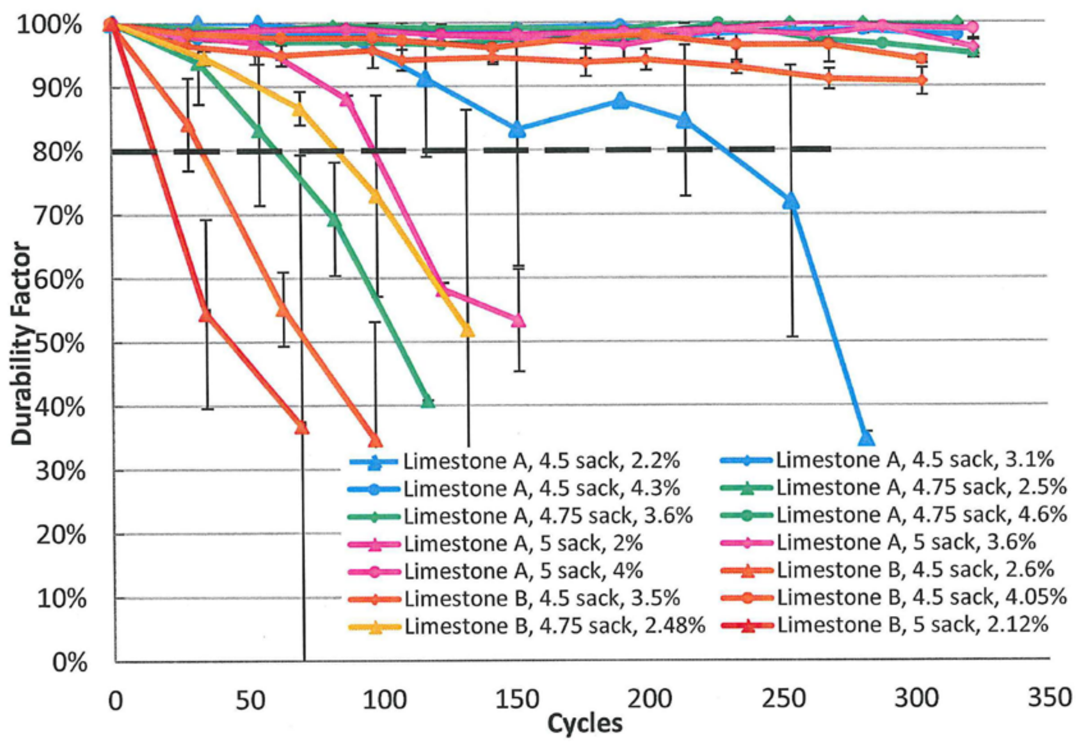


Figure 5-1 compares the durability factor of the mixtures throughout the number of cycles.

5.3.2 Shrinkage

Figures 5-2 and 5-3 compare the effects of shrinkage over time. While Figure 5-2 shows the expansion of the specimen throughout time, Figure 5-3 compares the weight loss percentage due to time.

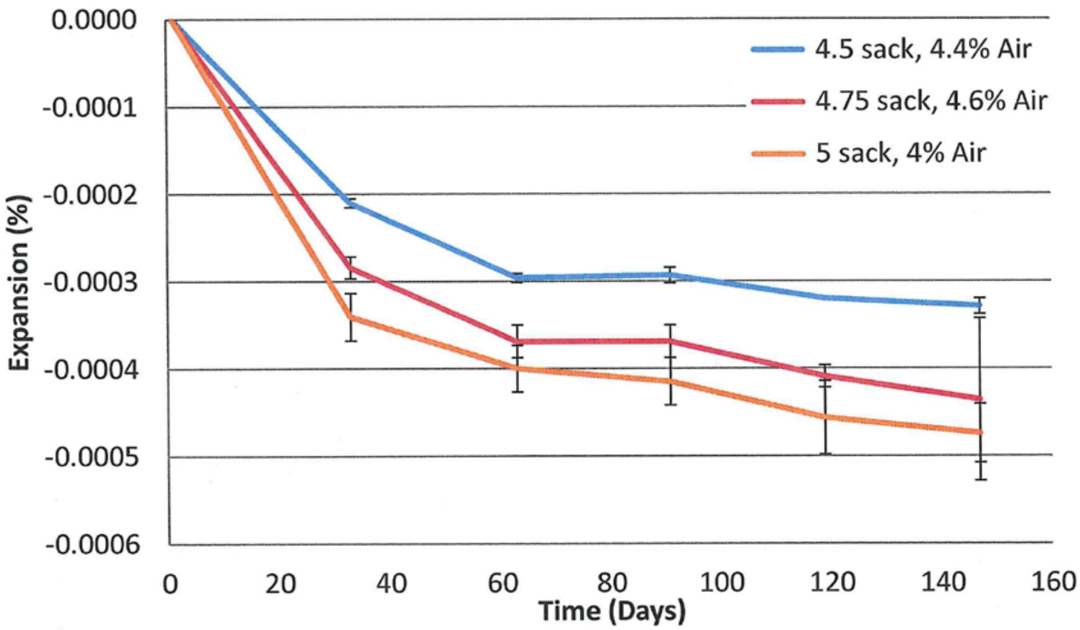


Figure 5-2 compares the expansion of Limestone A over time.

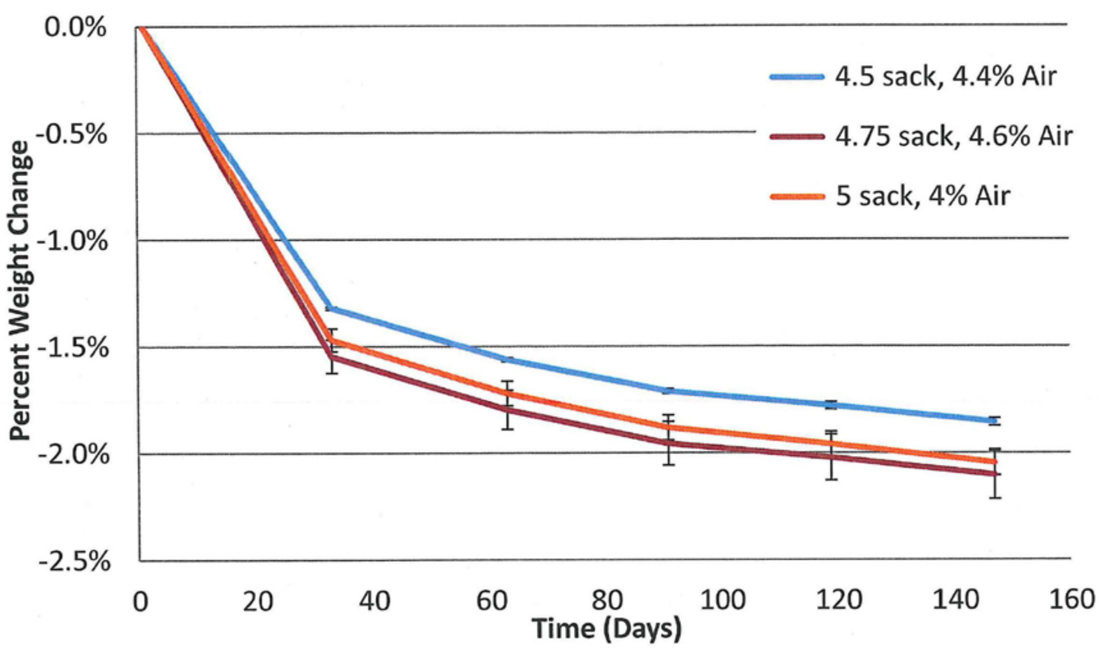


Figure 5-3 compares the percent weight change of Limestone A over time.

5.4 DISCUSSION

The optimized graded concrete mixtures performed similarly to higher paste content mixtures in freeze thaw durability. Figure 5-1 shows mixtures containing 2.5% air experienced a durability factor lower than 80% after approximately one hundred and ten cycles. However, mixtures containing at least 3.5% air successfully kept a durability factor above 90% through the required three hundred cycles. The mixtures investigated suggest the existing specifications for freeze thaw durability of concrete pavements do not need to be modified.

As more aggregate and less paste is used, the shrinkage measurements of elongation and weight loss are also reduced. Figure 5-2 shows decreasing the paste content from 5 to 4.5 sacks with a constant 0.45 w/cm will decrease the shrinkage by 130 x 10^{-6}. A concrete pavement having an expansion reduction of 130 x 10^{-6} is a significant reduction in shrinkage. Similarly, Figure 5-3 shows the percent weight loss of the specimens follows the same trend as percent expansion. The elongation and weight loss measurements confirm reducing the cement content and adding aggregate to the mixture can reduce the shrinkage of the mixture and therefore improve the durability.

5.5 CONCLUSION

The durability of drying shrinkage and frost damage for optimized graded concrete pavements was investigated. The following can be concluded:

- The freeze thaw durability performances of optimized graded concrete mixtures showed similar results to mixtures with higher paste contents that were not optimized.
- The mixtures investigated showed the existing specifications for freeze thaw durability of paving concrete do not need to be modified.
- As the shrinkage measurements of weight loss and elongation differences decrease, paste content is decreased in a mixture; paste reduction decreases the weight loss and the subsequent shrinkage of the concrete specimens.
- The durability measurements confirm reducing the cement content of a mixture can make improvements in the durability of a mixture.

CHAPTER 6 – CONCLUSION

This work led to many new findings, which include:

- In two different field comparisons, the Box Test performed comparably to a slip formed paving machine.
- There was no difference between mixtures evaluated with a single or sequential dosages of water reducer for the Box Test and only a minor variation in the Slump.
- The repeatability of a single operator adding WR dosage had an average absolute difference of 1.2 oz/cwt with a standard deviation of 0.8 oz/cwt.
- Multiple operators adding WR dosage had an average absolute difference of 1.7 oz/cwt with a standard deviation of 1.1 oz/cwt.
- The visual ranking of multiple evaluators showed agreement over 90% of the time.
- The Box Test was able to provide a quantitative comparison between different proportions of coarse aggregate to intermediate aggregate with a fixed sand content and the ratio of fine to a fixed coarse and intermediate aggregate ratio on the response to vibration.
- The Box Test proved to be a more sensitive tool than the Slump Test to evaluate a concrete mixture for the application of slip formed pavements.
- For the mixtures investigated, the location of the Shilstone chart did not predict the performance of the concrete.
- A large range of gradation values can be used without drastically impacting the workability of the concrete.

- Very low percent retained on individual coarse sieve sizes did not impact the workability of a mixture. However, it is not recommend for a gradation to be absent in multiple coarse sieve sizes because it may increase the amount of other sieve sizes and cause workability issues.
- The maximum size did not have any effect on the workability. However, the maximum size can affect the distribution of the gradation due to the limited range of sieve sizes being able to use.
- Using the materials in this research, amounts over 20% on 3/4" to #30 sieve sizes was determined to create workability issues.
- Percentage retained over 12% on the #16 and #8 created surface finishing issues for the mixtures investigated.
- Not only is the ideal bell shaped curve not practical for production purposes, but the high amounts of #8 and #16 in the gradation created surface finishing issues.
- Smaller sieve sizes of #50, #100, and #200 give a smooth surface finish.
- The total volume of fine sand (#30 to 200) is suggested to be between 24% and 34% for the mixtures investigated.
- The total volume of coarse sand (#8 through #30) should be no less than 15%.
- The compressive strength for the concrete mixtures investigated with optimized graded aggregate proportions and 4.5 sacks of cementitious material achieved 4,000 psi strength at 7 days.
- Gradation limits were produced and suggested to ODOT for implementation as a new specification.

- The freeze thaw durability performances of optimized graded concrete mixtures showed similar results to mixtures with higher paste contents that were not optimized.
- The mixtures investigated showed the existing specifications for freeze thaw durability of paving concrete do not need to be modified.
- As the shrinkage measurements of weight loss and elongation differences decrease, paste content is decreased in a mixture, and this decreases the weight loss and the subsequent shrinkage of the concrete specimens.
- The durability measurements confirm reducing the cement content of a mixture can make improvements in the durability of a mixture.

The findings allow a new specification to be created for the state of Oklahoma on optimized graded concrete pavements, a new laboratory and field test method has been established to investigate the performance of concrete for slip formed paving, and, finally, the durability of the recommended mixtures has been evaluated. The concrete created according to this specification will have a more predictable workability, higher durability, and more sustainability than typical concrete pavements. Additionally, the specification has the potential to save ODOT approximately $4.1 million per year and save over 5.4 billion BTUs, which is enough energy to power 400 Oklahoma homes a year. In addition there will be savings in the reduction of maintenance cost and increased durability.

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APPENDIX

PROPOSED OKLAHOMA DEPARTMENT OF TRANSPORTATION SPECIAL PROVISIONS FOR OPTIMIZED GRADED CONCRETE PAVEMENT

MIX DESIGN AND PROPORTIONING

If the contractor provides a concrete mixture meeting the specifications for optimized graded concrete pavement (OGCP), the minimum cementitious content may be reduced to 470 lbs/yd^3 [279 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 OGCP spreadsheet. This spreadsheet can be found here. The OGCP 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 24% and 34% of the aggregate content used.
- The total volume of coarse sand (#8-#30) must be 15% or greater.
- Limit the flat or elongated coarse aggregate to 15% or less at a ratio of 1:3 according to ASTM 4791.

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

Gradation Tolerance

Make necessary adjustments to individual aggregate stockpile proportions during OAG 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 517 lbs/yd^3 (307 kg/m^3).