OPTIMIZED GRADED CONCRETE
FOR SLIP FORMED PAVING

By

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OPTIMIZED GRADED CONCRETE
FOR SLIP FORMED PAVING

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Abstract: A study was conducted into the proportioning and gradation of concrete aggregates to reduce the paste volume of a mixture for the sole purpose of slip formed paving. Various nominal maximum aggregate sizes and different angular aggregates using five different mixture gradation proportions were evaluated with the slump test and a novel workability test for a concrete vibrator's performance called the box test. The results show the Shilstone chart was not accurate to predict the performance. Instead the individual percent retained chart was a better indicator of gradation performance in concrete.

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CHAPTER 1

INTRODUCTION

1.0 Background

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. For each jobsite, mixtures are designed to meet certain specifications such as water to cementitious material (w/cm) ratio, minimum amount of cement, desired compressive strength, and workability. With advances in the cement industry, a concrete mixture design is rarely controlled by the mixture's strength, but instead its workability.

Aggregate can drastically change the workability of a mixture. People have dedicated years to the development of aggregate tables and graphs in the mixture design of ACI 211. 1-91. Still, a dependable method to understand and to predict the workability of concrete due to aggregates has not been developed. The ACI 211 mixture design can offer a step in the right direction but many concrete mixture designs use roughly two-thirds aggregates of the total concrete's volume with enough cementitious material and water to obtain the workability for a specific application. A design process that mainly neglects the effects of aggregates and adds enough cementitious material and water to obtain a certain degree of workability has created multiple problems associated with large amounts of cement such as a higher amount of CO_2 emissions, an overall cost increase of concrete, and a lower serviceability life.

An immense need for the concrete industry has been to reduce the cement content but the development and implementation of reducing the paste content becomes a very complex subject due to the effects on the workability of the concrete. The workability issues associated with reducing the paste content can be explain by Duff Abrams statement:

> "Workability of concrete mixes is of fundamental significance. This factor is the only limitation which prevents the reduction of cement and water in the batch to much lower limits than are now practicable." (Abrams 1918)

1.1 Scope of Work

The main objective of the research was to find a concrete mixture that reduced the overall amount of paste using aggregates, but still obtain the workability for a slip formed pavement application. To lower the amount of paste used in a concrete mixture, the general philosophy has been to change the physical characteristics, gradations, and proportions of aggregates. Only a limited amount of research has been conducted on the impacts of workability by aggregates. Out of the general philosophy, common theories that change the required paste content have been surface angularity of aggregates, nominal maximum coarse aggregate size, and proportioning aggregates by gradation.

In this thesis we plan on investigating both the Shilstone workability chart and the individual percent retained chart to determine their ability to guide the use of aggregate gradation for concrete mixtures for slip formed pavement applications. A significant challenge to evaluating the workability of concrete comes from the lack of useful laboratory tests to evaluate a mixture’s performance to a slip formed paver. While the slump test (ASTM C 143) has been the most common technique to evaluate the workability of a mixture, it fails to be sensitive to changes in a mixture at very low levels of workability. Therefore, the first obstacle of the project was to create and develop a laboratory test to evaluate a mixture’s workability for a slip formed pavement application. Then a mixture’s workability can be measured and evaluated. When different physical aggregate characteristics, aggregate sizes, and aggregate proportions are changed, the performances of different mixtures can be compared.

CHAPTER 2

AGGREGATE PROPERTIES & PROPORTIONING

2.1 Introduction of Aggregates

The workability of a mixture can be drastically changed due to aggregate proportioning and the physical characteristics of aggregate. A dependable method to understand and predict the workability of concrete due to aggregates has not been developed. The physical characteristics of aggregates cannot be controlled, but the actual gradation of the aggregates can be much more easily controlled. Using regional available aggregates with volume proportions of roughly 60% coarse aggregate and 40% fine aggregate regardless of gradation have been used as the standard for a concrete pavement mixture. Efforts to reduce the cost and improve sustainability of concrete mixtures have pushed owners to pay closer attention to all aspects of their concrete mixtures. To maintain a certain workability for a slip formed pavement application, but still reduce the amount of paste has been an important topic for many years. The general philosophies effecting workability have thought to be the surfaceangularity of aggregates, nominal maximum size of coarse aggregates, and proportioning of aggregates by gradation.

2.1 Surface Angularity of Aggregates

The physical characteristic of aggregate angularity for a coarse or a fine aggregate has been one of the lending concepts changing the amount of paste required to achieve a certain workability. In many books such as the 14th edition of PCA's *Design and Control of Concrete Mixtures*, it states multiple times throughout the book, the angularity of the aggregates influence the workability of the concrete (Kosmatka et al. 2002). The mechanism of surface angularity was based on the degree of aggregate angularity influencing the amount of paste required to obtain a certain workability. A smooth river aggregate is less angular and should require less paste to cover the aggregate's surface than a crushed aggregate. For example, manufactured sand is more angular and should require more paste than river sand. Also, smooth river gravel should require less paste than a jagged crushed limestone.

2.2 Nominal Maximum Coarse Aggregate Size

A dominant concept in concrete mixture design has been the surface area principle. The ACI 211.1-91 requires different water amounts for each nominal maximum aggregate size (ACI 1990). The idea revolves around the claim using larger aggregate sizes will require less paste to achieve a certain workability and the use of smaller aggregate sizes will require more paste to achieve a certain workability. In 2004, Harrison explained this concept using different cubic shapes of 1.5" and ¾" to be packed into a specific volume. This concept indicated the 1.5" size took up more space and required less surface area than the ¾" size. He claimed using 1.5" coarse aggregate size requires less paste to achieve a certain workability (Harrison 2004).

2.3 Proportioning of Aggregates

One of the most sought after methods for understanding concrete has been the proportioning of aggregates. Over the years many theories on aggregate proportioning have submerged and can be grouped into the following: volume, gradation, void content, and surface area. Each of the theories can be supported by some logical reasoning. A limited amount of research has been conducted into these theories. To have a deeper understanding into the proportioning of aggregates, research needs to be conducted. The proportions by volume, gradation, and minimum voids will be investigated in this thesis. The proportioning of aggregates by the surface area theory will not becovered in this paper due to lack of time.

2.3.1 Proportioning of Aggregates by Volume

The amount of aggregates in a mixture can drastically impact the workability. If a mixture is too sandy, the workability can drastically decrease and the stiffness of the mixture increase. If the mixture does not have enough sand, the mixture is too bony and will not have the mortar to flow correctly. Over the years, three methods for proportioning aggregates by volume have surfaced: the 1-2-3 method, as received method, ACI 211, and the Shilstone chart method.

2.3.1.1 Proportioning of Aggregates by The 1-2-3 Method

The volume proportioning of aggregates using the 1:2:3 method, or a variation of this method such as 1:2:4, is the oldestknown proportioning method.It proportions aggregates and cement by measuring out a volume of cement, sand, and, rock. The 1:2:3 method uses large amounts of cement which cause a drastically increases the cost of the concrete.

2.3.1.2 Proportioning of Aggregates by As Received Method

Another proportioning by volume method is the as received volume method. It is used to design aggregate proportioning based on the percentage of rock and sand volumes by a quarry and sand source. For example, a typical concrete mixture consists of 60 % coarse aggregate and 40 % fine aggregate by total volume.

However, the theory over looks one gradation contributor to a concrete mixture design, the intermediate sizes. When aggregates are proportioned by the as received volume method, a mixture might have 40 % fine and 60% coarse aggregate, but the sand and coarse aggregates actually contains intermediates. Technically, the aggregate proportions would be something like 34% fine, 18 % intermediate, and 48% coarse. To help guide the user to proportion coarse, intermediate, and fine aggregates, the Shilstone chart method was developed.

2.3.1.3 Proportioning of Aggregates Using the Shilstone Chart Method

Starting in the late 1980s, James Shilstone revealed a well-graded mixture design process entirely based on the proportioning of the aggregate's gradation (Shilstone, 1990). From 20 mixture designs in Saudi Arabia, he constructed a chart and developed two equations to proportion aggregates by dividing a combined gradation into a coarse, intermediate, and fine section. To confirm the findings from the Saudi Arabia's aggregates, Shilstone replicated the results using Dallas aggregates. From Shilstone's experiences, he determined the workability was sufficient enough in certain areas of the chart and divided the chart into zones as shown in Figure 1. The Shilstone chart uses a coarseness and workability factor to proportion the coarse, intermediate, and fine aggregates, as shown below in equation 1 and 2.

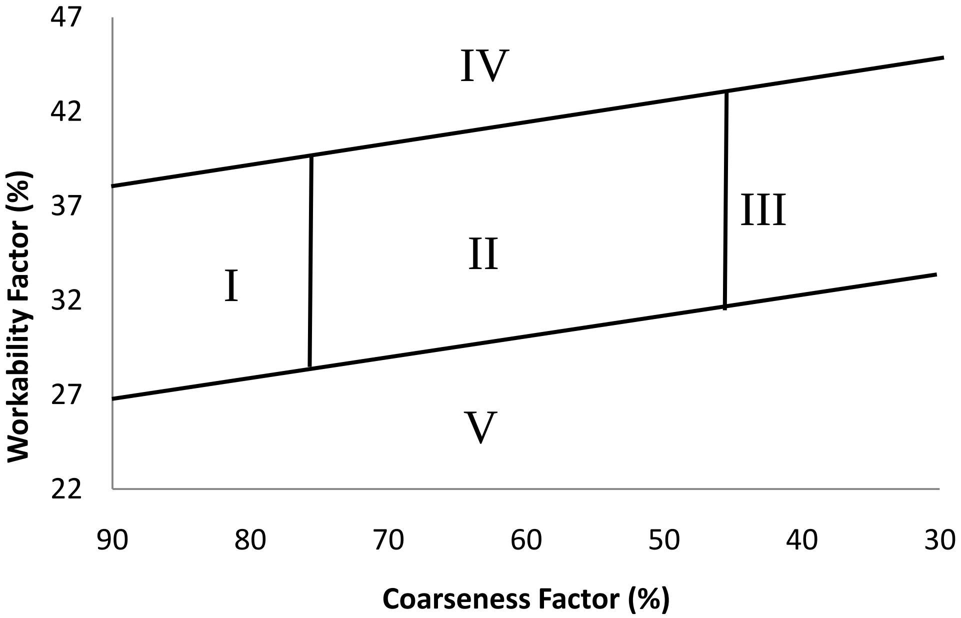


Figure 1.Shilstone chart

Coarseness Factor (CF) = (Q/R)*100 Equation 1

Workability Factor (WF) = W + (2.5(C-564)/94) Equation 2

Q= cumulative % retained on the 3/8 sieve

R= cumulative % retained on the no. 8 sieve

W= % passing the no. 8 sieve

C= cementitious material content in lb/yd^3

The chart is divided into five different zones that supposedly control gradation of a concrete mixture. While Zone I is supposed to be gap graded with very little amounts of intermediate, Zone II is supposed to be well-graded and the location of the optimal gradation for a concrete mixture design. Zone III has a large majority of intermediate and very little coarse aggregate. The Zone IV and Zone V correlate with the extreme sandiness and rockiness. Harrison recommend when designing optimized graded concrete for slab on ground applications to use a parallelogram in the middle of the Shilstone chart (Harrison 2004). While Harrison explained logically for a tighter region, no actual known data exits to supports this explanation. Yet, many current DOTs reference the parallelograms the best location for a slip formed pavement mixture. Even Shilstone suggested that paving mixtures do not need the same workability as other mixtures and therefore a lower workability factor could be used such as a gradation near the bottom of Zone II (Richard 2005). Unfortunately, little testing data has been published by Shilstone or others to validate the chart.

2.3.2 Proportioning of Aggregate by Gradation

Gradation describes the distribution of aggregate sieve sizes. Normally, a sieve analysis is taken and graphed in a cumulative percent passing chart, or individual percent retained chart. In the past concrete gradations have been largely neglected because the thought has been that gradation does not drastically affect the workability of concrete, but rather proportioning coarse and fine aggregate is enough. The negligence of gradation has created many workability problems because the lack of understanding gradation. If one could understand the mechanism behind gradation, a mixture's workability could be more predictable. To design a gradation, many different methods have developed using a packing formula, fitted to a line, or moved within a specified boundary.

2.3.2.1 The Power 45 Curve

Starting in 1907 with the Fuller curve, also called the power 45 curve, the notation of an ideal gradation was developed to optimize the aggregate material used and reduce the paste content (Fuller and Thompson 1907). The idea of optimizing proportions using gradation can be carried out by combining the as received gradation of coarse, intermediate, and fine aggregates in the belief of reducing paste by packing aggregates to minimize void content. To design a power 45 gradation, a combined gradation aligns a best fit to a straight line on the cumulative percent passing chart. The straight line is thought to be the maximum density of a combined gradation, which creates the minimum amount of voids in a mixture.

Once the gradation is developed in accordance with the method, the gradation for those particular aggregates is thought to become the ideal gradation to reduce the paste content. This concept has been known as an optimized graded mixture. The research behind an optimized graded mixture is very limited, but the concept of only a single gradation optimizing a mixture seems to be inconsistent with nature. To follow the basics of nature, a range of gradations should be able to optimize a concrete mixture with very limit difference in workability.

2.3.2.2 Minimum Voids

Another approach to reduce the paste content is to minimize the void content. The basic concept is to design a gradation by using formulas to calculate the minimum amount of voids allowed for the as received aggregates. The closer the aggregates are to being packed together, the lower the voids contents. While multiple packing models have been developed over the years, the assumptions in many packing models create difficulty into applying them because aggregates are suspended in a concrete mixture.

2.3.2.3 The Individual Percent Retained Chart

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. Shown in Figure 2, the intermediate, coarse, and fine aggregate are graphed in percent individually retained on each sieve size. When the aggregate gradation for a mixture is graphed on the individual percent retained, individual aggregate size distribution is easily clarified. The individual percent retained has been identified as a valuable decision factor. From experiences, people have specified a maximum boundary of 18 % retained and a minimum retained of 8 % as shown in Figure 3. No known research has been conducted to prove the limits.

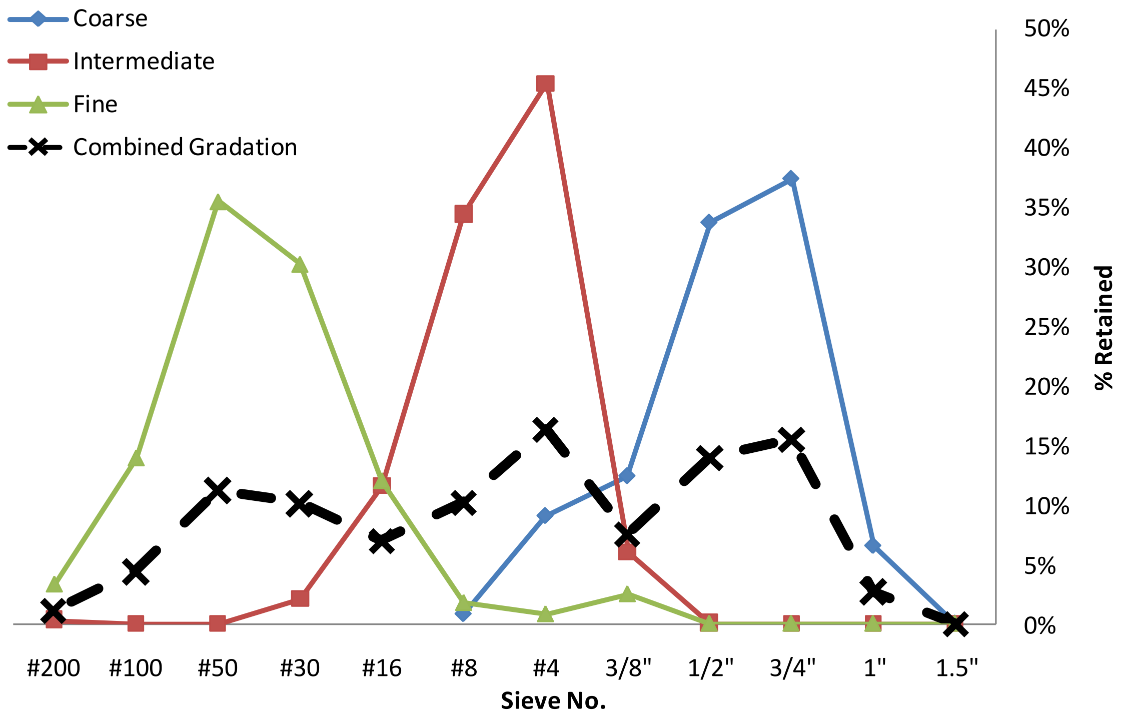


Figure2. A well graded combined gradation.

2.4 Proportioning of Aggregates Using the ACI 211 Method

The American Concrete Institute (ACI) has developed a mixture design process for proportioning aggregate called the ACI 211. It proportions aggregates using the fineness modulus (FM) and the nominal maximum aggregate size from Goldbeck and Gray's "b/bo" method (ACI 1990). Since the fineness modulus is not sensitive enough to the gradation of coarse aggregate, ACI 211 method can mainly be a helpful guide to designing a concrete mixture.

CHAPTER 3

MATERIALS & MIXTURE DESIGN

3.0 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150. The oxide analysis is shown below in Table 1. Note that only five out of the 45 mixtures used 20 % fly ash replacement. The other 40 mixtures had cement only. ASTM C 494 classified the fly ash as type F and the water reducer as a lignosulfonate mid-range WR. The river rock and manufactured sand were obtained from Texas and crushed limestone A, crushed limestone B, and river sand were from Oklahoma. From visual observations, the crushed limestone A and the crushed limestone B have similar angularities and shapes. A coarse and fine aggregate description is explained in Table 2. A sieve analysis for each of the aggregates was completed in accordance with ASTM C 136. Each of the aggregates has a maximum nominal aggregate size as shown in Table 3. Absorption and specific gravity of each aggregate followed ASTM C 127 for a coarse aggregate or ASTM C 128 for a fine aggregate. In Table 3 and Figure 3, the properties and sieve analysis of each aggregate are shown.

Table 1. Cement oxide analysis- type 1 cement

Chemical Test Results	
SiO_2	21.1%
Al_2O_3	4.7%
Fe_2O_3	2.6%
CaO	62.1%
MgO	2.4%
SO_3	3.2%
Na_2O	0.21%
K_2O	0.34%
Phase concentrations	
C_3S	56.7%
C_2S	17.8%
dC_3A	8.2%
C_4AF	7.8%

Table 2. Aggregate description

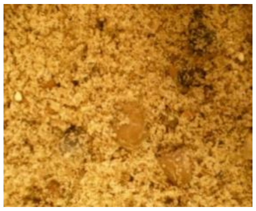
Aggregate	Photo of Aggregate	Description
Crushed Limestone A		Combination of low and high sphericity with a mid-angularity.
Crushed Limestone B		Combination of low and high sphericity with a mid-angularity.
River Gravel		Combination high and low sphericity with a well-rounded angularity.
River Sand		Fines with very few intermediate.
Manufactured Sand		Angular fines with intermediate particles.

Table 3. Properties and sieve analysis of each aggregate type

		Aggregate Type									
		1.5" Nominal Max Coarse		3/4" Nominal Max Coarse			3/8" Intermediate			Fine	
		Limestone A*	River Rock	Limestone A*	Limestone B*	River Rock	Limestone A*	Limestone B*	River Rock	River Sand	Man Sand*
Properties	Fineness Modulus	5.71	3.32	3.32	4.18	3.76	5.92	4.95	5.81	2.55	2.94
	Bulk Specific Gravity (SSD)	2.74	2.64	2.70	2.87	2.65	2.72	2.72	2.62	2.65	2.63
	Absorption (%)	0.45	1.55	0.66	1.14	1.26	0.58	3.37	1.95	0.55	0.70
Percent Passing the Sieve Number	1.5"	95.5	96.8	100	100	100	100	100	100	100	100
	1"	28.1	59.5	100	93.5	96.2	100	100	100	100	100
	3/4"	5.2	49.0	94.4	56.0	77.5	100	100	100	100	100
	1/2"	0.3	30.6	48.2	22.3	36.3	100	100	100	100	100
	3/8"	0.1	18.1	22.8	9.9	13.5	93.3	94.0	99.8	97.5	100
	#4	0.1	4.6	3.1	0.8	0.2	11.3	48.5	17.6	96.7	91.8
	#8	0	3.2	0.0	0	0.0	1.5	14.0	0.7	95.0	82.7
	#16	0	0	0	0	0	0.7	2.4	0.2	83.0	74.6
	#30	0	0	0	0	0	0.5	0.3	0.1	52.7	56.7
	#50	0	0	0	0	0	0.5	0	0.1	17.2	12.4
	#100	0	0	0	0	0	0.3	0	0.1	3.3	2.4
	Pan	0	0	0	0	0	0	0	0	0	0

*note: limestone was crushed limestone & man sand was manufactured sand.

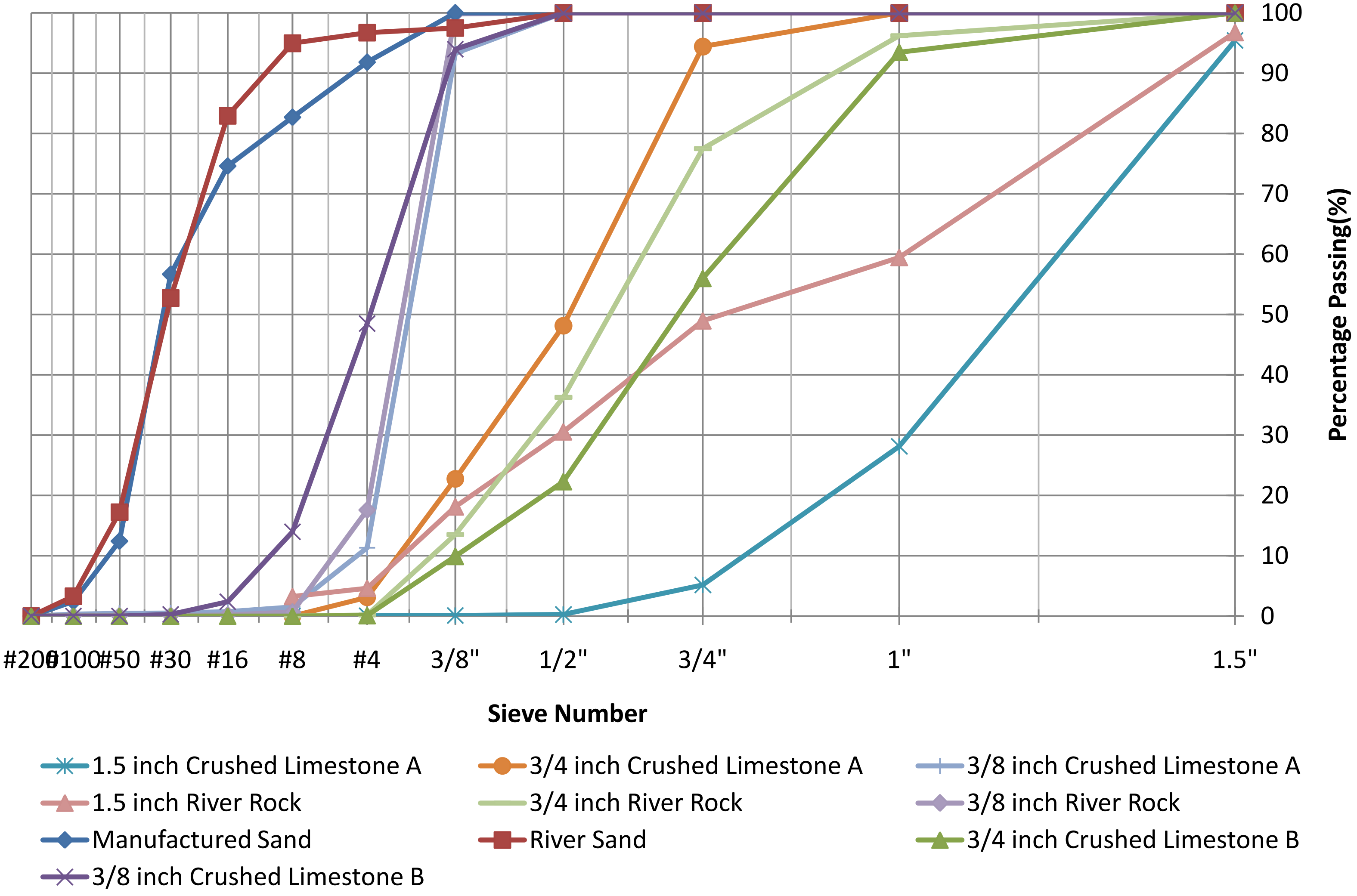


Figure3. Sieve analysis for each aggregate type

3.1 Mixture Design

To evaluate and compare performances of multiple mixtures, the paste content and w/cm ratio should be held constant. The w/cm was held constant at 0.45 and therefore the paste content at 7.03 ft^3/yd^3 or 26% of the mixture's volume.Each mixture had the equivalent of five sacks (470 lbs) of cementitious material per cubic yard of concrete and 211.5 lbs of water. To understand the workability impact of fly ash, mixtures using ¾" crushed Limestone A with river sand had two different cementitious combinations, either only cement as the cementitious material, or cement with a 20% fly ash replacement. Also, ¾" crushed limestone B with river sand combinations contain only cement with 20% fly ash. Described in Table 4 for each aggregate combination, up to five different gradations were examined, including the center and bottom center of the Shilstone chart, the minimum voids contents as determined by the Toufar method within Compass (The Transtec Group, 2004), a mixture close to the power 45 line, and mixture with 60% of the largest aggregate size and 40% of the fine aggregate size.

The software Compass is concrete mixture proportioning program developed by the Transtec Group for FHWA, which uses data from sieve analysis and specific gravities in packing models to estimate the voids content (The Transtec Group, 2004). Conventional wisdom is that by reducing the voids in the mixture then the designer is also reducing the volume of paste that is needed. The Toufar method was used in this research because the batch proportions were found to be the most reasonable when compared to the other two packing methods in the software package.

All of the mixtures were designed to intentionally hold the paste constant and vary the gradations of the mixtures. This allowed the impact of aggregate gradations on the workability and response to vibration of mixtures to be investigated and measured.The different aggregate combinations and gradation investigated for mixtures without and with fly ash can be presented below Table 5 and 6 respectfully. Also, Figures 4 through 14, gradations are compared for the individual aggregates and the mixtures investigated.

Table 4. Gradation description

Gradation	**Description**
Middle	Located in the middle of the Shilstone chart in Zone II, it has a coarseness factor of 60 and a workability of 35 as shown in Figure1.
Bottom	As shown in Figure 1 with the coarseness factor of 60 and workability of 30, the bottom middle is located in Zone II on the Shilstone chart.
60% CA, 40% FA	With no intermediate aggregate added, the gradation uses 60% of coarse aggregate and 40% of the fine aggregate by volume.
Power 45	Gradation follows the power 45 line. Typically used in the design of asphalt.
Minimum Voids	The minimum voids content produced by Compass using the Toufar Method.

Table 5. Mixture combinations without fly ash

Aggregate		Proportioning				
Coarse	Fine	Middle	Bottom	60/40	Power 45	Min Void
3/4" Crushed Limestone A	River Sand	x	x	x	x	x
3/4" River Rock	River Sand	x	x	x	x	x
1.5" Crushed Limestone A	River Sand	x	x	x	x	x
1.5" River Rock	River Sand	x	x	x	x	x
3/4" Crushed Limestone A	Man Sand*	x	x	x	x	x
3/4" River Rock	Man Sand*	x	x	x	x	x
1.5" Crushed Limestone A	Man Sand*	x	x	x	x	x
1.5" River Rock	Man Sand*	x	x	x	x	x

*****note: man sand is actually manufactured sand

Table 6. Mixture combinations with fly ash

Aggregate		Proportioning				
Coarse	Fine	Middle	Bottom	60/40	Power 45	Min Void
3/4" Crushed Limestone A	River Sand	x	x	x		
3/4" Crushed Limestone B	River Sand	x	x			
3/4" Crushed Limestone A sieved to 3/4" Crushed Limestone B gradation	River Sand	x				

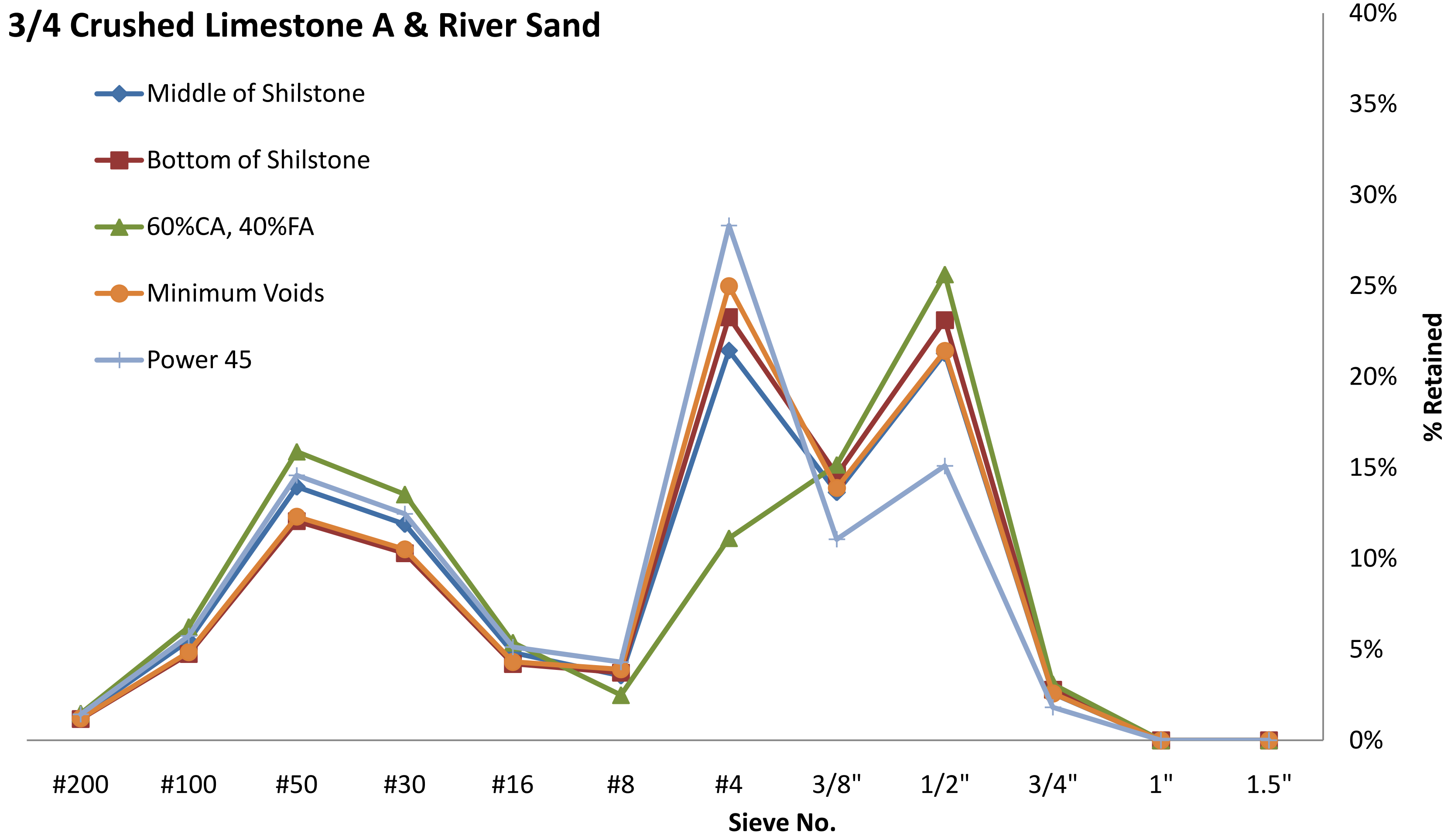


Figure 4. Sieve analysis for 3/4” crushed limestone A & river sand

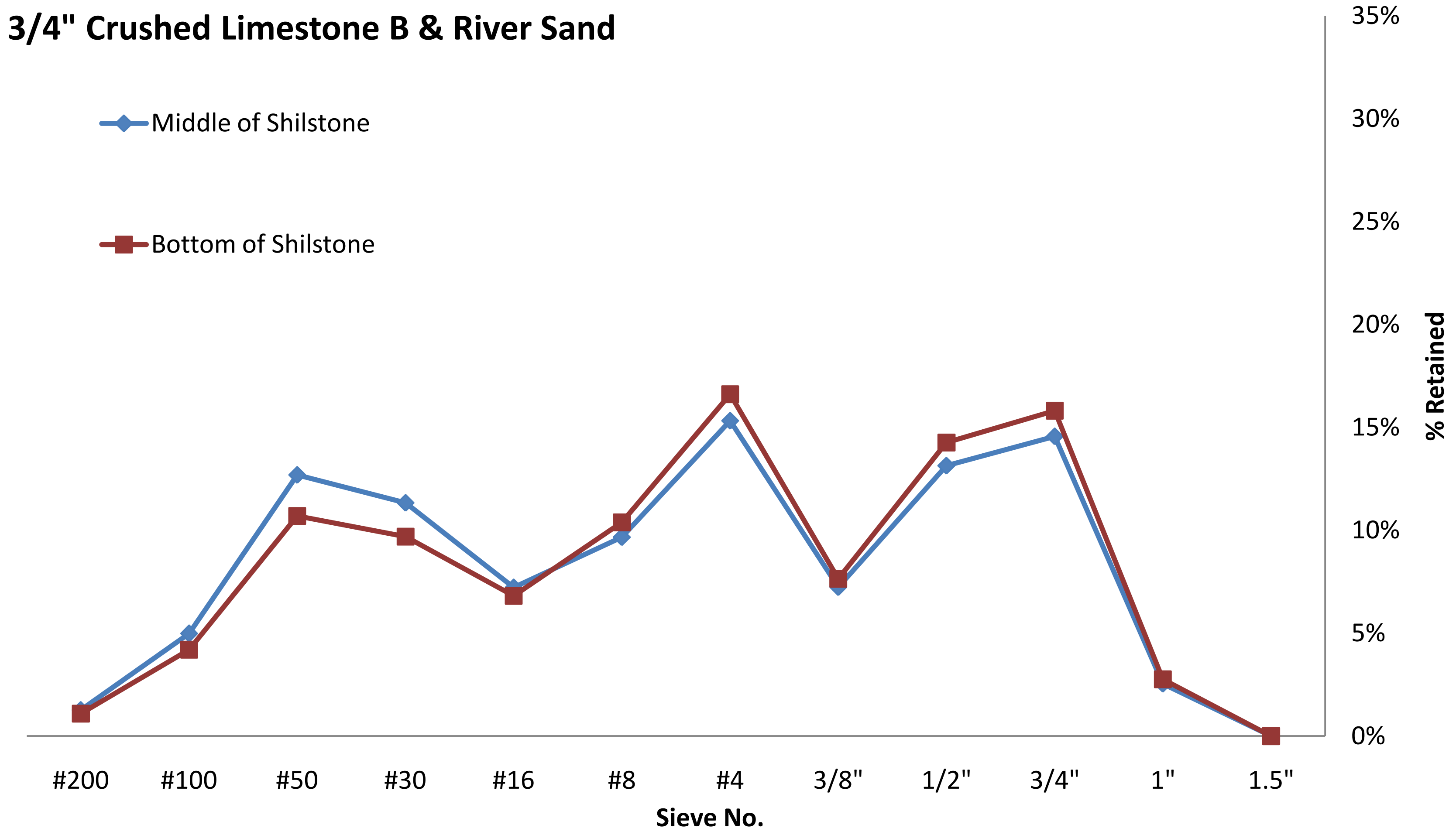


Figure 5. Sieve analysis for 3/4” crushed limestone B & river sand

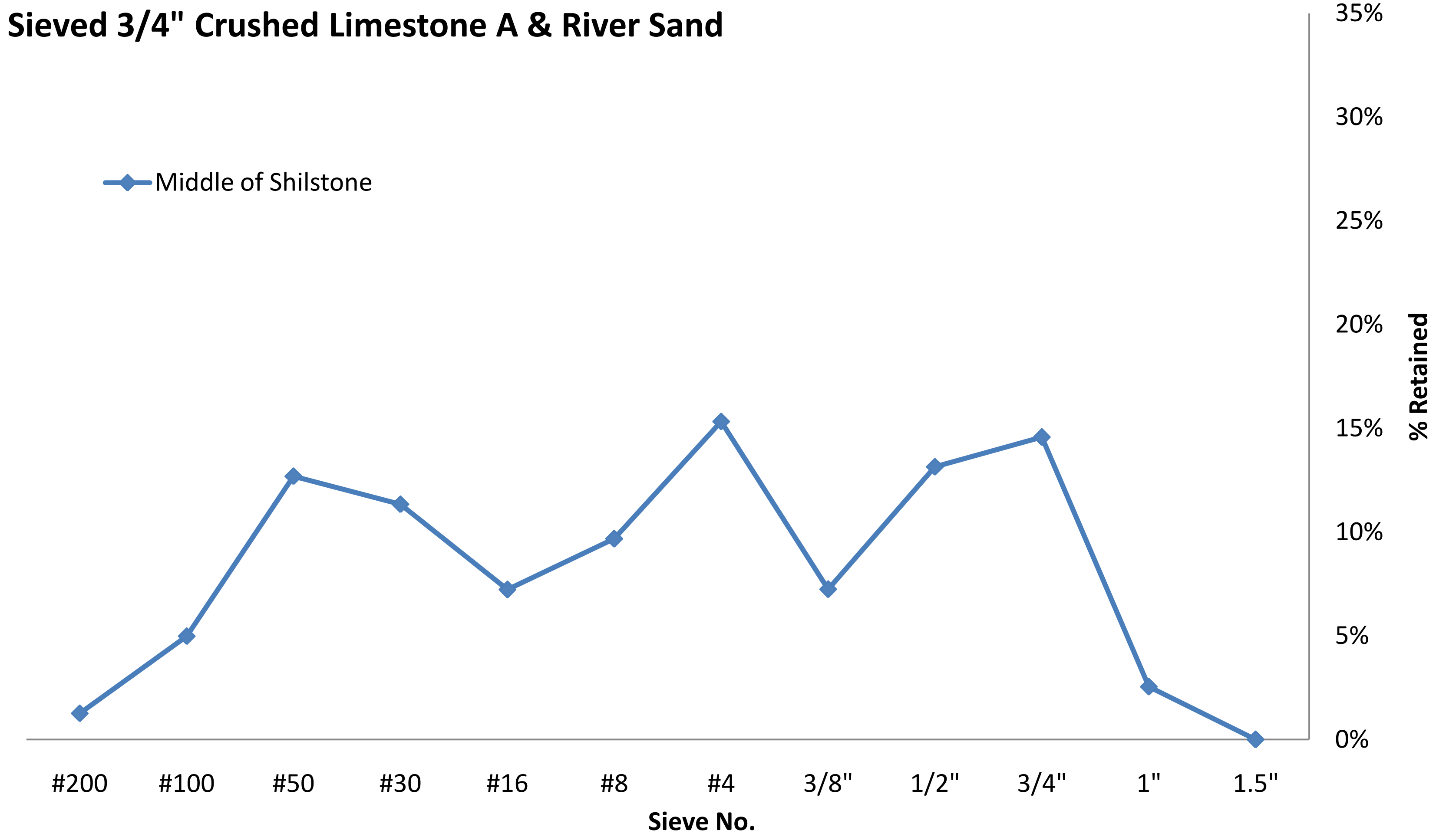


Figure 6. Sieve analysis for 3/4” crushed limestone A & river sand sieved to 3/4” crushed limestone B & river sand gradation

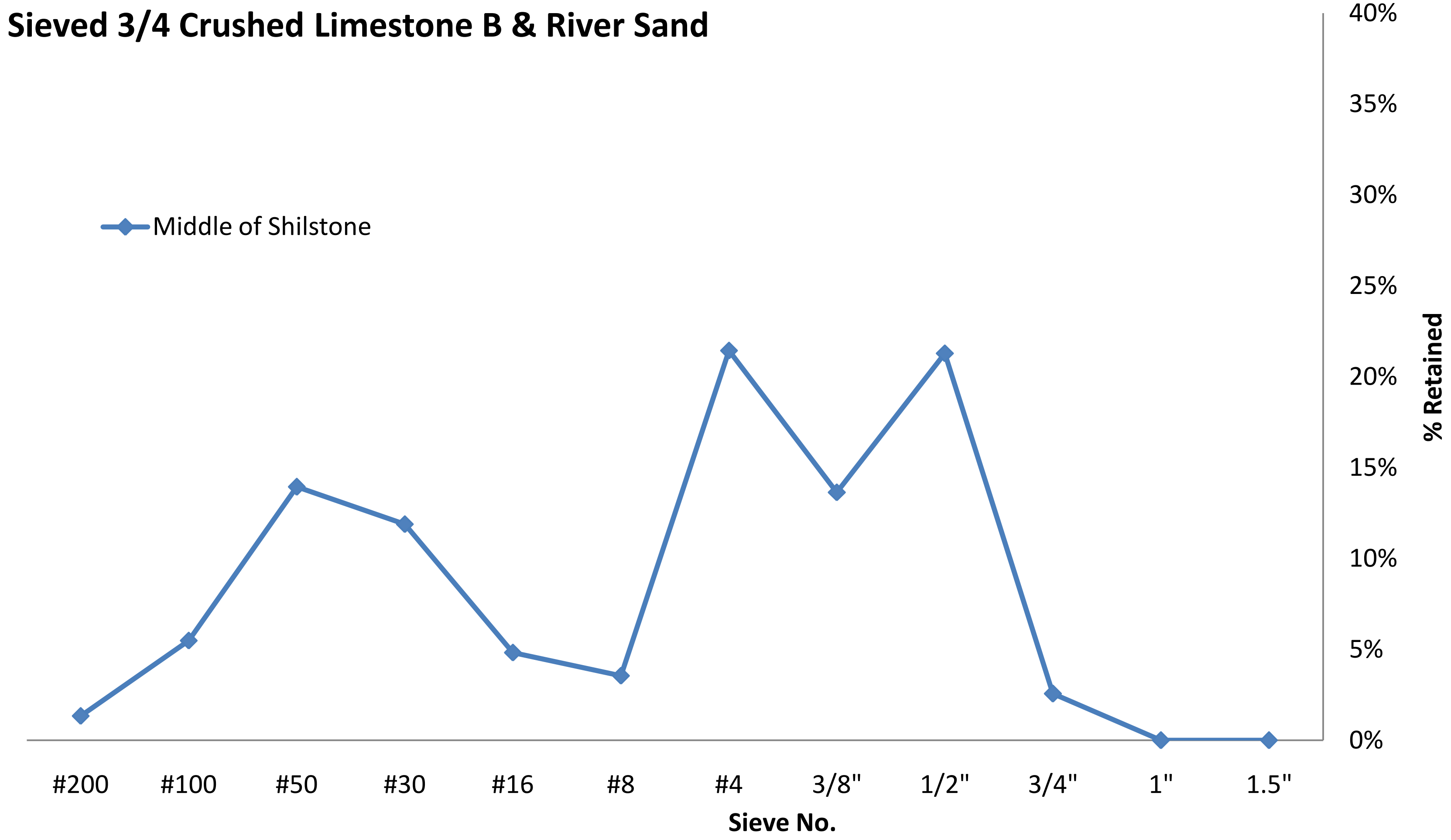


Figure 7. Sieve analysis for 3/4” crushed limestone B & river sand sieved to 3/4” crushed limestone A & river sand gradation

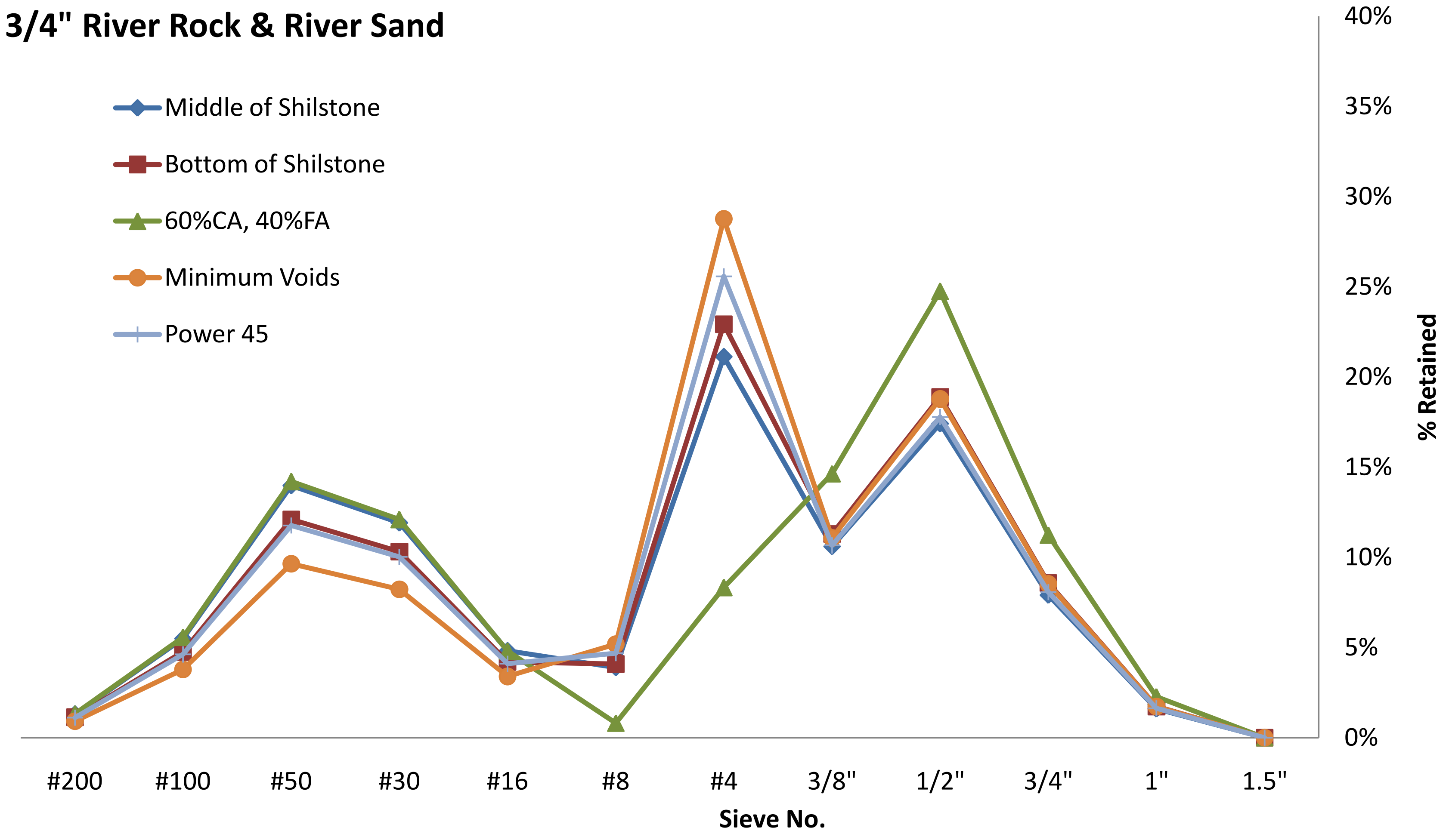


Figure 8. Sieve analysis for ¾” river rock & river sand

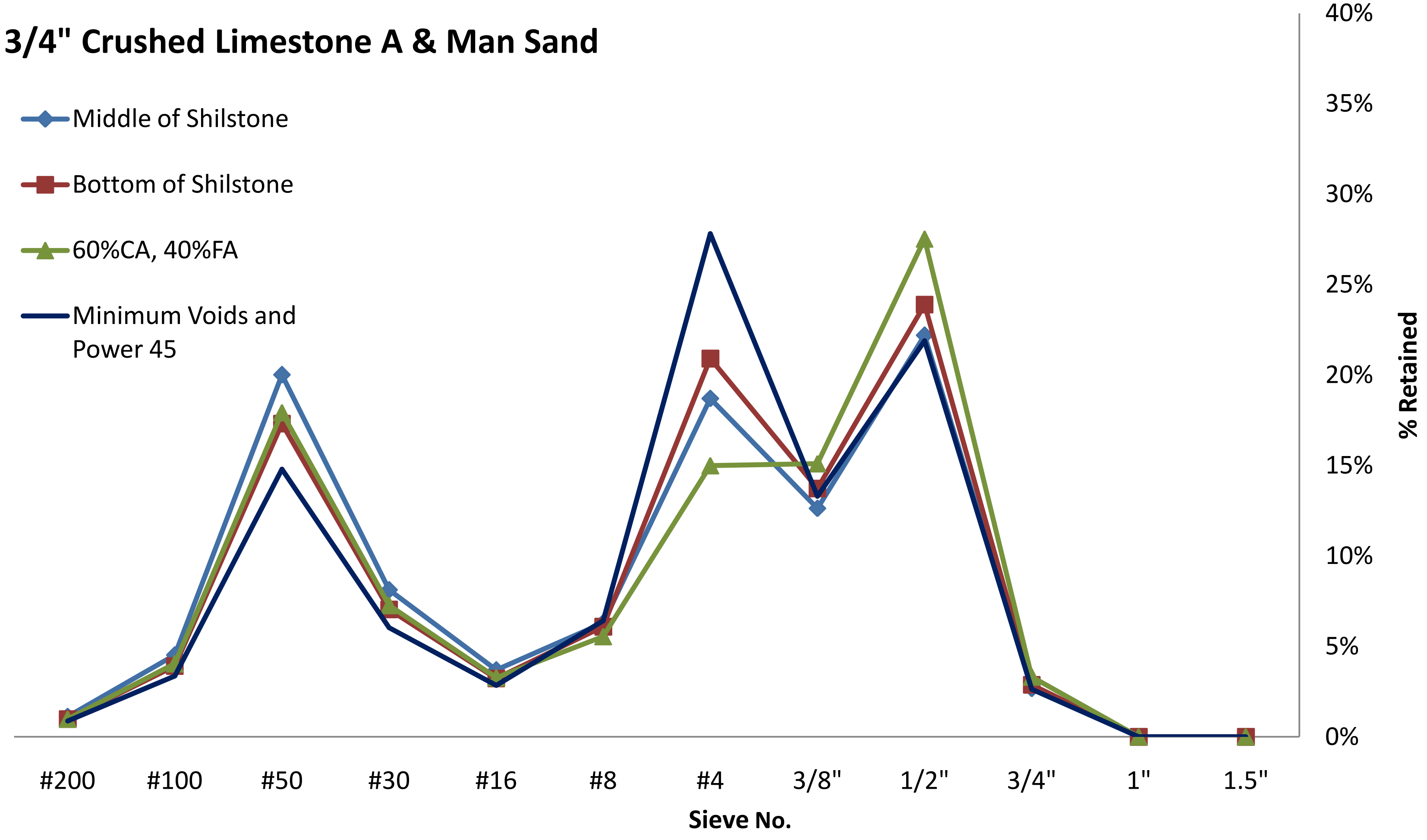


Figure 9. Sieve analysis for ¾” crushed limestone A & manufactured sand

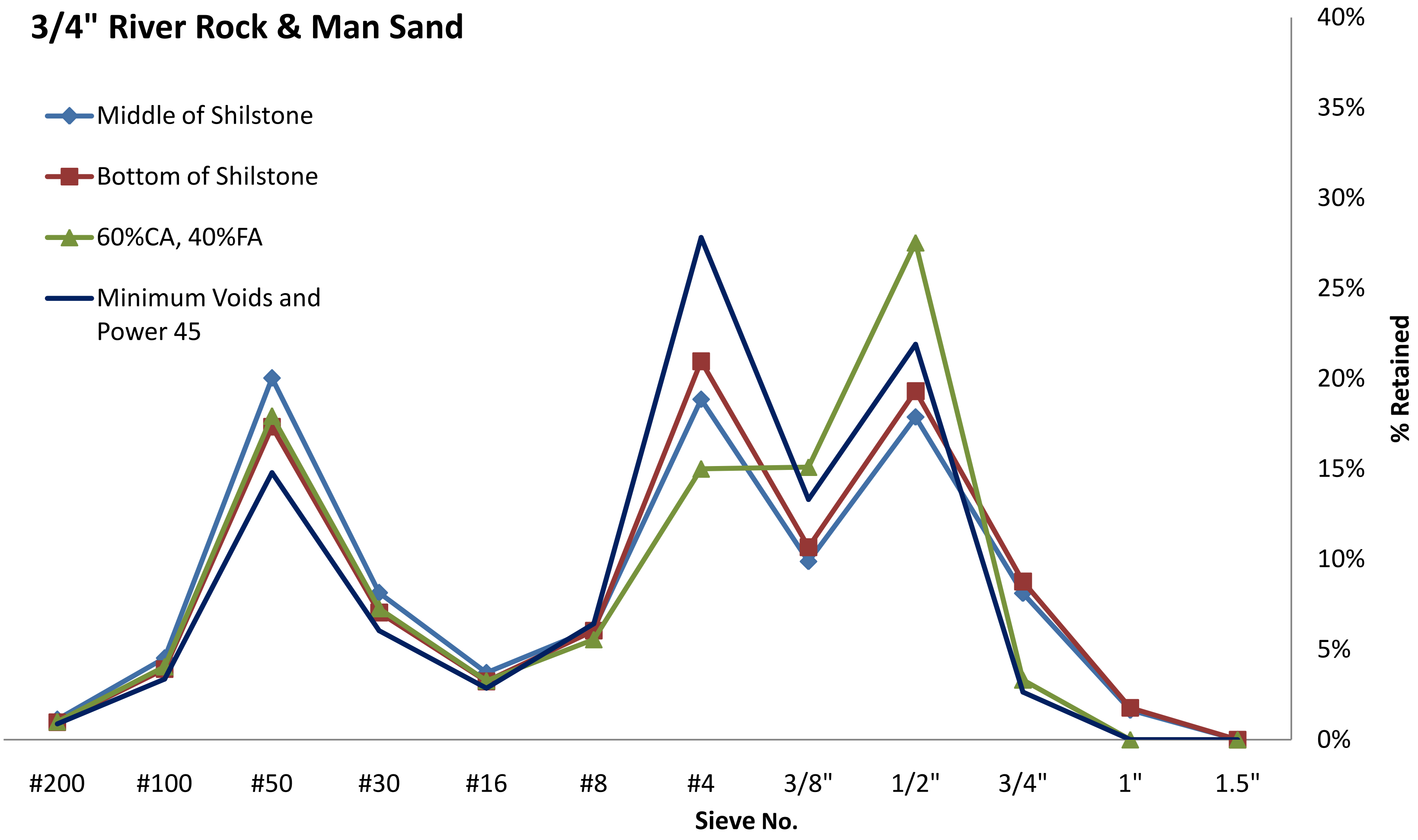


Figure 10. Sieve analysis for 3/4" river rock & manufactured sand

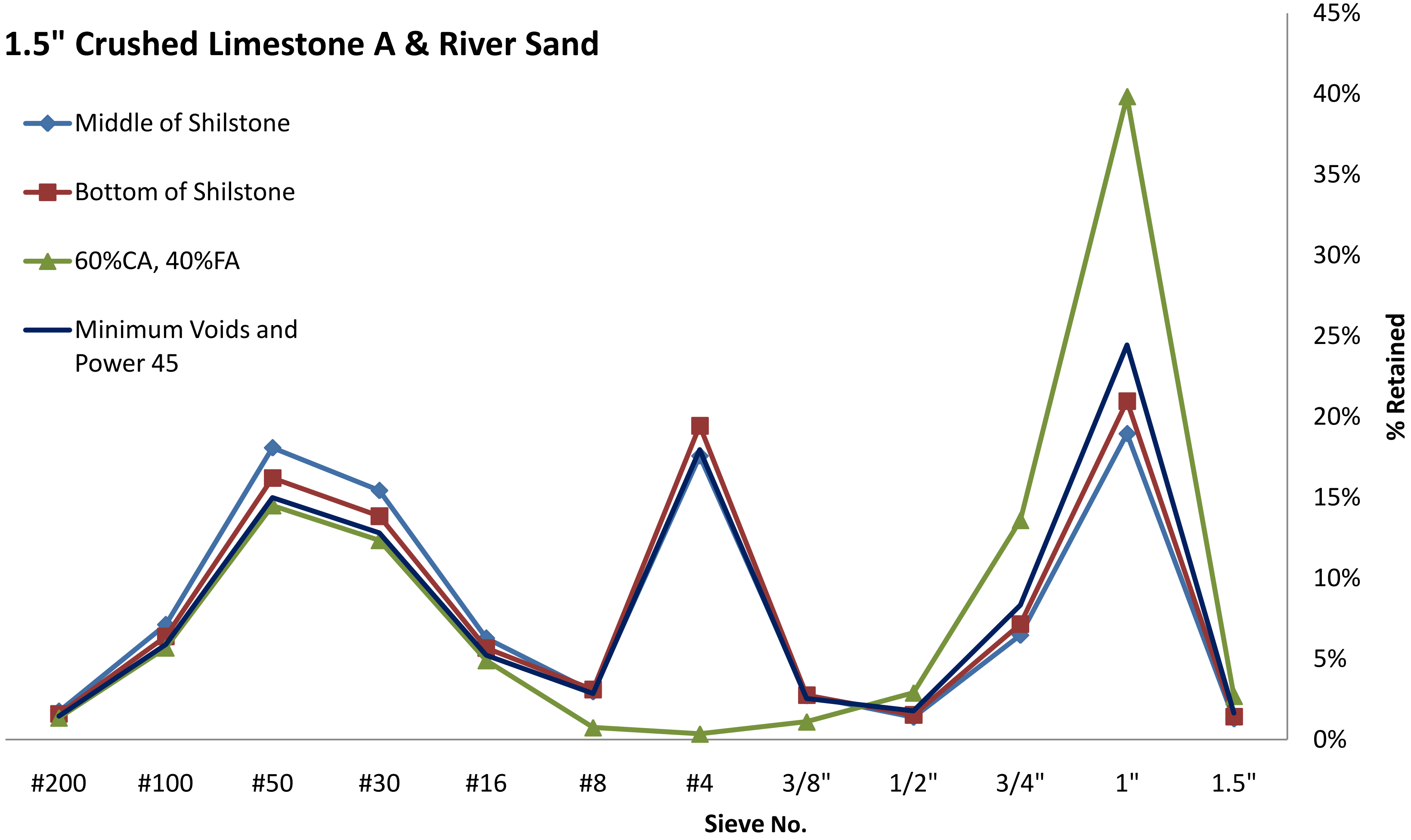


Figure 11. Sieve analysis for 1.5” crushed limestone A & river sand

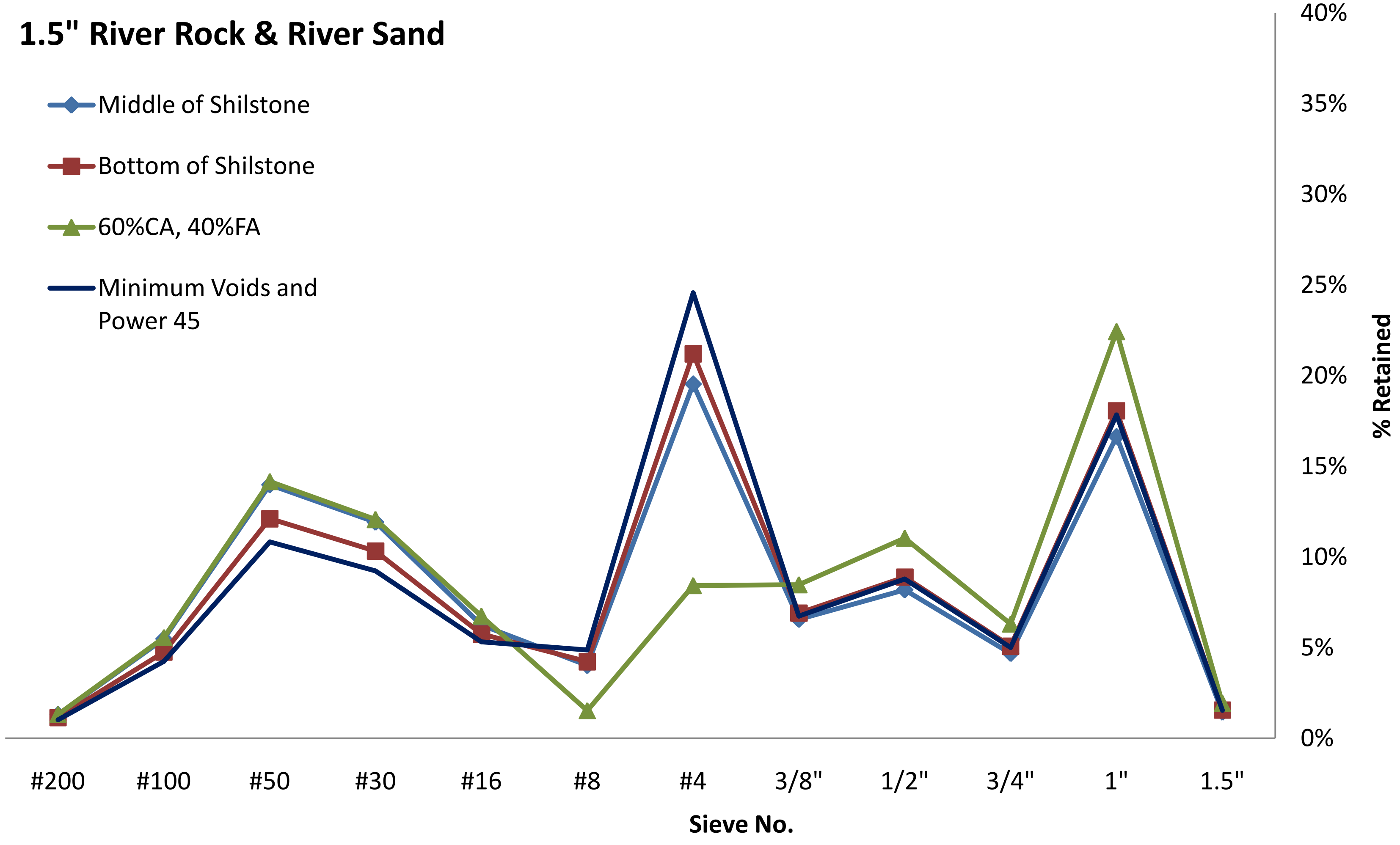


Figure 12. Sieve analysis for 1.5" river rock & river sand

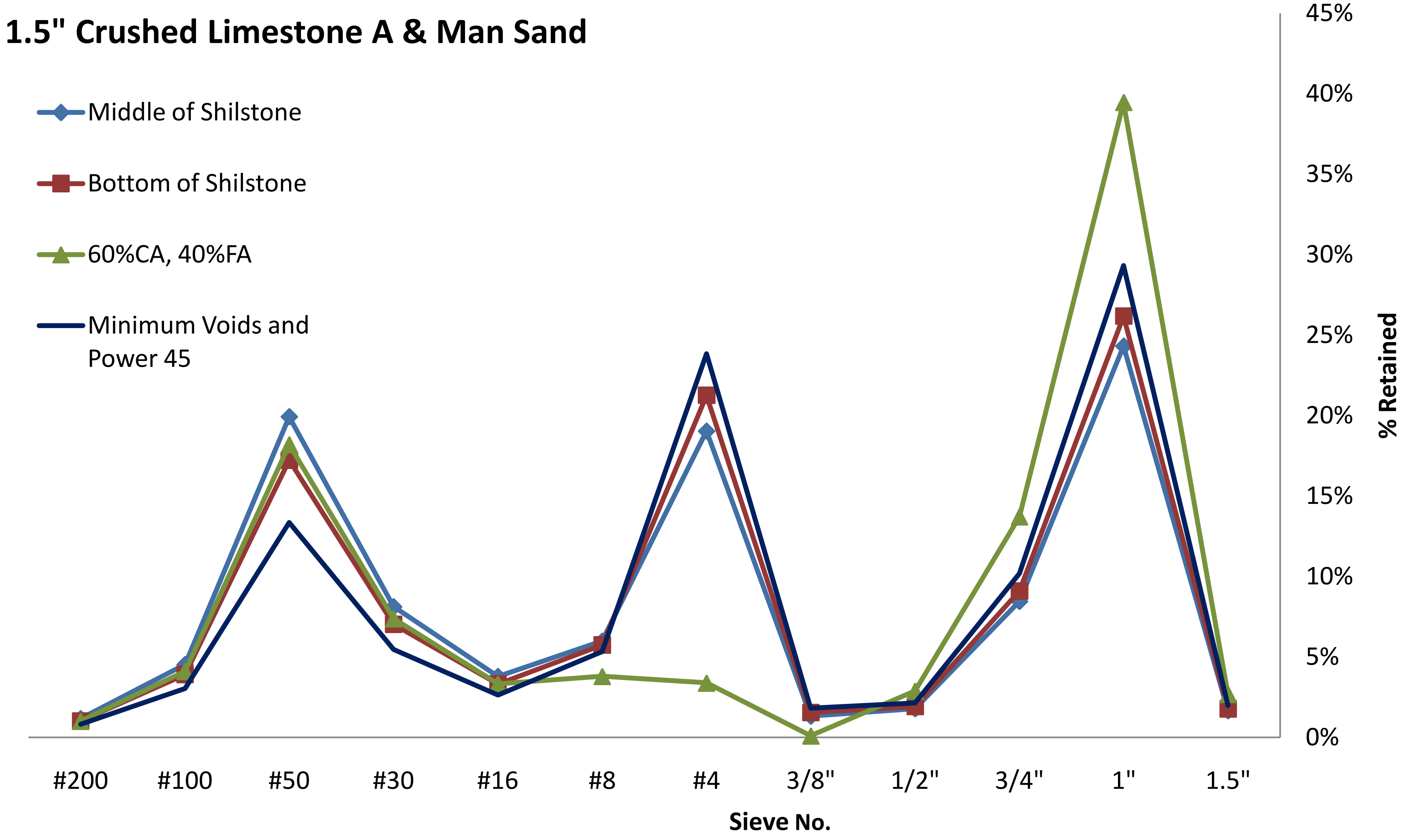


Figure 13. Sieve analysis for 1.5” crushed limestone A & manufactured sand

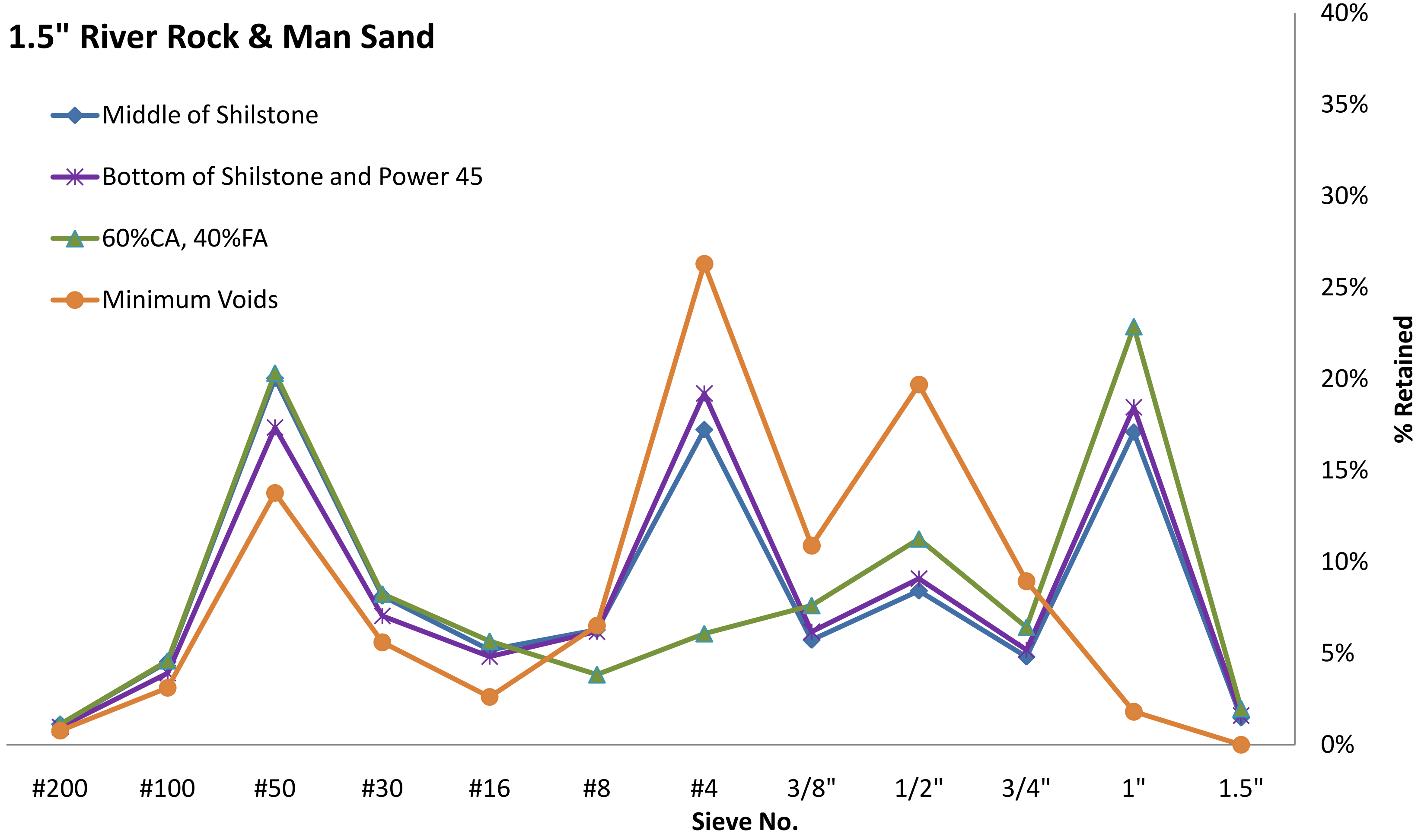


Figure 14. Sieve analysis for 1.5” river rock & manufactured sand

3.2 Mixing and Testing Procedure

Aggregates are collected from outside storage piles, and brought into a temperature-controlled laboratory room at 73°F (23°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. 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 air content (ASTM C 231), slump (ASTM C 143), unit weight (ASTM C 138), and a novel test method to examine the response to vibration called the box test.

CHAPTER 4

THE BOX TEST

4.0 INTRODUCTION

The concrete industry has made great advancements over the years and has created mixtures to easily meet multiple specifications. However, some specifications have been very difficult and allusive to meet. The industry has emphasized for years to design concrete mixtures based on specifications first and then the workability of concrete. The term workability can be very complex; However, T.C Powers described the generally meaning of the word in his book *The Properties of Fresh Concrete* by this statement:

> "The term "workability" is associated with experience, general impressions, and personal judgments involving not only the properties of fresh concrete, but also the myriad situations under which it is handled." (Powers, 1968)

The complexity of the concrete's workability can be created from numerous variables, but the most dependent variable for a mixture's workability is the application of the jobsite, such as a slip form pavement, a wall, a bridge deck, a slab, or a foundation. Obviously, a mixture designed for a wall would not be applicable for a slip formed pavement. A mixture for a wall needs a high flowability while a mixture for a slip form pavement needs to be able to be consolidated but stiff enough to hold an edge.

Many construction companies move from jobsite to jobsite using the materials available in that specific area to design and produce their own concrete. Contractors try to meet the specifications then if possible the workability for the jobsite's application. After designing a mixture for a slip formed pavement application, many times a contractor will perform a small batch mixture to evaluate the workability. The contractor will use his or her experience to evaluate the workability of a mixture, but the best and only certain method to evaluate a mixture for a slip formed paver is to use a slip formed paver.

4.1 Current Laboratory Tests for the Workability of Concrete

In a laboratory environment using a slip formed paver to evaluate a mixture's performance can create unnecessary problems and costs. Clearly, a laboratory method to evaluate a batch design for a slip form paver is necessary. To develop a measurement system for the workability of concrete has been a goal of engineers for years. Many people have created laboratory tests to measure the workability of concrete. According to Fulton in 1961, people have created over 50 workability test with very little success (Fulton 1961). A workability test should provide a useful indication for the ability to place and consolidate a pavement mixture. Some of the more popular tests developed to measure the workability of concrete is the slump test, the vebe apparatus test, and the vibrating slope apparatus.

4.1.1 The Slump Test (ASTM C 143)

For years people have used the slump test (ASTM C 143) to measure the workability of concrete, but the slump test cannot directly measure the workability of a mixture. The slump test does not mimic a slip formed paver's vibrator, the ease at which concrete can be placed, or the ability to be pumped. Instead the best indication of a mixture's workability is to use the mixture in the application intended.

For a concrete pavement, a slip formed paver uses vibrators to consolidate a low slump concrete that extrudes out of the back of the machine. A slip formed concrete mixture must be able to be placed and consolidated by the paver and not lose its edge as it leaves the paver. While the slump test has been the most common technique to evaluate the workability of a mixture, it fails to be sensitive to changes in the mixture at very low levels of workability. 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)

4.1.2 The Vebe Apparatus Test

For slip formed paving applications, the measurement of a mixture's performance to vibration is very important. As described in *The Properties of Fresh Concrete*, the vebe test measures a mixture's ability to change shapes under vibration (Powers 1968).The vebe apparatus test creates fundamental problems for the application of slip formed pavements. A slip formed pavement mixture is mechanically placed and vibrated for consolidation, but this test uses vibration to move concrete into a different shape. A very basic parameter of a workability test should be the specific flowability of a mixture must be applicable for the workability for an application. If a concrete mixture can be transformed into another shape, the mixture is evidently too flowable for a stiff slip formed pavement mixture. This is why the vebe apparatus test cannot be used to measure the workability of a slip formed pavement mixture.

4.1.3 The Vibrating Slope Apparatus

Another vibration test is the vibrating slope apparatus developed for the U.S Federal Highway Administration. The vibrating slope apparatus measures the rate of free flow on an angled chute subjected to vibration. It attempted to measure the yield stress and plastic viscosity of low slump concrete (Wong 2001). The vibrating slope apparatus mimics the ability of a concrete mixture to free flow from the tail end of a dump truck using vibration. The discharging of concrete using a dump truck is not the controlling workability factor in a slip formed pavement mixture because a dump truck does not have any problem unloading plain aggregates. A workability test for a slip formed pavement should measure the components of a slip formed paver rather than evaluating the minor dumping process.

4.2 Objectives

Many workability tests fundamentally create false parameters such as requiring a high flowable mixture to measure the workability of slip formed pavements that require a low flowable mixture, or measuring the ability of a concrete mixture to be dumped into a slip formed paver. To measure the impacts of different variables in a concrete mixture, a laboratory test needed to be developed to evaluate the workability of concrete for a slip formed pavement application. The concept of creating a useful laboratory test should evaluate a specific variable while the process is being mimicked, but on a much smaller scale. It is important to realize sometimes processes cannot be truly mimicked because expense or practicality. However, a laboratory test can still be useful as long as the test focuses on the most important component of a process.

4.3 Development of a laboratory vibration test

With the variety of different makes and models of slip formed paving machines and various operating procedures, to design a slip formed pavement laboratory method could be very complex and expensive. But a laboratory test for evaluating a concrete mixture needs to be quick, easy, and useful. In Figure 15, the components and the process involved in a slip formed paver are shown. Unlike the auger, striker, and tamper to complete their tasks, the hydraulic vibrator requires a minimum amount of paste and a low level of viscosity to consolidate concrete correctly.

A laboratory test was developed to mimic the performance of a concrete vibrator and then evaluate the performance of the mixture to a standard amount of vibration with a fixed vibrator head. Since the vibrator variables were held constant, the mixture could be changed to investigate the ability to respond to vibration and fill a known volume of material.

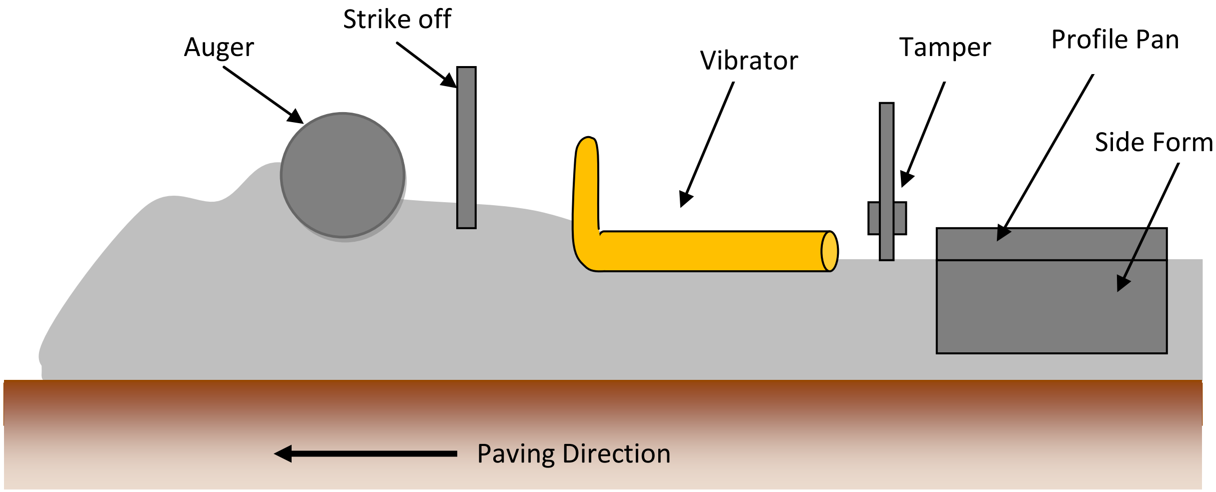


Figure 15. Components of a slip formed paver.

In Figure 16, a typical section of finished concrete using a slip formed paver. Each vibrator's ability to consolidate the concrete depends on the mixture, depth of the pavement, the speed of the machine, and the vibrations per minute of the vibrator. As shown in Figure 16, slip formed vibrators consolidate concrete in the horizontal direction. If a vibrator vertically consolidates the concrete in a two directions for the same time increment as a vibrator consolidating concrete in the horizontal direction, the difference should be minimal.

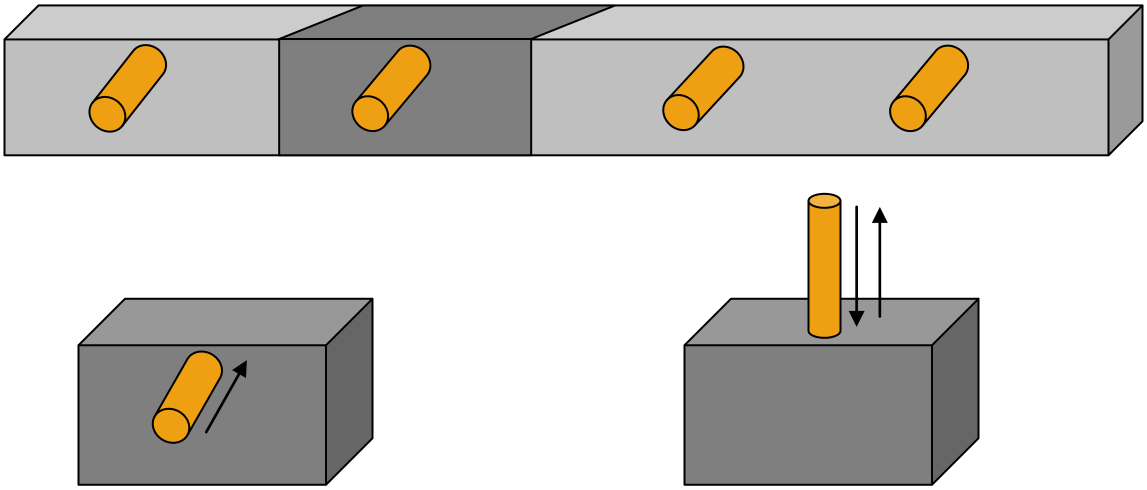


Figure 16. Isolating a vibrator in a section of concrete

4.4 The Box Test

A laboratory test was developed to evaluate the ability of an electric vibrator to consolidate a concrete mixture. By keeping the paste constant and adding a water reducer (WR) to change the yield stress, one can measure the amount of surface voids after vibration; it can help evaluate a mixture by the amount of WR added to have a standard amount of voids. Also, instead of vibrating sideways, the vibrator was placed in the middle top and down to simplify the easy of the test.

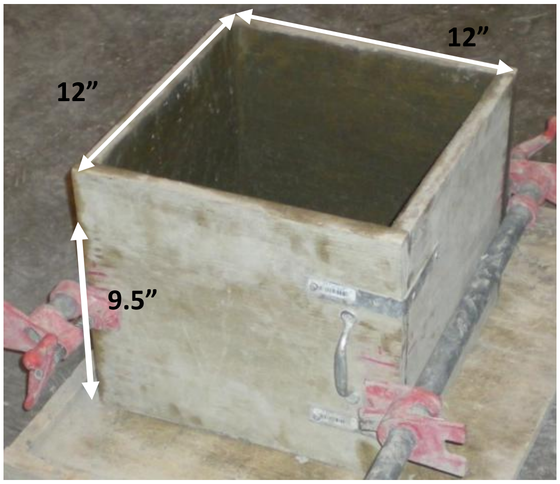


Figure 17. The box test volumetric dimensions**.**

The box test used a ½” plywood base with a length, width, and height of 12 inches using clamps to hold the box together as shown in figure 17. Figure 18 shows the different components of the box test. Each step of the box test process is shown in Table 6. Placed on the base, a 1 ft^3 wooden formed box was constructed and held together by clamps as shown in Figure 17. Concrete was uniformly hand scooped into the box up to a height of 9.5”. A hand held 1” head WYCO model number 922A electric vibrator with 12,000 VPM was used to consolidate the concrete by inserting it at the center of the box. The vibrator was lowered over three seconds to the bottom of the box and then raised over three seconds. The clamps were removed from the side of the box and the side walls were removed. A mixtures performance to vibration can be assessed by the surface voids. Each of the four sides was evaluated by visually comparing the side to Table 7. The average surface voids of the four sides should be calculated and give an overall number ranking of 1-4. If a mixture performed well to vibration, the overall surface voids should be minimal. However, if the sides have large amounts of surface voids, a mixture didn’t perform well to vibration. For a mixture to be considered performing well to vibration, the average of the four sides should be less than 30% surface voids, or a ranking of 2. Also, the box test can assess edge slumping. A straight edge can vertically measure each corner for top and bottom edge slumping as illustrated in Figures 19 and 20.

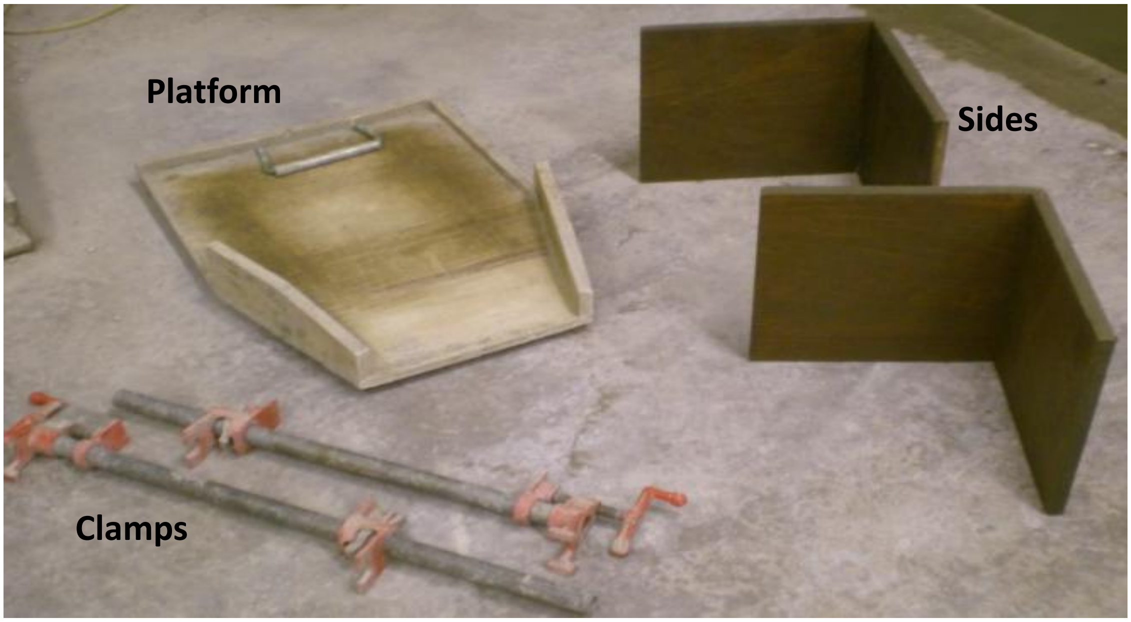
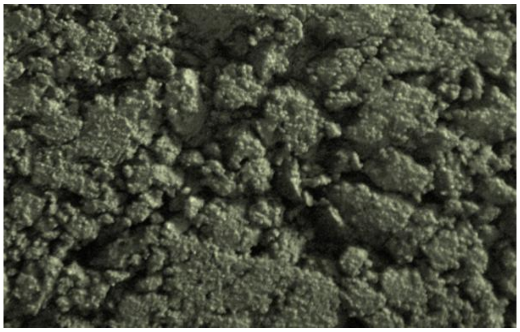
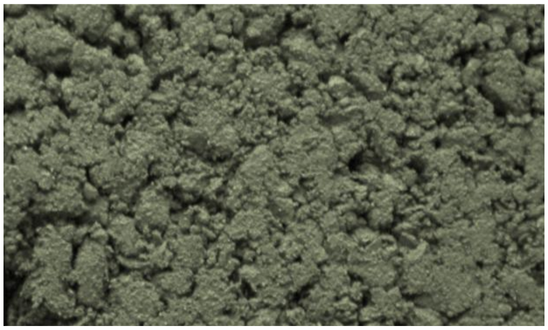
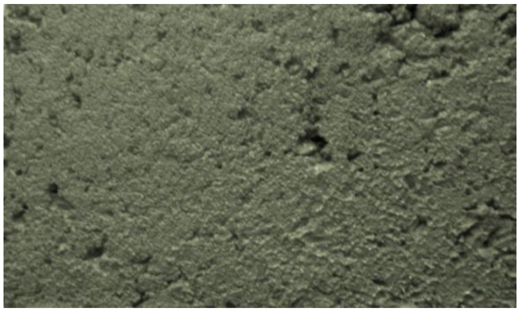
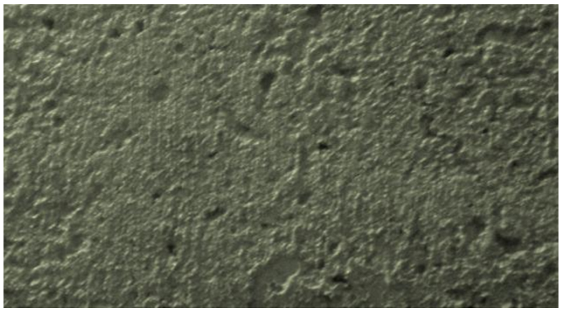


Figure 18. Different components of the box test.

Table 6. The different steps of the box test.

	
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.**

Table 7. The box test ranking scale.

	
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.

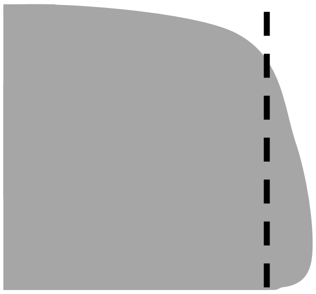


Figure 19. Bottom edge slumping

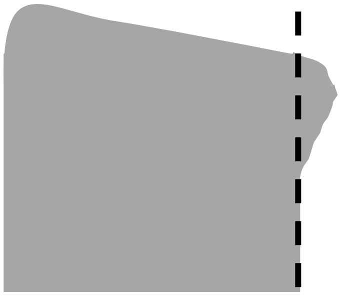


Figure 20. Top edge slumping

4.5 The Box Test Procedure

When a mixture recieves a ranking of a 3 or 4, the response to vibration was poor and a mixture needs more paste or a lower yield stress. To evaluate and compare multiple mixtures response to vibration, the paste content needs to be reduce until it is bounderline unresponsive to vibration. If the w/cm and paste volume are held constant, but the gradations varried, the mixture's performance to vibration can be measured by the amount of WR needed to pass the box test.

After a mixture was prepared as discussed in section 3.2, the slump test, unit weight, air, and the box test was conducted. If the box test failed, the material from the slump and box test were placed back into the mixture. The air test material was discarded and air was not tested until the mixture passed the box test. 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 was 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 C 39). In Figure 21, a flow chart visually shows the box test evaulation procedure. When conducting the box test procedure, the slump test is also conducted to the measure the increase in consistancy. To ensure intial set does not occur, all mixtures should be discarded after one hour in a temperature environment of 73°F (23°C).

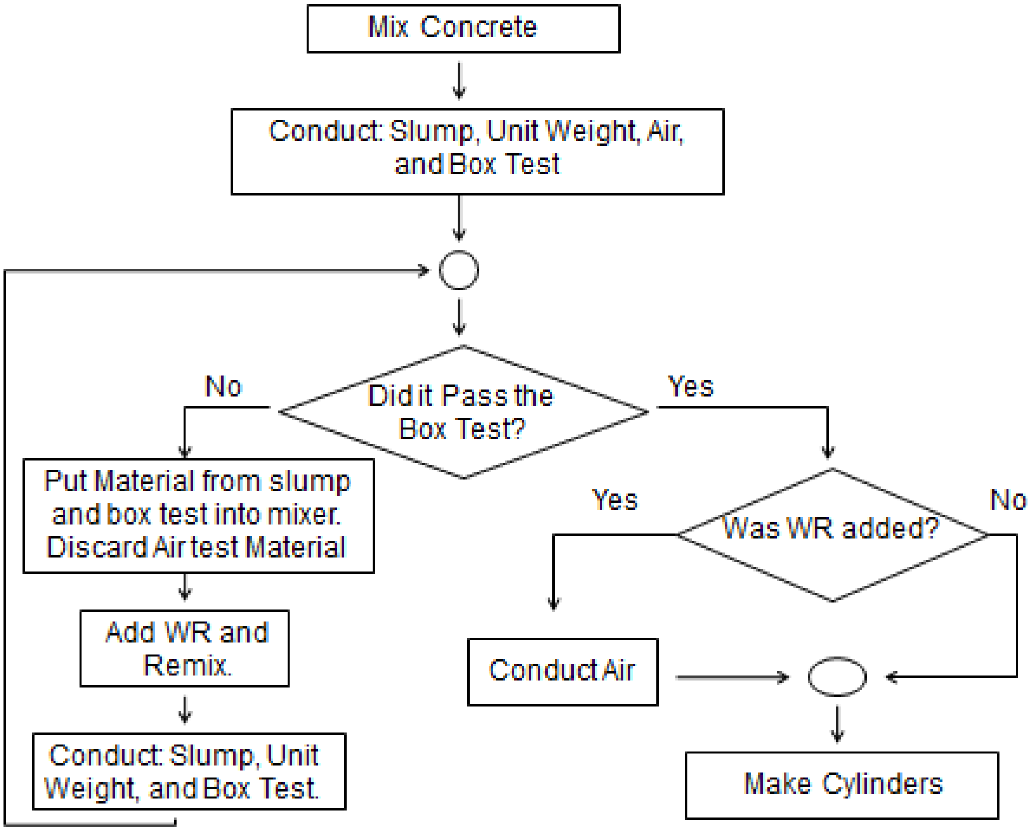


Figure 21. A flow chart of the box test procedure

4.6.0 Validation of Box Test

The box test has some variables that need to be addressed. Many of the variables deal with the effects of time, repeatability, and comparison of other operators. Another important factor in a workability test is performance in the field. In the sections below some of the variables were evaluated.

4.6.1 Effects of Time and Sequential Dosage

To investigate the impacts of the time and sequential dosage of the test procedure, a series of replicate tests were completed where a single dosage of WR was added instead of the sequential dosages. Six different mixtures were tested. Each of the original and replicated mixtures had similar fresh properties and similar amounts of surface voids.

4.6.2 Repeatability of a Single Operator Replication

To find the repeatability of the box test, eight mixtures were blindly replicated to compare the fresh properties and required WR dosage to pass the box test. The highest difference in WR to pass the boxt test was +/- 1.7 oz/cwt. Furthermore, the other properties of the mixtures were very similar. The WR difference reflects the operator's ability to measure a mixture's performance in the box test. Most likely, the WR difference could increase if another person with less experience completes the test.

4.6.3 Field Performance

The realization of a paver's hydraulic vibrator and a portable electric vibrator functioning differently, created uncertainties for the box test. To understand and find similarities between the box test and a slip formed paver, the box test was conducted in the field using a sample from a concrete mixture being paved with a slip formed paver. The box test was conducted with a slip formed pavement mixture on a highway jobsite and a city street jobsite. The mixtures on the two different jobsites seemed to have a direct correlation between the box test and the paver on those specific jobsites. On both jobsites, the box test was conducted three times. Using the box test ranking scale, six out of six box tests conducted passed with a ranking of a 2. The direct similarities of the box test ranking scale and the slip formed pavers used on those two jobsites doesn't necessarily mean this test will have similar results with every slip formed paver due to differences in vibrator spacing, paving speed, and vibrator frequency.

Field evaluations ensured the vibrator's strength and the box test's dimensions were at least comparable. It is important to realize the box test was only designed to evaluate a mixture's response to vibration and not to correlate directly with a slip formed paver. To create similar performances with a slip formed paver to the box test, the dimensions of the box test may need to be altered.   Also, the electric vibrator should be compatible with the one used in this test.

4.7 Discussion of Validation Results

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 fairly inexpensive compared to many other laboratory tests. Conducting and evaluating a mixture using the box test is quick and easy to perform. However, even a simplistic test can have some variables. A much larger validation of the box test needs to be conducted to evaluate the variables. The comparison of multiple operators also needs to be completed.

CHAPTER 5

RESULTS

Tables 8-10 is a compilation of the results from the fresh and harden properties of the mixtures completed. Figures 22-33 compares the Shilstone chart to each mixture’s WR dosage required to pass the box test. Figures 34-37 compare the WR dosage needed to pass the box test, compressive strength at 7 and 28 day, and the slump of the mixture when it passed the box test for the different investigated gradations.

Table 8.Results of the mixtures with ¾” maximum nominal aggregates with no fly ash

	Aggregate		Gradation				
	Coarse Fine	Properties	Middle of Shilstone	Bottom of Shilstone	60/40	Power 45	Compass Min Voids
3/4" nominal maximum size aggregate	**Crushed Limestone A River Sand**	WR (oz/cwt)	20.8	19.2	21.3	85.9	31.0
		Slump (inches)	0.50	1.75	1.00	0.50	1.25
		7 day fc (psi)	5160	4270	5080	6240	5040
		28 day fc (psi)	5820	5370	5930	8250	6340
		Air Content	2.5%	2.4%	3.2%	2.7%	2.9%
		Unit Wt	152.1	150.6	150.2	151.1	152.6
		Coarse	1553	1684	2015	1100	1561
		Intermediate	508	554	0	907	656
		Fine	1280	1107	1321	1338	1129
		CF WF	60 35	60 30	76.3 40	46.2 36.9	56.7 30.7
	River Rock River Sand	WR (oz/cwt)	15.3	17.9	17.2	18.6	6.7
		Slump (inches)	1.75	2.00	1.75	2.25	1.25
		7 day fc (psi)	4110	4710	4250	4850	4390
		28 day fc (psi)	4950	5220	5020	5100	4970
		Air Content	4.9%	3.4%	4.6%	3.4%	2.1%
		Unit Wt	147.8	148.7	147.3	149.4	151.0
		Coarse	1396	1516	1981	1427	1508
		Intermediate	597	650	0	770	885
		Fine	1302	1127	1321	1096	899
		CF WF	60 35	60 30	85.3 35.5	55.8 29.1	54.2 23.5
	Crushed Limestone A Man Sand	WR (oz/cwt)	23.0	35.6	32.2	31.8	31.8
		Slump (inches)	0.75	1.00	1.75	0.75	0.75
		7 day fc (psi)	4800	4920	4250	5010	5010
		28 day fc (psi)	5860	5660	5070	6140	6140
		Air Content	6.8%	4.9%	8.5%	3.9%	3.9%
		Unit Wt	145.3	147.1	141.5	148.2	148.2
		Coarse	1627	1749	2015	1599	1599
		Intermediate	236	319	0	665	665
		Fine	1461	1262	1311	1075	1075
		CF WF	60 35	60 30	69.1 31	52.5 25.4	52.5 25.4
	River Rock Man Sand	WR (oz/cwt)	21.5	21.0	20.9	20.1	20.4
		Slump (inches)	1.00	1.50	1.50	1.50	1.75
		7 day fc (psi)	3880	3990	3870	4260	4300
		28 day fc (psi)	4450	4240	4110	4550	4660
		Air Content	7.8%	7.3%	8.0%	7.9%	5.0%
		Unit Wt	142.6	140.5	141.3	141.8	145.8
		Coarse	1438	1553	1994	1348	1584
		Intermediate	370	454	0	481	686
		Fine	1478	1280	1297	1455	1016
		CF WF	60 35	60 30	77.6 30.4	55.4 34.4	55.4 34.4

Unit weight was measured in lbs/ft^3 & aggregate types were measured in lbs/yd^3

Table 9.Results of the mixtures with 1.5” maximum nominal aggregates with no fly ash

	Aggregate		Gradation				
	Coarse Fine	Properties	Middle of Shilstone	Bottom of Shilstone	60/40	Power 45	Compass Min Voids
1.5" nominal maximum size aggregate	Crushed Limestone A River Sand	WR (oz/cwt)	32.0	34.0	13.7	31.8	31.8
		Slump (inches)	1.25	1.50	1.00	1.50	1.50
		7 day fc (psi)	5420	5250	4520	4700	4700
		28 day fc (psi)	5970	5470	5430	6020	6020
		Air Content	3.5%	3.1%	3.7%	3.8%	3.8%
		Unit Wt	150.6	151.7	149.8	148.7	148.7
		Coarse	1205	1306	2046	1258	1258
		Intermediate	894	972	0	736	736
		Fine	1266	1092	1322	1369	1369
		CF WF	60 35	60 30	98.2 25.1	65.1 26.7	65.1 26.7
	River Rock River Sand	WR (oz/cwt)	22.2	26.6	26.1	25.1	25.1
		Slump (inches)	1.75	2.00	1.75	2.00	2.00
		7 day fc (psi)	5240	5160	4630	4980	4980
		28 day fc (psi)	5910	5990	5480	6070	6070
		Air Content	4.8%	3.2%	4.3%	2.3%	2.3%
		Unit Wt	147.8	150.0	147.6	151.2	151.2
		Coarse	1470	1596	1978	1631	1596
		Intermediate	522	569	0	846	569
		Fine	1288	1116	1307	802	1116
		CF WF	60 35	60 30	80.8 35.4	56.3 26.6	56.3 26.6
	Crushed Limestone A Man Sand	WR (oz/cwt)	27.9	20.8	20.4	31.8	31.8
		Slump (inches)	1.0	1.5	1.5	1.5	1.5
		7 day fc (psi)	3870	4520	4140	4600	4600
		28 day fc (psi)	4300	5300	4980	6530	6530
		Air Content	8.3%	5.9%	5.4%	1.8%	1.8%
		Unit Wt	138.3	145.5	146.7	154.2	154.2
		Coarse	1263	1356	2044	1515	1515
		Intermediate	644	756	0	892	892
		Fine	1443	1244	1315	961	961
		CF WF	60 35	60 30	89.1 31.5	60.9 22.8	60.9 22.8
	River Rock Man Sand	WR (oz/cwt)	19.5	19.3	21.0	19.3	25.9
		Slump (inches)	1.50	2.50	1.50	2.50	1.25
		7 day fc (psi)	4350	4080	4480	4080	4660
		28 day fc (psi)	4930	4740	5380	5630	5630
		Air Content	8.5%	3.7%	4.9%	2.3%	2.3%
		Unit Wt	141.4	149.3	146.7	151.0	149.3
		Coarse	1470	1596	1978	1596	1631
		Intermediate	522	569	0	569	846
		Fine	1288	1116	1307	1116	802
		CF WF	60 35	60 30	80.8 35.5	60 30	53.8 21

Unit weight was measured in lbs/ft³ & aggregate types were measured in lbs/yd³

Table 10.Results of the mixtures with 3/4” maximum nominal aggregates using 20% fly ash.

	Aggregate		Gradation		
	Coarse Fine	**Properties**	**Middle of Shilstone**	**Bottom of Shilstone**	**60/40**
3/4" nominal maximum size aggregate	**Crushed limestone A River Sand**	WR (oz/cwt)	8.3	16.1	17.1
		Slump (inches)	1.50	1.50	2.00
		7 day fc (psi)	5370	4340	5070
		28 day fc (psi)	6390	5900	5890
		Air Content	2.8%	2.5%	3.5%
		Unit wt (lbs/ft^3)	151.2	152.3	149.8
		Coarse (lbs/yd^3)	1553	1684	2015
		Intermediate (lbs/yd^3)	508	554	0
		Fine (lbs/yd^3)	1280	1107	1321
		CF WF	60 35	60 30	76.3 40
	Crushed Limestone B River Sand	WR (oz/cwt)	0.0	0.0	
		Slump (inches)	1.50	1.00	
		7 day fc (psi)	5270	4870	
		28 day fc (psi)	7340	6500	
		Air Content	1.3%	1.3%	
		Unit wt (lbs/ft^3)	155.0	155.1	
		Coarse (lbs/yd^3)	1449	1562	
		Intermediate (lbs/yd^3)	847	917	
		Fine (lbs/yd^3)	1121	850	
		CF WF	60 35	60 30	
	Sieved Crushed limestone A River Sand to Crushed limestone B River Sand	WR (oz/cwt)	0.0		
		Slump (inches)	0.50		
		7 day fc (psi)	4050		
		28 day fc (psi)	5570		
		Air Content	2.5%		
		Unit wt (lbs/ft^3)	151.4		
		Coarse (lbs/yd^3)	1308		
		Intermediate	756		
		Fine (lbs/yd^3)	1253		
		CF WF	60 35		
	Sieved Crushed limestone B River Sand to Crushed limestone A River Sand	WR (oz/cwt)	6.7		
		Slump (inches)	1.50		
		7 day fc (psi)	5280		
		28 day fc (psi)	7340		
		Air Content	2.4%		
		Unit wt (lbs/ft^3)	148.5		
		Coarse (lbs/yd^3)	1703		
		Intermediate	489		
		Fine (lbs/yd^3)	1236		
		CF WF	60 35		

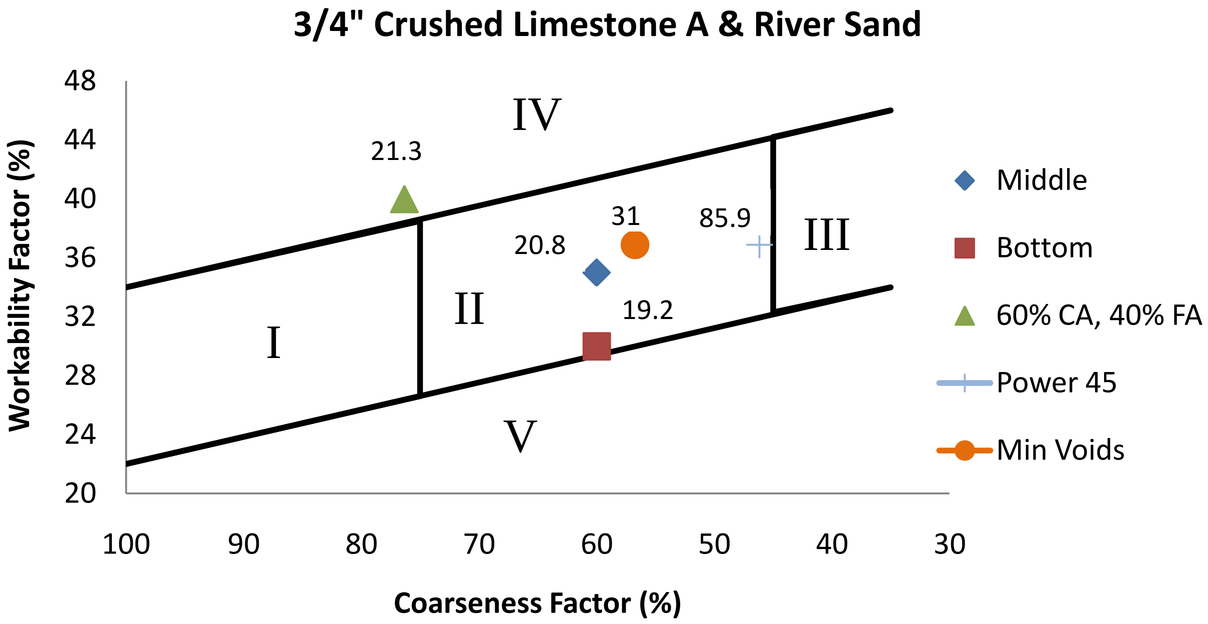


Figure 22. The results of the ¾" crushed limestone A & river sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

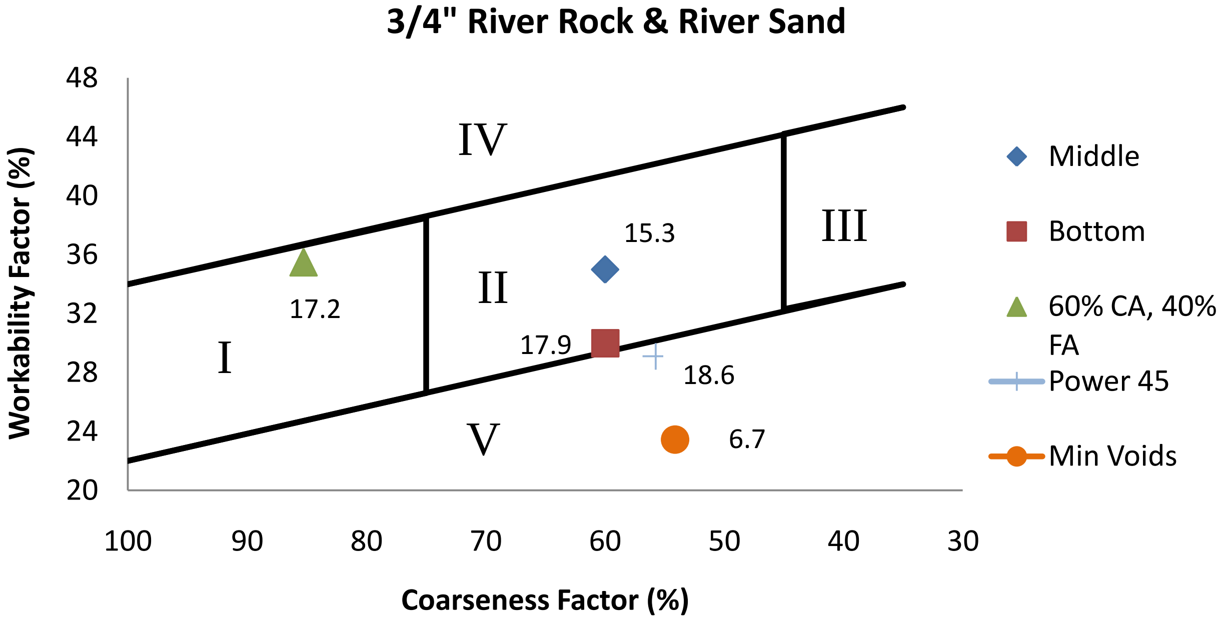


Figure 23.The results of the ¾" river rock & river sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

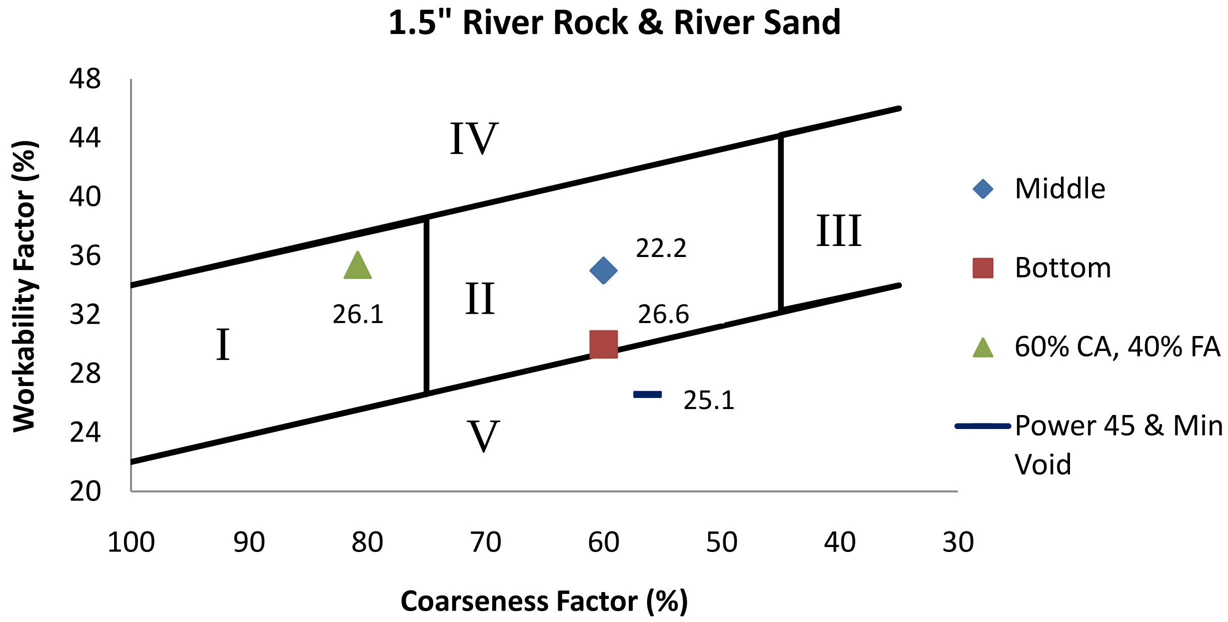


Figure 24. The results of the 1.5" river rock & river sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

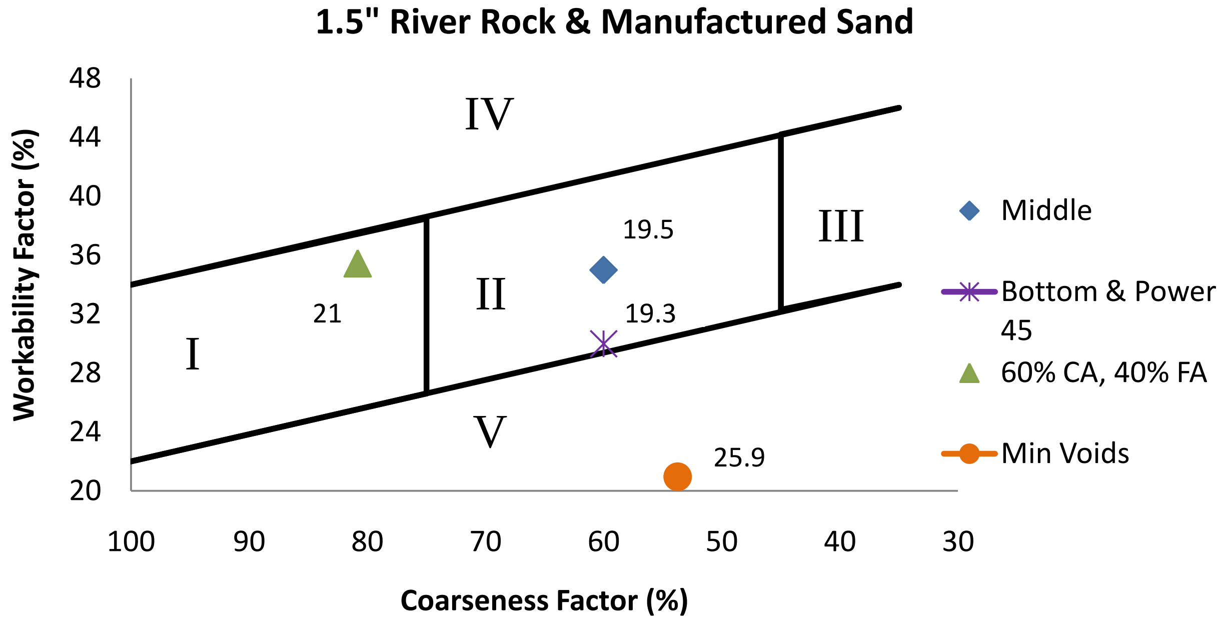


Figure 25. The results of the 1.5" river rock & man sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

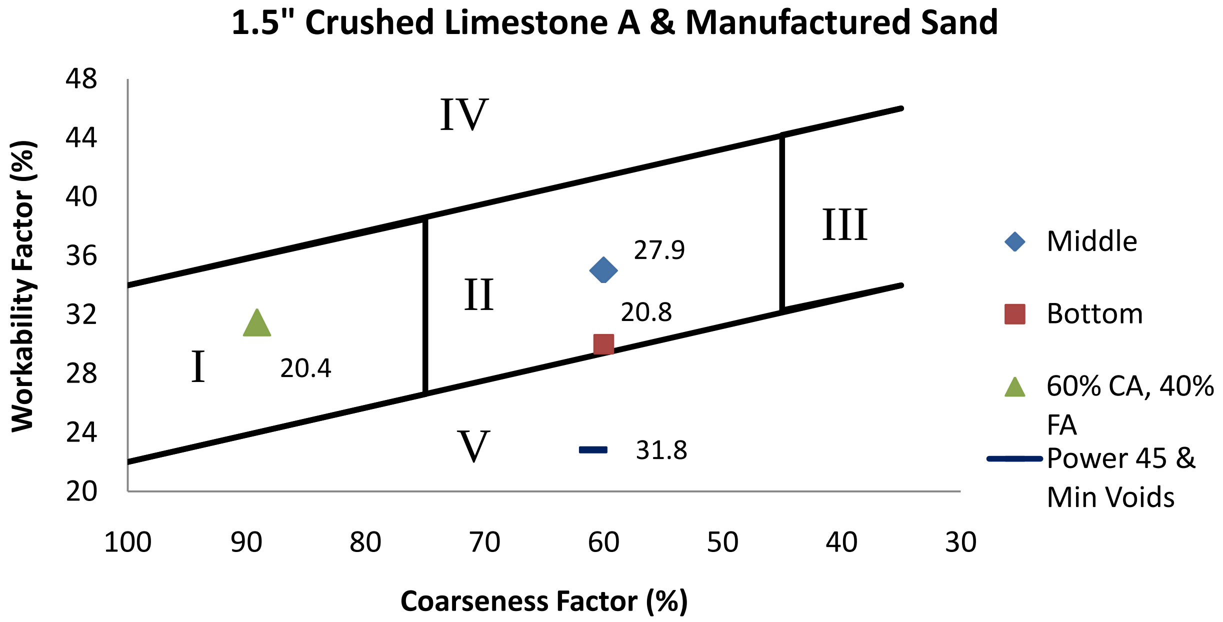


Figure 26. The results of the 1.5” crushed limestone A & man sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

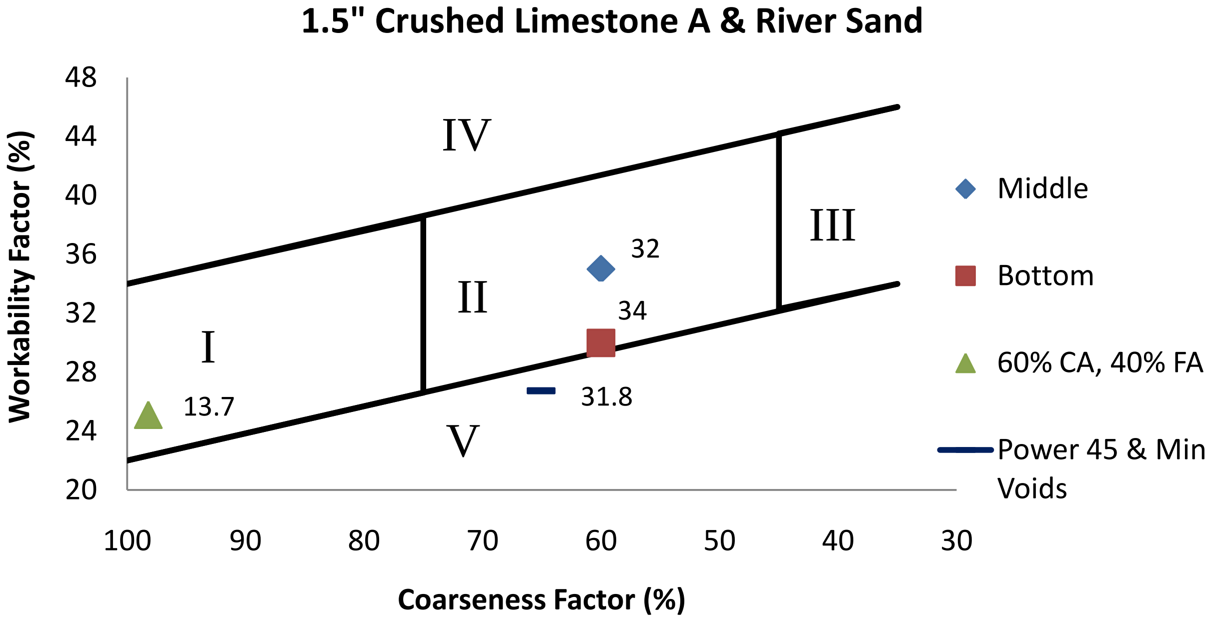


Figure 27. The results of the 1.5” crushed limestone A & river sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

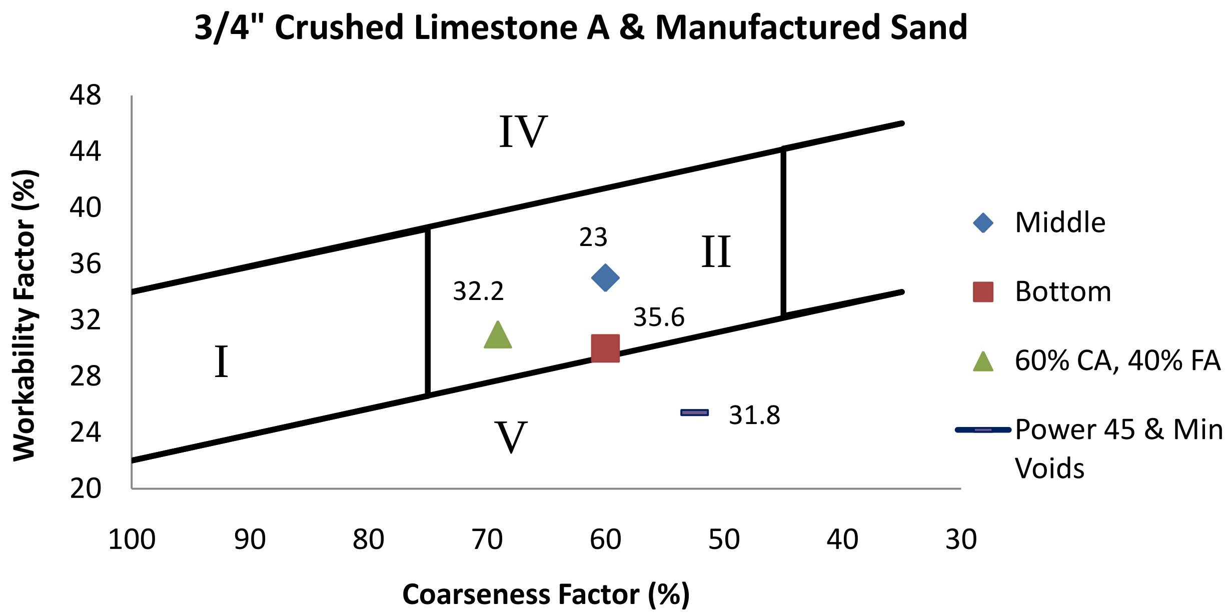


Figure 28. The results of the ¾" crushed limestone A & man sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

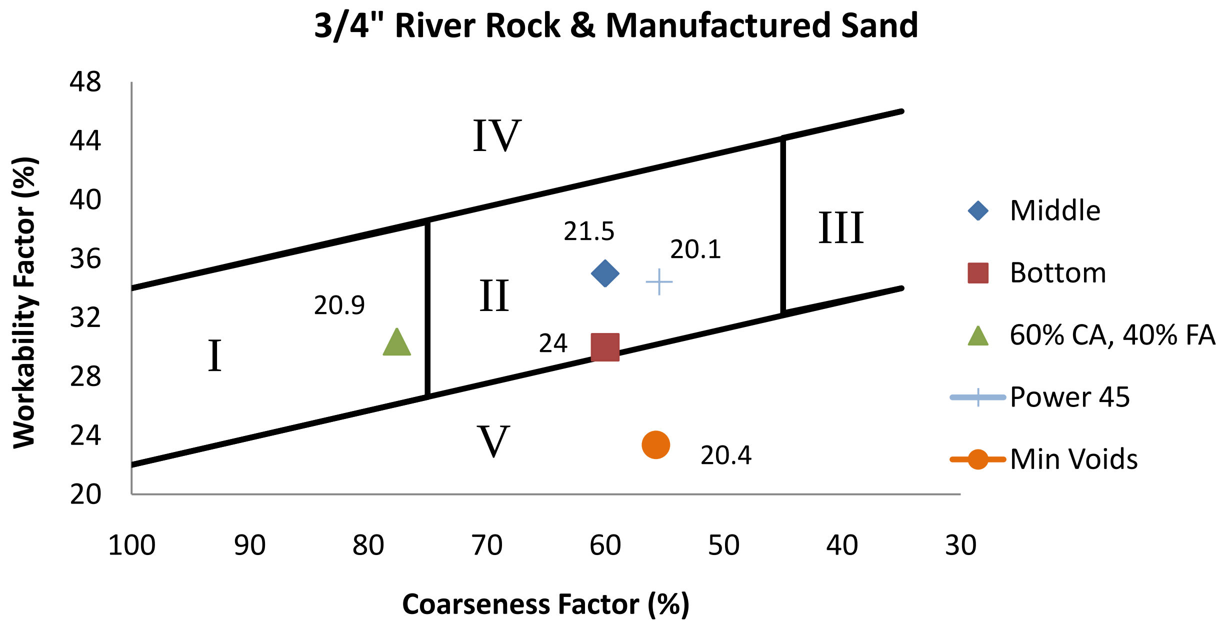


Figure 29. The results of the ¾" river rock & man sand plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

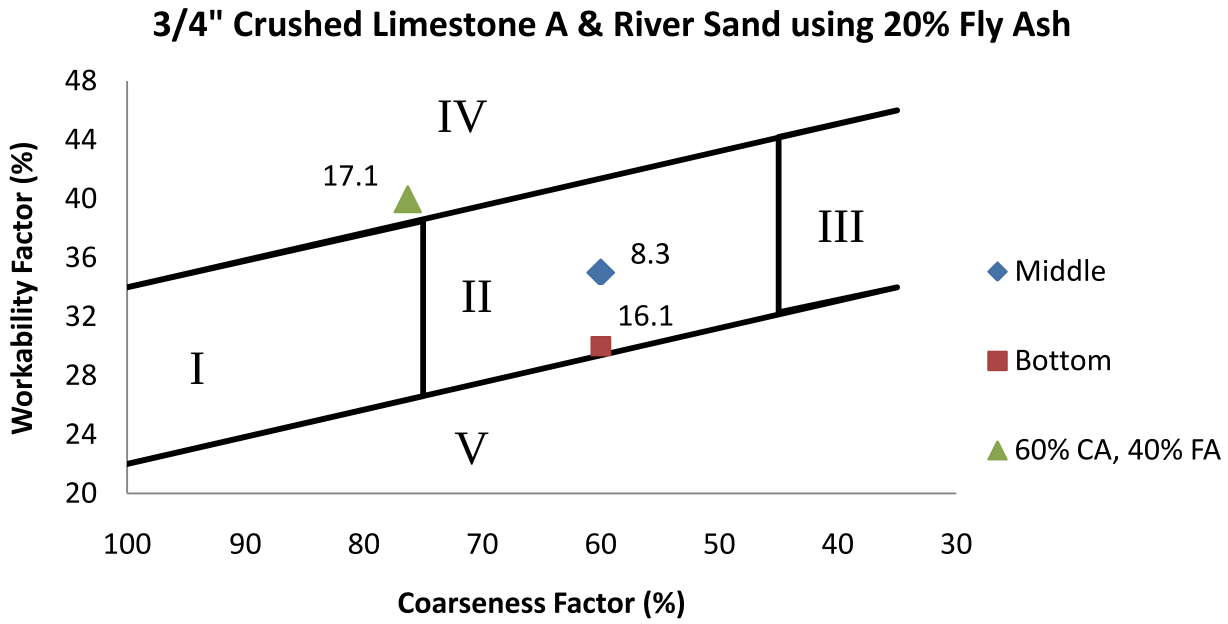


Figure 30. The results of the ¾" crushed limestone A & river sand using 20 % fly ash replacement plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

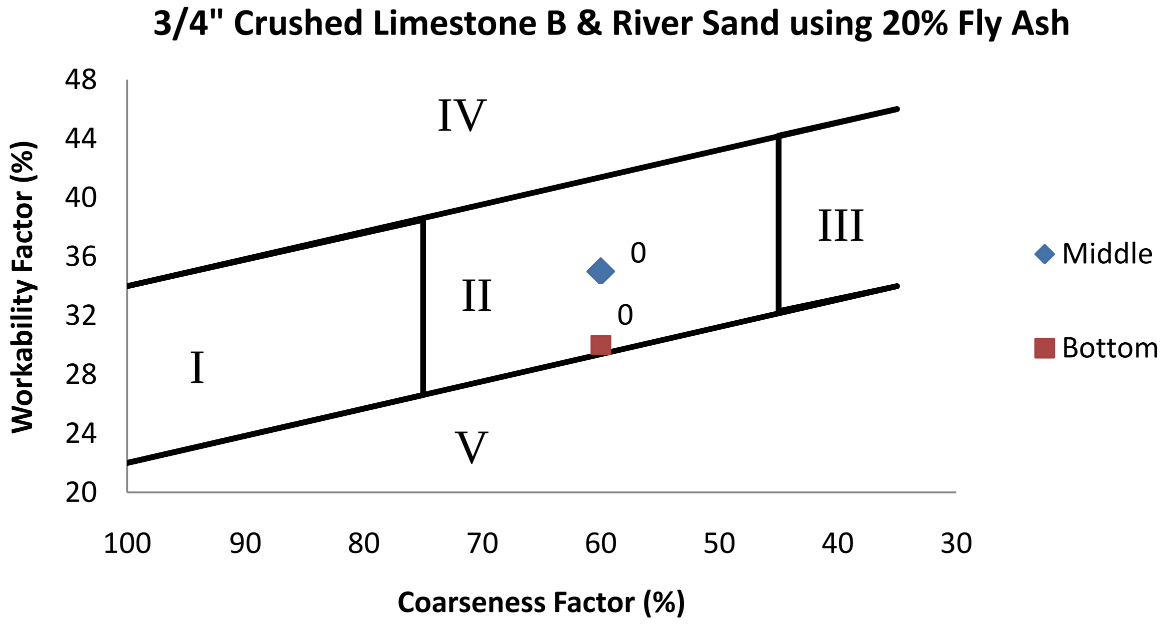


Figure 31. The results of the ¾" crushed limestone B & river sand using 20 % fly ash replacement plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

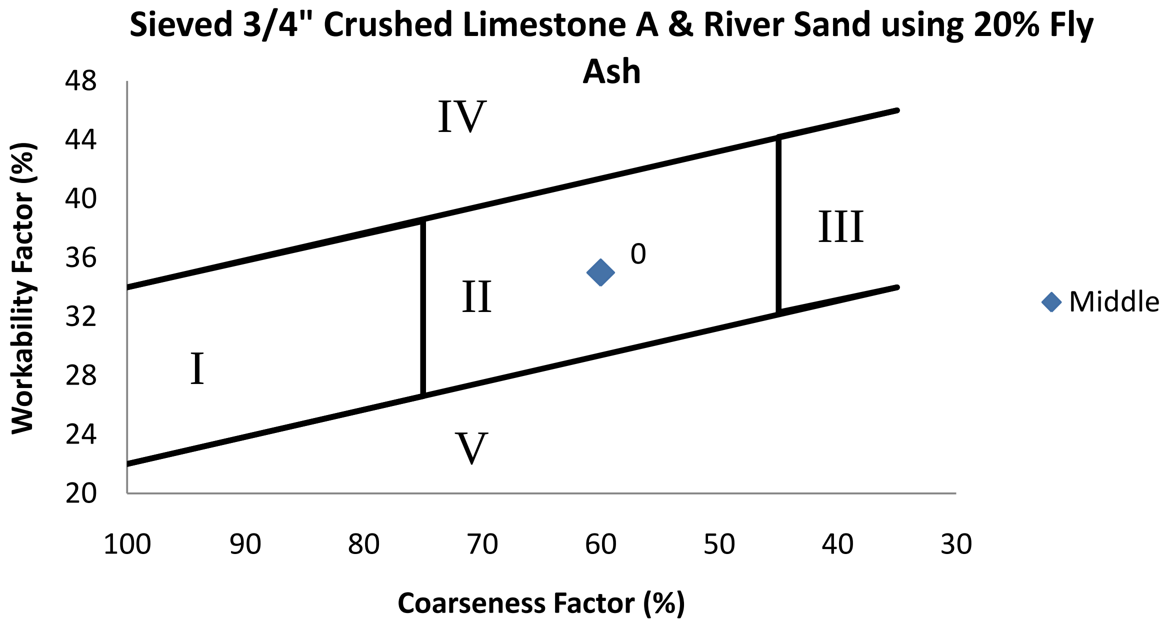


Figure 32. The results of the sieved ¾” crushed limestone A & river sand to ¾” crushed limestone B & river sand gradation using 20 % fly ash replacement plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

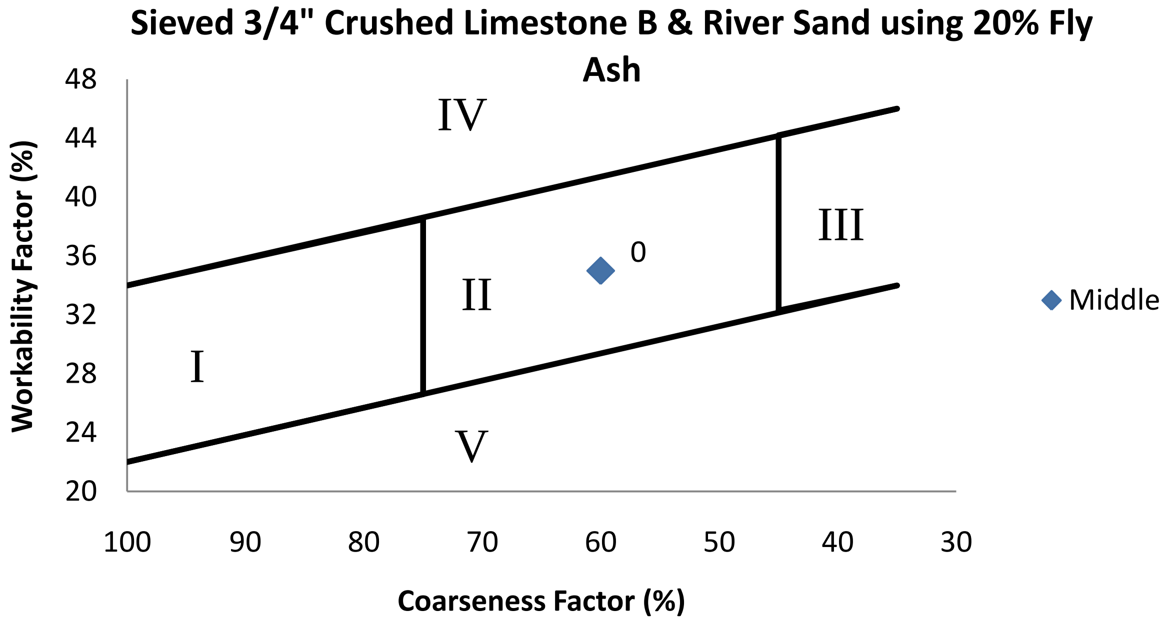


Figure 33. The results of the sieved ¾” crushed limestone B & river sand to ¾” crushed limestone A & river sand gradation using 20 % fly ash replacement plotted on the Shilstone chart. The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

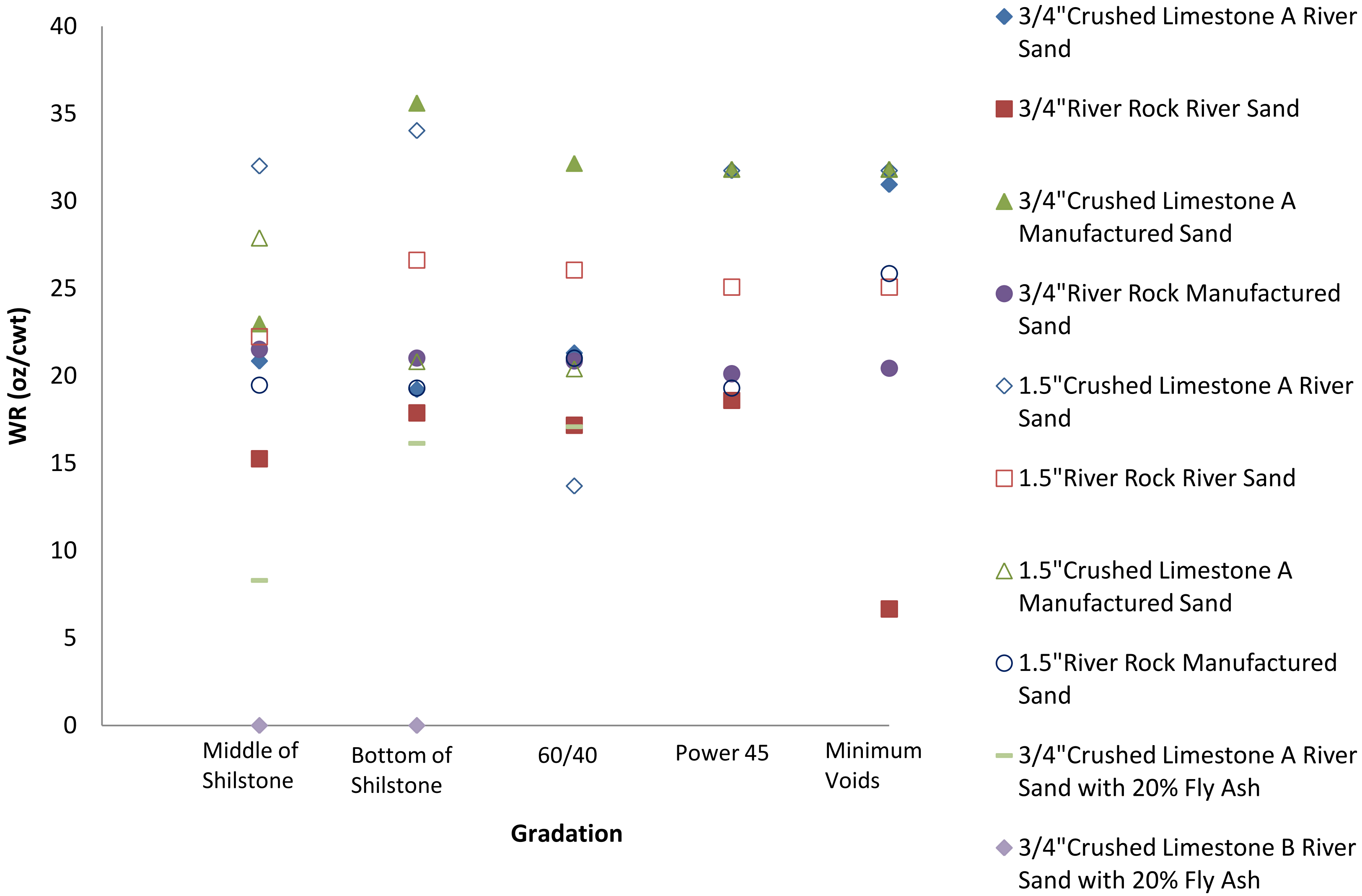


Figure 34. Gradation compared to the amount of WR to pass the box test.
Note: 3/4” crushed limestone and river sand with a power 45 had a 85.9 oz/cwt.

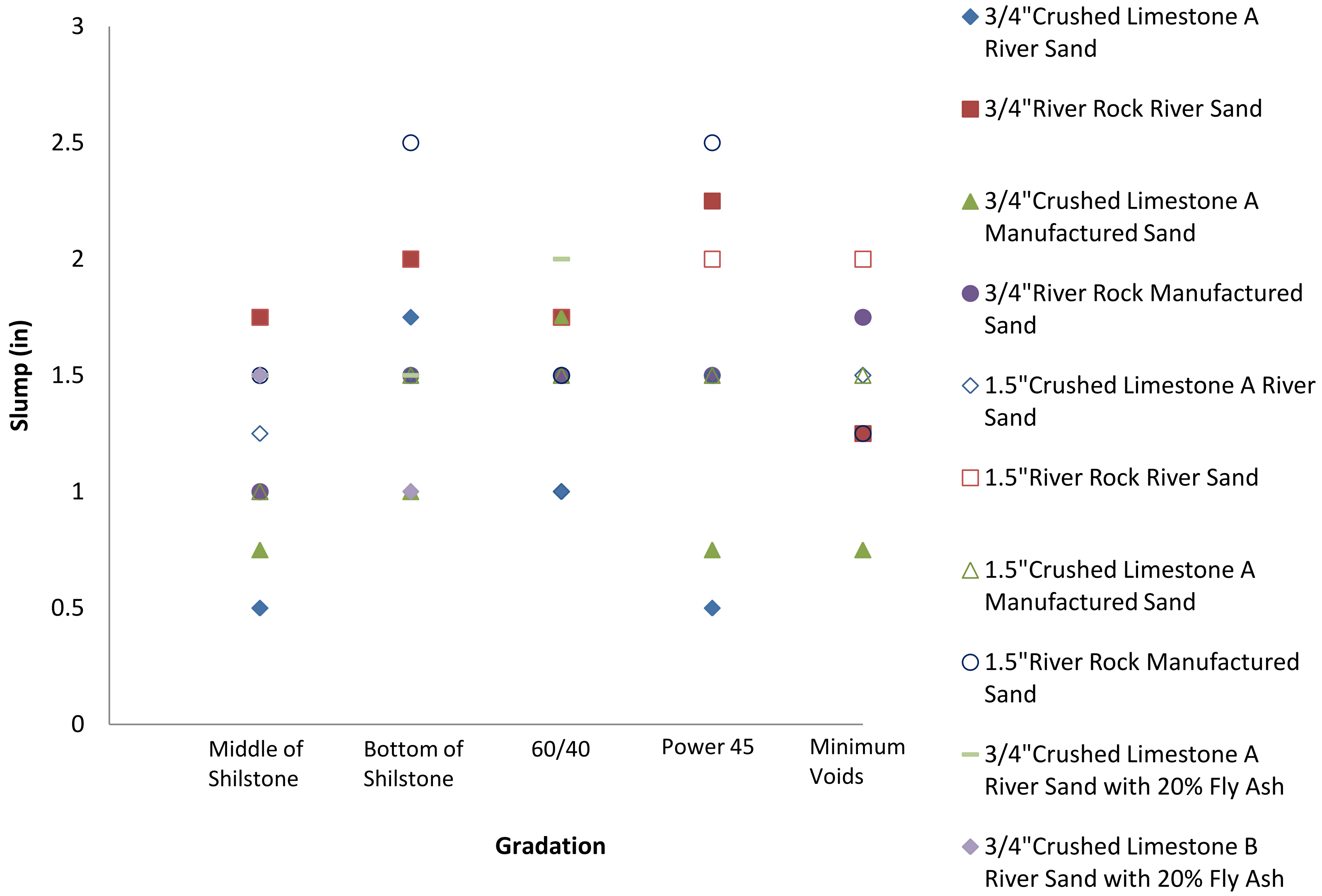


Figure 35. Gradation compared to slump measured when passing the box test.
Note the ¾" crushed limestone and river rock using river sand had the same slump.

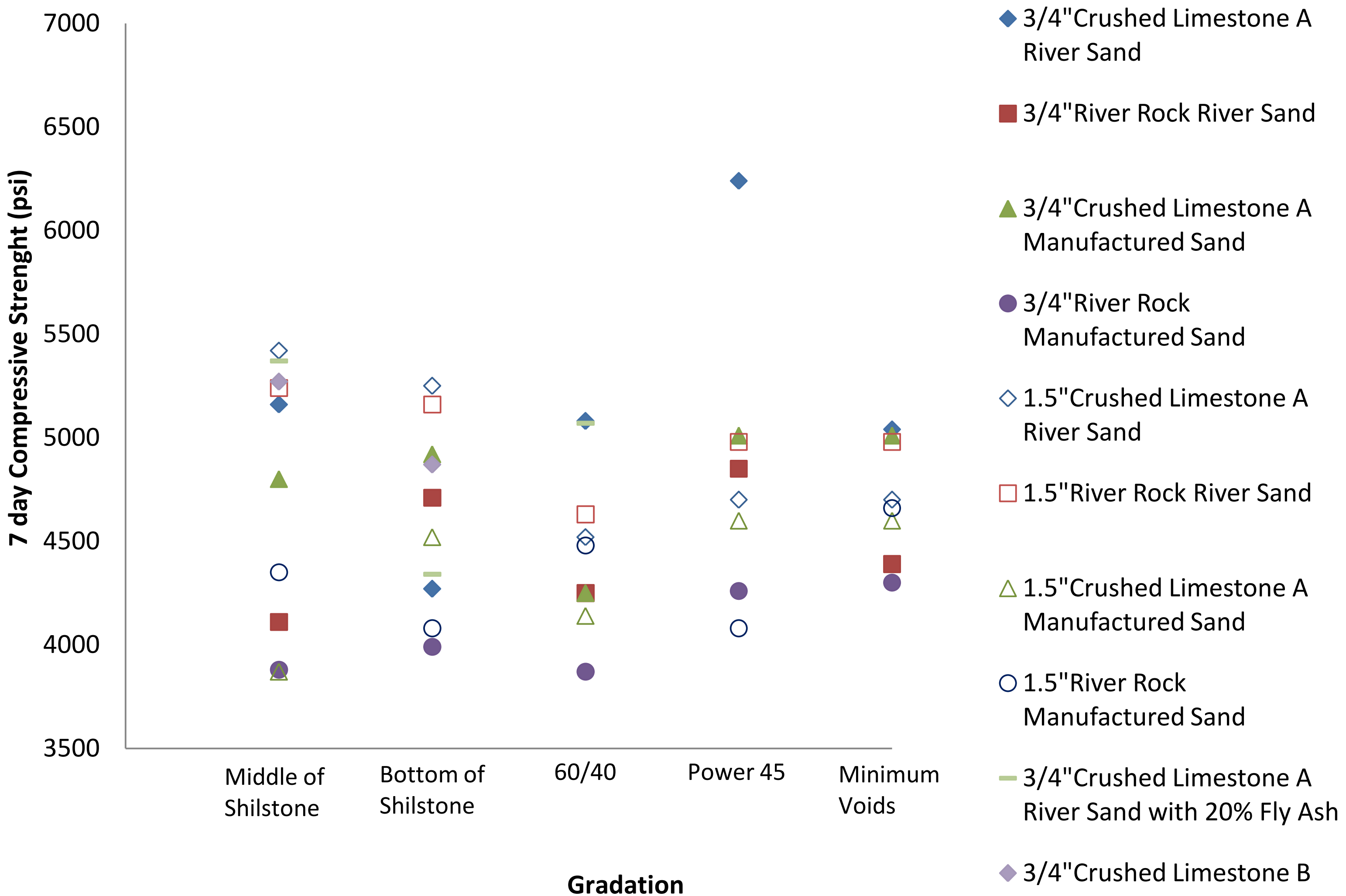


Figure 36. Gradation compared to the 7 day compressive strength.

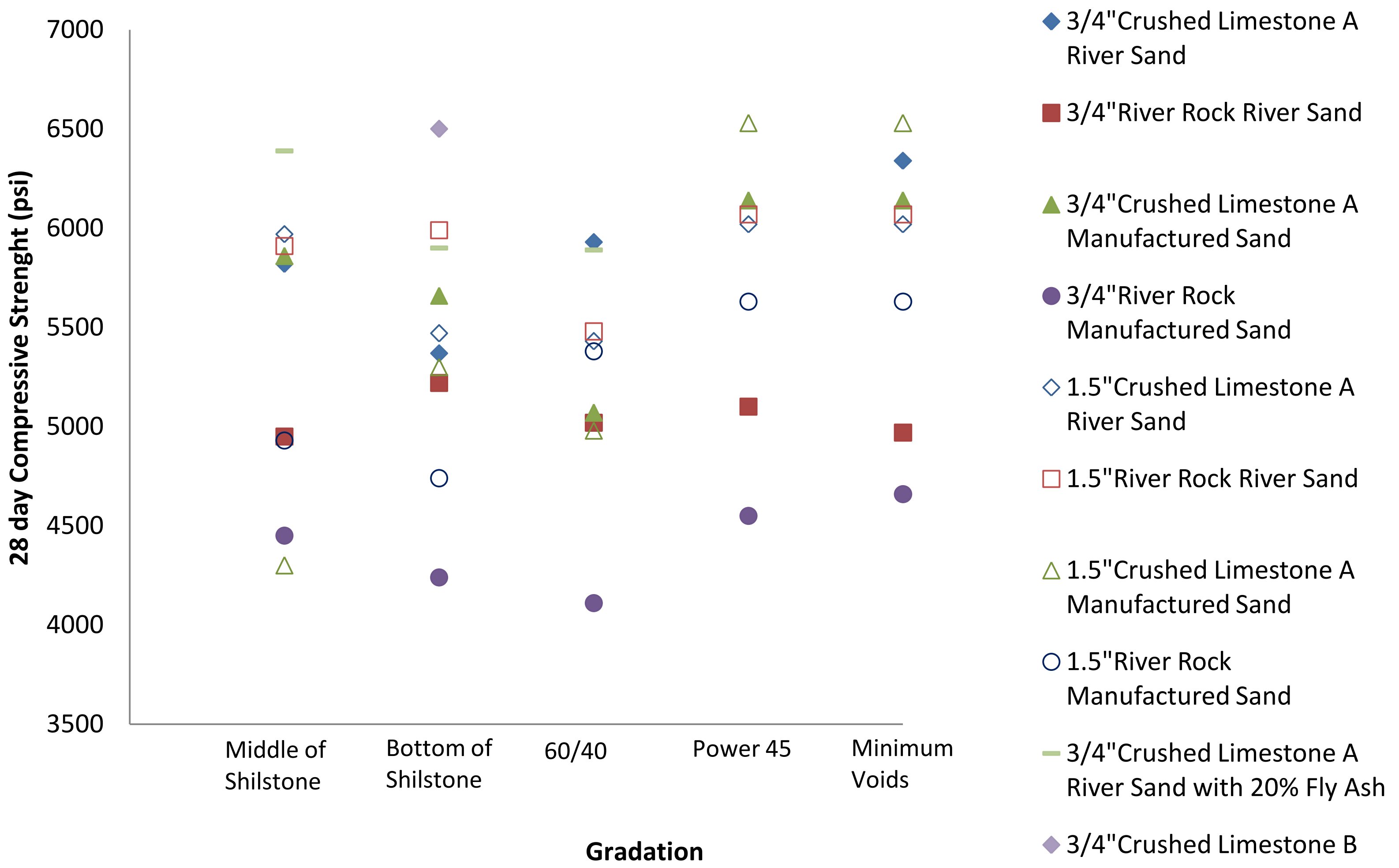


Figure 37. Gradation compared to the 28 day compressive strength.

Note: 3/4” crushed limestone and river sand with a power 45 had a 28 day compressive strength of 8250 psi.

CHAPTER 6

DISCUSSION

Looking at Figure 35, several general trends can be observed with different aggregate types. In order to pass the box test, the river rock required a higher slump than the crushed limestone. All combinations of the 1.5” coarse aggregate required a higher slump than the ¾” coarse aggregate to pass the box test. After each mixture passed the box test, the slump ranged between 0.5” and 2.5”, which corresponds to slumps found in conventional pavement. The results from the slump and box test did not always correlate. Shown graphically in Figure 35, the 1.5” river rock and manufactured sand had a 2.5” slump before passing the box test while ¾” crushed limestone A and river sand passed the box test with a 0.5”slump. When the same 3/4” crushed limestone A and river sand was used with a gradation that matched the power 45, the mixture required 85 oz/cwt of WR was needed for the mixture to pass the box test and the slump was only 0.5 “. It was found that different slumps were required for different aggregate gradation combinations to pass the box test. For example when looking at the gradations for mixtures in the middle of the Shilstone chart with different aggregates, the slump ranged from 0.5” to 1.75” while the WR dosage varied from 15.3 to 32 oz/cwt to pass the box test.

These results reinforce that the box test and slump test measure two different phenomena. While the box test measures the response to vibration, the slump test only measures the movement of the concrete downward from its own weight. Depending on the application for the concrete, the slump and/or box test may be useful to evaluate the performance. For slip-formed pavement applications we feel that the response to vibration or the box test is more useful. However, the slump test can quickly measure the consistency of multiple batches of the same mixture design. Also the slump test may be a more useful test than the box test for hand placed mixtures. This non uniform behavior between the tests is intriguing and suggests that one should not assume that concretes of the same slump will respond the same way to vibration. Instead, it is important to understand what properties of the mixture proportions, aggregate gradation, and characteristics lead to these differences in performance.

Two different types of crushed limestone were used in this study with similar angularities and shapes, but different gradations. As shown in Table 10, the ¾" crushed limestone B and river sand with 20% fly ash required zero oz/cwt of WR to pass the box test. To start understanding the mechanism that created the reduction in WR for ¾" crushed limestone B and river sand with 20% fly ash, a significant difference was identified in the individual percent retained graphs of Figures 22-33. To test if the gradation of the ¾" crushed limestone B and river sand with 20% fly ash had a large impact on the mixture's ability to respond to a vibrator, the ¾" crushed limestone A and river sand with 20% fly ash was sieved to the exact gradation of the ¾" crushed limestone B and river sand with 20% fly ash as shown in Figure 6. The WR dosage required to pass the box test decreased from 8.3 oz/cwt to 0 oz/cwt. As shown in Figure 7, the ¾" crushed limestone B and river sand with 20% fly ash was sieved to the exact gradation of the ¾" crushed limestone A and river sand with 20% fly ash and caused the WR dosage to increase from 0 oz/cwt to 6.7 oz/cwt. It is important to note that both mixture gradations were located in the same spot on the Shilstone chart and the performance to vibration was drastically different as shown in Table 10 and Figures 32 & 33. The sieving of aggregate to certain gradation proves using the Shilstone chart did not necessary influence the performance of a concrete mixture, but the actual distribution of each aggregate sieve size can improve the concrete's ability to respond to vibration.

For another example of the Shilstone chart failing to accurately predict how a mixture will perform in the box test, in Figure 34 the five mixture gradations using ¾" river rock and manufactured sand were in different locations on the Shilstone chart but needed similar amounts of WR to pass the box test. Also shown in Figure 34, five of the aggregate combinations there was no difference in WR required to pass the box test for gradations in the middle of the Shilstone chart and the mixtures with 60 % coarse and 40% fine aggregate. This suggests that including the intermediate aggregates in the concrete mixture does not necessarily have a consistent impact on the WR results of the box test. However, mixtures using intermediates had the ability to hold an edge while the 60 % coarse and 40% fine aggregate had a noticeable edge slump.

Several gradations were separated by an aggregate weight difference of only one hundred lbs/cy, but performed completely different. Shown in Table 8, the 3/4" crushed limestone A and river sand gradation of minimum voids and bottom of the Shilstone chart generate very similar weight amounts of sand, intermediate, and coarse aggregates, but used a difference of 11.8 oz/cwt. On the other hand, 3/4" river rock and manufactured sand gradation of power 45 and middle of the Shilstone chart produced very similar weight amounts of sand, intermediate, and coarse aggregates, but required only a slight difference in WR dosage. In fact, 3/4” river rock and manufactured sand receive similar WR dosages for all the gradations.

The box test and the slump test can be very useful in evaluating certain workability properties of concrete, but no other known laboratory test method has been able to successfully evaluate the rheology of low slump concrete. Useful visual observations about the ability to finish and shovel the mixtures were made during the sample creation but were not easily quantified. The mixtures in the center of the Shilstone chart and with the 60/40 gradation were the easiest to place and finish. Also, mixtures with river rock flowed better in the mixer than those with crushed limestone. From visual inspection, fly ash created a more flowable and a better surface finishability for each mixture investigated in this study. The response to vibration and slump with and without fly ash can be observed in Table 9 and 11 with the ¾” crushed limestone A and river sand. Some gradations had a large impact with the usage of fly ash but others had only a minor impact.

Looking at Figure 36, the mixtures using gradations with intermediate aggregates all had a 7-day strength over 3800 psi. The mixtures containing 1.5” river rock was stronger than those with ¾” river rock. As shown in Figure 37, the minimum voids and/or power 45 had the highest compressive strength for each combination while the 60/40 gradation mixtures had a consistently lower compressive strength. Both, the middle and bottom of the Shilstone chart mixtures had compressive strengths that varied widely. After failing the box test with a WR dosage above 85 oz/cwt, the 28 day strength of the power 45 mixture with ¾” crushed limestone A and river sand was higher 8200 psi. The compressive strength of the mixture could be affected by the power 45 gradation, or the high WR dosage. The extremely high dosage of WR delayed final set of the compression cylinders for 5 days. However, this set delay did not have an extreme impact on the 7-day compressive strength.

Using amounts more than 1200 lbs/cy of manufactured sand, gave high air contents and low unit weights. Also, both 1.5” & ¾” river rock and river sand combinations resulted in 4% and higher air content for the Shilstone middle of box and 60/40 gradation. The cause was not found during this testing.

CHAPTER 7

CONCLUSION

The effects of aggregate characteristics on concrete properties, such as vibration and strength were investigated using mixtures in which the paste content and the water/cement ratio were held constant. The results showed the maximum nominal aggregate sizes, the different aggregate proportions, the combinations of different aggregates, and different aggregate gradations all shown to impacted performance in the strength, slump, and the box test. Based on the data collected, the following have been found:

- The Shilstone chart does not necessarily predict the performance of a mixture's response to vibration.
- The distribution of aggregate gradation can drastically increase the workability of concrete.
- By using intermediate aggregate sizes to create a well-graded distribution, it did not always reduce the WR needed to pass the box test. Sometimes a 60/40 mixture performed better than a well-graded distribution. This suggests important aspects of gradation are not being addressed by these methods.

- Compared to 60/40 mixtures, a well-graded mixture tended to have a minor increase the compressive strength and a noticeable decrease in edge slumping due to more aggregate interaction.
- A distinct increase in the slump was observed with the majority of river rock mixtures compared to crushed limestone mixtures. The crushed limestone’s slump ranged from 0.5” to 1.5”, while the river rock’s slump ranged from 1” to 2.5”.
- For the aggregates used in this study, the different nominal maximum coarse aggregate sizes didn’t drastically affect the workability of concrete to vibration.
- The angularity of a crushed aggregate or a smooth river aggregate did not drastically affect the workability of concrete to vibration. For the aggregates used in this study, aggregate size distribution of a gradation affected the workability of concrete to vibration.

CHAPTER 8

FUTURE WORK

Development of the box test into a valid laboratory test is being completed. After conducting the box test multiple times on a highway pavement jobsite and a city street jobsite using a single slip form paver, it seemed to have a close similarities between the box test and a slip form paver. Since the vibration performance of slip form pavers can have a large difference in amplitude, the box test will not necessarily be similar to every slip form paver. The development goal of the box test is not to create a direct comparison with slip form pavers, but rather to create a laboratory test to measure the concrete's performance to vibration.

Understanding the impacts of the distribution of aggregate using an individual percent retained can be a very helpful tool in mixture design. The individual percent retained chart is a technique that has not been fully understood or thoroughly researched. This will be investigated in future work.

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