OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

INVESTIGATION OF OPTIMIZED GRADED CONCRETE FOR OKLAHOMA

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16. Abstract

This report presents the results of several novel test methods to investigate concrete for slip formed paving. These tests include the Box Test, a novel test to evaluate the response of concrete to vibration, the AIMS2, an automated test for aggregate shape and texture, and the use of a pan mixer to serve as a concrete rheometer. The results show that both the Box Test and AIMS2 tests seem to be useful and provide reliable data. The pan mixer results do not appear to be reliable. The establishment of these test procedures provides a basis for future investigations of materials and mixtures from the state of Oklahoma.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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Investigation of Optimized Graded Concrete for Oklahoma

Final Report: July, 2013

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Executive Summary

The goal of this research was to develop tools to better understand the complex relationship between the workability of concrete and aggregate gradation and characteristics in concrete mixture design. Currently, a limited amount of guidance has been produced on this topic. Furthermore, the small amount of guidance being used is not backed up by much experimental data. This work specifically investigates three different tools to help with this situation. They include the investigation of the response of a concrete mixture to vibration, the use of a concrete pan-mixer to evaluate the rheology of a concrete mixture, and the use of the AIMS II unit to investigate the characteristics of aggregates.

While not all these studies were a success, some of this work shows a great deal of promise for the future. A real effort was made in this work to investigate the robustness of these tests and to establish valid measurements techniques. This work is an outstanding foundation for work that is ongoing for the Oklahoma Department of Transportation to develop new aggregate gradation standards for the state of Oklahoma.

An outline of the finding of this work is give below:

- Results show that the Box test is a useful and repeatable tool to evaluate different mixtures for a slip formed pavement.
- The Box Test was able to show that the gradation of a mixture influenced the response to vibration. While the amount of coarse and intermediate aggregate largely varied with only a little change in workability, a small change in the amount of sand significantly affected the workability of the mixture.
- While the Slump Test does not provide a consistent measuring tool for low slump concrete, the Box test can be a useful tool.
- However, the repeatability of the pan-mixer based rheometer was poor. Addition work is needed to study the rheological properties of low slump concrete.

- After using the AIMS II to classify the aggregate characteristics of eleven coarse aggregate quarries and three fine aggregate sources that are mainly from Oklahoma, the study showed that some measurement parameters varied while others didn’t.

CHAPTER 1 – INTRODUCTION

A difficult objective for the concrete industry has been measuring and predicting the workability of a concrete mixture design. The specifications of a typical jobsite can be easily met, but the workability of the concrete mixture can be very allusive. This is can be created from numerous variables such as the paste's yield stress, paste volume, aggregate characteristics, and gradation. Each of these variables influence the workability of concrete, but an exact manipulation of each variable to the workability of concrete has been largely unknown. Typically, to obtain a certain workability, the paste volume and yield stress of a mixture are manipulated to accommodate the impacts of the aggregate characteristics and gradations. This is puzzling since about two-thirds of the total volume of concrete is aggregates.

While gradation has been classified according to ASTM C33, the aggregate characteristics do not have definite guidelines to be used in the fresh properties of concrete. Numerous claims have been made about different aggregate characteristics impacting the workability concrete. The majority of the aggregate claims revolve around the angularity, texture, and shape variation influences the workability of the concrete. For example, a river rock with low angular, well-shaped, and low textured aggregate will have less frictional resistances causing a better workability than a crushed limestone with high angularity, high texture, and extreme flatness and elongation. Therefore using a river rock should require less paste to achieve certain workability than a crushed limestone and will be more cost effectiveness of the concrete. Unfortunately, none known useful research has been conducted on these mechanisms for normal concrete mixtures.

A continuous need in the transportation industry has been to develop a workability test for slip formed pavements to evaluate these variables. Our research goal was to develop a workability test for a slip formed pavement and also to start classifying different aggregate sources. Eventually, we hope future research can use the aggregate classifications to measure the workability impacts of a mixture.

CHAPTER 2–THE BOX TEST

A difficult objective for concrete producers has been measuring and predicting the workability of a concrete mixture design. The specifications of a typical jobsite can be easily meet, but the workability of the concrete mixture can be very allusive. The complexity of the concrete's workability can be created from numerous variables such as the paste's yield stress, paste volume, aggregate characteristics, and gradation. Many of the variables are modified to a specific application, 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.

Current Laboratory Tests for the Workability of Concrete

Historically, the workability of a concrete mixture was determined by personal experience and judgment. To help measure the workability of concrete, multiple laboratory tests have been created, but only a few have been used in widespread implementation. The goal of a workability test should be to provide a useful indication for a mixture's ability to perform in a certain application. While the Slump Test (ASTM C143)[1] has been widely used as a specification for a mixture's workability, it fails to actually measure the concrete's workability, especially with high and low flowable concrete. In recent years, self-consolidating concrete's workability has been shown to be effectively measured by the L-box, J-ring (ASTM C1621)[2], and slump flow (ASTM C1611)[3]. Some of the more popular tests developed to measure a slip formed pavement has been the Slump Test, the Vebe Apparatus test, and the vibrating slope apparatus. However, the best predictable performance measurement seems to still be a slip formed paver. The focus of this work is to create a workability test for simulating the ability of a slip formed paver to place and consolidate a mixture. The boundary conditions of a slip formed pavement test should evaluate a mixture's ability to consolidated, but still stiff enough to hold an edge.

The Slump Test (ASTM C 143)

For years people have used the Slump Test (ASTM C 143)[1] 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. 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." [4]

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[5]. 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.

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[6]. 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.

Objectives

A laboratory test is needed to evaluate the workability of a slip formed pavement mixture. Developing a useful laboratory test involves being able to measure different variables in a quantitative process while not creating an extremely complicated process, or producing false parameters. It is important to realize that not all the slip formed paver processes can be mimicked in a laboratory test for reasons of expense and practicality. However, a laboratory test can still be useful as long as it captures the most important components of a process.

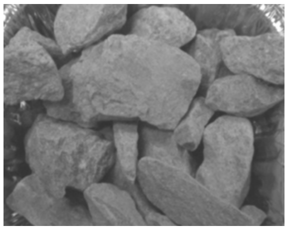
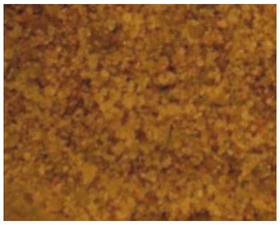
Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150[7]. Table 1 shows the oxide analysis of the cement. A 20 % fly ash replacement and a water reducer (WR) were used. According to ASTM C 494[8] the water reducer was a lignosulfonate mid-range WR and ASTM C 618[9] classifies the fly ash as type C. The different aggregates used in this research can be described in Table 2. Crushed limestone A, B, & C and fine aggregate A & B used in this research were from Oklahoma. The river gravel D used in this research was from Colorado. From visual observations, the crushed limestone A and the crushed limestone B have similar angularities and shapes. A sieve analysis for each of the aggregates was completed in accordance with ASTM C 136[10]. 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[11] for a coarse aggregate or ASTM C 128[12] for a fine aggregate. In Figure 1, the sieve analysis for each aggregate is shown.

Table 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%				

Table 2 –Description of the aggregates in the study.

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 Gravel D		Smooth and semi-spherical river gravel.
River Sand A		River sand.
River Sand B		River sand.

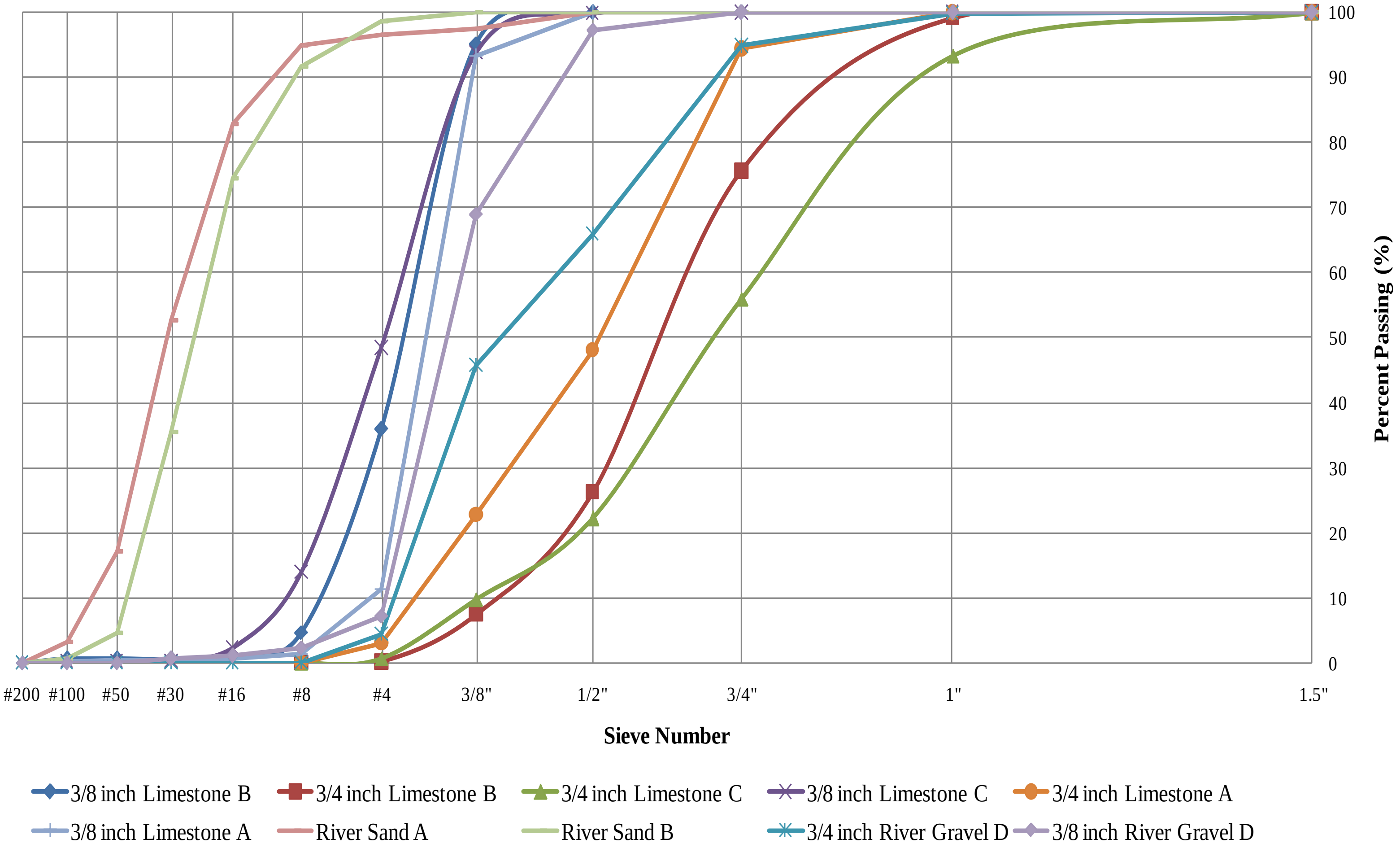


Figure 1 - Sieve analysis for each aggregate type.

Mixture Design

A slip formed pavement mixture contains only enough paste to consolidate the concrete, but still keep a stiff edge. If the paste content were able to be systematically altered, this would allow an investigation and measurement of different variable to mixture’s workability.Since the variables of aggregate characteristics and proportion gradations can affect the workability, the cementitious content varied from 4.5 and 5 sacks (423 to 470 lbs).All mixtures held a constant w/cm at 0.45 and used 20% fly ash replacement. Batch weights were designed with various aggregate combinations and gradations to evaluate the impacts of different gradations. The batch weights for the 28 different mixtures can be shown in Table 3.

Table 3–Summary of the mixture designs for this chapter (All units weights are given in lbs/yd³).

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

Mixing and Testing 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. 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[13], Slump[1], Unit Weight[14], and a novel test method to examine the response to vibration called the Box Test.

Development of the Box 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. Figure 2 shows the components of a slip formed paver. Of all the components shown, the vibrator contributes the majority of the energy applied to consolidate concrete. A common issue for a concrete mixture performing poorly with a slip formed paver is the unresponsiveness of mixture to consolidation.

In order to closely mimic the consolidation of a slip formed paver, a laboratory test was developed to 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 variability of different parameter with the test performance. Also, the laboratory test measures the ability of a mixture to hold an edge.

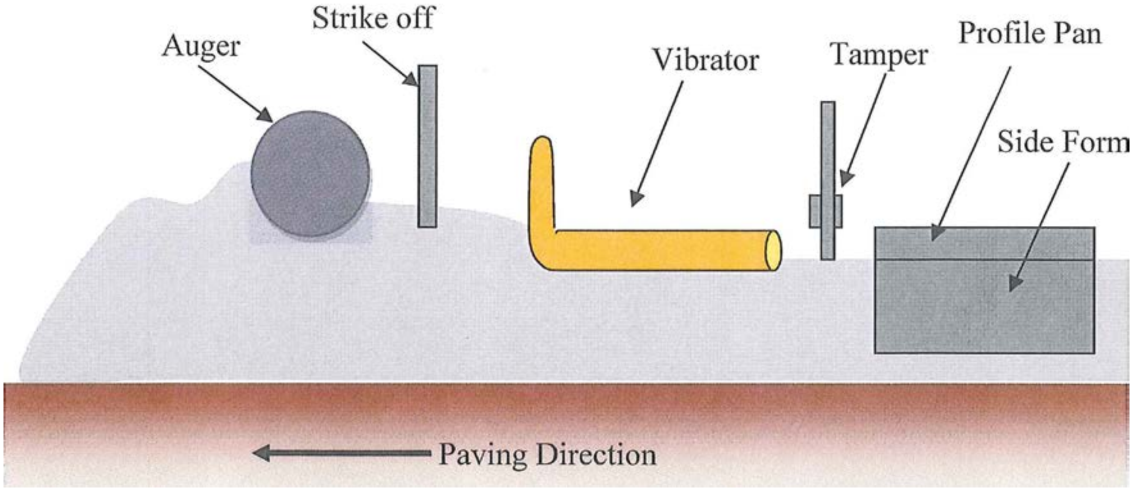


Figure 2 - Components of a slip formed paver.

In Figure 3, 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 3 slip formed vibrators consolidate concrete in the horizontal direction. To simplify the laboratory test, the response to vertical vibration in two directions is used instead of horizontal vibration. By reducing the rate of vibration, size of the vibrator head, and the time increment of a vibrator traveling through concrete, calculations were completed to approximate the same amount of energy in a typical field application to a vertical test.

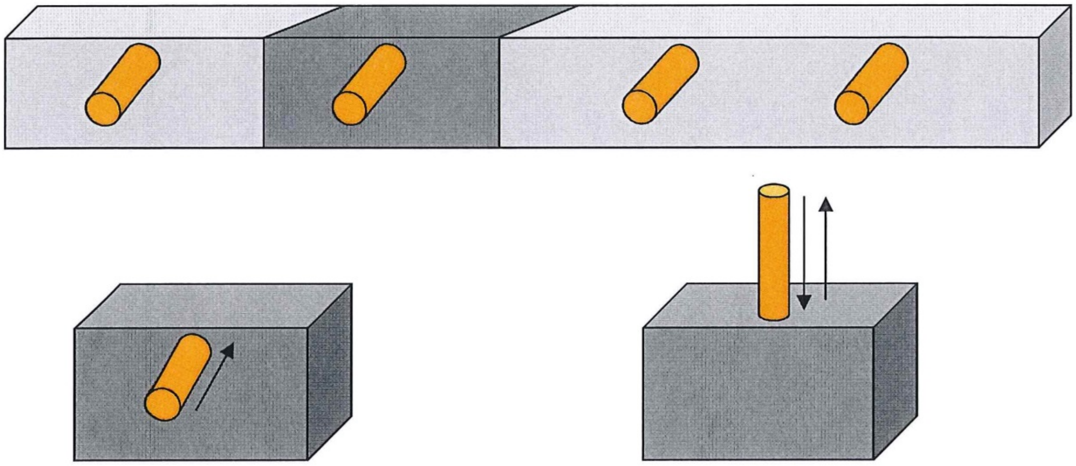


Figure 3 - Isolating a vibrator in a section of concrete.

Overview of the Box Test

Shown in Figure 4, the Box Test used ½” plywood with a length, width, and height of 12 inches using 2 inch L-brackets and 1.5 ft pipe clamps to hold the box together. Figure 5 shows the different components of the Box Test. Each step of the Box Test process is given in Table 4. Placed on the base, a 1 ft³ wooden formed box was constructed and held together by clamps as shown in Figure 4. Concrete was uniformly hand scooped into the box up to a height of 9.5”.

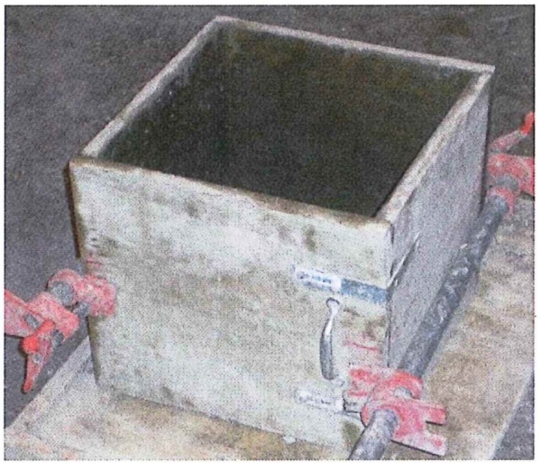


Figure 4 - The Box Test volumetric dimensions.

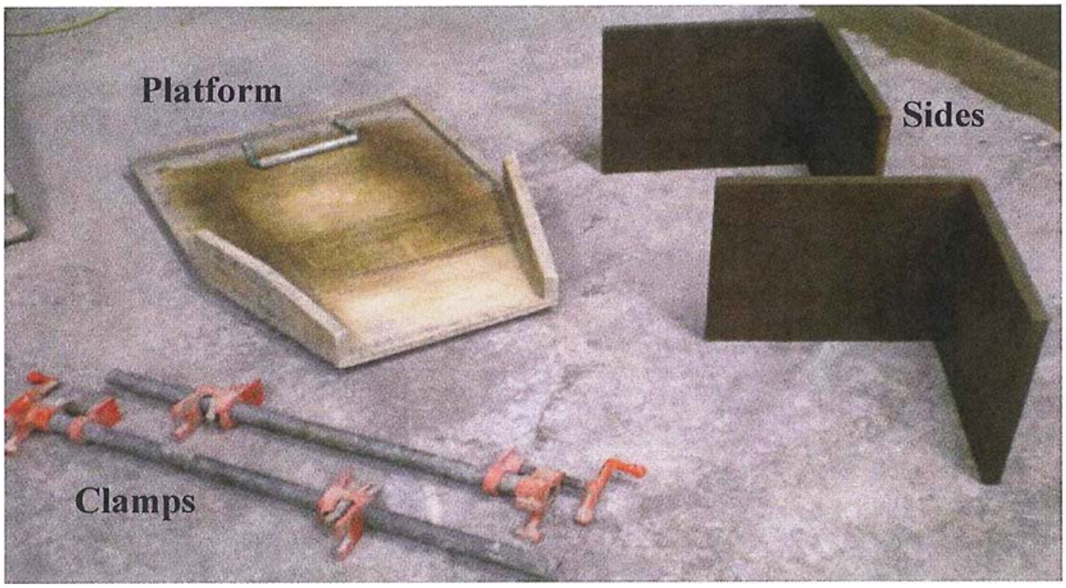


Figure 5 - Different components of the Box Test.

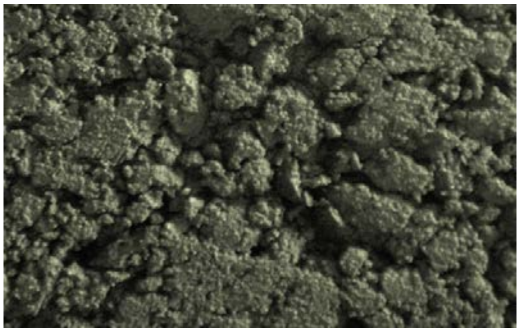
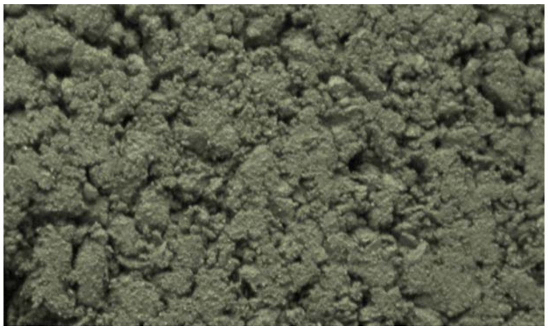
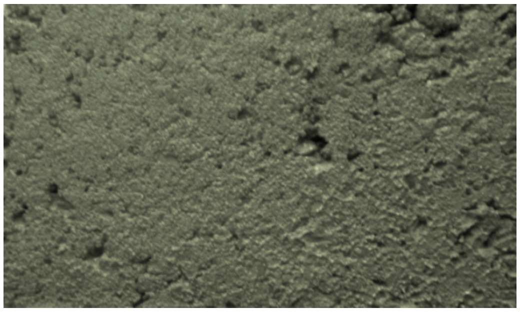
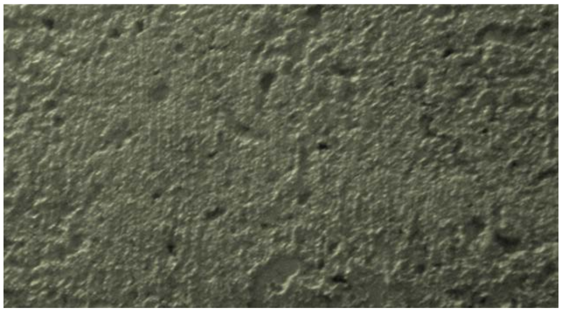
A hand held 1" square head WYCO model number 922A electric vibrator with 12,000 VPM was used to consolidate the concrete by inserting it at the center of the box. The vibrator was lowered over three seconds to the bottom of the box and then raised over three seconds. The clamps were removed from the side of the box and the side walls were removed. The response of a mixture to vibration can be assessed by the surface voids observed on the sides of the box. If a mixture performed well to vibration, the overall surface voids should be minimal because the mixture's mortar component was able to flow and fill these voids. However, if the sides have large amounts of surface voids, a mixture didn't perform well to vibration. Each of the four sides was evaluated by visually comparing the side to the images in Table 5. The average surface voids of the four sides were estimated and a number ranking between one and four was given to each side. 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. If a mixture response was poor to vibration with a 3 or 4 ranking, the sides or part of a side can collapse due to cohesive issues from lack of paste being in voids. In contrast, a ranking of 1 response was not chosen because many mixtures do not achieve less than 10% surface voids using a vibrator.

Table 4 - 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 5 - 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.

After a void count and ranking has been completed, edge slumping can be measured. Illustrated in Figure 6, a concrete mixture for slip formed pavement can experience top or bottom edge slumping. The horizontal displacement can be measured by placing a straightedge at a corner and horizontally using a tape measure at the highest extruding point.

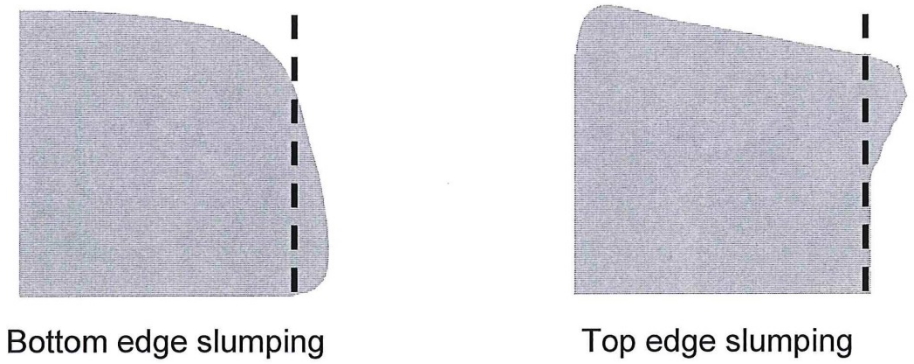


Figure 6– A visual representation of top and bottom edge slumping.

The Box Test Procedure

The Box Test can provide an useful way to compare the performance of low slump mixtures. When a mixture recieves a ranking of a 3 or 4, the response to vibration was poor. Adding more paste content or reducing the yield stress to a mixture will improve the performance. Adding cement or water increases the volume of the paste in the mixture and creates a more flowable mixture by reducing the internal friction. The yield stress can be measured by the amount of energy it takes to move the concrete. This can be achieved by adding water or water reducer (WR) to the mixture. If theminimum paste volume and w/cm are held constant with varring gradations, or aggregate characteristics, the mixture's performance to vibration can be measured by the amount of water reducer (WR) needed to pass the Box Test. Then the amount of WR to pass the Box Testcould be compared between mixtures with varring gradations or aggregate characteristics. This was achieved by making a concrete mixture and conducting the Box Test. If the mixture didn't pass the Box Test, water reducer was added and remixed until the mixture passed the Box Test. Mixtures that needed smaller amounts of WR performed better than mixtures than needed larger mounts of WR to pass the Box Test.

A more detailed description of the Box Test procedure is given below:

After a mixture was prepared as discussed in the mixing and testing procedure, the Slump Test, Unit Weight, air content, 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 Test, Unit Weight, and Box Test was conducted. If the Box Test failed again, the process of adding WR continued until the Box Test passed. Tyically, a WR dosage increments was close-to 2 oz/cw, but could varry depending on the amount of voids from the inital Box Test result. 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 4oz/cwt before testing again.Cylinders were then made according to ASTM C 192 and tested for the compressive strength[16]. In Figure 7, 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. All mixtures were evaluated over a one hour period in a 72°F (22°C) room. If the test was not complete within one hour, the sample was discarded to ensure intial set does not occur.

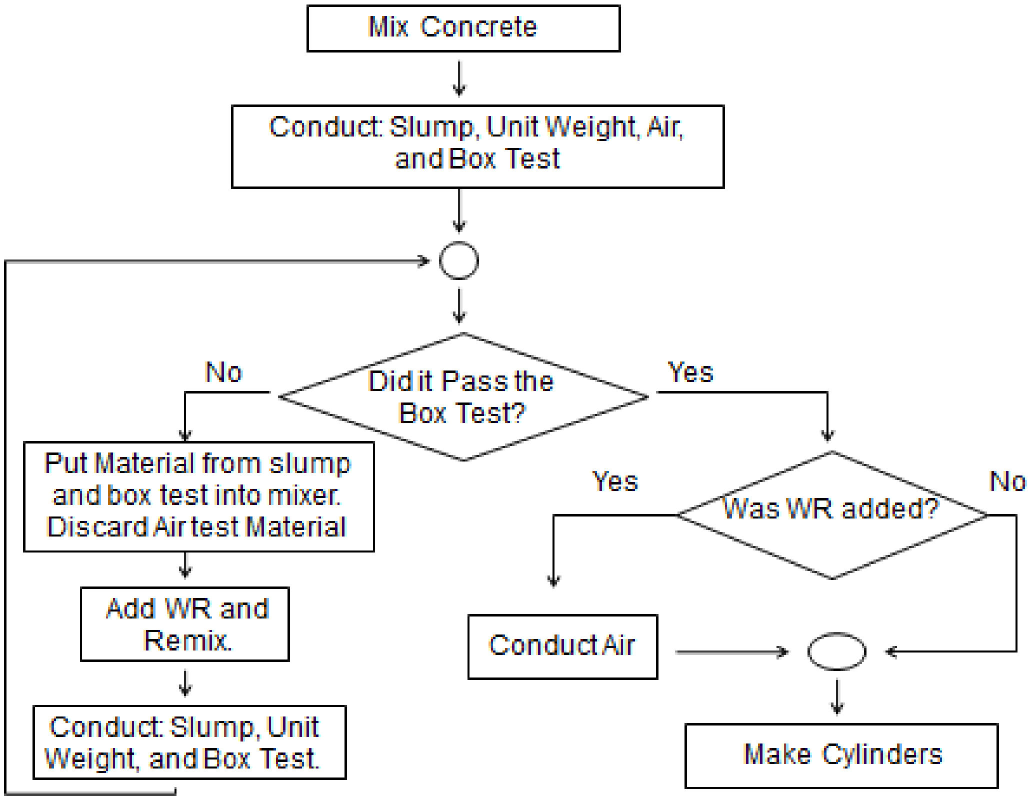


Figure 7 - A flow chart of the Box Test procedure.

Results of Validating the Box Test

A few variables need to be investigated into the Box Test should be validated. Dosage method, repeatability of a measurement, comparison of multiple operators, and multiple evaluation comparisons were investigated. Dosage method and repeatability of measurement used a response ranking of 2 because mixtures responding poorly to vibration can have sides or part of a sides collapse due to cohesive issues from lack of paste being in voids. In contrast, a 1 ranking response was not chosen because the surface voids could not be ranked if a mixture improved. Also, the Box Test was conducted on two mixtures being used by a slip formed paver and the results were evaluated using the Box Test ranking scale.

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 proceeding the resting period in final 3 minutes instead of the sequential dosages. As shown in Table 6, nine different mixtures were tested.

Table 6– 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

Repeatability of a Single Operator Replication

The result for the repeatability of WR dosage for a single operator was compiled in Table 7. Ten mixtures were blindly replicated to compare the fresh properties. For each mixture, the WR dosage added was enough to recieve a 2 ranking. The WR dosage statistics are also listed. For each mixture, the maxium difference is the highest amount of WR minus the lowest amount of WR. The percent difference is the maximum different divided by the average WR times 100

.

Table 7 - Single operator repeatability.

Mix	Original Box Test		Repeated Box Test		WR Statistics*		
	WR*	Slump	WR*	Slump	Average*	Max Difference*	% Difference
1	8.3	1.5	9.5	1.25	8.9	1.2	13.7
2	14.5	2	13.5	1.5	14.0	1.0	7.1
3	7.0	2	4.5	2	5.8	2.5	43.5
4	15	1.5	14.8	1.5	14.9	0.2	1.3
5	17.5	2	15.8	2	16.7	1.7	10.2
8	5.5	0.5	7.9	.5	6.7	2.4	35.8
9	5.8	1.25	6.9	1	6.4	1.1	17.3
10	14.5	1.25	15.2	1	14.9	0.7	4.7
11	7.3	0.5	6.2	0.5	6.8	1.1	16.3
12	3.8	1	3.4	0.5	3.6	0.4	11.1
					Average	1.23	16.1

*note: units are oz/cwt

Comparison of Multiple Operators

Shown in Table 8, another important comparison can be the WR variation between operators. Each operator added enough WR for a mixture to have a two ranking..

Table 8. Multiple operators comparison.

	Operator								
	A		B		C		WR Statistics		
Mix	WR*	Slump (in)	WR *	Slump (in)	WR*	Slump (in)	Avg. WR*	Max Diff.*	% Diff.
3	7	2	3.5	2	5.1	2	5.2	3.5	67.3
8	7.9	0.5	5.5	1	5.1	1	6.2	2.8	45.4
9	6.9	1	4.7	1.25	7.2	1.25	6.2	2.5	39.9
10	15.2	1	15.7	1	15.2	1	15.4	0.5	3.3
11	7.3	0.5	5.5	0.5	9.1	0.5	7.3	3.6	49.3
							Avg.	2.6	41.0

*note: units are oz/cwt

Multiple Evaluators

In Table 9 multiple evaluators visually used the boxes test ranking scale to evaluate the void range amount of different mixtures.

Table 9– Comparison of multiple evaluators using the Box Test.

		Evaluator		
Mix	WR (oz/cwt)	A	B	C
3	7	2	2	2
8	7.9	2	2	2
9	6.9	2	2	2
10	15.2	2	2	2
11	7.3	2	2	2
14	0	3	3	3
14	3.4	2	2	2
15	0	3	3	2
15	2.4	1	1	1
16	0	4	4	4
16	13.3	3	3	3

Field Performance

The portable electric vibrator used in the Box Test and a hydraulic vibrator used in a slip formed paver use different levels of energy to consolidate the concrete. Performance 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 jobsite and a city street jobsite. 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. The results are encouraging.

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 with different gradation to show the significance of the Box Test. The combined gradations were plotted on the individual percent retained chart. Figure 8 varies amounts of sand to coarse and intermediate. While holding the sand constant, Figure 9 varies the amounts of coarse to intermediate. In each figure the WR dosage is next to each mixture's label.

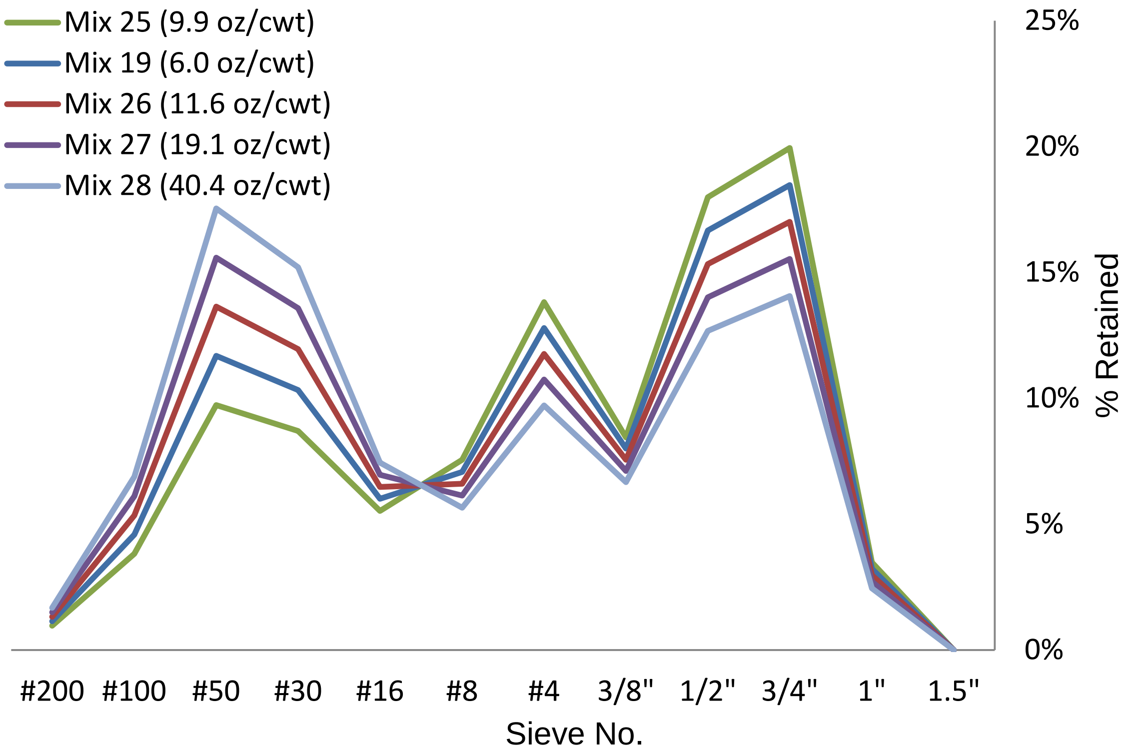


Figure 8 - Combined gradation of sand to intermediate and coarse aggregate.

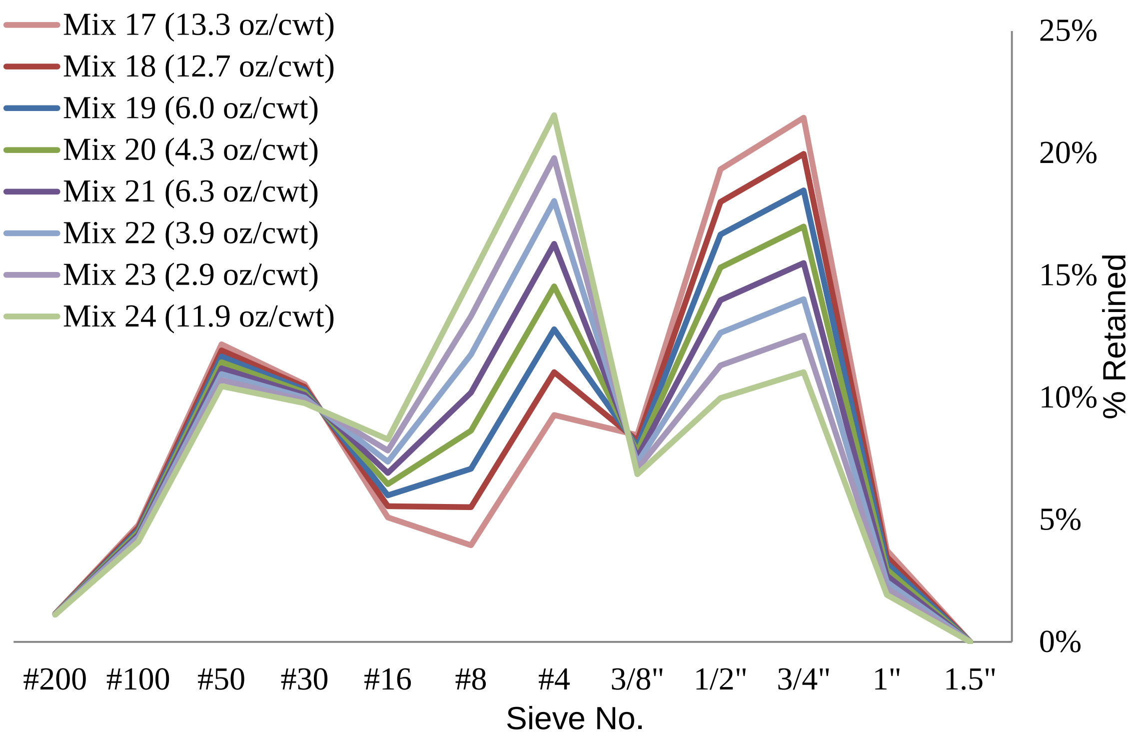


Figure 9 - Combined gradations of intermediate to coarse with constant sand amounts.

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's important to note, none of the mixtures used in this report had edge slumping issues. It seems that the visual ranking scale ranges were good indications of how well the concrete responded to vibration. Validations were conducted to determine how different variables impacted the surface voids of the Box Test. Dosage method, repeatability of a measurement, and comparison of multiple operators were the primary variables investigated and are discussed in the proceeding sections. Also, it should be noted in all of these results, a consistent slump measurement did not corresponded to a passing Box Test value. This will be discussed in more detail later, but it's a significant observation that is prevalent in all results.

Effects of Sequential Dosage

The comparison of the results on single and multiple dosages is shown in Table 6. Nine different mixtures were investigated to compare the response difference in multiple and single dosages. Neither the Box Test nor the Slump Test was affected whether a single or multiple dosage of WR was used.Each of the multiple and single dosage mixtures had similar fresh properties and similar amounts of surface voids.

Repeatability of a Single Operator Replication

As shown in Table 7, 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 boxt test was 2.5 oz/cwt with an average difference of 1.2 oz/cwt. This low repeatability suggests that the Box Test can be repeated accurately by a single user.

Comparison of Multiple Operators

The repeatability of multiple operators can be shown in Table 8. The maximum difference in WR dosage was 3.6 oz/cwt with an average value of 2.6 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. The slump of each replicated mixture varied by 0.5” or less

.

Multiple Evaluators

In Table 9 multiple evaluators were provided a surface to evaluate and independently visually rank the surface. Only one out of 11 evaluations had a different visual ranking. This suggests the visual ranking between users is quite consistent.

Applying the Box Test

Both Figure 8 and 9 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. It is interesting to note that in both figures, a range of gradations required a low amount of WR and would 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 varied largely with only little differences in WR dosage, a change in the amount of sand affected the workability of the mixture. This data is quite useful as these comparisons were not possible with previous testing methods.

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”). It should be noted that the slump tests were consistent for all repeated mixtures, but not a single slump value seemed to be fixed with a passing performance in the Box Test. This is a critical observation that supports this idea that the Slump Test does not provide a consistent measuring tool for low slump concrete and suggests the Box Test and the Slump Test are measuring two different phenomena.

Improvements to the Box Test

While the Box Test seems to be a very useful test to evaluate the suitability of a mixture for a slip formed pavement, it seems 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 have a low inconsistency, it could still be improved if a systematic point count was used to quantify the amount of voids on the surface. An image analysis technique or a simple transparent overlay could be placed on the concrete and individual points are counted.

While the scope of work did not include a closer examination of different mixing and consolidation procedures, it would be interesting to see. Until further work is completed, an emphasis should be taken to match the procedures and equipment as close as possible.

Practical Implications

It is important to realize the Box Test was only designed to evaluate a mixture’s response to vibration and not necessarily to correlate with the exact performance of a slip formed paver. 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 for laboratory or field usage. 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 provide a useful way to compare data.

Conclusion

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

1. Results show that the Box Test is a useful and repeatable tool to evaluate different mixtures for a slip formed paver.
2. A single dosage or multiple dosages of water reducer did not change results of the Box Test or Slump Test.
3. The repeatability of a single operator adding WR dosage had the largest difference of 2.5 oz/cwt with an average difference of 1.2 oz/cwt.
4. Multiple operators adding WR dosage had a maximum different of 3.6 oz/cwt with an average value of 2.6 oz/cwt.
5. The visually ranking of multiple evaluators was shown to be very consistent.
6. The Box Test was able to show the gradation of a mixture influenced the response to vibration. While the amount of coarse and intermediate largely varied with only a slight difference in WR dosage, a minor change in the amount of sand significantly affected the workability of the mixture.
7. While the Slump Test does not provide a consistent measuring tool for low slump concrete, the Box Test can be a useful tool.

Chapter 3 - Use of a Concrete Mixer to Evaluate the Rheology of low Slump Concrete Mixtures

Introduction

One of the most difficult and allusive areas in the concrete industry has been the workability of concrete. Workability is defined, according to American Concrete Institute (ACI), as a property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition. The most common method to measure workability of concrete is by the Slump Test[1]. However, a study comparing the Slump Test and workability of concrete by the National Ready-Mixed Concrete Association (NRMCA) and the National Institute of Standards and Technology (NIST) which proves that Slump Test is not a reliable method in terms of concrete workability[18]. This study showed that concrete mixtures with the same slump do not behave the same during placement. But the Slump Test is still used to describe the workability of concrete because it measures and incorporates all workability applications in a quick and simple manner.

It is important to note a large number of workability tests have been developed over the years. For only certain applications, a few of these workability tests have proven to be useful. However, a single workability test has not been proven to effectively predict the workability of concrete at all ranges. Therefore, there is a need to measure the workability of concrete using a single tool.

One approach to encompassing the workability ranges of concrete has been to look at the rheology, which is the study of the flow of a liquid from external pressures. Although rheology has been used as a useful tool in a number of fields of material science, only recently has it been investigated in the concrete's workability. This chapter describes an attempt to use a common laboratory shear pan-mixer to measure the rheological properties of concrete mixture. In order to do this, a computer system with input and output control was installed on the pan-mixer. The computer system allows the user to control the speed, torque, current, or voltage and monitor the other three variables. A total of seven identical mixes were made during this project to examine the potential for using this equipment to measure the rheology of low to high flowable mixtures.

Experimental Methods

Material

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150[7]. Table 10 shows the oxide analysis of the cement. A 20 % fly ash replacement and a water reducer (WR) were used. According to ASTM C 494[8] the water reducer was a lignosulfonate mid-range WR and ASTM C 618[9] classifies the fly ash as type C. Also used is a superplasticizer that meets ASTM C1017[17] type I. A single Oklahoma crushed limestone and river sand were used in this research. A sieve analysis for each of the aggregates was completed in accordance with ASTM C 136[10]. Absorption and specific gravity of each aggregate followed ASTM C 127[11] for a coarse aggregate or ASTM C 128[12] for a fine aggregate. In Figure 10, the sieve analysis for each aggregate is shown.

Table 10 – 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%				

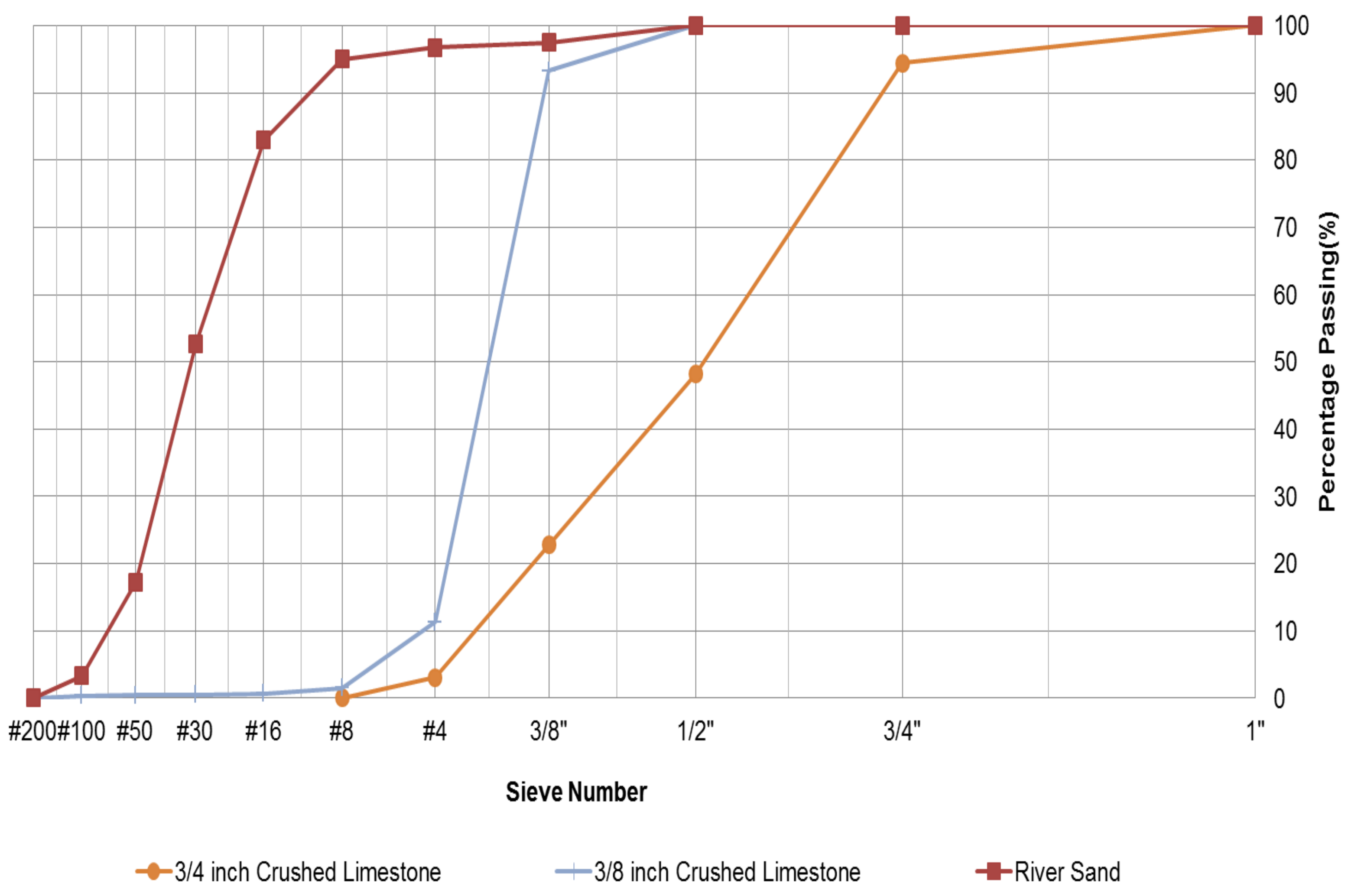


Figure 10 - Sieve analysis for each aggregate type.

Mixture Design

Before comparing the flowability measurements of different mixtures, a single mixture should be replicated multiple times to ensure the flowability measurements are reliable and repeatable. A single mixture was design to have a low flowability and a water reducer was added to increase the flowability. To measure the differences in flowability, each of the mixtures used consistent mid or high range WR dosages. Since the initial mixture required a low flowability, the paste content was 5 sacks (470lbs) with a constant 0.45 w/cm and 20% fly ash replacement. Table 11 contains the batch weights of the mixture designed used.

Table 11– The batch weight used.

Materials	Weight(lbs./cy)
Cement	376
Fly ash	94
Coarse	1553
Intermediate	508
Fine	1280
Water	212

Mixing and Testing Procedure

Pan Mixer

To measure the rheology of the concrete, a pan mixer with a control and monitoring system on a computer was used. A pan-mixer was used to allow a more consistent flowability than a drum mixer. As shown in Figure 11 the pan-mixer uses two different components, a bowl and a lid attached with blades to mix the material into concrete. While using a rotational bowl to hold the material, the blades rotate in the opposite direction of the bowl to mix. The control and monitoring system allows voltage, current, torque, and speed to be measured and controlled. For this research, the rpm of the mixer were controlled and the voltage, current, and torque were monitored. A low flowability mixture should require more torque, voltage, and current to maintain a constant speed than a higher flowable mixture.

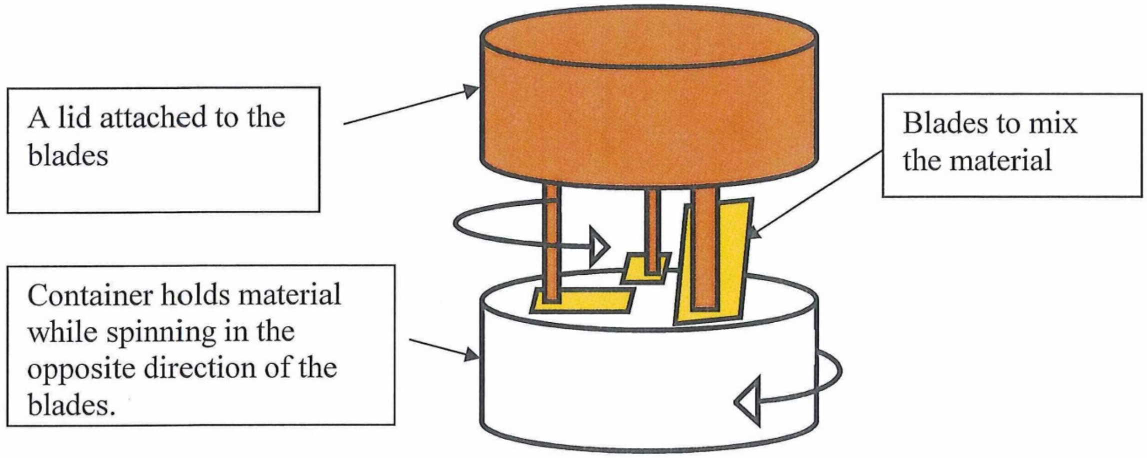


Figure 11- The different components of the pan-mixer.

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 mixing bowl were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The entire premixing stage kept a constant the pan-mixer speed of 1400 rpm.

Using the Pan-Mixer to Measure the Rheology of the Concrete

After the premixing stage was complete, the slump of the mixture was tested. Then a mixture's flowability was measured using the amount of torque, current, and voltage used to move the mixture at different speeds intervals. Three interval speeds of 1400 rpm, 942 rpm, and 462 rpm with 300 seconds per a speed interval were used to collect flowability measurements. To measure the changes in a mixture's flowability, a water reducer was added and remixed for three minutes at 1400 rpm. Again, the slump and flowability measurements were taken. Finally, a second water reducer dosage was added and remixed for three minutes at 1400 rpm. The slump and flowability measurements were taken. For a graphical representation of this procedure is shown in Figure 12.

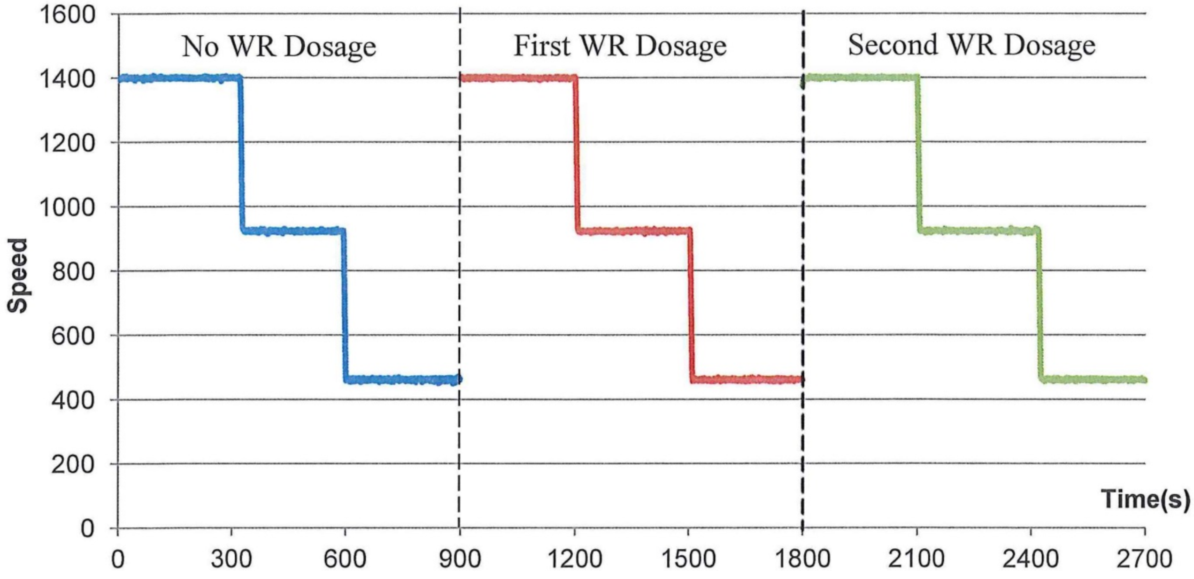


Figure 12 –The pan mixer speed intervals with increasing amounts of WR.

Results

A total of seven mixtures were made in this project. In four mixtures used a mid-range water reducer and three mixtures used a high range water reducer. The dosage amounts of a mid-range or high range were consistently close in each dosage stage. For the first stage using no WR, the slump ranged from 1” to 1.5”. For the mid-range WR, the first dosage had a slump of 2” to 2.5” and the second dosage had a 3” to 4” slump. For the high range WR, the first dosage had a slump of 5 to 6.5” and a second dosage slump of 7” to 9”.

Each of the figures below has a line with the standard deviation for the torque. Figure 13 compares the workability change of a mixture with the use of a WR. It graphs the changes in speed to the torque percent of the pan-mixer. Figure 14 shows different torque with respect to three different rpm that was used during the initial mixing. The torque and speed of the first dosage of a WR is shown in Figure 15. And the second dosage of WR is shown in Figure 16.

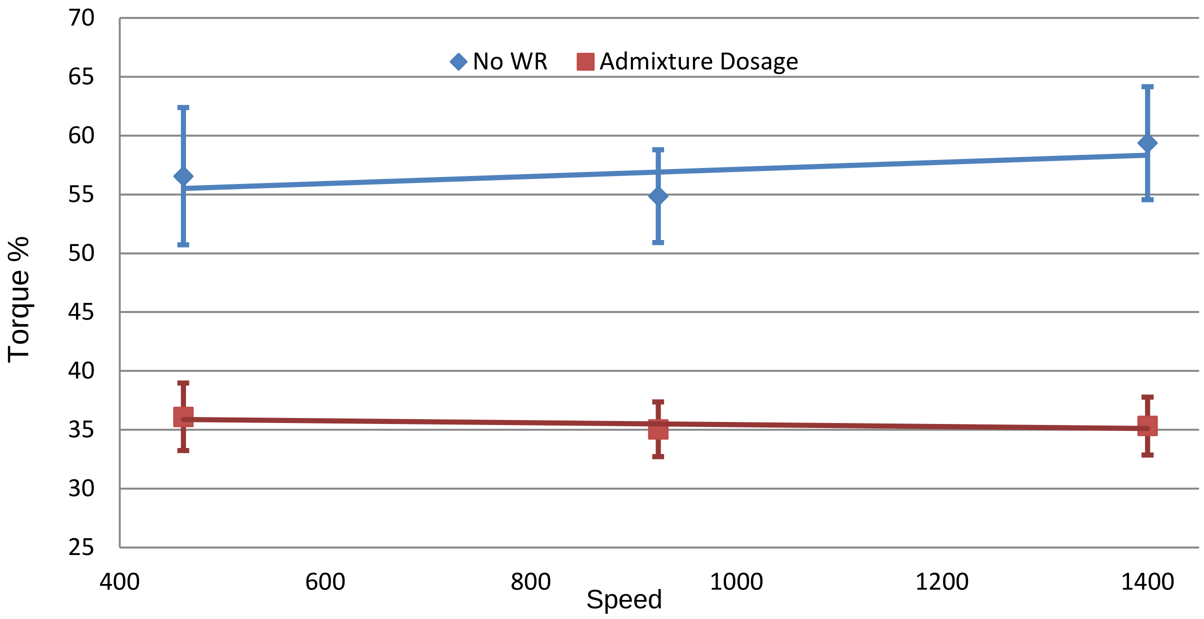


Figure 13 –Changes in torque using a WR.

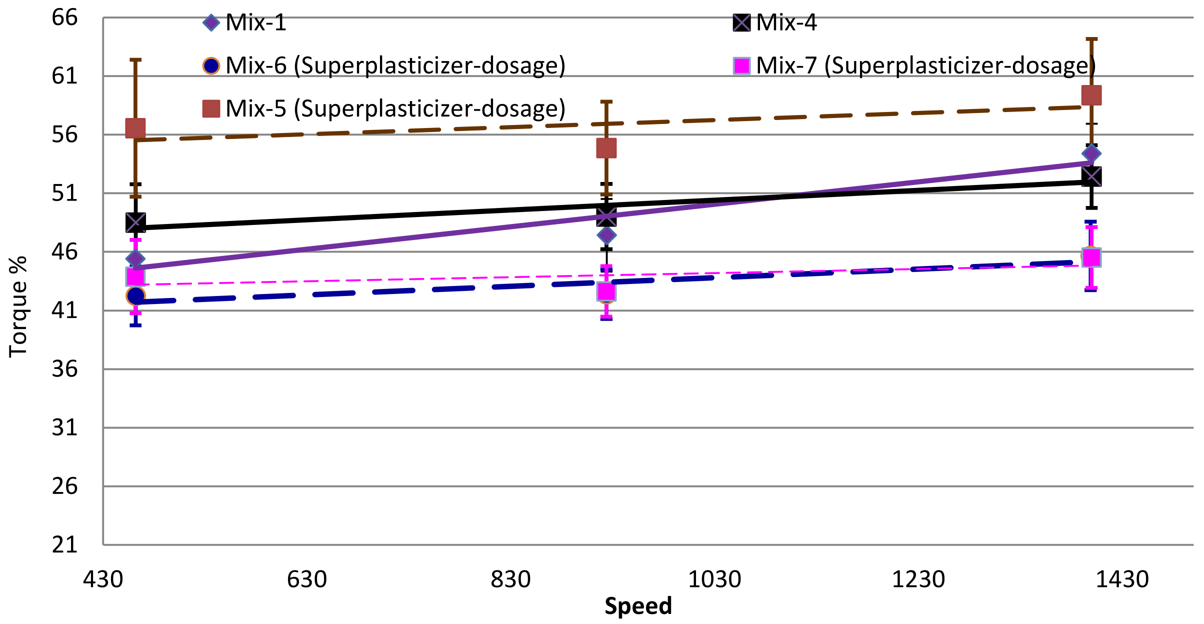


Figure 14– Measuring torque at three interval speeds with no WR.

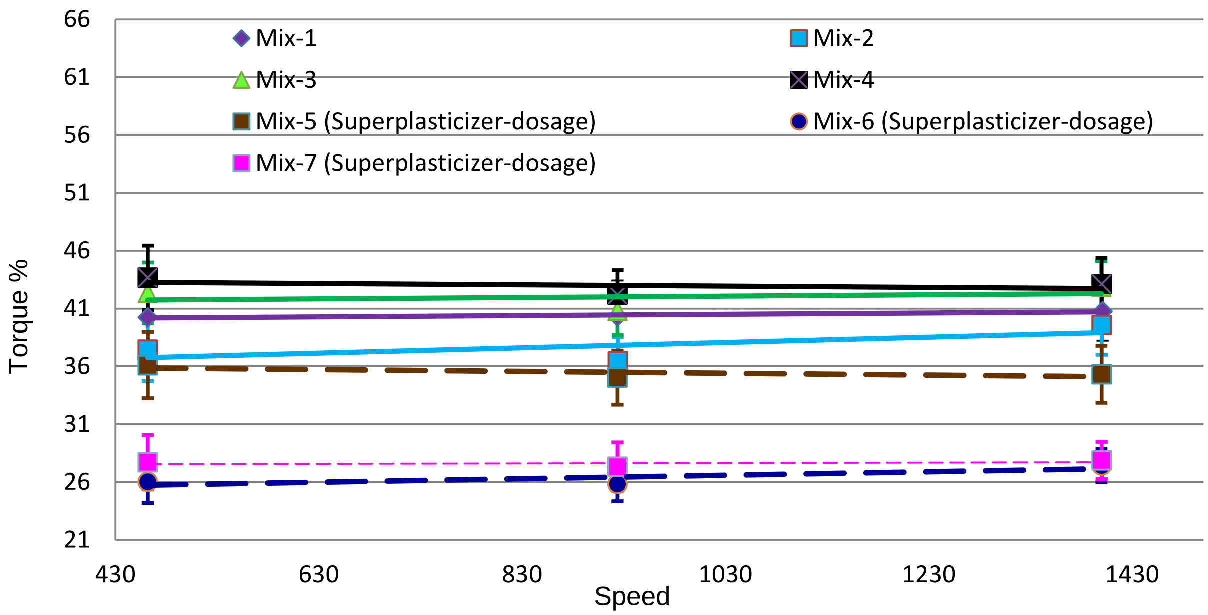


Figure 15 –First WR dosage measuring torque at the interval speeds.

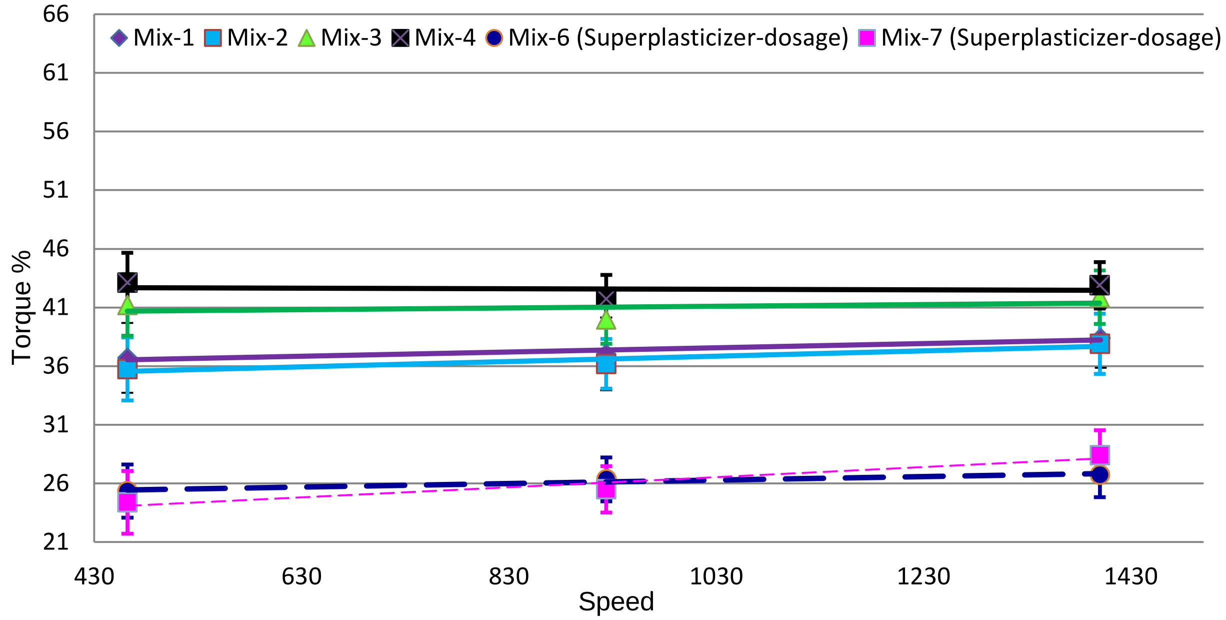


Figure 16- Second WR dosage measuring torque at the interval speeds.

Discussion:

The rheological characteristics of the mixture were attempted to be characterized using the torque, current, voltage and speed from the pan mixer. The same mixture design was replicated seven different times and the torque was measured at similar slump values.

In Figure 14, the slumps of the different mixtures were all very close, but they didn't have similar torque values. Since the seven different mixtures had the same batch weights and similar slumps, this shows the pan-mixer is not very repeatable.

Looking at Figures 13, 14 and 15, the WR reduced the amount of torque and increased the slump. This follows the thought process as the slump increased the mixer requires less energy or torque to force the blades through the concrete. However, Figure 15 and 16 has a significant difference in slump, but not a large change in torque. This could suggest the pan-mixer requires a certain torque to move the different components. A more sensitive pan-mixer might have a better chance of measuring the flow of a low slump mixture.

Conclusion

The following conclusions were formed:

- The pan-mixer was unable to consistently measure the torque percent of the concrete with similar slumps.
- However, the pan-mixer could consistently measure if a mixture had a low slump, or a mid to high slump.
- A mid-range slump could not be differentiated from a high valued slump.
- A higher sensitive pan-mixer might be able to measure the flow of low slump mixtures.

CHAPTER 4 – INVESTIGATION OF AGGREGATE CHARACTRISTICS FOR CONCRETE WITH THE AIMS II

Introduction

About two-thirds of the total volume of concrete is aggregates. However, the workability impacts of aggregate characteristics and gradation on concrete have been largely neglected. While gradation has been classified according to ASTM C33, the aggregate characteristics do not have definite requirements to be used in concrete.

Numerous claims have been made about different aggregate characteristics impacting the workability concrete. The majority of the aggregate claims revolve around the angularity, texture, and shape variation influences the workability of the concrete. The mechanisms of packing and frictional resistance have been the two leading believes behind the workability effects on aggregates. Typically the packing mechanism of aggregates is explained using a dry packing model. It is an approach to determine the ability of an aggregate's gradation, shape, and angularity to fill a volume by measuring the amount of voids. For example, a very flat and elongated shape will take up less space than a cubical or spherical shape. However, the frictional resistance focuses on the different aggregate variables that impede the flow of a concrete mixture. These aggregate variables contributing to frictional resistance include the shape, angularity, and gradation of the aggregate. For example, a river rock with low angular, well-shaped, and low textured aggregate will have less frictional resistances causing a better workability than a crushed limestone with high angularity, high texture, and extreme flatness and elongation. Therefore using a river rock should require less paste to achieve a certain workability than a crushed limestone and will be more cost effectiveness of the concrete. Unfortunately, none known research has been conducted on these mechanisms for normal concrete mixtures.

Other aggregate impacts besides the workability can impact the concrete. For concrete pavements with transverse cracking, faulting of joints and cracks, punch outs, and spalling at joints and cracks have been attributed to coarse aggregate particle shape and angularity[19]. This mechanism has been contributed to the bond strength between cement paste and the aggregate's shape, angularity, and surface texture[20]. In other words, the bond strength increases as aggregates become rougher and more angular[21]. Weak bonding of aggregates in concrete pavements has been attributed to longitudinal and transverse cracking, joint cracks, spalling, and punch outs[22]

A necessitate into understanding the workability of concrete and other factors creating problems in concrete is to classify aggregate characteristic. A basic classification has been to measure angularity, texture, and different variations of shape. In the past, only a human eye with some basic measuring tool could only classify the aggregate characteristics. However recently, computer imaging systems are starting to be incorporated into classifying aggregate characteristics. One of the more advanced systems this research will be using is the AIMS II. The main goal of this chapter is to evaluate various aggregate characteristics using the **A**ggregate **I**maging **M**easurement **S**ystem **2** or **AIMSII**.

Materials

Eleven coarse aggregate and three fine aggregate were analyzed using the AIMS II. As shown in Table 12, the aggregates types used are: nine limestones, one sandstone, two river gravels, one manufactured sand, and two river sands. The majority of the aggregate sources are from the state of Oklahoma with the exception of Lamar from Colorado and Cleburne and Wright from Texas. The aggregate sources are commonly used in concrete. Other than Cleburne and Wright, all of the aggregates studied are approved by Oklahoma Department of Transportation. A sieve analysis of each aggregate type can be shown in Figure 17.

Table 12 – Source Type and name of each aggregate investigated.

	Type	Source Name
3/4" Nominal Max Coarse	Limestone	Richard Spur
	Limestone	Drumright
	Limestone	Pryor
	Limestone	Okay
	Limestone	Coleman
	Limestone	North Troy
	Limestone	Davis
	Limestone	Hartshorne
	Sandstone	Sawyer
	Limestone	Cooperton
	River Gravel	Cleburne
	River Gravel	Lamar
Sand	River	Arkhola
	River	Dover
	Manufactured	Wright

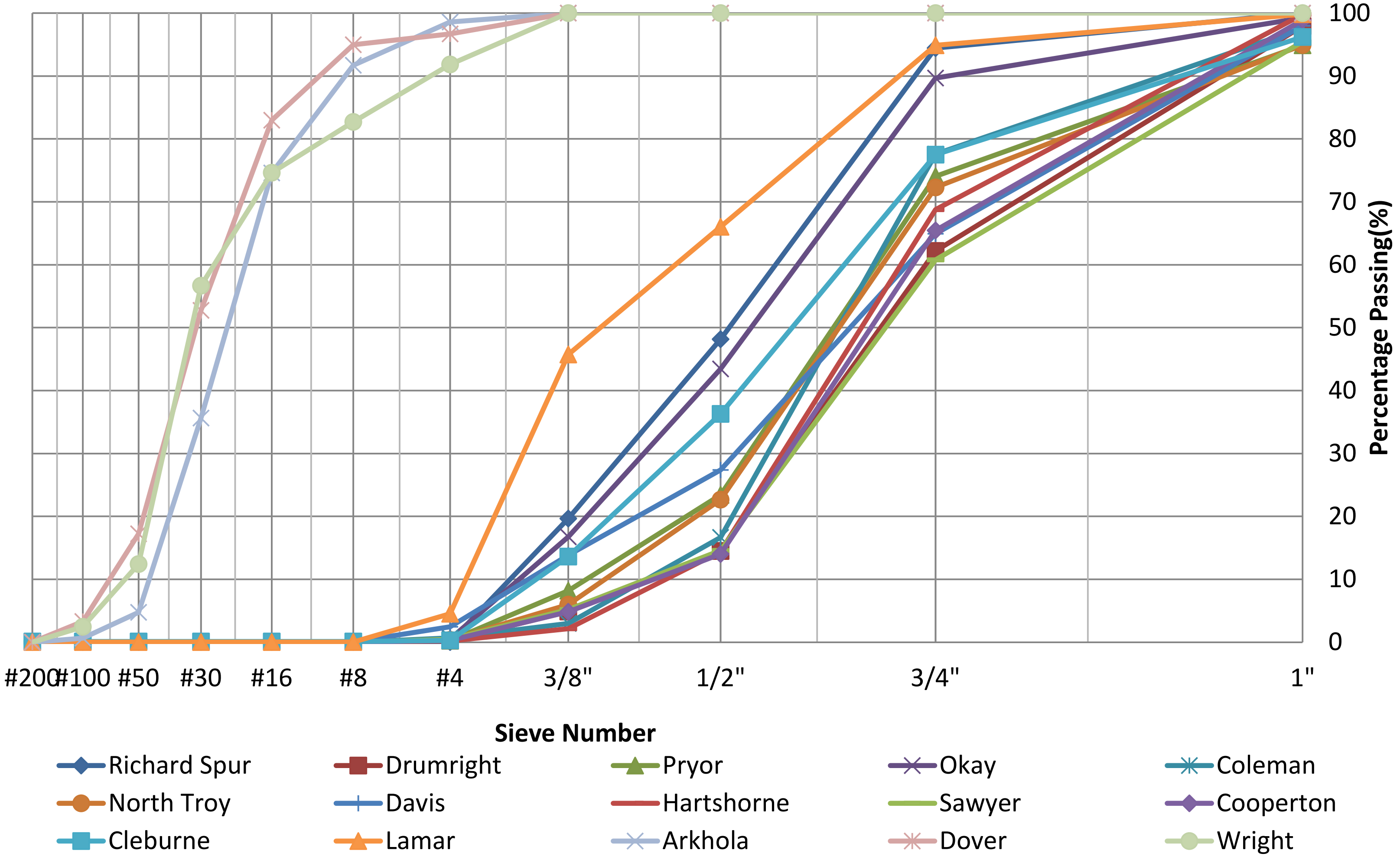


Figure 17- Sieve analysis of each aggregate being analyzed by the AIMS II.

Testing Procedure using the AIMS II

According to past work, the AIMS II has been proved to be relatively good repeatability, reproducibility, and sensitivity[23]. The development of the method can be found by Masad[24]. The specific objective of this project was to quantify aggregate characteristics from different quarries and sand sources. Each aggregate source was sieved into individual sieve sizes, washed, and analyzed using the automated AIMS II system. The AIMS II measures coarse and fine aggregate differently. Any sieve size at or above 4.75mm (no.4) will be measured for angularity, sphericity, surface texture, 3-dimensional shape and flat and elongated. However, the aggregate characteristics differ in that anything below the 4.75mm (no.4) will only have angularity and a form 2D measurement.

Coarse Aggregate Specific Measurements

To examine coarse aggregate the AIMSII investigates aggregates that are washed and separated by sieve size retained on a 4.75-mm (No. 4) and larger. The aggregate sample is placed on a tray that is rotated past three different lighting levels. These include a back light, top light, and lighting to measure the texture of the aggregates. The tray rotates, positioning the aggregates in the back lighting and under the camera for imaging. Each particle silhouette is captured and the centroid of the outline determined. A second tray scan is performed using top lighting for the height measurement. A third scan captures the texture of the sample. These three allow analysis of coarse aggregates shape, angularity, texture, and particle dimensions. From these measurements the system provides the following values for each aggregate:

- Coarse Aggregate Angularity (AIMS Angularity Index ranges from 1 to 10000)
- Coarse Aggregate Texture (AIMS Texture Index ranges from 0 to 1000)
- Coarse Aggregate Sphericity (AIMS Sphericity Index ranges from 0 to 1)
- Coarse Aggregate Flat and Elongated

These measurements will be discussed in further detail in the coming sections. However, more details on the system design and how it operates can be found in reference[24].

Gradient Angularity

Gradient Angularity applies to both fine and coarse aggregate sizes and describes variations at the edge of the particle that impact the overall shape. The gradient angularity quantifies changes along a particle boundary with higher gradient values indicating a more angular shape. Gradient angularity has a relative scale of 0 to 10000 with a perfect circle having a small non-zero value. It is analyzed by quantifying the change in the gradient on a particle boundary[25] and is related to the sharpness of the corners of 2-dimensional images of aggregate particles. Shown in Figure 18 below, the gradient method starts by calculating the inclination of gradient vectors on particle boundary points from the x-axis (horizontal axis in an image). The average change in the inclination of the gradient vectors is taken as an indication of angularity. Figure 19 shows the AIMS II measurement for angularity.

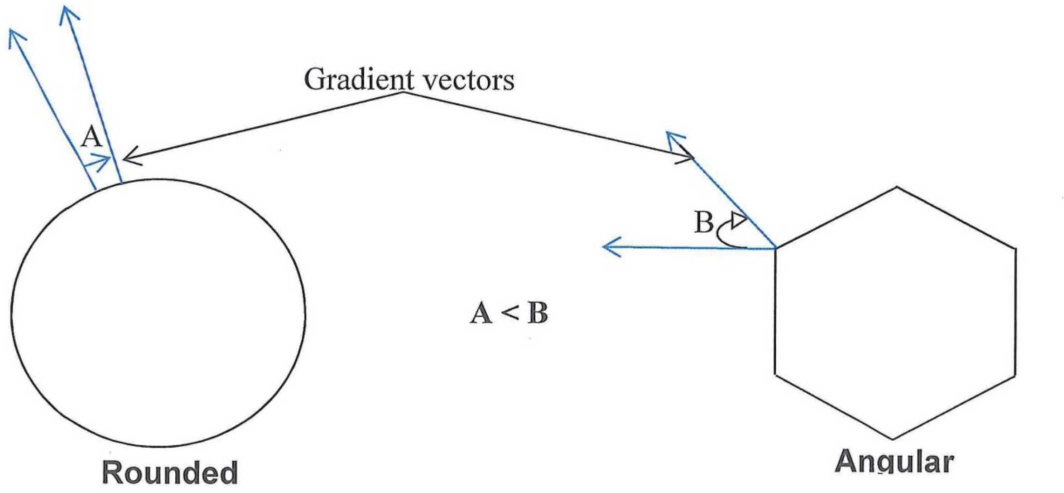


Figure 18 - Gradient Vector for Smooth vs. Angular Particle[25].

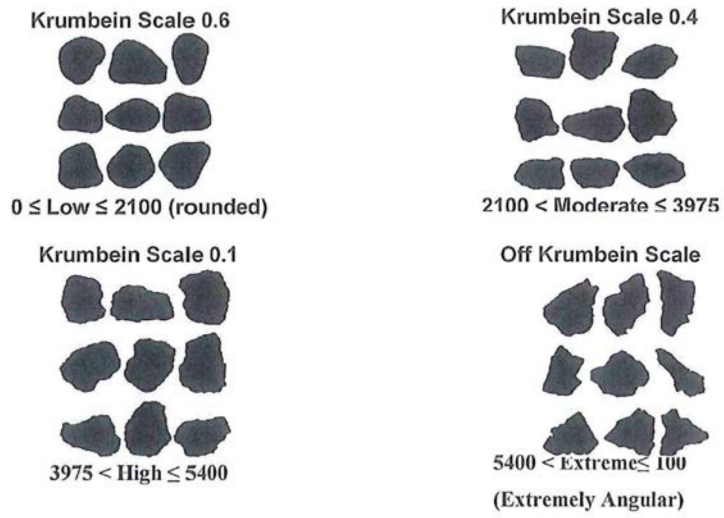


Figure19 - Fine and Coarse Aggregate Angularity Ranges[26].

Texture

Texture describes the relative smoothness or roughness of aggregate particles' surfaces. AIMS Texture applies to coarse aggregate sizes only and describes surface micro-texture, features less than approximately 0.5 mm in size which are too small to affect the overall shape. Texture has a relative scale of 0 to 1000 with a smooth polished surface approaching a value of 0. The AIMS Texture analysis uses the wavelet method to quantify texture[27,28,29]. The wavelet analysis gives the texture details in the horizontal, vertical, and diagonal directions in three separate images. The texture index at a given decomposition level is the arithmetic mean of the squared values of the wavelet coefficients for all three directions. The texture index is expressed mathematically as follows:

$$TextureIndex = \frac{1}{3N}\sum_{i=1}^{3}\sum_{j=1}^{N}\left[D_{i,j}\left(x.y\right)\right]^{2} \qquad (3.1)$$

where n refers to the decomposition level, N denotes the total number of coefficients in a detailed image of texture; i takes values 1, 2, or 3, for the three detailed images of texture; j is the wavelet coefficient index; and (*x*, *y*) is the location of the coefficients in the transformed domain. Fletcher[29] found that texture can be least affected by color or dust particles on the surface of the particles by using a certain level of low resolution and detailed images. In Figure 20, a texture scaled was developed with images and a range of numbers.

0 ≤ Low (Smooth) ≤ 200 200 < Moderate ≤ 500

500 < High ≤ 750 750 < Extreme ≤ 1000

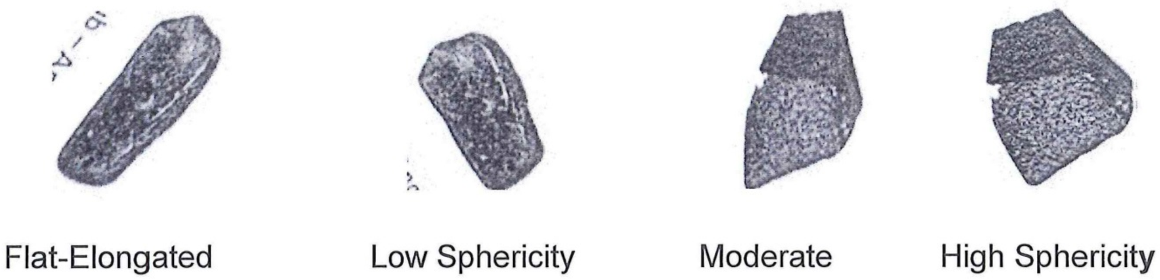
Figure 20 - Coarse Aggregate Texture Range

Sphericity

Using sphericity the form is quantified in three dimensions. The three dimensions of the particle the longest dimension (dL), the intermediate dimension (dI), and the shortest dimension (ds) are used in equation 3.2 for sphericity and shape factor.

$$Sphericity = \sqrt[3]{\frac{d_s . d_I}{d_L^2}} \tag{3.2}$$

The two major and minor axes are analyzed from the black and white images (Eigenvector analysis) while the depth of the particle is measured by auto focusing of themicroscope[29].



Flat-Elongated Low Sphericity Moderate High Sphericity

Figure 21 - Cluster Classification Charts for Different Aggregate Properties[23].

Flat & Elongated, Flat or Elongated

The flat and elongated test measures the percentage of particles above a specified dimension ratio, rather than distribution of relative sizes[27].Flat & Elongated represents the ratio of the particle dimensions as described in Equations below:

Flatness Ratio: $$\text{Flatness} = \frac{d_s}{d_I} \qquad (3.3)$$

Elongation Ratio: $$\text{Elongation} = \frac{d_I}{d_L} \qquad (3.4)$$

Flat & Elongated Value: $$\text{L/S} = \frac{d_L}{d_s} \qquad (3.5)$$

where: dS = particle thickness (shortest dimension)
dI = particle width (intermediate dimension)
dL = particle length (longest dimension)

Flat or elongated is the ratio of the particle dimensions described in Equation below:

Flat or Elongated Value (ForE): $\frac{d_I}{S}$ or $\frac{d_L}{d_I}$ ≥ Ratio (i.e.: 1, 2, 3…) (3.6)

Coarse Aggregate Angularity Texture Value (CAAT)

Coarse Aggregate Angularity Texture (CAAT) is a combined angularity texture value described in Equation 3.7 below:

$$CAAT = 10XTX + 0.5XGA \tag{3.7}$$

Fine Aggregate Specific Measurements

To examine fine aggregate the AIMSII investigates aggregates that are washed and separated by sieve size passed on a 4.75-mm (No. 4) down to retained by 0.075mm (No. 200). The aggregate sample of approximately 50 grams for each size is spread uniformly around the tray trough. Only one scan of the tray is needed, and backlighting is used in this analysis for the larger fine sizes. The tray rotates and images are captured until the desired particle count (150 in this project) is reached. Images are evaluated to remove touching particles from the analysis. The system provides the following measures for fine aggregate particles.

- Fine Aggregate Angularity (AIMS Angularity Index ranges from 1 to 10000)
- Fine Aggregate Form 2D (AIMS Form 2D Index ranges from 0 to 20)

Form 2D

AIMS Form 2D applies to fine aggregate sizes only and quantifies the relative form from 2-dimensional images of aggregate particles. The form index Form 2D is expressed by Equation below. Form 2D has a relative scale of 0 to 20. A perfect circle has a Form 2D value of zero.

$$Form2D = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{R_{\theta+\Delta\theta} - R_{\theta}}{R_{\theta}} \tag{3.8}$$

Where: R_θ is the radius of the particle at an angle of θ

$\Delta\theta$ is the incremental difference in the angle

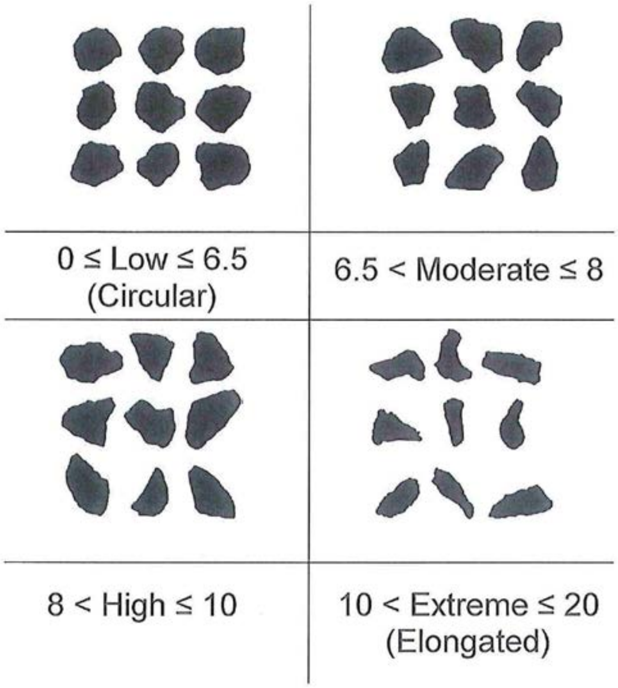


Figure 22 - Fine aggregate form 2D ranges.

Results

Each aggregate source was analyzed using the AIMS II. After analyzing each sieve size, similar to what currently is being done for aggregate gradation, each of the shape characteristics from each sieve size is presented by cumulative distribution instead of single average value for each property. Dealing with the distribution of aggregate characteristics rather than average indices is advantageous for the development of reliable specifications given the high variability in shape characteristics within an aggregate sample[28]. The next step is to statistically analyze the data and assign or identify aggregate groups based on distribution of data acquired. Analyzing the data based on their distribution suggests much more reliable approach to data interpretation[28]. (Note: characteristics acquire using AIMS has been compared to, laboratory performance tests and field test[28]).

Figure 23 shows texture index vs. aggregate percent frequency. Figure 24, which is angularity index vs. aggregate percent frequency, present the angularity of the aggregates. Figure 25 has the sphericity results of each coarse aggregate. Figure 26 the X-axis shows flat and elongated factor which comes from Eq. 3.6. In Figure 26 the X-axis shows flat and elongated factor which comes from Eq. 3.6. Figure 27 and 28 show the fine aggregate characteristics of angularity and form 2D, respectively.

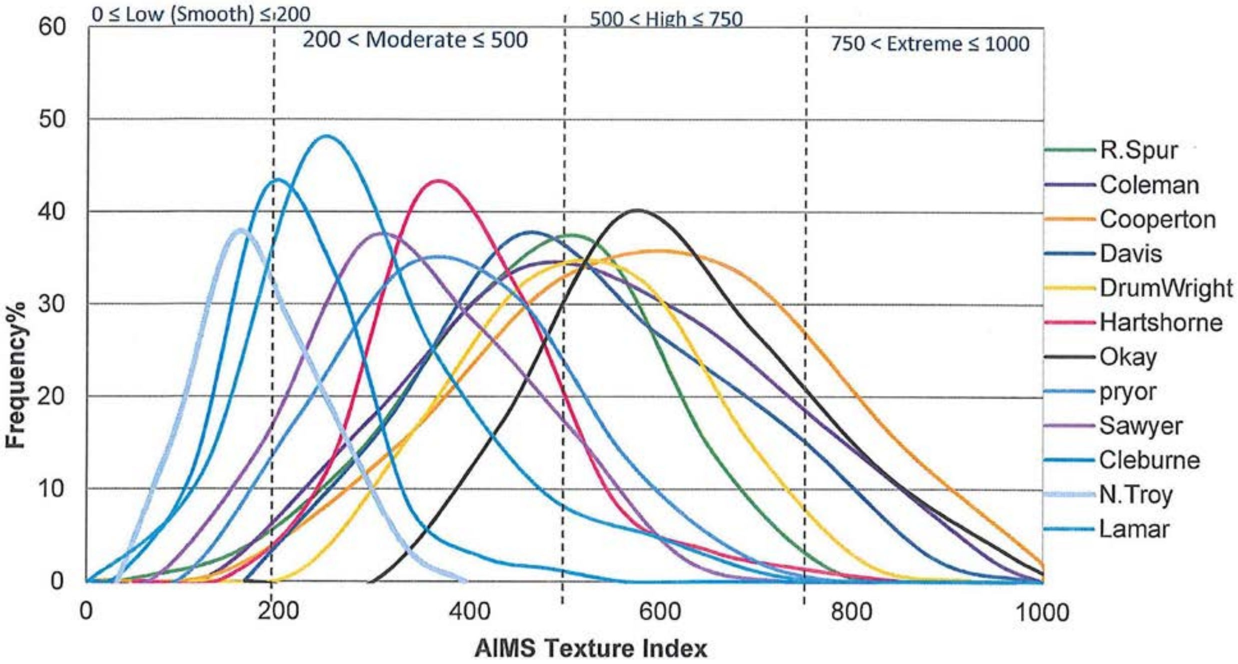


Figure 23 – AIMS measuring texture index of coarse aggregate.

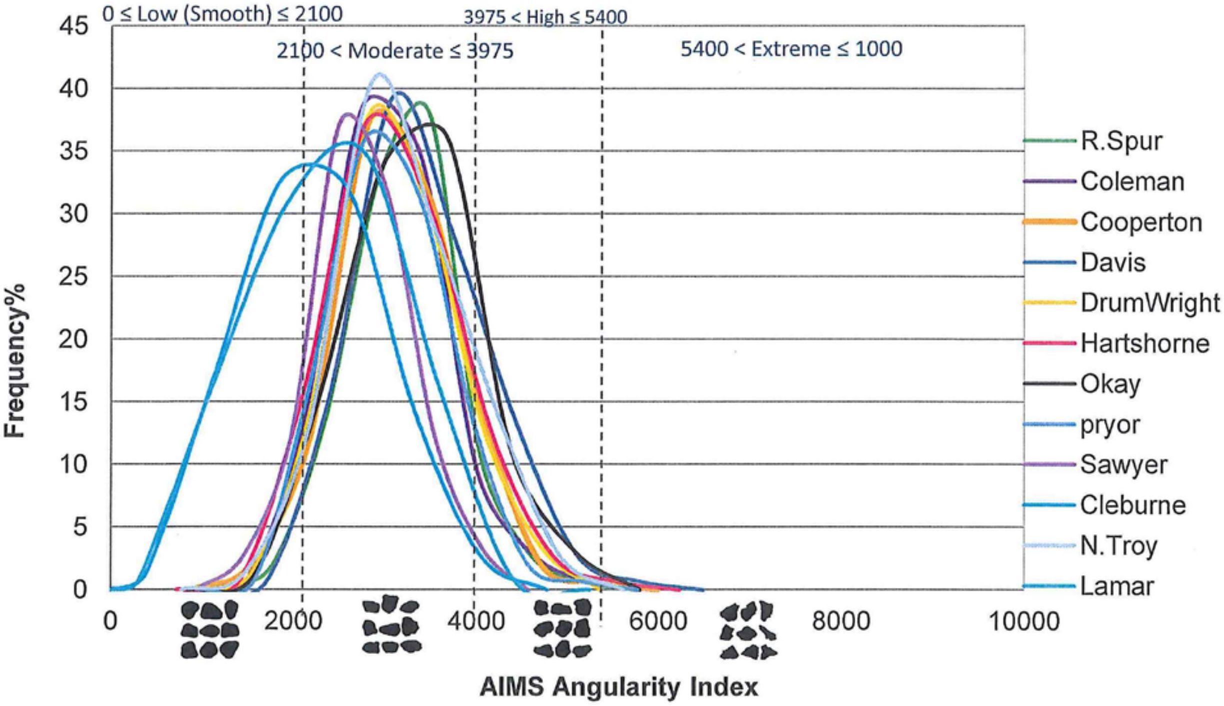


Figure 24- AIMS measuring angularity of coarse aggregate.

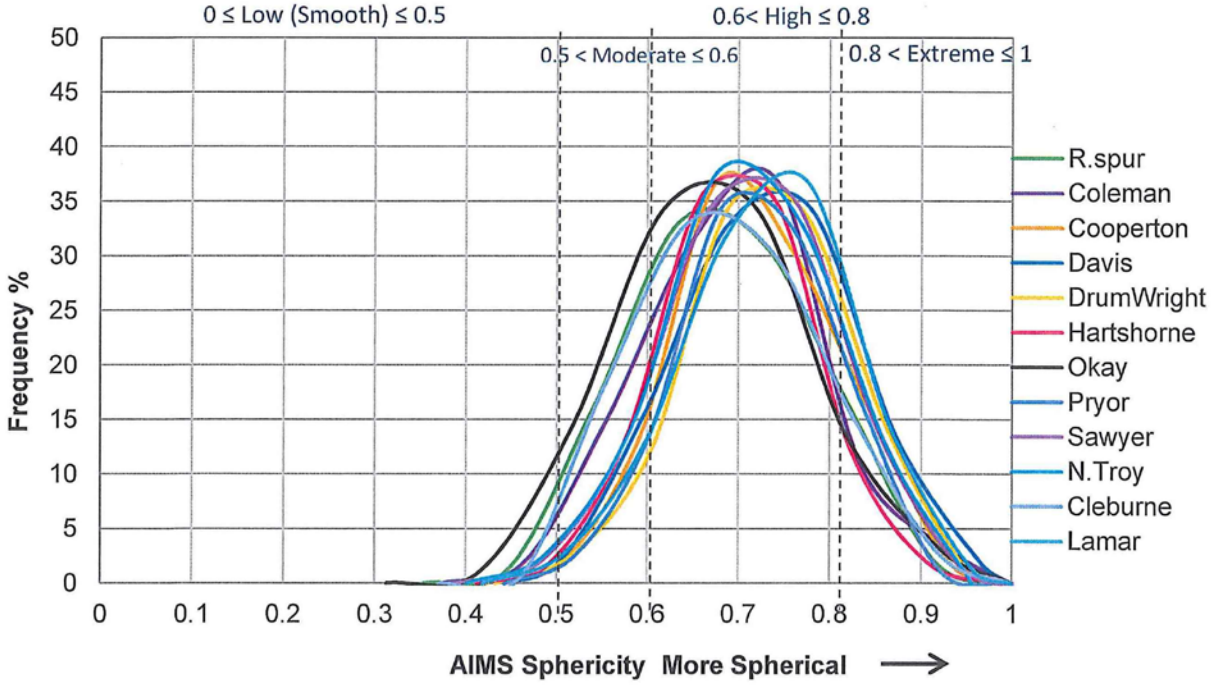


Figure 25 –AIMS measuring the sphericity index of coarse aggregate.

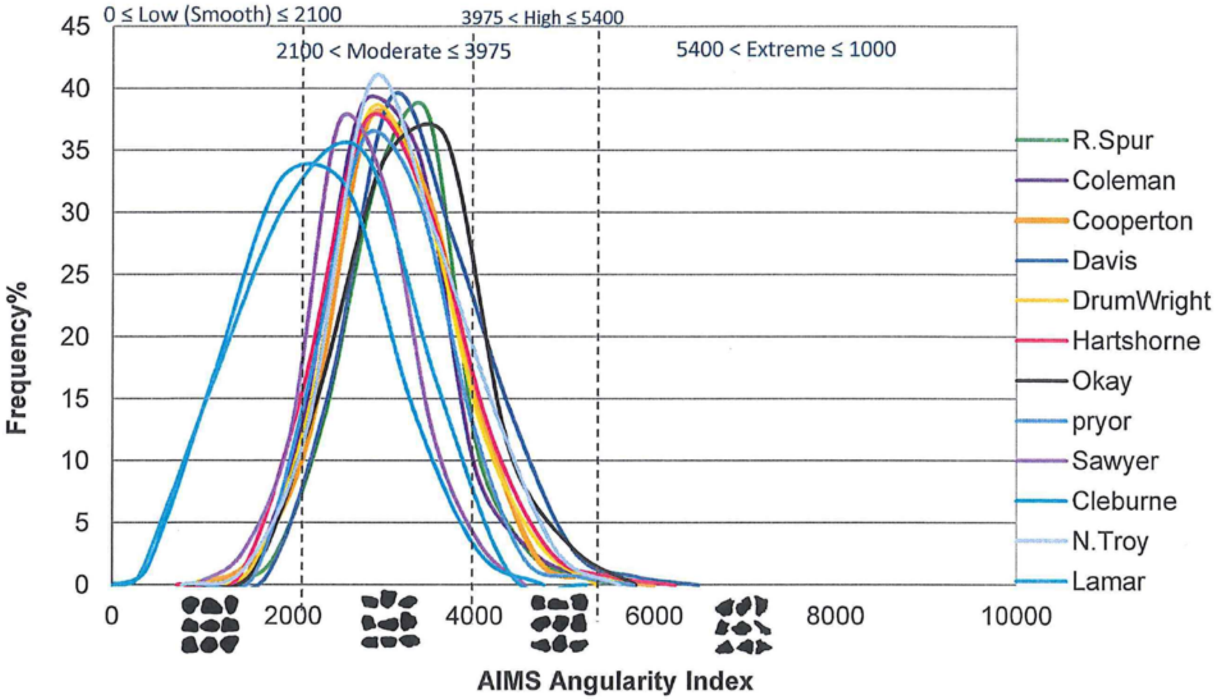


Figure 26 - AIMS measuring flat and elongated of coarse aggregate

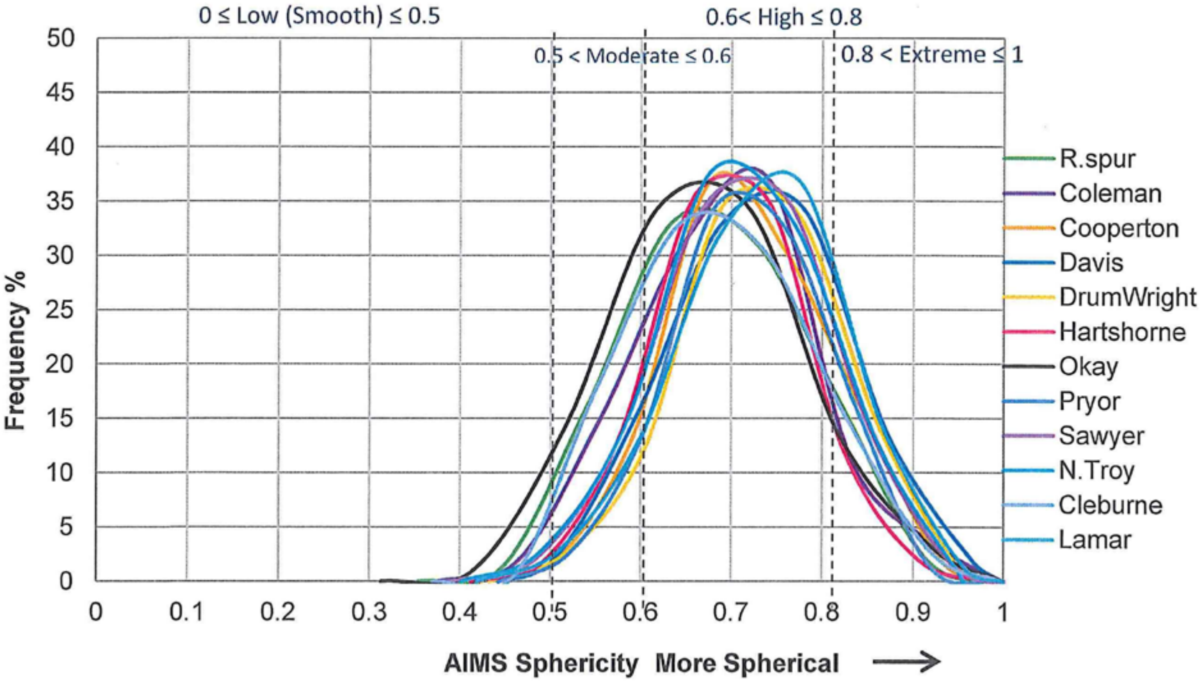


Figure 27 - AIMS measuring the angularity of fine aggregates.

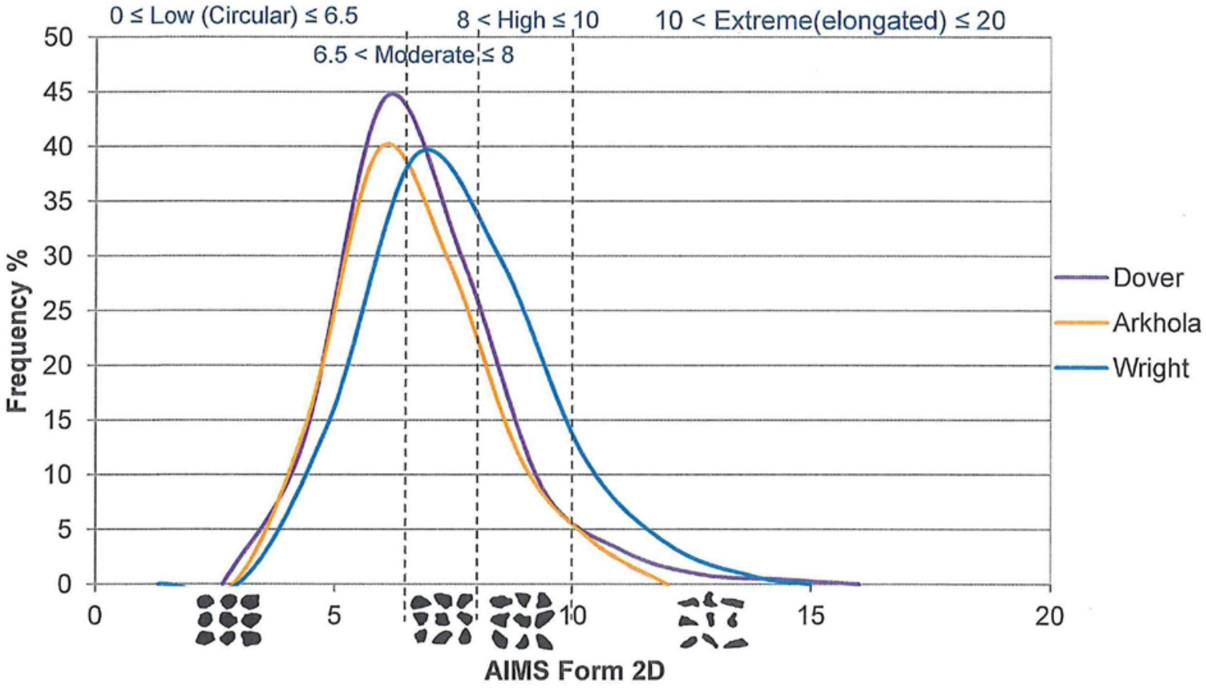


Figure 28 – AIMS measuring the form 2D index of fine aggregate.

Discussion

Texture

Figure 23 shows texture index vs. aggregate percent frequency. As one can see, coarse aggregate image analysis results show that North Troy, Cleburne, and Lamar have relatively low texture in comparing to other aggregates. Likewise, these 11 aggregates can be divided into three zones with low, moderate, and high texture. Aggregate with moderate texture are Sawyer, Hartshorne, and Pryor. On the other hand, because of the fact that aggregates from a quarry come with a wide range of texture rather than a single specific number that can be assigned to the aggregates, some of these aggregate such as Richard Spur, Davis, Drum Wright, Coleman, Okay, and Cooperton are located in the graph where their texture range vary from moderate all way through high and extreme zone. So in order to separate the aggregates from one another it was preferred to use peak of each line which is an indication of where most of particles fall into. According to this fact, Cooperton is an aggregate with high and extreme texture while Richard Spur, Davis, Drum Wright, and Coleman are considered to have high texture. As for Okay, despite of having higher texture than other aggregates that fell into high texture zone, it is still identified as high texture.

Angularity

Figure 24, which is angularity index vs. aggregate percent frequency, present the angularity of the aggregates. The results show that Cleburne and Lamar have the least angularity among all the aggregates which is in accordance to what we expected considering they are both river rock. According to the fact discussed in the previous section, all the other aggregates, despite of having minor differences in their peak point are all within the moderate zone.

Sphericity

In Figure 25 as one moves toward the right side, aggregates become more and more spherical. The graph shows that all the aggregates from different quarry have sphericity range of 0.4 (low sphericity) to 1 (high spherical). The only difference is the percent that falls under each category. According to this fact, Okay has the least amount of spherical particle among all the other aggregates and it follows by Richard spur, Pryor, and Coleman. Lamar and Davis on the other hand; have the most amount of spherical particle. All the other aggregates have relatively the same amount of spherical particle.

Flat & Elongated

In Figure 26 the X-axis shows flat and elongated factor which comes from equation 3.6. In this graph as one moves toward the right side particles become more and more flat and elongated. As it is shown in the graph, Okay is one aggregate that stands out among all the others for being extremely flat and elongated. Coleman and Richard spur contain more flat and elongated particles after Okay. The rest of the aggregates have relatively close amount of flat and elongated particle.

Angularity of Fine Aggregate

Figure 27 shows that Dover and Arkhola have relatively the same amount of angularity and they fall into category of moderate range. Wright on the other hand, has a wider range of angularity that varies from moderate range to high. Wright is manufactured sand and it was expected to have a higher angularity than natural sand. According to the following graph it is considered to have moderate and high angularity.

Form 2D

As it was explained in previous part a perfect circle has a Form 2D value of zero. Therefore, as one moves forward to the right of this graph particles become less and less circular. Figure 28 shows a large amount of Dover and Arkhola particles belong to low zone which is a circular range. Wright on the other hand, is manufactured sand and it contains more moderate and high range particles. This indicates that Wright particles are less circular comparing to Dover and Arkhola which are natural sand.

Conclusion

Eleven coarse aggregates were characterized using AIMS II. The study showed that texture varies considerably among aggregate samples. North Troy, Cleburne, and Lamar had relatively low texture in comparing to other. Aggregates with moderate texture are Sawyer, Hartshorne, and Pryor. Cooperton is an aggregate with high and extreme texture while Richard Spur, Davis, Drumwright, Okay, and Coleman are considered to have high texture.

Angularity data shows Cleburne and Lamar have the least angularity among all the aggregates which is in accordance to what we expected considering they are both river rock. All the other aggregates, despite of having minor differences fall within the moderate zone. As for sphericity of aggregates, Okay has the least amount of spherical particle among all the other aggregates and it follows by Richard spur, Pryor, and Coleman. Lamar and Davis on the other hand; have the most amount of spherical particle. All the other aggregates have relatively the same amount of spherical particle. Flat and elongated is another characteristics of aggregates that was measured using this method. According to Fig. 9 Okay is one aggregate that stands out among all the others for being extremely flat and elongated. Coleman and Richard spur contain more flat and elongated particles after Okay. The rest of the aggregates have relatively the same amount of flat and elongated particle.

Angularity and form 2D are two characteristics of fine aggregates that was measured using AIMS II. Fine aggregates that were tested through this method are Dover and Arkhola as an example of natural sand and Wright which is manufactured sand. Data shows that Dover and Arkhola have relatively the same amount of angularity and they fell into the category of aggregate with moderate angularity. Wright on the other hand, has a wider range of angularity that varies from moderate range to high.

When it comes to form2D, date showed that a large amount of Dover and Arkhola particles belong to low zone which is a circular range. Wright on the other hand, is manufactured sand and it contains more moderate and high range particles. This indicates that Wright particles are less circular comparing to Dover and Arkhola which are natural sand.

CHAPTER 5 – CONCLUSION

Two different methods to evaluate the performance of a low flowable mixture were tested. Also, different aggregate characteristics were evaluated using the AIMS II. The following conclusions were made with this research:

- A workability test was developed to evaluate a low flowable mixture’s response to vibration called the Box Test.

- The rheology of low slump was attempted to be measured using a pan-mixer, but a consistent measurement was not found.

- Different aggregate characteristics were evaluated from many different sources, especially aggregate sources approved for the Oklahoma Department of Transportation.

CHAPTER 6 – FUTURE WORK

While obtaining these results for aggregates in Oklahoma is a great accomplishment, more work is needed to understand what these measurements mean. This includes the relationship between aggregate shape characteristics from AIMS II, concrete mixture proportions, and performance. This should be done for all major applications of concrete with different levels of workability.

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