AGGREGATE PROPORTIONING FOR SLIP FORMED PAVEMENTS AND FLOWABLE CONCRETE

By

MARLLON DANIEL COOK

Bachelor of Science in Civil Engineering
Oklahoma State University
Stillwater, Oklahoma
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Master of Science in Civil Engineering
Oklahoma State University
Stillwater, Oklahoma
2013

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Dissertation Approved:

Dr. M. Tyler Ley

Dissertation Adviser

Dr. Bruce W. Russell

Dr. Stephen Cross

Dr. Peter Clark

Name: MARLLON DANIEL COOK

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Abstract: This is an investigation into developing a relationship between aggregate proportioning and the workability of concrete for slip formed pavements and flowable concrete applications. Workability tests were developed for each application. Various aggregate proportioning techniques and aggregate concepts were evaluated. The aggregate proportioning technique based off gradation was shown to predictably change the workability of the concrete. Almost 800 different mixtures were conducted to validate workability tests and also develop gradation and proportioning limits for slip formed pavement and flowable concrete applications. These gradation and proportioning limits were further investigated to find insights into a mechanism.

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CHAPTER I

BASIC CONCRETE MIXTURE DESIGN AND WORKABILITY CONCEPTS

1.0 Introduction

Concrete can be used in a road, bridge, highway, dam, parking lot, house, foundation, and many other structures [1, 2, 3, 4, 5, 6, 7]. As shown in Table 1-1, a basic concrete mixture is composed of four different components: cement, water, sand, and rock. To enhance the properties of concrete, admixtures can also be added. The various components of a concrete mixture can be mixed together, transported to a certain location, placed into forms, and molded into the desired shape. Eventually, the concrete will "harden" and can be used for the purpose intended.

Table 1-1. Description of component in concrete

Component	Description	Types
Cementitious Material	• The glue that binds concrete together	Hydraulic cements, fly ash, slag, silica fume [1, 2, 5, 6]
Water	• Water reacts with cementitious material • Effects the strength, durability, and workability of the concrete	Potable water, nonpotable water, recycled water [1, 2, 5, 6]
Sand	• Influences the ability of a mixture to be placed, molded, and surface finished. • Coarse sand and fine sand help to further explain behavior	Natural sand, manufactured sand [1, 2, 5, 6, 8]
Rock	• Acts as an inert filler to reduce shrinkage	Crushed stone, crushed gravel [1, 2, 5, 6, 8]
Admixture	• Supplement to enhance the behavior of concrete	Air-entrainers, water reducers, retarders, accelerators [1, 2, 5, 6]

1.1 Cementitious material & water

Cementitious material can be any material contributing to the hydration process including the vast collections of cement, fly ash, slag, and silica fume [1, 2, 5, 6]. To hydrate the cementitious material, water is added. This combination of water and cementitious material is called paste. In fresh concrete, paste will contribute to the fluid properties of the mixture, but the harden state of paste will behave as a solid material with strength. One of the most important paste parameters has been the ratio of water-to-cementitious material (w/cm) [1, 2, 4, 5, 6, 7]. Common w/cm value ranges from 0.38 to 0.6. This ratio changes the strength, porosity, and durability of the mixture. As higher ratios are used then the mixture will have lower strengths, porosity, and durability properties [1, 2, 4, 5, 6, 7].

Another important parameter of a mixture has been the volume of paste. If a constant w/cm is used, the reduction of the water required in a mixture will also be a reduction in the cement content. This concept is called reducing the paste or the cement and water. If large volumes of paste were used, a mixture production cost will increase from cement prices and will be more prone to plastic shrinkage cracking, drying shrinkage cracking, and curling [1, 2, 8, 9, 10]. If low volumes of paste were used, the mixture may have poor workability [1, 2, 5, 7, 9, 10, 11]. Again, the workability of a concrete mixture is highly dependent on the w/cm and paste volume. This relationship is very important to the overall performance from workability of the fresh concrete to the durability of the concrete throughout the service life.

1.2 Aggregate

Aggregate is between 60 to 80% of the overall mixture volume, aggregate has been thought to be a filler to limit the quantity of cement which causes a reduction in the cost of cement and the dry and plastic shrinkage. In addition to a filler the aggregate is a suspended component of the concrete mixture influencing the workability of the concrete. Table 1-2 describes various aggregate concepts developed by others to help explain how the aggregate can impact the workability of concrete.

Table 1-2. Description of aggregate concepts effecting workability

Aggregate Concepts	**Description**
Nominal Maximum Coarse Aggregate Size	• Larger aggregate sizes require less surface area [2, 5, 8]. • Used in the ACI Method [2, 12].
Angularity & Texture	• These aggregate characteristics impede rheological properties of concrete. It also requires more paste around each particle [4, 6].
Shape	• Flat and/or elongated shaped aggregate creates poor packing and impedes the rheological properties of concrete [4, 6, 8].
Surface Area	• Higher surface areas require more paste around each particle [2, 4, 6]. • This is used in a number of design methods [4, 11, 13].
Gradation	• Describes the particle size distribution of the aggregate [8, 11] • This can be measured by individual percent retained chart cumulative percent passing chart, fineness modulus, or coarseness factor chart [8, 9, 10, 11].
Packing	• Various methods have been developed to predict the quantity of space an aggregate gradation can take up. [4, 8, 14] • Examples include dry-rodded unit weight [25] and various analytical models: Toufar [15], Deward [16], and CPM [17].

1.2.1 Gradation

Gradation has been one of the most commonly used aggregate concepts [1, 2, 8, 11]. The term gradation describes the particle size distribution of the aggregate and can be measured using a sieve analysis [2, 8]. A gradation of a coarse, intermediate, and fine aggregate can be classified or specified using aggregate standards such as ASTM C 33 [23]. ASTM C 33 limits were derived from practical experience of aggregate and concrete producers and do not guarantee performance. For concrete mixtures it has been commonly to specify an ASTM C 33 fine aggregate gradation and a #57 ASTM C 33 coarse aggregate gradation to be blended together into a single combined gradation. These combined gradations can be graphed and then evaluated through various gradation performance concepts in Table 1-3.

Table 1-3. Description of Gradation Concepts

Gradation Concepts	Description
Individual Gradation	• Individual percent retained on each sieve size for a stock pile [1, 5, 8, 11]
Combined Gradation	• Distribution of multiple combined aggregates sources [1, 5, 8, 11].
Nominal Maximum Coarse Aggregate Size	• Puts a special emphasis on the large coarse aggregate sieve sizes [1, 2, 8].
Individual Percent Retained	• Evaluates the percent amount retained on a sieve size [1, 8, 11].
Overall Distribution Descriptions	• Description of a general distribution trend such as gap-graded, well-graded, open graded, or uniformly graded [1, 5, 8, 11].
Fineness Modulus	• Uses one number to describe the particle size distribution of the aggregate for an individual or combined gradation [2, 4, 8, 11, 21]. • Popularized by Duff Abrams [21]
Individual Percent Retained	• Graphical gradation technique with focus on individual sieve size [1, 2, 8, 9, 10, 11] • Commonly called 8-18 or Hay-stack graph [11]
Cumulative Percent Passing	• Graphical gradation technique with focus on overall distribution • Sieve sizes can be graphed in various spaces such as log scale or Talbot equation raised to the power 0.45. [1, 4, 8, 9, 10, 11, 22]
Coarseness Factor Chart	• Graphical gradation technique focusing on the volume distribution of coarse, intermediate, and fine aggregate. [1, 8, 9, 10, 11] • Commonly known as the Shilstone Chart [10, 11]

1.2.2 Shape of aggregate

Extremely elongated and/or flat shaped aggregates affects the impedance of the flow and therefore the workability of the concrete [2, 4, 5, 6]. Furthermore, the workability performance based off a gradation technique may not necessarily be accurate. If a coarse aggregate is significantly poorly shaped, the workability predictability of the gradation curve may change largely. More research needs to be conducted in the relationship between the shape of the aggregate and the workability of the concrete.

2.0 Concrete mixture design

Every location has different materials and therefore vastly different optimum concrete mixture design. A number of factors impact the mixture proportions such as: different aggregate sources, cementitious requirements, w/cm, and workability application [1, 2, 3, 4, 5, 6, 7]. In other words, the proportioning amount of the individual concrete components together into a single composite material has historically been a very challenging topic. Furthermore, concrete mixture design process has even been referred as "black magic" due to illogical methodology of many concrete mixture design experts to design a mixture. Unfortunately, many concrete mixture designs are produced through a large number of iterations. This is done due to lack of science to help predict the performance of these materials. If a workability issue occurs on a project, the mixture design variables are typically changed until the issues is resolved. The adjustment to correct the issue may or may not be rational, but the mixture is performing well. This is a good example of how more knowledge is needed to improve concrete mixture designs.

2.1 Proportioning of paste

Paste is the combination of water and cementitious material. Since the cementitious material is typically the most expensive ingredient, concrete producer try to lower the quantities of paste in the mixture. Unfortunately, this reduction of paste can drastically effect the workability of the concrete. The volume, properties, and composition of the paste depends on the workability of the concrete. Since the majority of mixtures will have a required maximum w/cm, mixture design experts sometimes look towards using aggregates effectively to reduce paste content and optimize the mixture [1, 2, 8, 9]. For example, normal concrete mixtures for slip formed pavement and flowable applications commonly require between 5.5 sacks (517 lbs.) and 8 sacks (752 lbs.). But effective usage of aggregates in the mixture can reduce cementitious content by a sack (94 lbs.) and therefore range from 4.5 sacks (423 lbs.) to 7 (658 lbs.).

2.2 Proportioning of aggregate

A method for proportioning aggregate correctly has not yet been perfected. This difficult proportioning task can be very complex because the gradation, shape, and characteristics of the aggregate changes in every the local geology region. Several theories have been presented over the years and can be categorized into five aggregate proportioning techniques as shown in Table 1-4 [7]. Some of these techniques have been commonly used in the field, others have been used only in a laboratory setting.

Table 1-4. Various Proportioning Methods for Aggregate

Aggregate Proportioning Techniques	Description	Common Technique
Volume or Weight	• Proportion a certain volume percent or weight values for aggregate.	3:2:1 [1, 2, 4, 7] or 60% coarse aggregate and 40% fine aggregate [[1, 2]]
Combined Gradation	• Proportion using the whole particle distribution of aggregate.	Individual percent retained, cumulative percent passing, and coarseness factor chart [7, 8, 9, 10, 11]
Maximum Packing Density	• Proportion aggregate based off the maximum voids content of the aggregate blend.	Dry-rodded unit weight [24] and various analytical models: Toufar [15], Deward [16], and de Larrad [17].
Range of Voids Content	• Proportion aggregate based off a certain range of voids content.	
Surface Area	• Minimum amount of SSA will give the most workable concrete.	Specific Surface Area [4, 11, 13]

2.3 Proportioning concrete to meet a specification

Often mixture designs have specific demands. The quantity of aggregate, cement, and water must be proportioned to meet certain specifications such as w/cm, compressive strength, durability, sustainability, and workability [1, 2, 3, 4, 5, 6, 7, 8]. Table 1-5 describes the main performance category requirements of concrete mixture designs. While some these specifications of a mixture are commonly met without large difficulties, others can be very complex to meet with the available materials. This workability requirement can be very problematic due to the lack of developed knowledge in concrete aggregate proportioning and concrete workability fields.

Table 1-5. Performance Requirements of a Concrete Mixture

Performance Requirement	Description	Performance Techniques
Workability	• Ability to place, consolidate, and surface finish fresh concrete.	Slump [25], Visual Observations [3], L-Box [26], Box Test [27]
Strength	• Amount of force the concrete was designed to withstand.	Compression strength, flexural strength, specifying w/cm [2, 6]
Durability	• The ability of the concrete to withstand a surrounding environment.	Specifying w/cm , air-entrainment, durable aggregates, low permeability [2, 5, 6]
Sustainability	• The ability of the concrete to be serviceable within an environment.	Meets strength, durability, and workability requirements [6]
Economical Cost	• Minimum material cost to blend mixture composition together.	Optimized graded concrete [1, 2, 7, 9]

2.4 Concrete proportioning methods

After discussing the various components and requirements of a concrete mixture design, a mixture design can be developed. Mixture designs procedures can be something as simple as 1:2:3 volume method [4, 7] to more complex methods like the ACI 211 [2, 12]. Whether mixture design specialist want to admit it or not, this process is not an exact science [4]. Most mixture design methods use one of the aggregate proportioning methods in Table 1-3 and modifying the paste properties and volume of the paste to meet the specifications in Table 1-4. For a strong, durable, and sustainable concrete mixture, a w/cm can be specified. Then batch mixtures are assessed and adjusted for meeting the workability, strength, and other specification properties of the concrete. This is especially true for the workability of the concrete.

3.0 Workability of concrete

The workability of concrete describes the ability of a fresh concrete mixture to be mixed, placed, consolidated, and surface finished for a specific application [1, 2] As shown in Fig. 1-1 and Fig. 1-2, concrete can be poured using many different applications. However, a concrete mixture may be excellent for a slip formed pavement applications, but very poor performance in a pumpable mixture for a bridge deck. In other words, the workability requirements of concrete change depending on the application.

Fig. 1-1 shows various workability applications for flowable concrete.

Fig. 1-2 shows low flow concrete being placed with a slip formed paver.

3.1 Workability behavior of fresh concrete

A mixture design should have the basic concept to proportion the available materials together for a specified application to best allow the ability of the concrete to be placed, molded, and surface finished. The different applications such as slip formed paving, a footing, slab on grade using a concrete chute, and pumping the concrete into a wall may each require different workability behaviors of a concrete mixture. The workability properties of concrete came be broken down into five different concrete behaviors: stiffness, flowability, finishability, cohesion, and richness. Important for slip formed pavement applications, stiffness expresses the amount of effort required to initiate movement of the concrete. Flowability describes the continuous mobility of the concrete. Finishability states the easy at which the concrete mixture can be surface finished. Cohesion describes the ability of the mixture to stay together, or not segregate. Finally, richness explains the proportioning of sand and paste. When these behaviors start becoming poor, a mixture will begin having workability issues.

4.0 Workability issues of concrete

If a concrete mixture has problems being properly mixed, consolidated, and surface finished, the mixture has workability issues. Multiple reasons can create each of these workability issues such as the proportions were poorly designed [2], the quality control needs to be tighter [1], or the mixture was designed for another application [2]. Table 1-6 shows the common workability issues of concrete: flowability, consolidation, cohesion, edge slumping, and surface finishability [1, 2, 5].

Table 1-6. Workability Issues

Workability Issue	**Description**
Inadequate Flow	• Difficulty of a mixture to continuously flow [2, 7].
Stiffness	• Inability of a mixture to begin flowing [2, 6, 7].
Harsh Finishability	• Difficulty removing undesirable surface imperfections [2, 6].
Edge Slumping	• Inability of a freshly placed slip formed paving mixture to hold an edge [1].
Cohesion Issues	• Behaves as two separate substances due to lack of cohesion [1, 2, 6].
Poor Consolidation	• Inability to remove voids in a mixture [1, 2, 3].

4.1 Inadequate flow and stiffness

One of the most common workability issues has been inadequate flow. The amount of flow required depends on the application. Addition paste or WR can be used to create higher flowable mixture. The flow will usually relate to the stiffness of the mixture. Later chapters will further talk about the rheology of concrete better describe and understand these properties.

4.2 Consolidation issues

Another important workability task has been the consolidation of concrete. When concrete is being places, some of the mixture may not be fully distributed through the cross-section of the structure and therefore creates voids. Consolidation is the process of removing voids in the concrete. Consolidation can be commonly completed by vibrations through mechanical or hand methods such as an internal vibrator, hand rodding, or tamping. This can be greatly emphasized for the applications of slip formed pavements and walls.

4.3 Cohesion issues of fresh concrete

From mixing to the final surface finishing of concrete, the materials and proportion amounts should function together into a single composite material. This ability of a mixture to be held together while being moved is called cohesion [5]. As shown in Fig. 1-3, the concrete mixture was not a cohesive mixture and had major segregation. If a mixture cannot hold itself together, segregation, edge slumping, and finishability issues can easily occur [5]. For example from field experience some pumped concrete mixtures would have poor aggregate gradation and actually cause the coarse aggregate and paste to segregate as the mixture follows out of the hose. Other experiences have shown mixtures following down a concrete chute with the coarse aggregate and paste separating directly after leaving the end of the chute. Both of these segregated mixtures were very difficult to place, consolidation, and surface finishability.

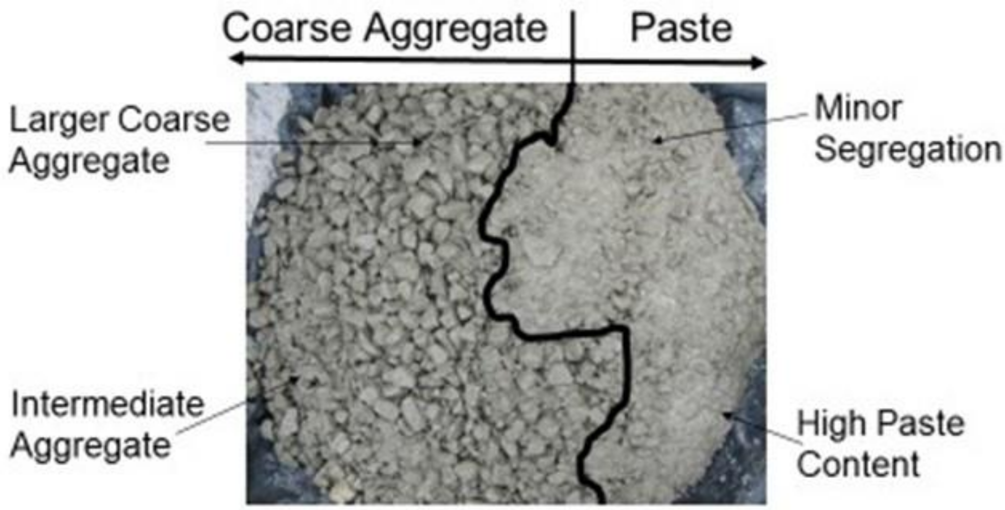

Fig. 1-3 shows a mixture with major segregation issues.

4.4 Edge slumping issues

With slip formed pavements a common workability issue is edge slumping. After the concrete has been placed and consolidated by the paver, the side forms shape each edge of the pavement as shown in Fig. 1-2. However, sometimes concrete cannot adequately hold an edge and top or bottom edge slumping can occur as illustrated in Fig. 1-4.

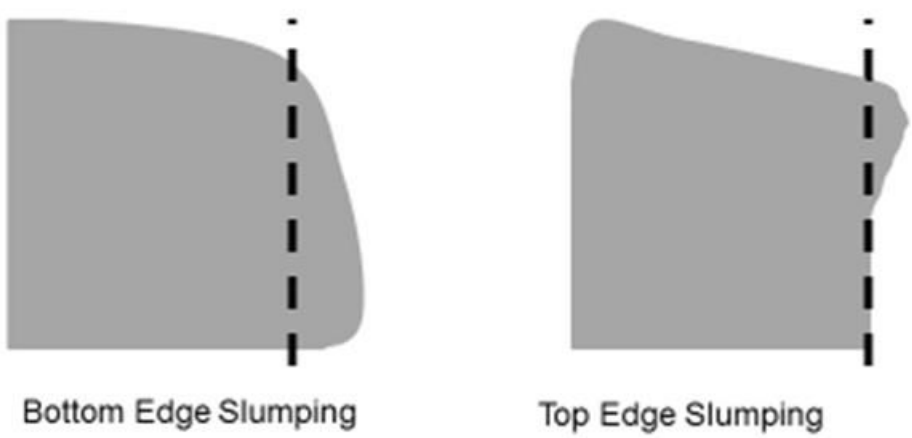

Fig. 1-4 illustrates bottom and top edge slumping.

4.5 Surface finishability issues

Concrete is commonly surface finished using various tools with the end results of a smoother, more level, and aesthetically pleasing concrete surface. As shown in Fig. 1-5, surface finishing of floating was achieved by the ability of the concrete to cling to the tool and be moved around the surface. This ability of a mixture to cling to other things is called adhesion (stickiness). Without this adhesion property, the finishing surface of concrete could not be adequately accomplished. Typically, factors effecting adhesion are paste content, cementitious material, w/cm ratio, admixtures, and gradation. These factors change the interaction between the concrete surface and the finishing tool.

Fig. 1-5 shows a float finishing the surface of the concrete.

5.0 Measuring the workability of concrete

While measuring the workability of concrete may seem simple, one of the most sought-after achievements in the concrete industry has been a test to adequately measure the workability of the concrete [4]. For example, the Slump Test [25] has been the most specified workability test, but it measures the sag of concrete under its own weight [27, 28] The ability of a mixture to fall will not dramatically indicate if the mixture will be suitable for building a floor slab or bridge deck. Not only does the workability performance of a concrete mixture change depending on applications, but the important properties of fresh concrete change as well. This inability to adequately measure the workability of concrete has created much controversy over the impacts of various mixture components effecting the workability of concrete and the dependability of any workability test to measure the workability of fresh concrete [3]. This challenge has been a major focus of this dissertation. Other chapters focus on the development of useful workability test methods.

6.0 Understanding the aggregate effects on workability

In the field mixtures contractors commonly add additional water in the mixture to achieve a certain workability. As long as the mixture does not increase over the specified w/cm ratio, this should not create concrete durability issues. Unfortunately, if a concrete mixture was created with deficient ingredients such as low quantities of sand, contractors will add large volumes of water to a mixture and can actually create even poorer workability. In other words, additional volumes of water or paste cannot "fix" a poorly proportioned mixture. More quantities of sand need to be added. Unfortunately, a single proportioning method for aggregates have not been quantified and proven to adequately indicate the workability performance of concrete. Like previously discussed, the five different general aggregate proportioning techniques have been developed: These are proportioning aggregate by weight or volume, combined gradation, maximum density, range of voids content, and surface area. Also various aggregate concepts have also further contributed to help explain the effects of aggregate on the workability performance of concrete.

7.0 Objective

The main goal of this research was to further advance the knowledge of aggregate proportioning and also develop practical specifications for concrete producers. To achieve this goal, workability tests for slip formed pavements and flowable concrete applications were developed. The following chapters were presented.

- Chapter 2: Develop workability tests for slip formed pavement applications.
- Chapter 3: Evaluate various aggregate concepts to find useful aggregate proportioning method.
- Chapter 4: Develop coarse aggregate gradation limits for slip formed pavement applications.
- Chapter 5: Develop fine aggregate gradation limits for slip formed pavement applications.
- Chapter 6: Develop workability tests for flowable concrete applications.
- Chapter 7: Develop coarse aggregate gradation limits for flowable concrete applications.
- Chapter 8: Develop coarse aggregate gradation limits for flowable concrete applications.
- Chapter 9: Aggregate Mechanism
- Chapter 10: Conclusions

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CHAPTER II

A WORKABILITY TEST FOR SLIP FORMED PAVEMENTS

1.0 Introduction

Currently, concrete mixtures are designed to meet strength and durability specifications while also providing sufficient workability for the desired application. Producing a concrete mixture that meets all of these requirements can be allusive and highly iterative [1, 2, 3, 4, 5, 6]. Although tests exist to evaluate the strength and durability of a concrete mixture, only a few reliable tests can evaluate the workability of fresh concrete.

The workability of a mixture is a combination of the paste volume and yield stress, aggregate characteristics, and aggregate gradation [7, 8]. While each of these variables has been known to be important, no tool exists that allows a quantitative impact of these variables for concrete pavements. When mixtures have insufficient workability, it has been common to increase the cement and water content of the mixture. This can increase cost and decrease the sustainability and durability of the concrete [2].

A concrete mixture for a slip formed pavement must be stiff enough to hold an edge after leaving the paver, but workable enough to be consolidated by vibration. This paper presents a simple and economical test method to evaluate the ability of a mixture to consolidate under vibration and subsequently hold a vertical edge under its weight.

1.1 Current laboratory tests for the workability of concrete

Historically, the workability of a concrete mixture was determined by experience. Multiple laboratory tests have been created to measure workability [2, 6, 9, 10, 11, and 12], but none are applicable for slip formed paving. The goal of a workability test should be to provide a standard measurement that evaluates the performance of a mixture in the desired application.

While the Slump Test ASTM C143 [11] has been widely used as a specification to evaluate workability, it is not useful for mixtures with low flowability [2, 6]. 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." [13]. The Remolding Test [6], Vebe Apparatus Test [9] and other similar vibratory tests [9] measures the ability of a mixture to change shapes under vibration. However, transformation of a concrete mixture into a shape may measure the consolidation of a mixture, but promotes mixtures that are too flowable to hold an edge. The vibrating slope apparatus measures the rate of free flow on an angled chute subjected to vibration. While the test was designed to measure the yield stress and plastic viscosity of low slump concrete, it was found to be highly variable and not recommended [9]. The common denominator for these workability tests is the inability to evaluate the workability window required for a slip formed paver. The mixture must be able to be consolidated by vibration, but also stiff enough to hold an edge as it leaves a paver.

1.2 Objectives

A straightforward and inexpensive test is needed to evaluate the ability of a mixture to be placed with a slip form paver. Once this test is developed, it can be used as a tool in quantifying the impacts of many workability variables. It is important to realize not all processes of a slip formed paver can be or should be mimicked for reasons of expense and complexity. Instead, the focus of this work is to simulate the important components of the paving process. This study presents a new test method to simulate the placing of a concrete mixture for slip formed paving, develops a systematic methodology to use this test to evaluate a mixture, establishes the variance of this procedure, and finally shows the utility of the test to evaluate different aggregate gradations. These contributions provide new tools for both practitioners and researchers.

2.0 Development of the Box Test

A common performance issue for a concrete mixture being placed with a slip formed paver is the unresponsiveness of the mixture to consolidation [3]. Another common performance issue of a fresh concrete pavement is edge slumping, which is an edge deformation after the fresh concrete is placed, consolidated, and extruded from a slip formed paver. However, developing a laboratory test method to evaluate these performance issues would be very complex and expensive due to the variety of the different makes and models of slip formed paving machines and various operating procedures. In order to closely mimic the consolidation of a slip formed paver and provide awareness of possible edge slumping issues, a laboratory test was developed to evaluate the performance of a mixture to a standard amount of vibration and subsequently hold an edge.

Of all the slip formed pavement components, the vibrator contributes to the majority of the energy needed to consolidate concrete. The ability to consolidate fresh concrete is dependent on the workability of the mixture, the dimensions of the section being consolidated, and the speed and power of the vibrator [18]. A slip formed paver uses a hydraulic vibrator to produce the high amplitude, low frequency vibration to consolidate concrete [18]. To minimize the impacts of the air content, it is recommended that a vibrator on a slip formed paver has a frequency range of 5,000 to 8,000 vibrations per minute with a speed less than 36 inches per minute [1, 3]. These vibrator heads are typically 2.25 inch in size with an average spacing of 12 to 16 inches and placed towards the top surface of the concrete.

However, it was not possible to use a hydraulic vibrator and make this test easy to implement. Instead, a 1 inches square head electric vibrator, which is commonly used in portable consolidation applications, was used. Calculations were utilized to find the energy that a concrete paver imparts to a concrete section when traveling at 36 inches per minute at 16 inches spacing. The concrete dimensions, vibrator frequency, head size, and time of vibration were adjusted to have comparable energy of a hydraulic vibrator on a paver. Also, instead of a single horizontal direction of a vibrator on a slip form paver, the test uses a two-directional vertical path to consolidate the concrete. To still obtain a comparable energy with a two-directional path, the time was adjusted to provide the concrete with similar amounts of consolidation. In Fig. 2-1, each component of the Box Test is displayed. Fig. 2-2 shows the 1 ft^3 wooden formed box that consists of a 0.5 inch plywood with a length, width, and height of 12 inches with 2 inch L-brackets in two corners. Two pipe clamps with a span of 18 inches were used to hold the other two corners together.

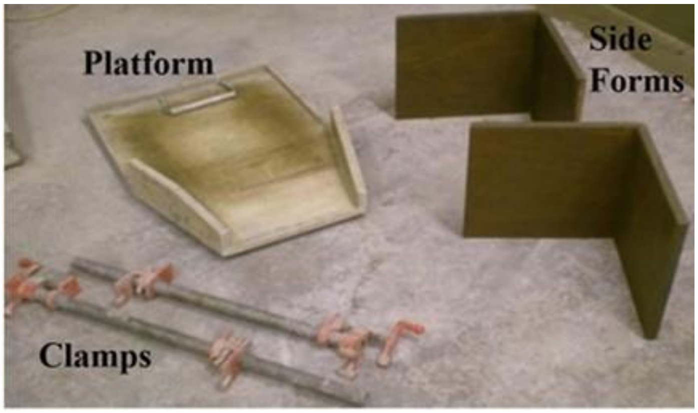

Fig. 2-1. Each component of the Box Test.

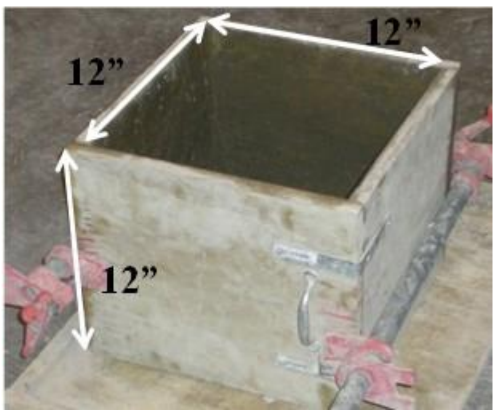

Fig. 2-2. Assembled components and inside dimensions.

Each step of the Box Test is given in Fig. 2-3. Concrete was uniformly hand scooped into the box up to a height of 9.5 inches. A 1 inch square head vibrator at 12,500 vibrations per minute used to consolidate the concrete by inserting it at the center of the box. The vibrator was lowered for three seconds to the bottom of the box and then raised upward for three seconds. Immediately, the clamps were detached from the side wall forms and then both side wall forms were removed.

	
Step 1	**Step 2**
Assemble the components. Hand scoop mixture into box until the concrete level is 9.5”.	From the top surface of the concrete, vibrate straight downward for 3 seconds.
	
Step 3	**Step 4**
Now, vibrate straight upward for 3 seconds. Then remove vibrator.	After removing the clamps and forms, inspect the sides for surface voids and edge slumping.

Fig. 2-3. The four steps of the Box Test.

The response of a mixture to vibration can be assessed by the surface voids observed on the sides of the box using Fig. 2-4. If a mixture responded well to vibration, the overall surface voids should be minimal because the vibration waves were able to transfer through the concrete and remove these voids [16]. However, if the sides of the concrete mixture had large concentrations of surface voids, it did not respond well to vibration. The average number of surface voids for each of the four sides were estimated with a number ranking using Fig. 2-4 and an overall average visual ranking was given to each test. The average of four sides with 10-30% surface voids, or a ranking of 2 for a mixture was deemed a good vibration response and an acceptable concentrations of voids.

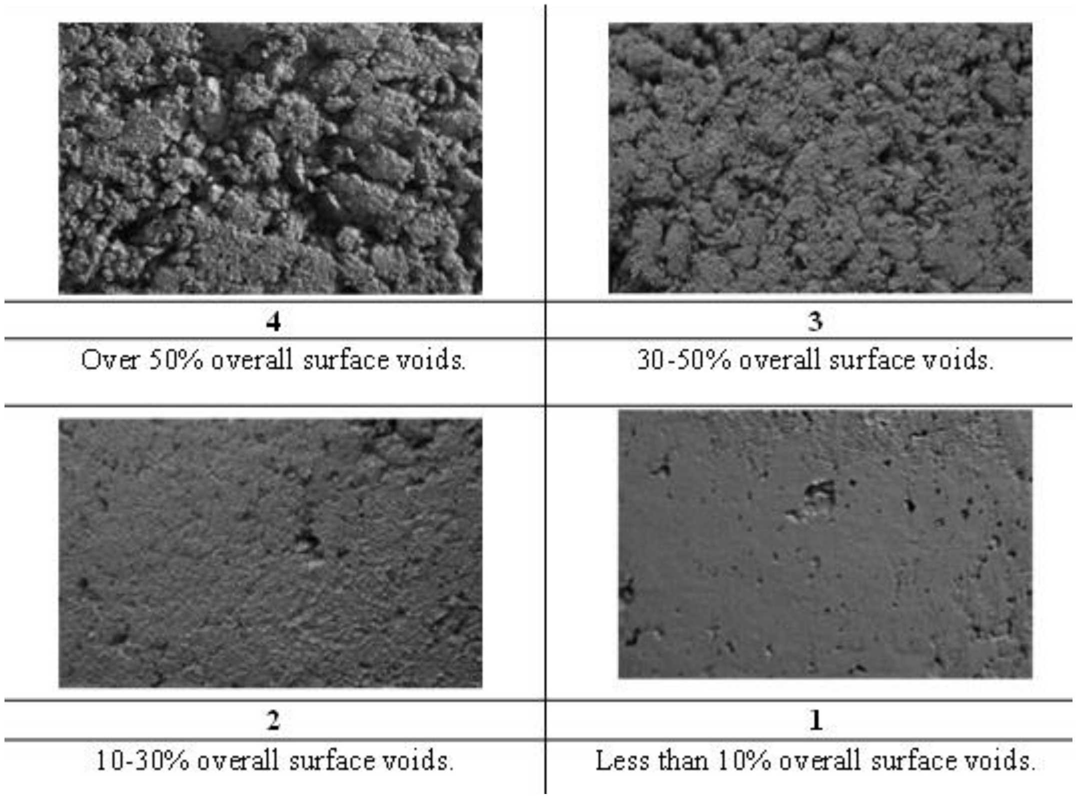

Fig. 2-4. Percentage and numerical surface void values.

Finally, top and bottom edge slumping can be measured to the nearest 0.25 inch by placing a straightedge at a corner and horizontally using a tape measure to find the length of the highest extruding point.

2.1 The Box Test procedure for comparing the workability of mixtures

When a mixture is not workable enough, paste or WR can be added to increase the workability of the mixture. By adding paste or WR, it can reduce the yield stress of a mixture and improve the response to vibration. Using this same concept with the Box Test, when a mixture receives a ranking of a 3 or 4, the response to vibration was poor. Additional WR or paste can be added to achieve the required workability. However, WR will be used for this research because increasing the paste content will largely change the volume of the mixture, which is not desireable.

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

2.2 Detailed description of the Box Test procedure

After a mixture was prepared, the Slump and the Box Test were conducted. If the mixture did not receive a visual rating of 2 as shown in Fig. 2-4 then the material from the slump and Box Test were placed back into the mixer. The mixer was turned on and a discrete amount of WR was added. After three minutes of mixing, the Slump and Box Test were conducted. This proccess was continued until the mixture was observed to receive a visual ranking of 2. Typically, WR dosages of 2 oz/cwt increments was used. The dosage value varried depending on the concentration of voids observed. For example, if the Box Test was conducted and the mixture was found to have close to 50% overall surface voids, the operator may need to add 4 oz/cwt before testing again. In Fig. 2-5, a flow chart shows the procedure for comparing the workability of mixtures using the Box Test. All mixtures were evaluated within a one hour period in a 72°F room. If the test was not complete within one hour, the sample was discarded to ensure intial stiffening did not affect the results.

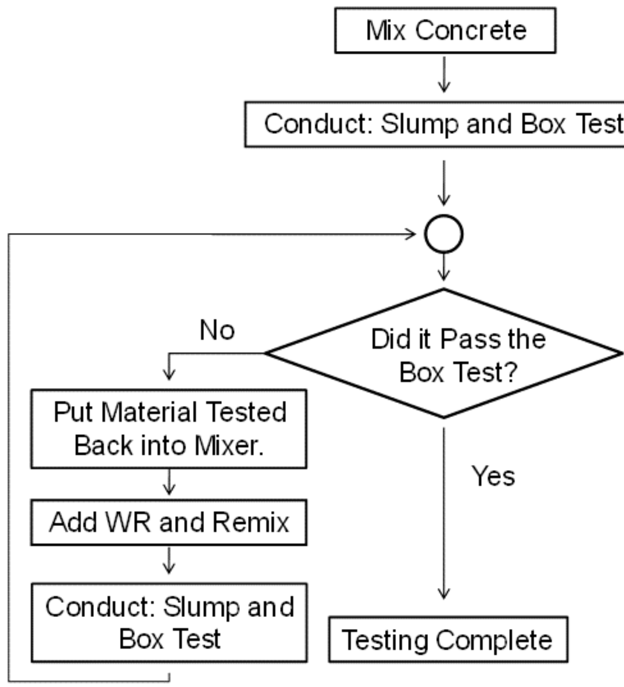

Fig. 2-5. Flow chart of the Box Test procedure for comparing the workability of mixtures**.**

3.0 Material and methods

3.1 Materials

The concrete mixtures investigated were prepared using a Type I cement that meets the requirements of ASTM C 150 [14]. All mixtures contained 20 % by mass of an ASTM C 618 Class C fly ash [15]. The water reducer (WR) was a lignosulfonate mid-range [16] with the manufacturer's maximum recommended dosage of 12 oz. /cwt of cementitious material. Three different crushed limestone A, B, & C and a river gravel D each have a nominal maximum of 0.75 inch coarse and 0.375 inch intermediate. Visually, the crushed limestones are angular while the river rock is rounded. Also, crushed limestone B is visually flatter than crushed limestone A & C. Two different river sands were also used. The gradations of the aggregates used in this study vary. These different materials were included to highlight the applicability of the test to a wide range of materials. More detailed descriptions of the materials and a sieve analysis can be found in another publication [17].

3.2 Mixture design

A slip formed pavement mixture should contain enough paste to allow the concrete to be consolidated, but still keep a stiff edge. Since the aggregate characteristics and gradation can affect the workability, the cementitious material content varied from 423 to 470 lbs. with 20% fly ash replacement and a constant w/cm at 0.45. To keep the variables low in this research, air entraining admixtures (AEAs) were typically not used. However, to investigate the effects of AEAs on surface voids, a wood rosin AEA was used on nine different mixtures. Table 2-1 shows the twenty-eight different mixture designs were used in this paper. The WR doses for each mixture investigation will be presented later.

Table 2-1. Summary of the Mixture Designs per Cubic Yard.

Mix	**Quarry**	**Sand Source**	**Coarse** (lbs.)	**Int.** (lbs.)	**Sand** (lbs.)	**Cement** (lbs.)	**Fly Ash** (lbs.)	**Water** (lbs.)
1	A	A	1551	507	1266	376	94	212
2	A	A	1680	553	1094	376	94	212
3	A	A	2004	0	1303	376	94	212
4	B	A	1645	411	1212	376	94	212
5	B	A	1244	764	1264	376	94	212
6	A	B	2004	0	1313	376	94	212
7	A	B	1606	406	1289	376	94	212
8	C	A	1247	959	1303	339	84	190
9	C	A	1352	1042	1124	339	84	190
10	C	A	2137	0	1318	339	84	190
11	C	A	1497	902	1128	339	84	190
12	C	A	1643	762	1129	339	84	190
13	C	A	1458	851	1210	339	84	190
14	D	A	952	1116	1276	339	84	190
15	D	A	1032	1224	1084	339	84	190
16	D	A	1111	1332	892	339	84	190
17	C	A	2171	287	1106	339	84	190
18	C	A	2024	447	1085	339	84	190
19	C	A	1874	605	1064	339	84	190
20	C	A	1728	765	1043	339	84	190
21	C	A	1579	927	1023	339	84	190
22	C	A	1431	1089	1003	339	84	190
23	C	A	1283	1252	984	339	84	190
24	C	A	1133	1416	964	339	84	190
25	C	A	2016	656	883	339	84	190
26	C	A	1734	555	1247	339	84	190
27	C	A	1588	502	1429	339	84	190
28	C	A	1445	450	1616	339	84	190

3.3 Mixing and testing procedure

Aggregates are collected from outside storage piles, and brought into a temperature-controlled laboratory room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun. Then a representative sample was taken for a moisture correction.

At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure the aggregates were evenly distributed. Next, the cementitious material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump and the novel test method called the Box Test, whose aim is to examine the response to vibration.

4.0 Results

A number of variables were investigated to validate the Box Test and the procedure for comparing the workability of mixtures. These variables included: effects of sequential dosage, repeatability of a mixture by single and multiple operators, and comparison of visual rankings from multiple operators. A limited number of tests were also completed in the field with a side-by-side comparison to a slip formed paver.

4.1 Validating the Box Test

4.1.1 Multiple evaluators

Three different evaluators used the visual number ranking scale to evaluate the void range concentrations of eleven different mixtures. Ten out of eleven evaluations had the same average ranking from the three evaluators. The single inconsistent evaluation was composed of two evaluators ranking the mixture as a three while the other evaluator gave the mixture a ranking of two. This suggests that the area of surface voids was close-to the boundary between a two and three.

4.1.2 Measuring edge slumping

The twenty-eight mixtures investigated displayed straight edges and differed by less than 0.25 inch. This suggests the mixtures would have satisfactory performance in the field.

4.1.3 The effects of air entrainment on visual ratings

A series of nine mixtures without any additional air entrainment were conducted using the Box Test. Next the mixtures were replicated with various concentrations of air entrainment. Using three different evaluators to visually rank the surface voids, the results showed the visual ranking was the same whether AEA was used or not. It was observed the addition of AEA slightly lowered the surface voids. This may be due to the AEA increasing the workability of the mixture. However, the AEA did not change the visual ranking.

4.1.4 Comparison to a slip formed paver

Comparisons between the Box Test and two different slip formed pavers on two different job sites were completed. On both jobsites, three different truckloads of fresh concrete were adequately placed and consolidated with a slip formed paver. After a test sample was taken from each truckload, the Box Test was performed. Each sample had a consistent satisfactory visual ranking of a two and no edge slumping.

4.2 Validating the procedure for comparing the workability of mixtures

4.2.1 Effects of sequential dosage

To investigate the impacts of sequential WR dosages of the test procedure over time, nine replicate mixtures were evaluated where a single dosage of WR was added during the initial mixing procedure instead of the sequential dosages used in the test procedure over time. Table 2-2 shows the results of the Slump and the Box Test were found to be very similar between replicate mixtures.

Table 2-2. Comparison of Single and Multiple Dosages.

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

4.2.2 Repeatability of a mixture by single and multiple operators

The result for the repeatability of WR dosage for a single operator is shown in Table 2-3. Ten mixtures were blindly replicated to compare the fresh properties. For each mixture, the WR dosage added was enough to recieve a 2 ranking. The average percent difference was 16.1% with a standard deviation of 13.5%. The average absolute difference in WR was 1.2 oz./cwt with a standard deviation of 0.8 oz./cwt.

Table 2-3. Single Operator Repeatability.

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

In Table 2-4, five different mixtures were repeated with three different operators. This allowed ten different comparisons to be made. Each operator added enough WR for a mixture to have a two visual ranking. For each mixture the average WR value and the absolute difference, which was the absolute value difference between the two WR values, was given. The percent difference was the absolute difference divided by the average WR expressed in percent.

Table 2-4. Multiple Operator Repeatability.

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

4.2.3 Evaluating gradations using the Box Test

With the w/cm and paste content held constant, the Box Test was used on a variety of mixtures to show the ability of the Box Test to make quantitative comparisons between different gradations. The combined gradations were plotted on the individual percent retained chart. Fig. 2-6 holds the sand volume constant and varies the volume of coarse to intermediate. Fig. 2-7 holds the coarse to intermediate ratio constant and varies the volume of sand. In each figure, the WR dosage required to pass the Box Test is given in the legend.

5. Discussion

5.1. The Box Test

The Box Test was a useful and consistent tool for evaluating the response of a concrete mixture to vibration and simultaneously holding an edge. It was important to note the majority of mixtures investigated had less than a 0.25 inch edge slump and therefore edge slumping could not be throughly evaluated. It seemed that the visual ranking scale was a useful indication to how the concrete responded to vibration. Also, it should be noted that a consistent slump value did not corresponded to a passing Box Test value. This will be discussed in more detail later, but this was a significant observation that is prevalent in all results.

5.2. Procedure for comparing the workability of different mixtures using the Box Test

5.2.1 Effects of sequential dosage

Nine different mixtures were investigated to compare the response consistency in multiple and single dosages. Whether a single or multiple dosage of WR was used, the slump value varied while the Box Test value stayed consistent. This makes logical sense due to the concrete being in the induction stage of hydration.

5.2.2 Repeatability of a mixture by single and multiple operators

In Table 4, ten different mixtures were blindly replicated by a single operator. From those mixtures the largest difference in WR to pass the box test ranking scale was 2.5 oz./cwt with an average absolute difference of 1.2 oz./cwt and a standard deviation of 0.77 oz./cwt. This suggests a single user can complete the test to 2.74 oz/cwt with a 95% confidence interval. Since this was close-to the same size of a single dosage of WR in this testing, it was considered to be satisfactory.

The repeatability of multiple operators was shown in Table 2-3. The maximum difference in WR dosage was 3.6 oz/cwt with an average value of 1.7 oz/cwt and a standard deviation of 1 oz. /cwt. These values were higher than values obtained from a single operator. The results were to be expected since some variance in replicating the same concrete mixture, subjectivity in the dosage of WR, and the visual ranking. However, these values were not extreme and still provide a useful comparison method between mixtures. With a 95% confidence interval, two tests from multiple operators should be repeatable to 3.9 oz/cwt or about the size of two separate dosages of WR for this testing. The slump of each replicated mixture varied by 0.5 inch or less, but a consistent value of slump was not shown with the Box Test results.

5.2.3 Using the Box Test to compare the workability of different mixtures

Both Fig. 2-6 and 2-7 use the WR dosage required to achieve a pass ranking in the Box Test to compare the performance of aggregate gradations with fixed paste content. The gradations requiring a higher dosage of WR are less desirable than a gradation requiring a lower WR dosage. Both figures have a range of gradations requiring a low amount of WR and would be expected to perform well. Gradations outside of this range seemed to require significantly higher amounts of WR with only small changes in gradation. While the volume of coarse and intermediate varied largely with only little differences in WR dosage, a change in the volume of sand had a greater impact on the workability of the mixture. This data was useful as these comparisons were not possible with previous testing methods and will be discussed further in future publications.

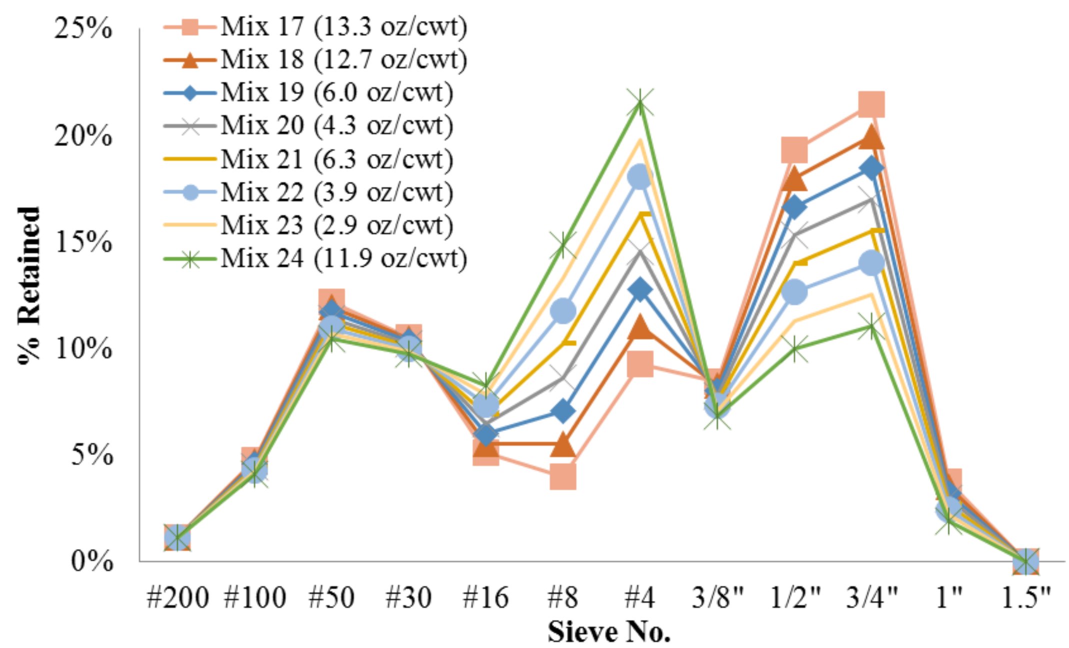

Fig. 2-6. The Box Test measuring the gradation changes of intermediate to coarse aggregate with a fairly constant sand volume.

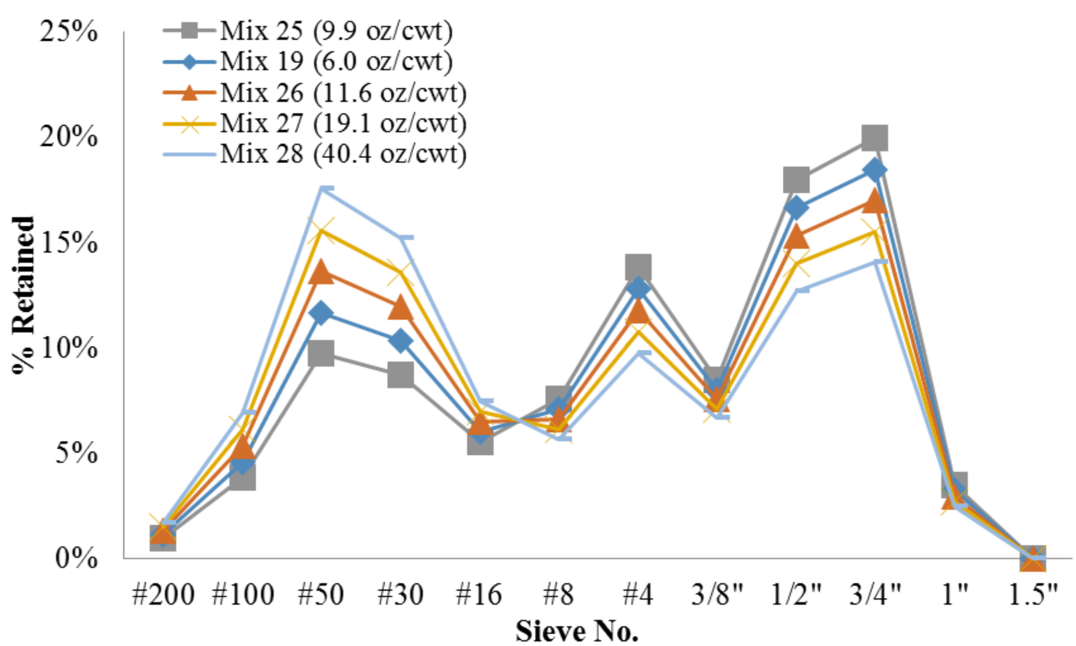

Fig. 2-7. The Box Test measuring the gradation changes of sand to coarse aggregate.

5.3 Slump and Box Test measurements

Even though the slump values were consistent between all repeated mixtures, a single slump value did not correspond with a passing performance in the Box Test. When a mixture passed the Box Test, the slump value was within the typical range for a concrete pavement mixture (0 in. to 2 in.) [1]. This is a critical observation supports the idea that the Slump Test does not provide a consistent measuring tool for concrete used in slip formed paving. It further suggests the Box Test was more sensitive to these mixtures.

5.4 Improvements to the Box Test

While the Box Test was a useful test to evaluate the workability of a mixture for a slip formed pavement, improvements could still be made to the Box Test and the procedure for comparing mixtures.

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 found to be within acceptable ranges to make comparisons between concrete mixtures. This was especially true for single operators.

Although the visual ranking scale was found to be very consistent, it could still be improved if a systematic point count method was used to quantify the concentration of voids on the surface similar to the hardened air void analysis. An image analysis technique or a simple transparent overlay could be placed on the concrete and individual points could be counted and compared to the total area, which was the same technique used in ASTM C 457 and other work [19, 20].

Additional work could be completed to determine the sensitivity level of the test for different mixing and consolidation procedures. Further evaluation with field concrete and the Box Test would also be beneficial. Edge slumping measurements could also be further investigated by determining the impacts of different sample heights to real edge slumping measurements in the field.

5.5 Practical implications

The Box test was designed to be a simple and inexpensive test using common equipment available in the concrete industry. It was important to realize the Box Test was designed to evaluate the response of a concrete mixture to vibration while simultaneously holding an edge and not necessarily to correlate with the exact performance of a slip formed paver.

The procedure for comparing the workability of mixtures was able to quickly and easily evaluate mixtures in a useful and quantitative process. By using this procedure, it can make valuable assessments of different mixture proportions to improve the concrete mixture design process for slip form paving. However, the WR dosage required to achieve the desired response to vibration was likely higher than field requirements.

6.0 Conclusion

An outline for the Box Test and the procedure for comparing the workability of mixtures using the Box Test was given and the variability of the test was investigated. The results show the Box Test and the procedure for comparing mixtures are both useful and repeatable tools to evaluating different mixtures for slip formed paving.

The following points were made:

- This work shows the Box Test provides a simple and quantitative tool to evaluate the impact of different mixture variables for slip formed pavement mixtures.
- The consistency of multiple evaluators to visually measure surface voids was shown to be over 90%.
- In two different field comparisons, the Box Test performed comparably the same as a slip formed paving machine.
- No difference was found between mixtures evaluated with a single or multiple dosage of water reducer for the Box Test.
- The repeatability of a single operator adding WR dosage had a maximum expected difference of 2.5 oz. /cwt and an average absolute difference of 1.2 oz. /cwt.
- Multiple operators adding WR dosage had an average absolute difference of 1.7 oz. /cwt and a maximum expected difference of 3.9 oz. /cwt.
- The procedure using the Box Test was able to provide a quantitative comparison of the mixture proportions for coarse, intermediate, and fine aggregate on the response to vibration.

These findings will be useful to help guide design a concrete mixture for slip formed paving. Work is ongoing to use the Box Test to make a quantitative comparison between a number of mixture design variables that were not previously possible. Results will be provided in future publications.

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CHAPTER III

THE EFFECTS OF COARSE AGGREGATE ON THE WORKABILITY OF SLIP FORMED CONCRETE PAVEMENTS

1.0 Introduction

A large volume of the concrete construction market comes from slip formed concrete pavements. These contractors travel to various locations and commonly design and produce concrete mixtures using local aggregate sources [1]. Most concrete mixtures use the fundamental concepts outlined in The *Design of Concrete Mixtures* by Duff Abrams in 1918 [2], where mixture designs should be required to meet certain specifications such as water-to-cementitious material ratio (*w/cm*), compressive strength, durability, sustainability, and workability [1, 2, 3, 4, 5, 6, 7, 8]. Today, the goal for many concrete producers has been to not only meet these basic specifications of a mixture design, but also create the most economical mixture as possible. This is typically done by reducing the binder content in a mixture and therefore decreasing the total cost and environmental impact of the concrete and improving the sustainability of the structure. Since a constant *w/cm* is often maintained, the reduction of cementitious binder also reduces the paste volume. However, reducing the paste content of a mixture can affect the workability to the degree that it will no longer be a constructible mixture [3, 9, 10, 11, 12].

1.1 Aggregate concepts

To obtain paste reduction while maintaining workability, concrete producers have looked towards using aggregates more effectively in a mixture design. This concept has been called optimized graded concrete [9]. Various aggregate theories have been developed for reducing the paste content [6, 8, 9, 11, 14, 15]. A collection of these concepts and their applicable theories are outlined in Table 3-1. Each concept can be supported by some logical reasoning, but a limited amount of quantitative research has been conducted into these principles [18, 17, 16, 19, 21, 22, 23, 24]. One goal of this paper is to provide further insights into the effectiveness of these aggregate methods.

Table 3-1. Description of aggregate concepts effecting workability

Aggregate Concepts	Description
Nominal Maximum Coarse Aggregate Size	• Larger aggregate sizes require less surface area [8, 11, 14]. • Used in the ACI Method [13].
Angularity & Texture	• These aggregate characteristics impede rheological properties of concrete. It also requires more paste around each particle [8].
Shape	• Flat and/or elongated shaped aggregate creates poor packing and impedes the rheological properties of concrete [8, 11].
Surface Area	• Higher surface areas require more paste around each particle [6]. This is used in a number of design methods [6, 14, 15].
Individual Percent Retained	• The amount of aggregate particles retained on each individual sieve size should be within a certain range [17, 18, 19].
Cumulative Percent Passing	• The total aggregate particles smaller than a sieve size range [18, 19, 20].
Fineness Modulus (FM)	• A single number used to describe the size distribution of the total aggregate particles [2].
Packing	• Various methods have been developed to predict the volume of space an aggregate gradation can take up. [8, 19, 25, 26] • Examples include dry-rodded unit weight [25] and various analytical models: Toufar [27], Deward [28], and Lefarrad [29].

In this paper the term *gradation* refers to the size distribution of the aggregates and the term *proportion* refers to the volume of these aggregates. Both of these terms are important to the design of concrete mixtures and this paper.

1.2 Combined gradation techniques

Concrete producers commonly use graphical gradation techniques to proportion different available aggregate products for optimized graded concrete. The more popular techniques have been the power 45 chart, the individual percent retained (IPR) chart, and the coarseness factor chart. Unfortunately, guidelines for the development and use of these techniques have been "rules of thumb" using field experience [10, 17, 18, 20].

1.2.1 Power 45 chart

First proposed by Fuller for concrete pavements in 1907 [20] and now used frequently by the asphalt industry, the power 45 chart plots a combined gradation with the sieve size raised to the 0.45 power on the cumulative percent passing chart [18]. Commonly, a straight line is plotted on the chart from the origin to the nominal maximum (NM) size with some boundary limits. Many have proportioned a gradation based off the best-fit of the straight line, which closely represents the maximum density of a combined gradation and therefore creates the minimum volume of voids for an aggregate combination [18, 19]. To allow a combined gradation to fit a straight line, the sieve size values should be calculated using the Talbot grading equation [26]. The most common and traditional approach has been to use the 0.45 as the exponent in the equation [1], but various exponent values ranging from 0.3 to 0.6 have been used with diverse success [6, 19, 20, 21].

1.2.2 Individual percent retained (IPR) chart

Another common technique used has been to plot a combined gradation on the individual percent retained (IPR) chart. This technique graphically evaluates "excess" and "deficient" percentage amounts retained on each sieve size of a gradation. Traditionally, a suggested maximum boundary of 18% and minimum of 8% for each sieve size ranging from 0.75" to #50 was used. Alternate ranges have been suggested with a maximum ranging between 15-22% and a minimum ranging of 5-12% retained on each sieve [17]. However, only a limited amount of research has been conducted to demonstrate the validity of the limits [18, 21, 23].

1.2.3 Coarseness factor chart

Using his experiences from various projects around the world, James Shilstone Sr. developed an aggregate proportioning process through a combined gradation using two equations to plot a single point on a chart [9, 12]. The chart is commonly divided up into different zones for aggregate proportions [9, 11, 18]. An example of the chart was shown in Fig. 5. Some have even went as far as dividing Zone II into different subzones for different applications [18]. In recent years, many United States Departments of Transportations have created a more limited area within Zone II of the chart for slip formed pavements [18]. Yet, Shilstone suggested the bottom of Zone II would best for this application [18]. Unfortunately, little testing data has been published by Shilstone or others to validate the chart [18, 21, 23].

1.3 Voids content

Another aggregate technique has been to proportion based on the voids content. This premise suggests minimizing the voids content of the aggregate component in a mixture and this should in turn require less paste to fill the spaces in-between the aggregate particles. Further void content concepts were summarized and expanded by Powers [6]. His work is credited as the foundation for the most popular packing models [27, 28, 29]. Unfortunately, the complexity and lack of material parameters has limited the use of packing models in field applications [15].

Three different packing techniques were considered in this paper. The combined dry-rodded unit weight [25] has been an empirical method to measure the volume of voids for a compacted mixture of the coarse and fine aggregates in a container of a known volume. The modified Toufar method [27] and the compressible packing model by de Larrard [29] have been two popular packing models for calculating the voids content. The modified Toufar method calculates the packing density using the loose and compact unit weights of each aggregate with assumptions that compensate for shape and diameter [27]. The compressible packing model uses the packing density with correction parameter for the wall effect of the coarser grains and the loosening effect exerted by the finer particles [29]. Other publications provide more information on these models [27, 29].

1.4 Specific surface area

The surface area concept states each aggregate gradation requires a certain volume of paste to cover each particle [4, 6, 15]. The concept suggests for a fixed paste content and aggregate volume, lower surface area gradations will require more paste to achieve a certain workability over mixtures with lower surface areas [6]. In order to make quantitative comparisons, it is common to divide the surface area by the volume and call this the specific surface area (SSA). Various methods have been used to calculate the specific surface area of a mixture [6, 14, 15]. For this research, an estimated specific surface area was calculated for each sieve size by counting the number of particles per a given volume, assuming spherical particles with angularity factors [6] with a diameter of the middle distance between the passing and retained sieve size. Similar methods have been used in other publications [6, 14, 15].

1.5 Objectives

Quantitative comparisons are needed to determine how different aggregate concepts and gradation techniques impact the workability of fresh concrete for slip formed paving applications. This work aims to provide a deeper understanding by comparing the effectiveness of these different concepts and proportioning techniques with workability tests for slip formed pavements.

2.0 Materials and methods

2.1 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [32]. The water reducer (WR) was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [33]. Table 3-2 displays various aggregate details. Angularity and texture were measured using AIMS II as reported in other publications [38]. The flatness and elongation of the coarse aggregate was measured on a 1:2 ratio by ASTM D 4791 [39]. This ratio was found to be necessary to determine the shape differences. Information on these aggregates can be found in other publications [35, 36, 37, 38].

Table 3-2. Description of the Proportioning Methods

Source	Type	NM Size (in.)	ASTM C 33 Gradation	Angularity/ Texture	Flatness (1:2 ratio)	Elongation (1:2 ratio)
A	Limestone	1.5	#467	Moderate / High	27%	1%
A	Limestone	0.75	#57	Moderate / High	18%	8%
A	Limestone	0.375	#8	Moderate / High	26%	4%
B	Limestone	0.75	#57	Moderate / Low	14%	5%
B	Limestone	0.375	#8	Moderate / Low	12%	6%
C	River Gravel	1.5	#467	Low / Low	37%	3%
C	River Gravel	0.75	#57	Low / Low	27%	6%
C	River Gravel	0.375	#8	Low / Low	8%	2%
D	Natural Sand	#4	Fine Aggregate	Low / Low	n/a	n/a

Note: NM size was referring to the nominal maximum size of the coarse aggregate.

2.2 Mixture design

To investigate the impacts of the coarse aggregate, all of the mixtures were designed with a water-to-cement ratio (w/c) of 0.45 and a paste content of 26% of the mixture volume. Each mixture had 470 lbs. /yd³ of cement per cubic yard of concrete and 211.5 lbs. /yd³ of water. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with a wide-range of aggregate variables. The mixtures were designed to have low paste content or a high aggregate content so that the impact of the aggregate gradation on the workability of the mixture would be magnified. Table 3-3 shows the methods of aggregate proportioning used in this investigation. These methods were chosen to investigate a wide range of recommended aggregate proportioning methods with the same materials. The batch weights of the mixtures can be found in Table 3-4.

Table 3-3. Description of the Proportioning Methods

Proportion Method	Description
Middle of Coarseness Chart	• Located in the middle of the Coarseness Factor chart in Zone II (CF= 60 & WF= 35), • A number of United State Department of Transportation specify this point for optimized graded concrete [18, 9].
Bottom of Coarseness Chart	• Located on the bottom of Zone II (CF= 60 & WF= 30) • Shilstone recommended this area for slip formed pavements [18, 9].
60% CA, 40% FA	• The gradation uses 60% of coarse aggregate and 40% of the fine aggregate by volume. This mixture has no intermediate aggregate added. • This is a common method for proportioning concrete mixtures.
Power 45	• Combined gradation proportioned to best-fits the power 45 line [18].
Estimated Minimum Voids	• The estimated minimum voids content produced by the Toufar Method [26, 27].

Table 3-4. Mixture Results and Batch Weights

Nominal Max. Coarse Aggregate Type	Properties	Aggregate Proportioning Method				
		Middle	Bottom	60/40	Power 45	Estimated Min. Voids*
1.5" Limestone A	WR (oz./cwt)	32.0	34.0	13.7	31.8	31.8
	Coarse (lbs./cy)	1205	1306	2046	1257	1257
	Int. (lbs./cy)	893	973	0	737	737
	Fine (lbs./cy)	1266	1092	1321	1369	1369
¾" Limestone A	WR (oz./cwt)	20.8	19.2	21.3	85.9	31.0
	Coarse (lbs./cy)	1552	1684	2014	1101	1561
	Int. (lbs./cy)	507	555	0	907	656
	Fine (lbs./cy)	1279	1107	1321	1338	1129
¾" Limestone B	WR (oz./cwt)	0.0	2.1	20.6	1.8	1.6
	Coarse (lbs./cy)	1244	1347	2151	1943	1053
	Int. (lbs./cy)	957	1038	0	320	1321
	Fine (lbs./cy)	1229	1055	1325	1202	1052
1.5" River Gravel	WR (oz./cwt)	22.2	26.6	26.1	25.1	25.1
	Coarse (lbs./cy)	1470	1596	1979	1632	1596
	Int. (lbs./cy)	523	570	0	846	570
	Fine (lbs./cy)	1288	1116	1306	802	1116
¾" River Gravel	WR (oz./cwt)	15.3	17.9	17.2	18.6	13.8
	Coarse (lbs./cy)	1396	1515	1981	1428	1509
	Int. (lbs./cy)	597	651	0	770	885
	Fine (lbs./cy)	1301	1128	1321	1096	898
¾" Sieved Limestone A	WR (oz./cwt)	6.9				
	Coarse (lbs./cy)	1123				
	Int. (lbs./cy)	978				
	Fine (lbs./cy)	1256				
¾" Sieved River Gravel	WR (oz./cwt)	3.0				
	Coarse (lbs./cy)	1099				
	Int. (lbs./cy)	920				
	Fine (lbs./cy)	1278				

Note: estimated min. voids was determined by using the modified Toufar method.

2.3 Mixing and testing procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken to determine the moisture content to apply the correction. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump Test [40] and the Box Test [41].

2.4 Using the Box Test to evaluate the workability of mixtures

The most specificed method to measure the workability of a concrete mixture has been the Slump Test [1, 6], which commonly ranges between 0 to 3 inches for slip formed pavement applications. However, the Slump Test has not been sensetive enough to accurately predict the workability of a slip formed pavement mixture [1, 41]. The construction process of slip formed paving requires theworkability of a mixture to be flowable enough under vibration for consolidation, but still able to maintain an edge after the vibration has stopped and the side forms were removed.

To better investigate the workability of concrete for slip form paving, the Box Test was developed to evaluate the response of concrete to vibration and then subsequently hold an edge [41]. The Box Test was conducted as follows: 1) freshly mixed concrete was place into temporary fixed wood forms, 2) a hand-held vibrator with a specified size and speed was used to consolidated the concrete at a fixed time with a controlled entry and exit location, 3) the forms were removed, 5) the concrete was visually inspected to assess if the sides were properly consolidated, and 6) a straight edge can be used to measure edge slumping. Like a slip formed paver, this test requires the concrete to be workable enough to consolidate under vibration but still have enough cohesion to hold an edge when the forms were removed.

The Box Test has shown similar performance results as a slip formed paver in the field. For this testing a mixture was assumed to have good workability performance if the edge slumping was less than 0.25 inches and the sides had less than 30% surface voids measured visually. This performance critieria will be referred to as “passing the Box Test”. These requirements have been previously discussed in past publications [41].

The Box Test can be further used to quantitatively compare the workability between mixtures. In the field if a mixture has poor workability, it is common to add water, cement, and/or WR to improve the workability. For this research, the paste volume and *w/cm* were held constant and discrete dosages of WR was added to the mixture until the mixture achieved satifactory performance in the Box Test. The single operator repeatability of WR dosage was found to be 2.74 oz/cwt with a 95% confidence interval. In otherwords, if two mixtures are compared and do not differ more than 2.74 oz/cwt, they can be considered to have the same workability as measured by the Box Test. A more detailed description and validation of this procedure can be further viewed in Chapter 2 of this dissertation and other publications [41, 37, 35].

3.0 Results

To reiterate, each mixture had the same paste volume and water content, but the aggregates were chosen based on five different aggregate proportioning methods. The workability performance of each mixture was measured by the WR required to pass the Box Test. Since the water and binder content was fixed in the mixture, the WR dosage required was an indirect workability measurement of the Box Test. This means mixtures requiring the lowest amount of WR were the most desirable.

Table 3-4 shows the batch weights and the WR dosage required to pass the Box Test. Fig. 3-1 compares the WR dosage required to pass the Box Test for different aggregate proportioning methods. Fig. 3-2 compares the aggregate proportioning method to the slump measurement when a mixture passed the Box Test. Fig. 3-3 compares the WR dosage to void content from the combined dry-rodded unit weight, modified Toufar method, and compressible packing model. The specific surface area and WR dosage was compared in Fig. 3-4. The amount of WR dosage required for all the mixtures were plotted on the coarseness factor chart in Fig. 3-5. While Fig. 3-6 through 3-9 plot the gradations on the IPR chart, Fig. 3-10 through 3-14 displays the cumulative percent passing using the power 45 chart. Also, Fig. 3-6 through 3-14 display gradations based on a range of WR dosage required to pass the Box Test and follows: red was poor performance (more than 20 oz./cwt), yellow was not desirable performance (between 10 oz./cwt and 20 oz./cwt), and green was good performance (below 10 oz./cwt).

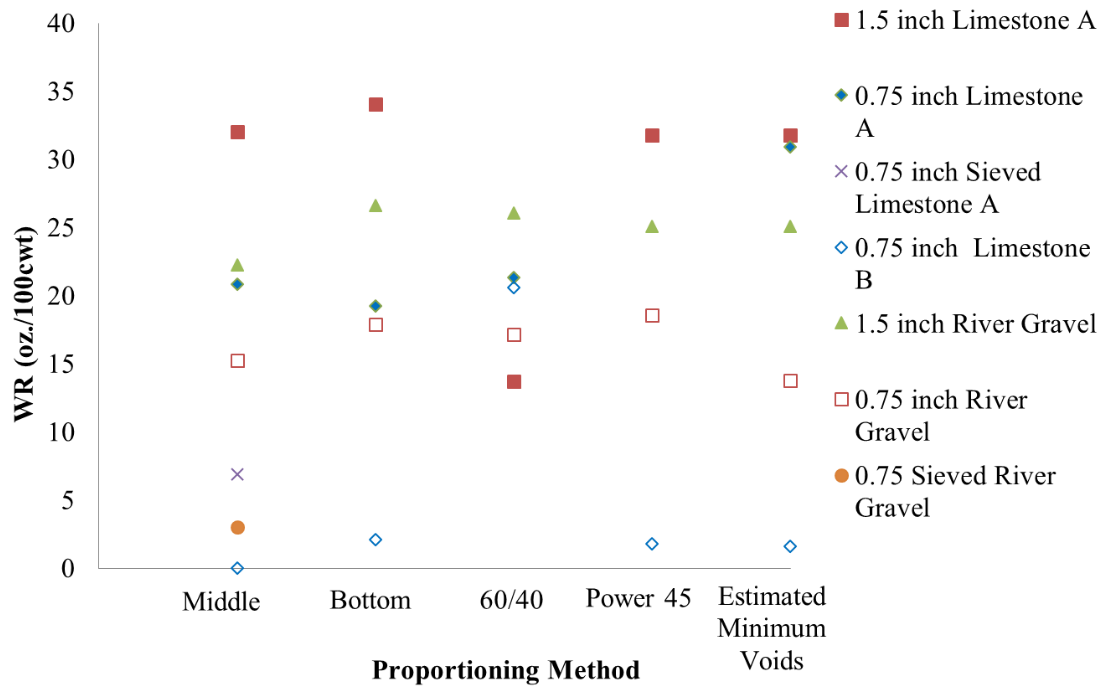

Fig. 3-1. Compares gradation to the amount of WR to pass the box test.
Note: ¾" Limestone A with a power 45 required 85.9 oz./cwt of WR and so it is not included on the chart.

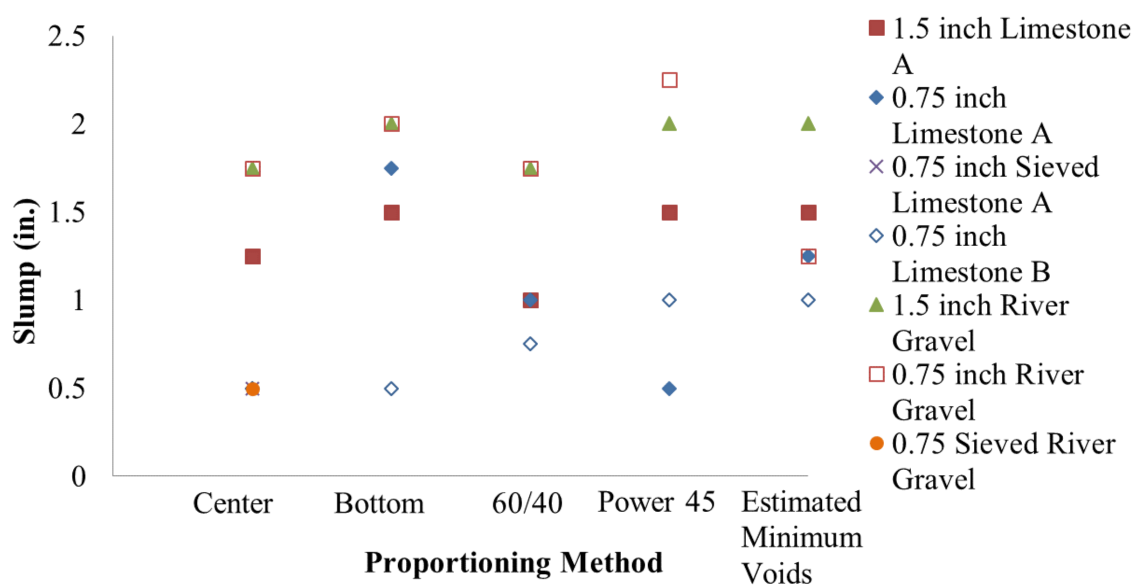

Fig. 3-2. Compares gradation to the slump value when mixture passed the Box Test.

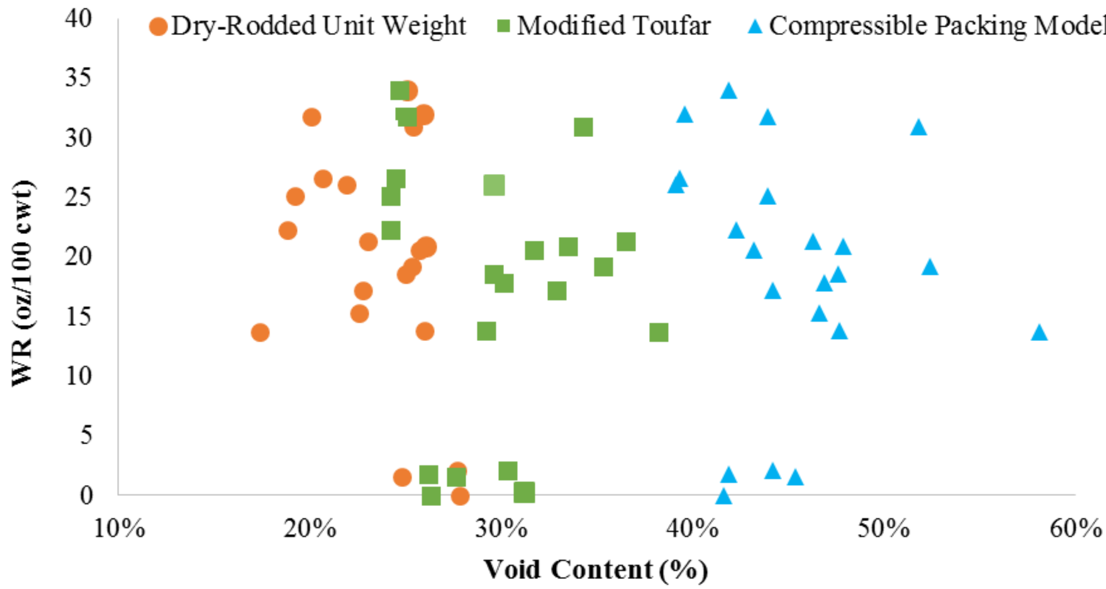

Fig. 3-3. Void content versus WR dosage required to pass the Box Test.
Note: ¾" Limestone A with a power 45 required 85.9 oz./cwt of WR. This mixture had a dry-rodded unit weight, modified Toufar, and compressible packing model had a voids content of 24.07%, 32.5%, and 46.6%, respectfully.

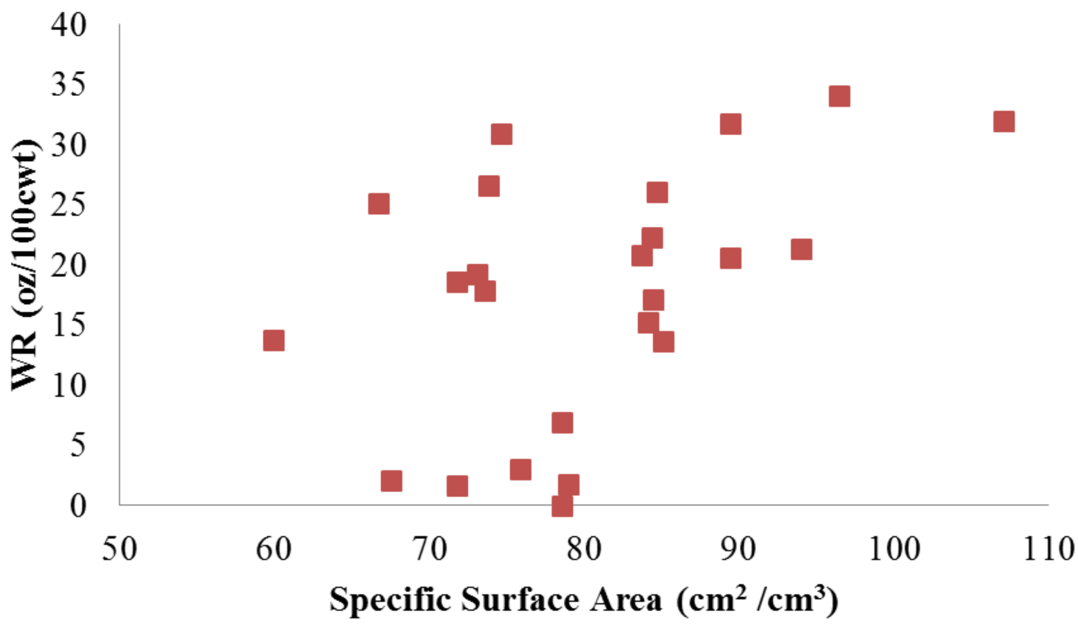

Fig. 3-4. Specific surface area versus WR dosage required to pass the Box Test.
Note: ¾" Limestone A with a power 45 required 85.9 oz./cwt of WR and specific surface area of 87.9 cm^2/cm^3.

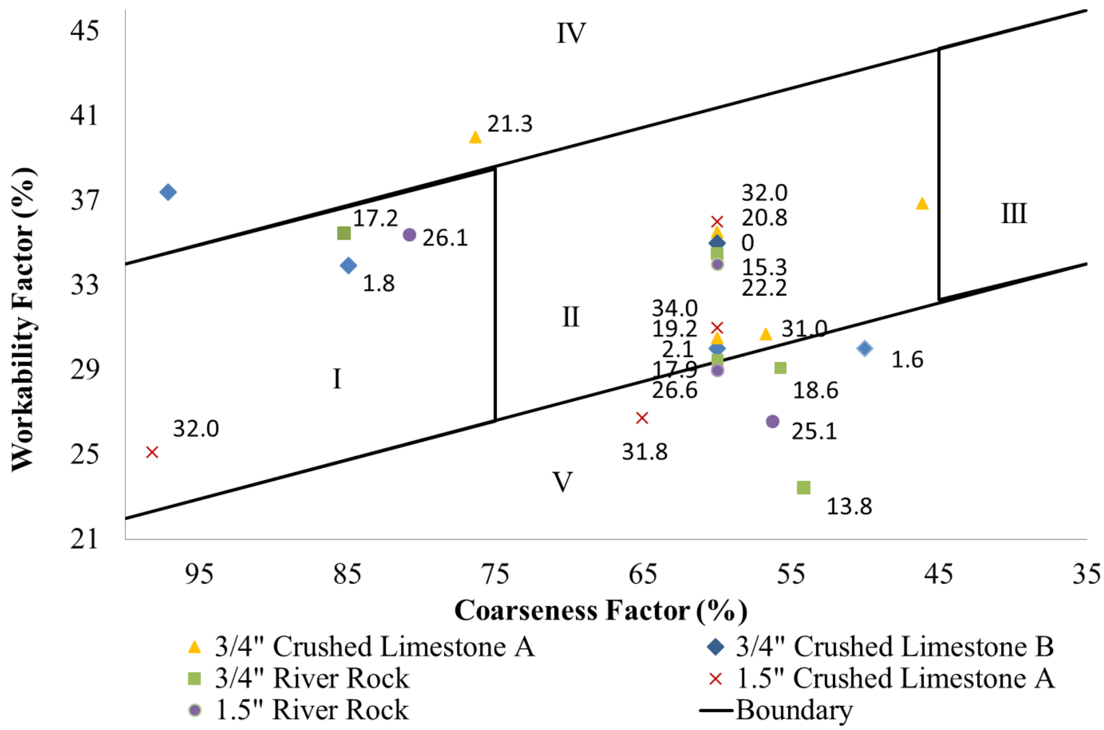

Fig. 3-5 WR dosage required to pass the Box Test in (oz./cwt) plotted on the Coarseness Factor Chart.

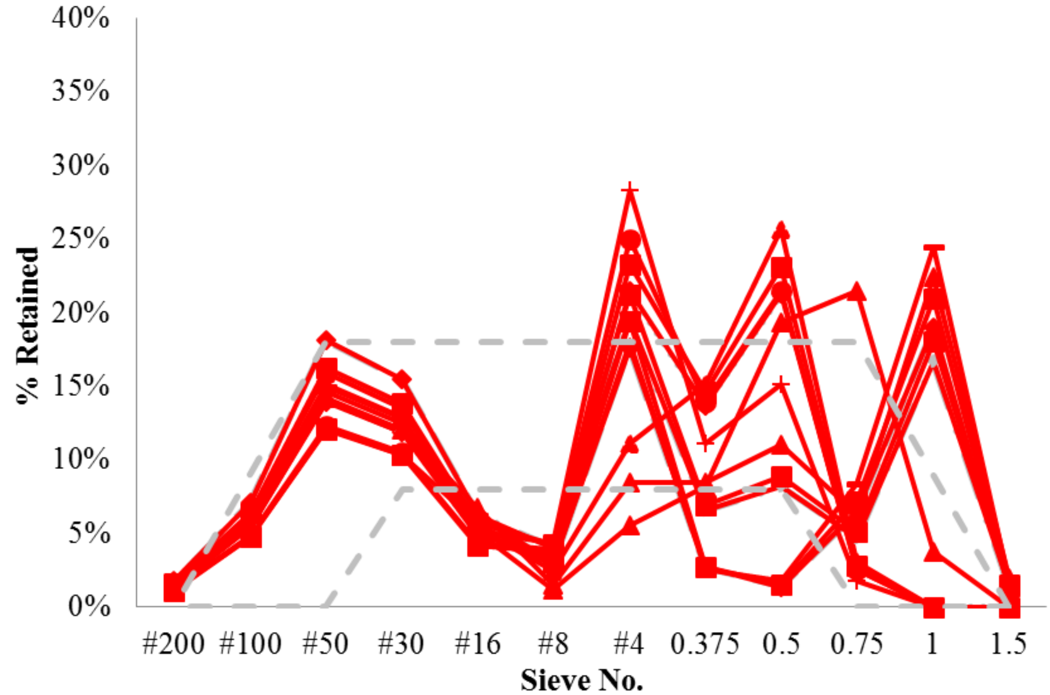

Fig. 3-6. Gradations requiring more than 20 oz./cwt required to pass the Box Test on IPR chart.

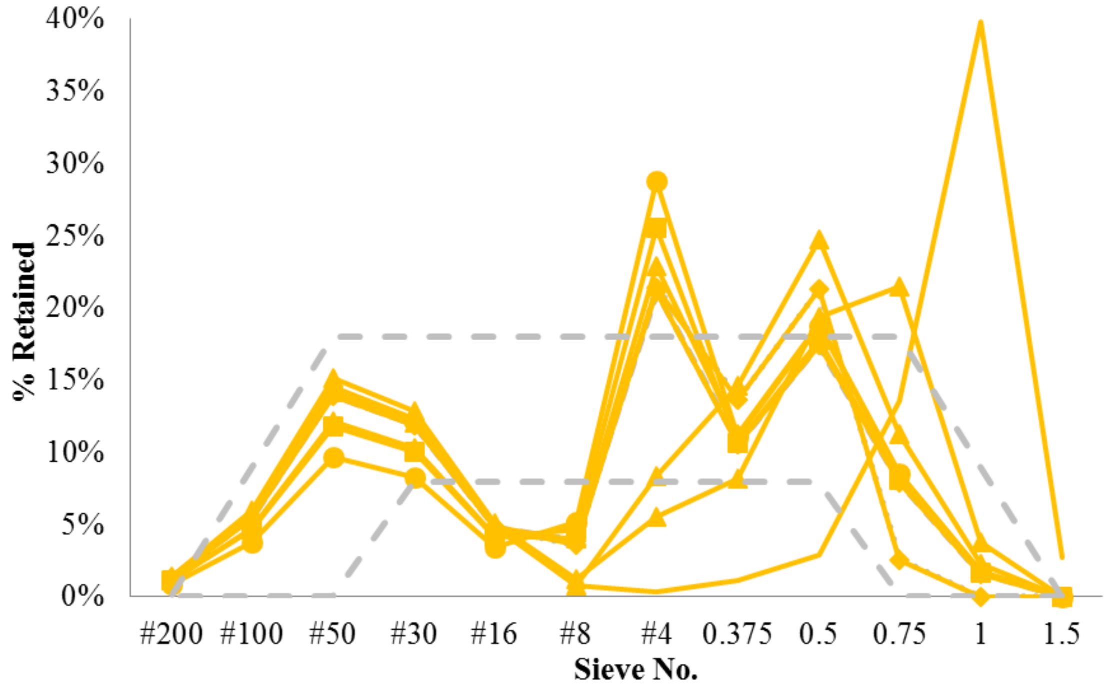

Fig. 3-7. Gradations requiring between 10 oz./cwt and 20 oz./cwt required to pass the Box Test on IPR chart.

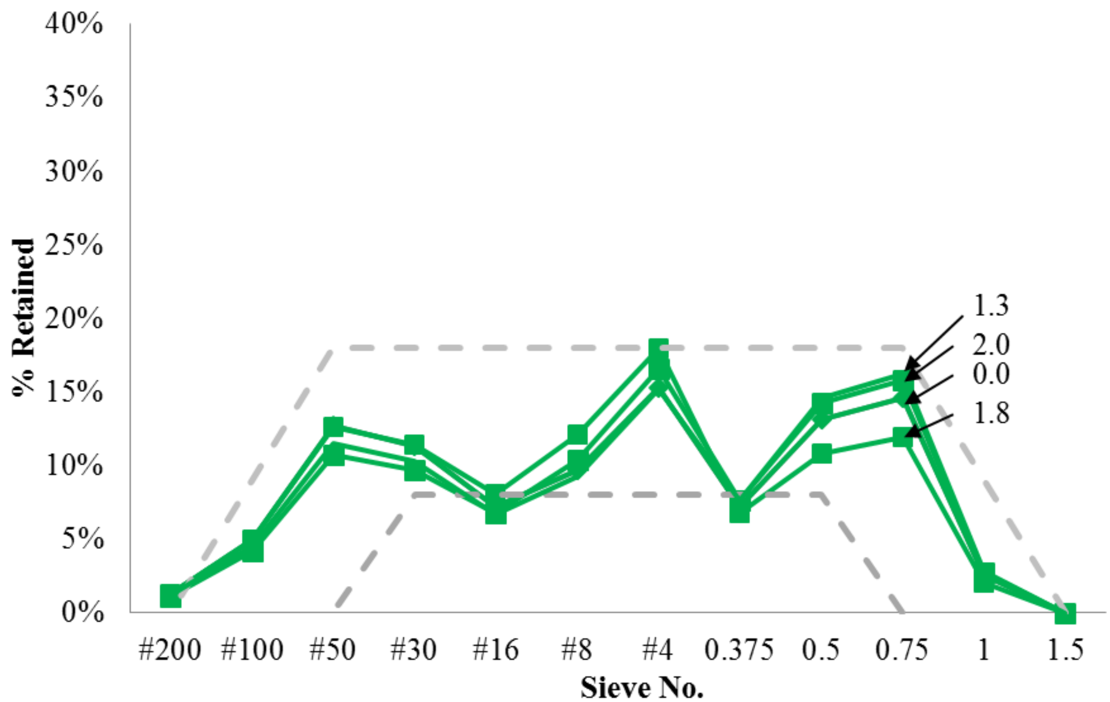

Fig. 3-8. Gradations requiring less than 10 oz./cwt required to pass the Box Test on IPR chart.

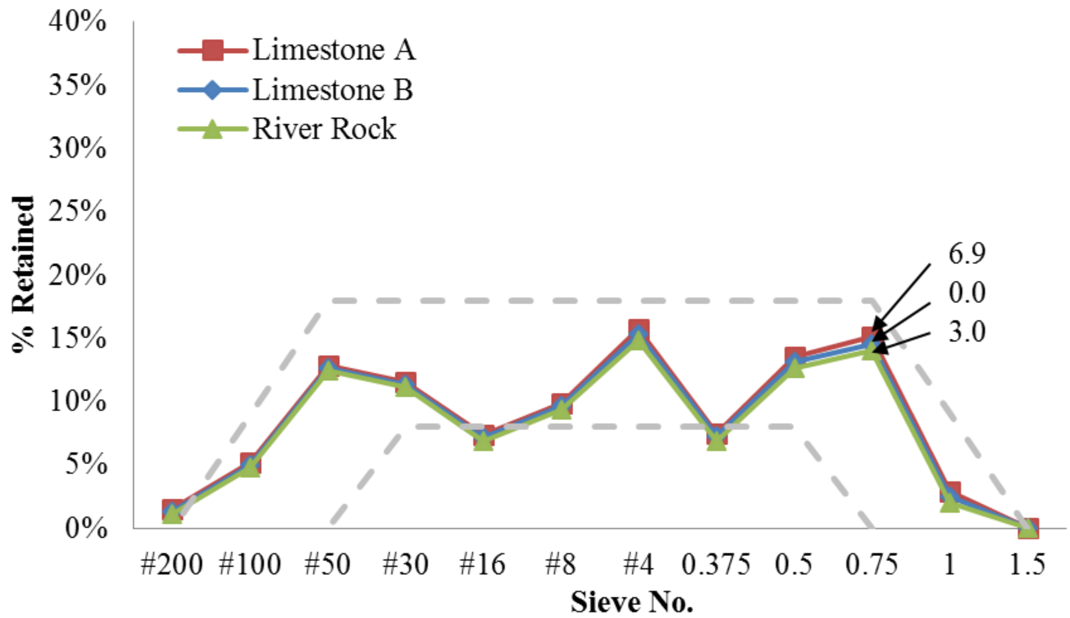

Fig. 3-9. Sieved gradations showing WR (oz./cwt) required to pass the Box Test on IPR chart.

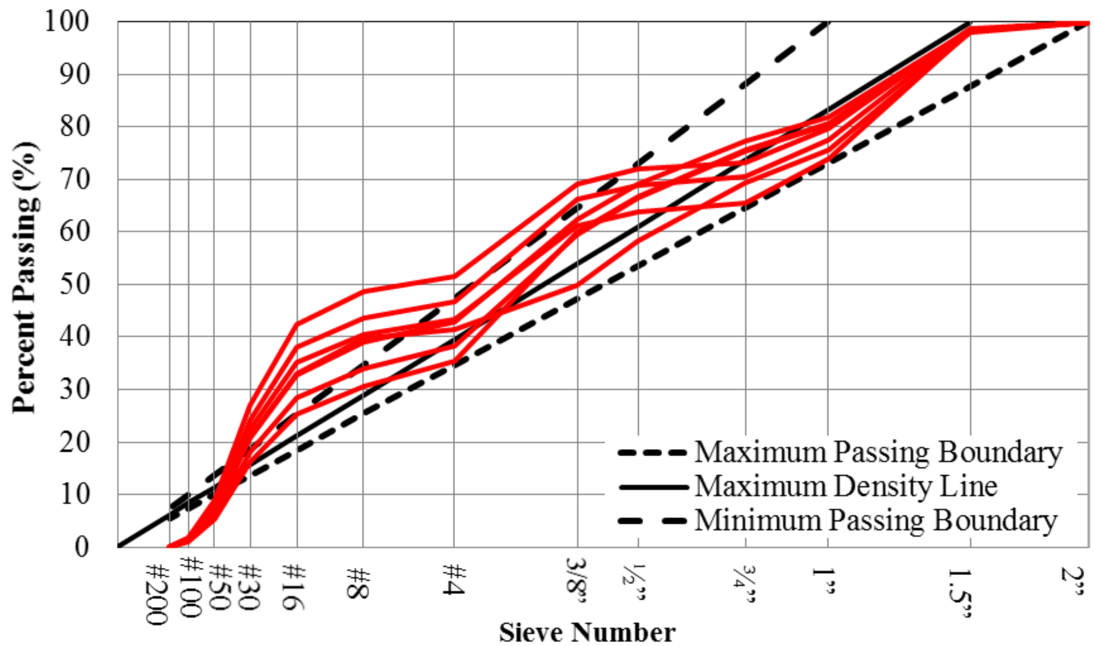

Fig. 3-10. Gradations requiring more than 20 oz./cwt required to pass the Box Test on the Power 45 chart.

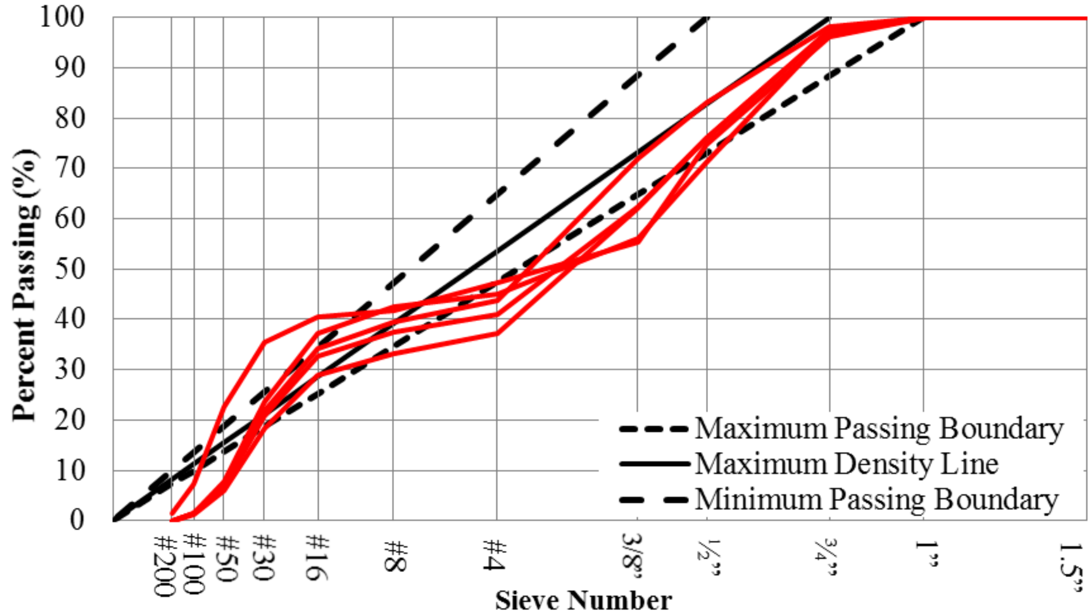

Fig. 3-11. Gradations requiring more than 20 oz./cwt required to pass the Box Test on the Power 45 chart.

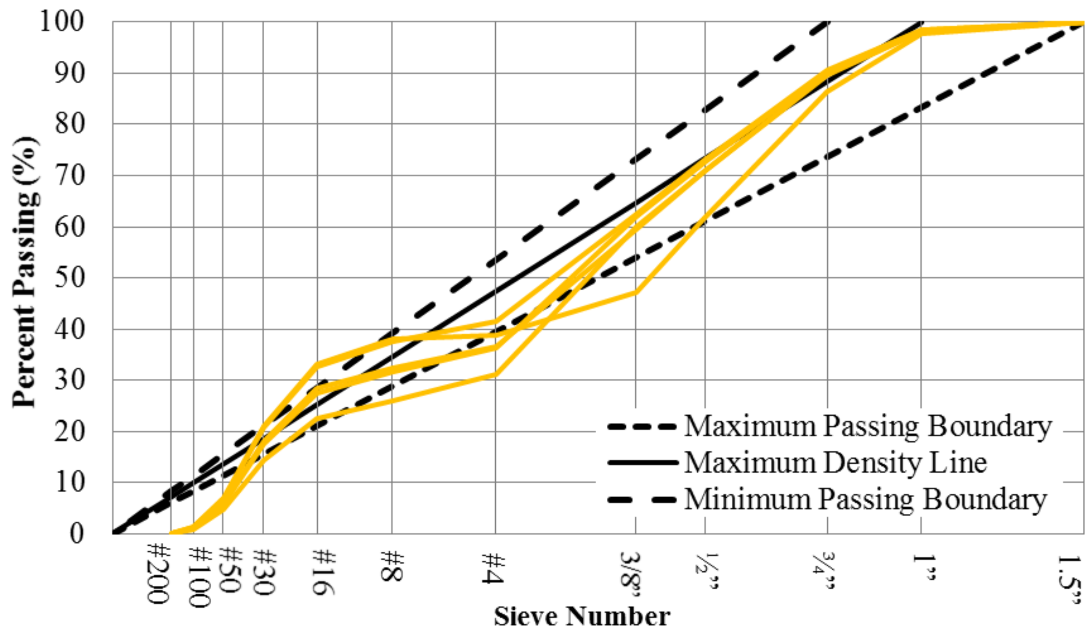

Fig. 3-12. Gradations requiring between 10 oz./cwt and 20 oz. /cwt required to pass the Box Test on the Power 45 chart.

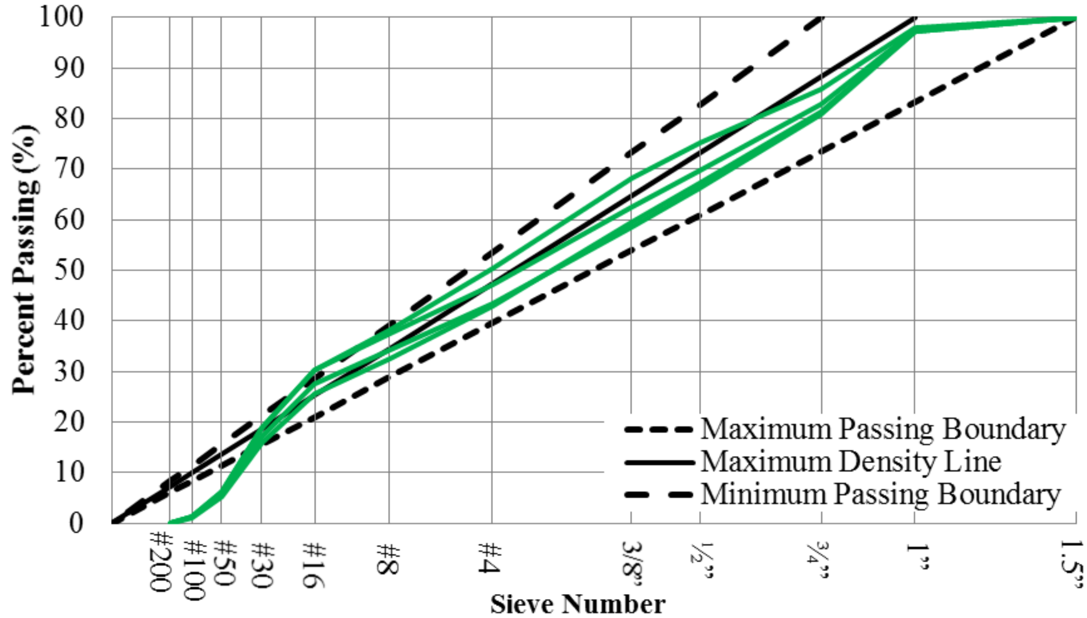

Fig. 3-13. Gradations requiring less than 10 oz./cwt required to pass the Box Test on the Power 45 chart.

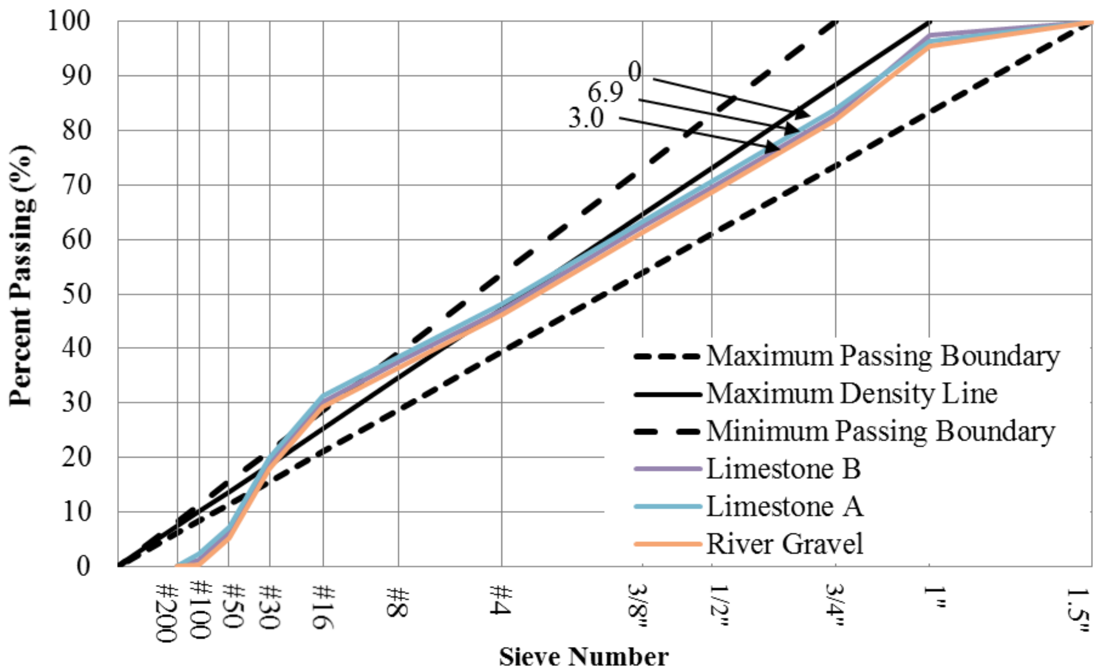

Fig. 3-14. Sieved gradations showing WR (oz./cwt) required to pass the Box Test on Power 45 chart.

4.0 DISCUSSION

4.1 Box Test vs. Slump Test

A common workability specification for slip formed paving uses a slump value range 0 to 3 inches. As shown in Fig. 3-2 when mixtures passed the Box Test, the slump ranged between 0.5 inches and 2.25 inches. These range of slump values corresponds to the conventional values for slip formed paving specification, but it also shows the inconsistences of the slump measurements with the Box Test performance. This emphasizes that the Box Test and the Slump Test do not measure the same phenomena. While the Box Test measures the thixotropic nature of the concrete through the response of vibration and the ability to hold an edge, the Slump Test measures the downward movement of the concrete from its own weight. Even though this slump behavior may not be useful for the determining the ability to respond to vibration, some have tried to connect it to the static yield stress [8, 29].

4.2 Voids content and specific surface area

Neither the voids content nor the specific surface area were useful tools for determining the workability of the concrete mixtures investigated. In Fig. 3-3 and 3-4, mixtures possessing close-to the same voids content or specific surface area had large WR differences. In other words, similar voids content values or specific surface areas values did not necessarily exhibit the same workability. However, the mixtures requiring low amounts of WR did tend to have lower specific surface area values and lower voids content values using the modified Toufar method and the compressible packing model. This suggests these techniques may be able to suggest a range of useful values but other criteria is playing a critical role in workability behavior of these mixture.

4.3 Coarseness factor chart

Fig. 3-5 shows a wide range of WR values varied largely at the same coordinate of coarseness factor chart. For example, the middle of the coarseness factor chart required anywhere between 0 and 32 oz./cwt. Furthermore, the ¾" and 1.5" river gravel mixtures were located at different points within the chart but required very similar amounts of WR to pass the Box Test. Lastly, when comparing the bottom of the coarseness factor chart and the estimated minimum voids mixtures that used 0.75 inch limestone A, these mixtures were only a short distance apart on the coarseness factor chart, but had a WR difference of almost a 30 oz./cwt. These results demonstrate that a single location, or region on the coarseness factor chart does not predict the workability performance in the Box Test for these materials and mixtures. This data suggests other underlining mechanisms were effecting the workability performance that could not be addressed in the coarseness factor chart technique.

4.4 Individual percent retained (IPR) charts

The IPR chart was shown to be a useful tool for predicting the workability of concrete. Fig. 3-6 through 3-8 shows WR required decreases as the gradations became closer to meeting the 8-18 boundary limits. While most mixtures required high amounts of WR, the 0.75 inch mm crushed limestone B mixtures that met the 8-18 boundary limits of IPR chart required none to only a small amount of WR. To distinguish between the effects of gradation and some other phenomena such as the shape, angularity or texture of the aggregate, limestone A and river gravel were sieved to the exact same gradation as 0.75 inch limestone B in the middle of the coarseness factor chart that required 0 oz. /cwt. As shown in Fig. 3-9 each of these sieved mixture required low amounts of WR to pass the

Box Test and demonstrates gradations within certain IPR chart limits can have improved performance over the other gradations.

4.5 Aggregate characteristics and shape

Since the gradations in Fig. 3-9 were sieved to be the same distribution, the impacts of the aggregate characteristics as described in Table 3-2 can be compared. The texture and angularity was measured using the AIMS II and the shape measurement used at 1:2 ratio of ASTM D 4791 to measure flatness and elongation. While the elongation of the coarse aggregates were all similarly low, the flatness varied largely. Limestone B, which had low texture, moderate angularity, and 14% of the particles exceeded the 1:2 flatness ratio, did not require any WR to pass the Box Test. The river gravel had low angularity and low texture but 27% of the particles exceeded the 1:2 flatness ratio. This lead to the river gravel requiring 3 oz./cwt of WR. Similarly, limestone A had 27% of the particles exceeding the 1:2 flatness ratio with moderate angularity and texture and required even higher amount of WR. This shows the shape, angularity, and texture of the aggregate effects the workability of the concrete with the flatness being very important. More work is needed to quantify the degree of influence from the shape and aggregate characteristics on the workability of concrete, but it was observed that gradation had a much higher degree of impact than the shape, texture, and angularity of the materials used.

4.6 Evaluating gradation with the power 45 chart

The gradation performance using the power 45 charts of Fig. 3-10 through 3-14 looks similar to the IPR chart whereas the WR required decreases as the gradations became closer to meeting the limits. However, some of the gradations in Fig. 3-12 were barely out of the gradation limits, but required over 11 oz./cwt of WR. In Fig. 3-7 the IPR chart can easily highlight this high sieve size amount, but the power 45 chart lacks the detail to locate the high sieve size amounts using just the slope between two sieve sizes. This lack of detail in the power 45 charts shows why the IPR chart can be a more useful tool for evaluating a combined gradation. Furthermore, the boundary limits of the chart were not practical for the fine aggregate content of #4 sieve size and smaller due to the tightly spaced format of this chart.

4.7 Nominal maximum coarse aggregate size

Common concrete mixture design methods such as the ACI 211 [13], use the nominal maximum coarse aggregate size as an input into the workability of the mixture. As the nominal maximum size increases, the workability of the mixture was predicted to increase [8, 13]. As shown in Table 3-4, by using a larger nominal maximum coarse aggregate sizes actually reduced the workability of the concrete in several situations. One benefit of a larger nominal maximum aggregate size was that it uses a higher number of sieve sizes. This allows the gradation to be spread over a larger number of sieves and thus reducing any high amounts on any one sieve. The findings reinforce the usefulness of aggregate gradation with the IPR chart as it was easy to observe a high percentage of aggregate on a single sieve size.

4.8 Proportioning with the power 45 and estimated minimum voids content

Proportioning aggregate using a best fit line on the power 45, or the estimated minimum voids content of the Toufar method both focused on providing minimum voids of an aggregate combination and therefore produced mixtures with the same proportions. Mixtures using 1.5 inch limestone A, 0.75 inch limestone A, and 1.5 inch river gravel required more than 25 oz./cwt of WR. After comparing these high WR gradations to the lower WR gradations in IPR charts, these mixtures were proportioned with lower amounts of fine aggregate and excessive amounts of intermediate aggregate. The performance of the best fit line power 45 and the estimated minimum voids mixtures varied largely and created harsher mixtures that sometimes did not contain adequate amounts of sand for proper consolidation. Others have also found similar performances using minimum voids to proportion mixtures [3, 43]. These results suggest that using minimum voids content is not recommended for proportioning concrete mixtures for slip formed pavements. Other mechanisms seem to be effecting the workability of the mixture.

4.9 Proportioning with a 60/40 blend & additional intermediate aggregate

Proportioning a coarse aggregate and a fine aggregate by volume has been used for many years. Recently, an intermediate aggregate has been added in some cases in the hopes of reducing the paste content and improving the workability. Table 3-4 shows the batch weights of five different aggregate proportioning methods and the WR performance in the Box Test. The use of intermediate aggregate had varied performance enhancements. Even though 1.5 inch limestone A mixtures proportioned the intermediate aggregate using four different proportioning methods, the 60/40 blend without intermediate required 18 oz./cwt less than the other four mixtures. However, the 0.75 inch limestone B mixtures showed adding an intermediate aggregate can be used effectively to increase workability by reducing high amounts of a sieve sizes. Lastly, some mixtures such as middle of the coarseness factor chart and estimated minimum voids content using the modified Toufar method of 0.75 inch limestone A had similar batch weights, but required a large difference in WR. These findings demonstrate proportioning by a fixed volume or the use of additional intermediate does not necessarily increase the workability of a mixture. This again reinforces the critical importance of examining the aggregate gradation with the IPR chart.

4.10 Practical implications

Although the mixtures in this work used a single paste volume that was lower than typically mixtures, it allowed for a comparison of different aggregate concepts and proportioning techniques with the workability tests of slip formed pavements. If higher paste volumes and lower amounts of aggregate were used, it would not have been sensitive enough to compare the different aggregate proportioning concepts and gradation techniques. Furthermore, the WR dosages were a comparative tool to indirectly measure the workability of the concrete. These mixtures with low paste contents and high WR dosage requirement would not have to be used in practice.

This research provides an important quantitative comparison of several different gradation methods. The results suggest that not all gradation techniques are equal and that the IPR chart was able to provide a tool that was easy to use and provided the best guidance in proportioning aggregates for slip formed paving applications. While many "rules of thumb" have been proposed by practitioners that may work in some cases, this paper has shown that these methods do not consistently work and that the combined aggregate gradation must be controlled.

The current gradation specifications for individual sizes suggested by ASTM C 33 are very broad [19]. This means that general specifications of amounts of #57 stone, #8 intermediate, and an ASTM C 33 fine aggregate does not guarantee a quality aggregate gradation and cannot be used by themselves to help guide quality aggregate proportions. Instead aggregate proportions should be chosen based on the combined grading of the aggregates as plotted on the IPR Chart. Limits outside of the typical 8-18% are actively being investigated and alternates are being suggested [44, 45].

Aggregate characteristics and shape was another important contributor to workability performance. Even though the aggregates similarly met the ASTM D 4791 flatness specification of less than 15% on 1:5 ratio required by many [19], the shape of the two limestone sources was observed to look drastically different. An ASTM D 4791 ratio of 1:2 flatness was shown to depict the differences. This shape specification needs to be further developed and determine the shape impacts of the workability of the concrete. However, for these materials investigated the individual aggregate gradations had a more prominent role.

5. CONCLUSION

Various coarse aggregate concepts were investigated to determine the workability impacts of slip formed paving concrete. Using the Box Test, the research shows that gradation has a significant impact on the workability of concrete mixtures for concrete pavements. These findings also show some impacts of shape. While proportioning of aggregate can be complex, some general recommendations can be made. Based on the data collected using these specific aggregate sources, the following have been found:

- The coarseness factor chart, specific surface area, minimum voids content using the dry-rodded unit weight, modified Toufar method, and the compressible packing model were not helpful tools in understanding the workability behavior of concrete for slip formed pavements.
- Both the power 45 and IPR Chart showed the best insight to how a gradation would impact the workability of the concrete. However, the IPR Chart was easier to use

than the power 45 Chart and so is recommended to investigate if the aggregate gradation has too high a value on a single sieve.

- Proportioning aggregate to a best fit line on the power 45 chart or an estimated minimum voids content of the modified Toufar method tended to produce harsher mixtures.
- Mixtures using larger nominal maximum coarse aggregate sizes did not necessarily improve the workability.
- The angularity and shape of the aggregates used did play a role in the workability of the mixture but were not as significant as the gradation.

Understanding the gradation limits of an IPR Chart was shown to be an important step in proportioning aggregate and improving the workability of concrete mixtures for slip formed paving. This would allow the paste content to be reduced, which lowers the subsequent cost and improvements in the durability, and sustainability of the concrete. The shape of the coarse aggregate was shown to play a role in the workability and this should be studied in more detail. Research is ongoing to make improved recommendations for the boundaries of the IPR Chart [44, 45].

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CHAPTER IV

INVESTIGATION OF COARSE AGGREGATE GRADATION ON THE WORKABILITY OF SLIP FORMED CONCRETE PAVEMENTS

1.0 Introduction

A large amount of the concrete construction market comes from slip formed concrete pavements. These contractors travel to various locations and commonly create concrete mixtures using the local aggregate sources [1]. Since quarries and sand sources will have varying aggregate characteristics, shape, and gradations, these variables will change the mixture design proportions at each jobsite location. For achieving the required workability the cement content of a mixture may have to be increased and therefore creating a higher overall cost of the concrete and more probability of durability issues occurring [1, 2, 3]. One method has been advocated using aggregates effectively in a mixture design to obtain the paste reduction. This concept has been called optimized graded concrete [1, 2, 3]. A collection of aggregate concepts have been developed to help achieve optimized graded concrete as shown in Table 4-1. Each of these concepts have been shown to effect the workability of the concrete, but the performance impacts of gradation tends to be the focus of optimized graded concrete. However, more developed knowledge is needed on this gradation topic.

Table 4-1. Description of aggregate concepts effecting workability

Aggregate Concepts	Description
Nominal Maximum Coarse Aggregate Size	• Larger aggregate sizes require less surface area [4, 5, 6]. • Used in the ACI Method [4].
Angularity & Texture	• These aggregate characteristics impede rheological properties of concrete. It also requires more paste around each particle [5, 6, 7].
Shape	• Flat and/or elongated shaped aggregate creates poor packing and impedes the rheological properties of concrete [5, 6, 7, 8].
Surface Area	• Higher surface areas require more paste around each particle. This is used in a number of design methods [5, 6, 7, 8, 9 10]
Gradation	• Describes the particle size distribution of the aggregate [11, 12] • This can be measured by individual percent retained chart [1, 3, 11], cumulative percent passing chart [1, 3, 11, 13], fineness modulus [14], or coarseness factor chart [1, 3, 11].
Packing	• Various methods have been developed to predict the amount of space an aggregate gradation can take up. [8, 15, 16] • Examples include dry-rodded unit weight [17] and various analytical models: Toufar [15], Deward [18], and Lefarrad [19].

1.1 Gradation

While sand can be commonly used without crushing and screening, stone has to be quarried out of the ground, crushed, and screened into desired particle sizes. The term gradation describes the particle size distribution of the aggregate and can be measured using a sieve analysis [12]. A gradation of a coarse, intermediate, and fine aggregate can be classified or specified using aggregate standards such as ASTM C 33 [20]. ASTM C 33 limits were derived from practical experience of aggregate and concrete producers and do not guarantee performance. For concrete mixtures it has been commonly to specify an ASTM C 33 fine aggregate gradation and a #57 ASTM C 33 coarse aggregate gradation to be blended together into a single combined gradation. These combined gradations can be graphed and classified. It is important to point out that gradation does not necessarily take into account the impacts of shape or other aggregate characteristics.

1.1.2 Classifying combined gradations

Well-graded, gap-graded, open graded, and uniformly graded have been broad terms to help describe the overall amount retained on each sieve size for a gradation [6, 12]. While a gap-graded mixture can be described as a gradation distributed with lacking amounts of the middle sieve sizes, a well-graded mixture should be distributed widely through all the sieve sizes. Uniformly graded distributions only retain material on one sieve size and open graded distribution retains amounts on a few sieve sizes. Since the workability of a fresh concrete mixture requires a variety of coarse and fine aggregate sieve sizes in a combined gradation, open-graded and uniformly graded mixtures have not been commonly used [6, 12]. This requirement of various sieve sizes has created large discussions over gap-graded and well-graded performances in a concrete mixture.

Even though gap-graded concrete has been the most common gradation classification for concrete mixtures [1], many have promoted the benefits of well-graded mixtures such as reducing paste content, minimizing edge slumping, decreasing segregation, and increasing durability [3]. This well-graded concept has generated several gradation curves [21-23] and even the “ideal bell shaped” curve has been suggested to describe the most ideal well-graded distribution [3] and thought to be the optimal gradation for reducing a mixture to the minimum volume of paste content possible.

1.1.3 Combined gradation techniques

To further determine if a gradation was gap-graded or well-graded, a variety of coarse, intermediate, and fine aggregate stockpiles can be proportioned together into a combined gradation and plot using gradations techniques such as the power 45 chart [8, 13], the individual percent retained (IPR) chart [1], and the coarseness chart [3]. Unfortunately, the guidelines these techniques have been "rules of thumb" developed from field experience [10, 17, 18, 20]. While the power 45 chart has been the most widely used graphical representation of a gradation, it tends to hide the amount on a sieve size and only show general trends of multiple adjacent sieve sizes as shown in Chapter 3 and also other publications [24]. Also, the coarseness factor chart was not able to show performance tends. But previous research has shown valuable insight using the IPR chart.

1.1.4 Individual percent retained (IPR) chart

While the individual percent retained (IPR) chart has been termed the "8-18 chart" due to traditional field developed minimum of 8% and maximum of 18% gradation limits, others have named it the "Haystack chart" due to gradations commonly outline a haystack shape [11]. For example, Fig. 4-1 plots a single combined gradation with the stockpile distributions of an intermediate gradation, a coarse gradation, and fine gradation This IPR chart can be used to show excessive and deficient amounts of a sieve size in a combined gradation and can also further assist in adjustments through volume changes of the given aggregates, or adding additional aggregate. Unfortunately, only field experience has been used to determine the excessive and deficient sieve size amounts. The maximum limits can range from 15 to 22 % and minimum limits ranging from 5 to 12 % for each sieve size [1, 11, 25, 26] Since the area under the curve in the percent retained chart has a total volume of 100%, changing the amount of a sieve size will also change another sieve size or sizes. Furthermore, previous publications demonstrate the usefulness of this graphical method to compare and evaluate the data from various concrete mixtures and aggregate gradations [35, 36].

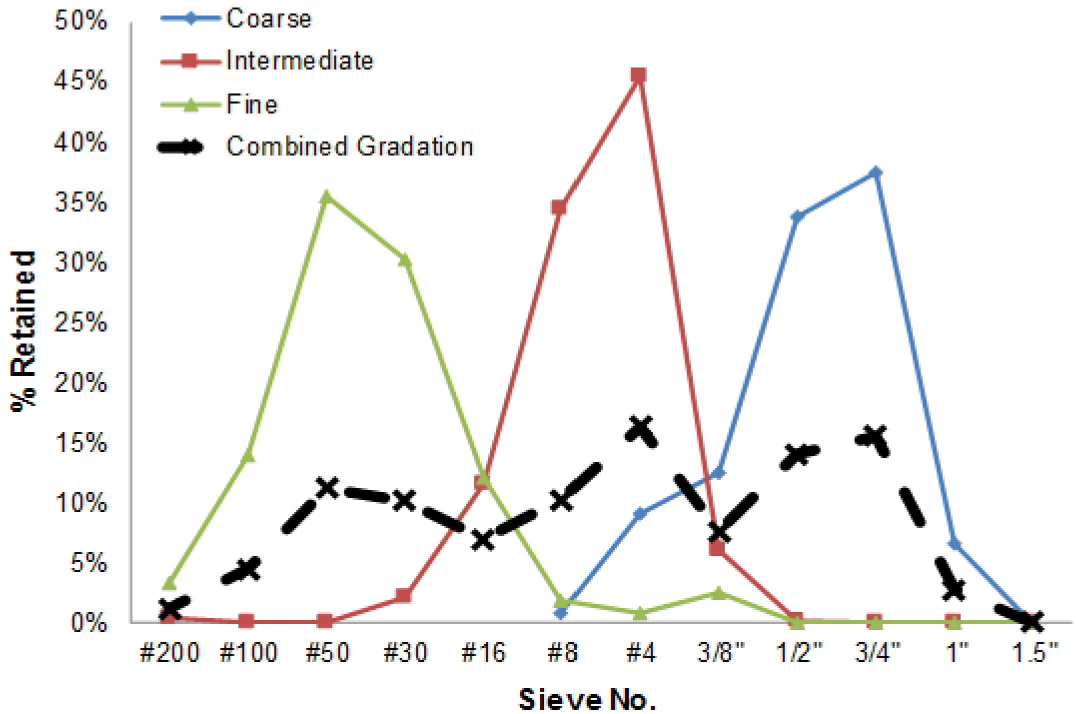

Fig. 4-1. Individual gradations blended into a combined gradation

1.1.5 Nominal maximum size

Another aggregate concept has been the nominal maximum coarse aggregate size, which has been defined as one sieve size larger than the first sieve size to retain 10% [12]. Others have slightly skewed the definition of nominal maximum coarse aggregate size to mean slightly different terms [4, 12], but this will be the referred definition used in this paper. This aggregate concept expresses that the nominal maximum size will change surface area by changing the volume of paste required each individual particle [6, 26]. If a larger nominal maximum size was used, it should require less paste around each particle and give the mixture more paste for a better workability. However, this work found the specific surface area (SSA) of a 1 inch sieve size compared to a ½ inch sieve size only changes 0.5

cm^2 / cm^3. This is insignificant compared to fine aggregate sieve size values of more than 80 cm^2 / cm^3. For more information on the calculations of SSA, refer to the methods sections of Chapter 9 in this dissertation.

1.2 Objectives

Many different methods and guidelines can be used to choose the aggregate proportions of a concrete mixture. This investigation provides a deeper understanding into the effects of the coarse aggregate gradation on the workability for a slip formed pavement mixture by examining laboratory mixtures using various aggregate gradations. If designers can have better guidelines for aggregate proportioning decisions, concrete mixtures will have a more predictable workability.

2.0 Materials and methods

2.1 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [27] with 20% ASTM C 618 [28] class C fly ash replacement by weight. The water reducer (WR) was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [29]. To measure the gradation effects of coarse aggregate, a single sand source was used and three different coarse aggregates. The gradations and nominal maximum sizes of the coarse aggregate varied largely because the investigation required the process of sieving to develop various gradations and nominal maximum sizes. For more information on the aggregate, it can be found in other publications [2, 30].

2.2 Mixture design

To investigate the impact of the coarse aggregate, all of the mixtures where designed with a water-to-cementitious material ratio (w/cm) of 0.45 and a paste content of 24.2% of the mixture volume. With 20% class C fly ash replacement, each mixture had 423 lbs. /yd³ of cementitious material per cubic yard of concrete and 190.4 lbs. /yd³ of water. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

2.3 Sieve procedure for creating a gradation

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

2.4 Mixing and testing procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken to determine the moisture content to apply the correction. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump Test [31] and the Box Test [32]. After the WR dosage procedure was completed, the surface finishability was determined.

2.5 Using the Box Test to evaluate the workability of mixtures

The most specificed method to measure the workability of a concrete mixture has been the Slump Test [1, 8], which commonly ranges between 0 to 3 inches for slip formed pavement applications. However, the Slump Test has not been sensetive enough to accurately predict the workability of a slip formed pavement mixture [1, 32]. The construction process of slip formed paving requires theworkability of a mixture to be flowable enough under vibration for consolidation, but still able to maintain an edge after the vibration has stopped and the side forms were removed.

To better investigate the workability of concrete for slip form paving, the Box Test was developed to evaluate the response of concrete to vibration and then subsequently hold an edge [32]. The Box Test was conducted as follows: 1) freshly mixed concrete was place into temporary fixed wood forms, 2) a hand-held vibrator with a specified size and speed was used to consolidated the concrete at a fixed time with a controlled entry and exit location, 3) the forms were removed, 5) the concrete was visually inspected to assess if the sides were properly consolidated, and 6) a straight edge can be used to measure edge slumping. Like a slip formed paver, this test requires the concrete to be workable enough to consolidate under vibration but still have enough cohesion to hold an edge when the forms were removed.

The Box Test has shown similar performance results as a slip formed paver in the field. For this testing a mixture was assumed to have good workability performance if the edge slumping was less than 1/4" and the sides had less than 30% surface voids measured visually. This performance critieria will be referred to as "passing the Box Test". These requirements have been previously discussed in past publications [32].

The Box Test can be further used to quantitatively compare the workability between mixtures. In the field if a mixture has poor workability, it is common to add water, cement, and/or WR to improve the workability. For this research, the paste volume and *w/cm* were held constant and discrete dosages of WR was added to the mixture until the mixture achieved satifactory performance in the Box Test. The single operator repeatability of WR dosage was found to be 2.74 oz/cwt with a 95% confidence interval. In otherwords, if two mixtures are compared and do not differ more than 2.74 oz/cwt, they can be considered to have the same workability as measured by the Box Test. A more detailed description and validation of this procedure can be further viewed in other publications [30, 31].

Gradations requiring high WR dosages are not as desirable as those that require low dosages. For this research, any mixture shown to have a WR demand higher than 10 oz. /cwt was determined to have poor workability. This high dosage of WR suggests that a higher volume of paste is needed in the mixture for satisfactory performance, and this is not desirable as the goal of this work is to minimize paste content. It should be noted that the authors are not suggesting that the indicated WR dosages would match the required WR dosage for the field due to different effectiveness of admixture type, operator techniques, and various slip formed paver equipment. Instead, the WR dosage requirements should be used as a comparison tool for indicating the workability of a mixture at varying gradations.

2.6 Surface finishability

A very important property of fresh concrete is the ability to finish the surface. On a slip formed paver, the pan profile is used to achieve the initial surface finish. It is essential that the paver and if required the finishers behind the paver are able to provide the necessary surface finish without significant effort. A simple way to evalute surface finishability of concrete is to use a magnesium hand float with an experienced concrete finisher to investigate the surface finishability of each mixture. 1). After a mixture was discharged into a wheelbarrow, a magnesium handfloat float was turned sideways to strike off any high spots. 2). The float was then placed on the surface at one end of the sample with a consistent angle and a light downward force of the hand. 3). The float was then passed over the surface to the other end of the sample and began smoothing the surface. 4). After each pass, the surface was observed if adquate smoothness was achieved. If a large number of passes with a hand float were required to smooth the surface, the mixture was deemed difficult to surface finish.

3.0 Results and discussion

The purpose of the research was to develop coarse aggregate sieve sizes (#4 and larger) limits for a combined gradation in order to better control the workability of a concrete mixture design. Each combined gradation will be plotted using the individual percent retained chart with the WR dosage that allowed this combined gradation to pass the Box Test. Since the area under the curve in the percent retained chart has a total volume of 100%, if the amount of a sieve size was reduced, another sieve size or sizes must increase. Again, the WR dosage requirements were used as a comparison tool for indicating the workability of a mixture at varying gradations. Gradations requiring high WR dosages are not as desirable as those that require low dosages. For this research, any mixture shown to have a WR demand higher than 10 oz. /cwt was determined to have poor workability.

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

3.1 Coarse and intermediate gradation

To begin investigating the minimum and maximum gradation limits, Fig. 4-2 shows gradations with a fairly constant sand, but varying coarse to intermediate aggregate volumes with the WR dosage required to pass The Box Test. The five different gradations in the middle of the chart had similar WR amounts, which ranged from 2.9 oz. /cwt to 6.3 oz. /cwt. When the combined gradation required WR dosages over 10 oz. /cwt, visual observations showed that certain particles were not able to stay cohesively within the mixture. This caused workability issues due to this increase of segregation. Additionally, the gradation with the lowest amount of intermediate and highest amount of coarse aggregate required over 43.0 oz. /cwt and had large segregation and edge slumping issues. It is intriguing that the workability of the mixture so suddenly deteriorated due to the change in aggregate gradation. The lack of intermediate aggregate coupled with over 20% coarse aggregate on a single sieve size did not allow the mixture to respond to vibration. This observation suggests the intermediate sizes of #4, #8, and #16 in a mixture may help provide cohesion. This supports findings by Neville [6].

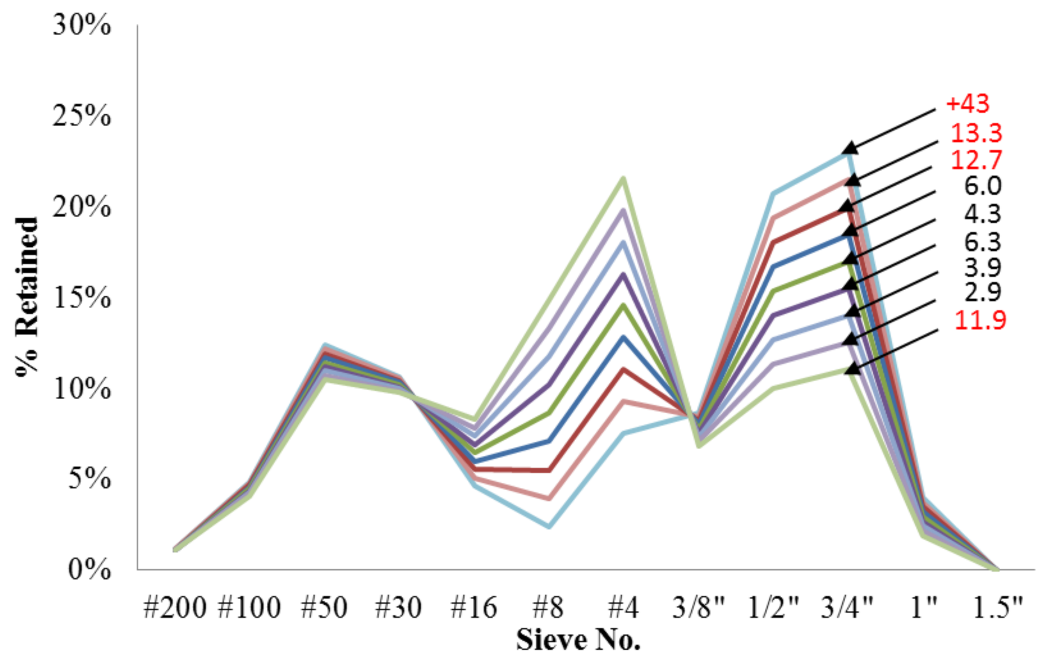

Fig. 4-2. Varies coarse to intermediate gradations with WR (oz. /cwt) required to pass the Box Test.

3.1.1 Using other aggregate sources

From Fig. 4-2 the individual maximum sieve limits for the #4 to 0.75" sieve sizes were found such as 0.75" sieve could not exceed 20% while the #4 sieve size should be limited to 22%. To validate these upper limits, Fig. 4-3 uses a crushed river gravel and Fig. 4-4 uses crushed limestone B. From the results, the #4 and 0.375" sieve again could exceed 20% by only a few percentage while the 0.5" sieve could not exceed 20% without reducing workability. Both of these figures show that the previously established gradation limits of 20% were still simple, conservative, and relevant limits.

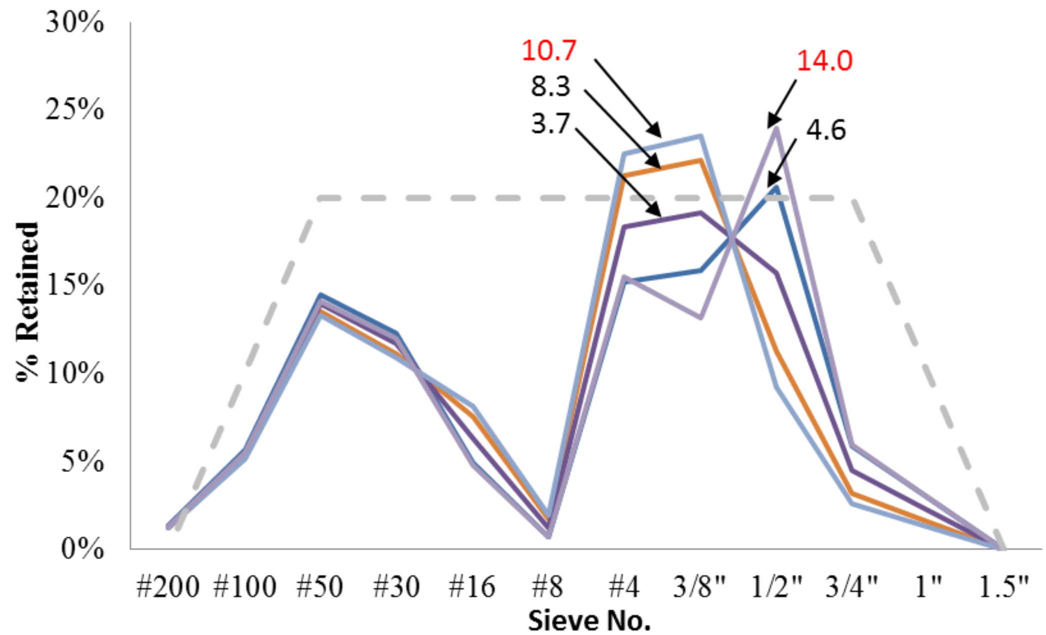

Fig. 4-3. Various river gravel A gradations with WR (oz./cwt) required to pass the Box Test.

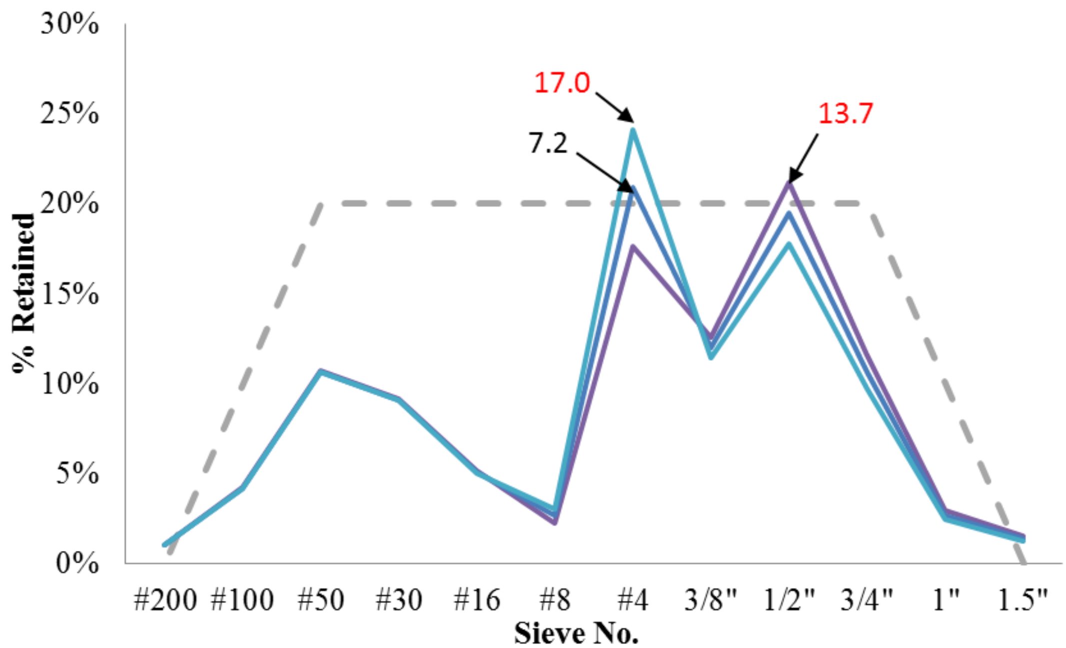

Fig. 4-4. Various limestone B gradation with WR (oz./cwt) required to pass the Box Test.

3.1.2 Maximum boundary limit

Due to excessive amounts of a particular sieve size creating workability problems, maximum sieve size limits from the field have been proposed and range from 15 to 22 % for each sieve size [11, 25, 26]. The results of this paper did consistently showed excessive amounts can create workability issues. Even though the maximum limits did slightly vary, a simplify gradation limit of 20% could be set for a single sieve size ranging from #4 to 0.75". The 20% retained on the #4 to 0.75" sieve size range will be a reoccurring trend throughout these results and serve as a key finding of this work.

3.2 Theoretical bell shaped curve

As discussed previously it has been suggested that an ideal packing of aggregates should be obtained with a bell shaped curve on the percent retained chart. This ideal bell shaped curve fits within the 8-18 field limits. In Fig. 4-5 the ideal bell curve and a practical combined gradation curve had very similar amounts of WR. It should also be noted the bell shaped curve had poor finishability as shown in Fig. 4-6. When a hand float began to surface finish the fresh concrete, the high amounts of #8 and #16 emerged from the concrete surface and flew into the air. After 15 passes with a hand float, paste began coming to the surface. Now when the hand float passed over the surface of the concrete, the high amounts of #8 and #16 tore holes in the concrete surface. A hand float made another 30 passes before it was concluded to not be possible achieving a satisfactory surface finish. Similar finishability problems have been seen with manufactured sands in the field and these problems were likely attributed to the sieve size distribution #8 and #16. To summarize, not only was the ideal bell shape curve not practical, but this data suggests the ideal bell shaped curve produces a mixture with more problems than other practical gradations and was therefore not recommended

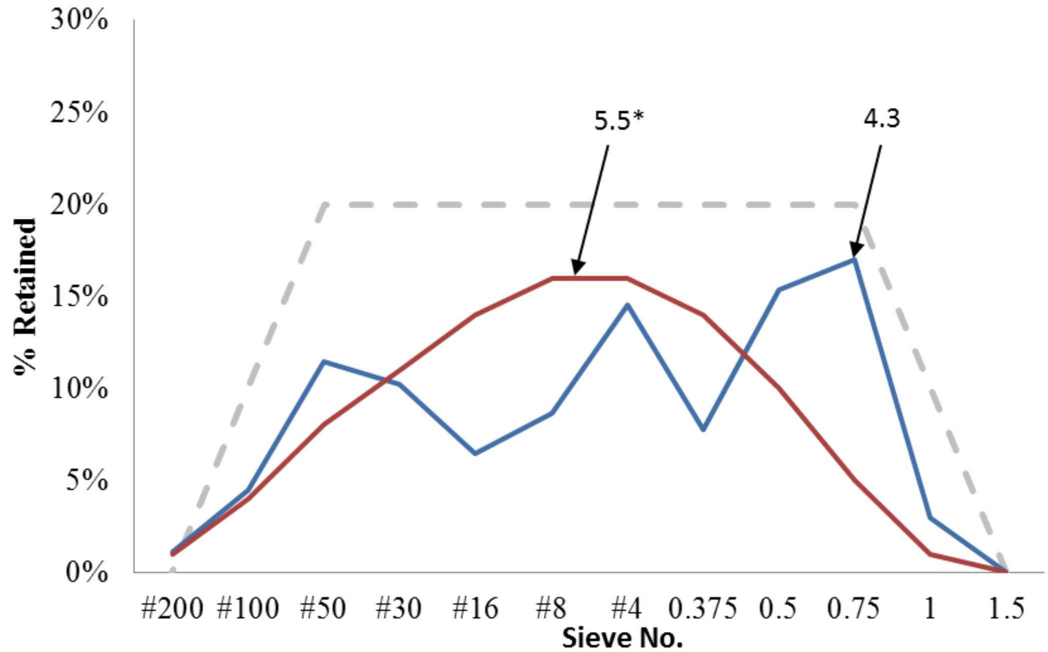

Fig. 4-5. Idea bell shaped curve and a practical gradation with WR (oz./cwt) required to pass the Box Test.

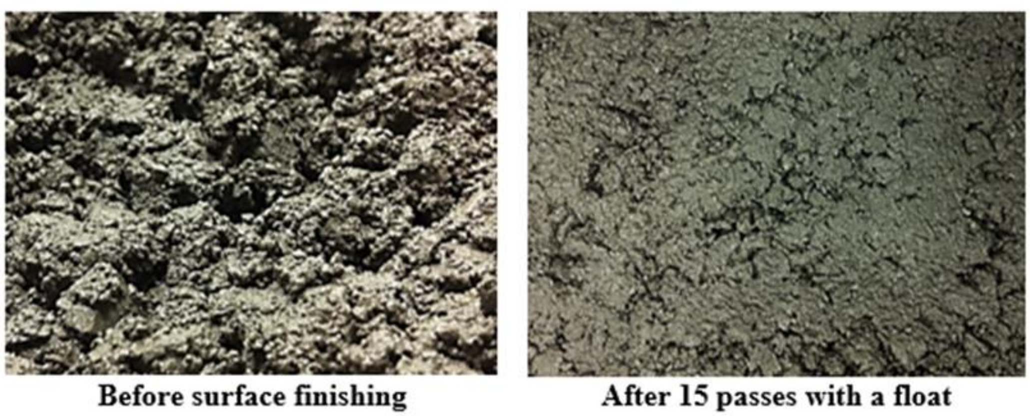

Fig. 4-6. Harsh finishability pictures of the idea bell shaped curve.

3.3 Minimum boundary

Several of the gradations in this research have contained low values of certain aggregate sizes. These low spots in the gradation have been called "valleys" and are commonly thought to reduce the workability of the mixture and should be avoided. To investigate the impacts of valleys on gradation curves, Fig. 4-7 has three different gradations that has a single valley, a minor valley, and no valley on the 0.375" sieve size. The results show a gradation having a single valley or no aggregate retained on the 0.375" sieve does not affect the performance of the mixtures. It should be noted that while changing the gradation of this mixture no single sieve size was greater than 20%.

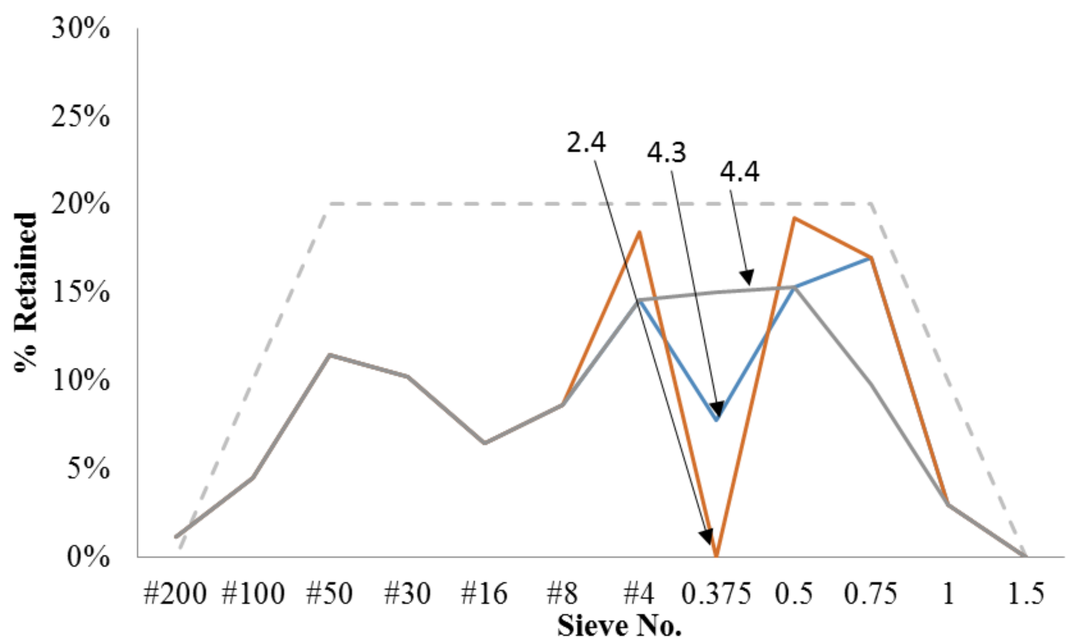

Fig. 4-7. Different degrees of single valley gradations with WR (oz./cwt) required to pass the Box Test

To further investigate the performance of varying degrees of a valley, the gradations of two adjacent sieve sizes were varied as shown in Fig. 4-8. Two of the gradations performed satisfactorily, but the gradation not containing any 0.375" and 0.5" sieve sizes had an increase demand in WR of 4.5 oz./cwt. The higher WR demand mixture contained large amounts of 0.75" and #4 aggregate sizes, which was near the maximum boundary limit of 20% limits of those sieve sizes. In other words, a major double valley does not seem to effect the workability of concrete unless the double valley forces other sieve sizes to exceed a maximum boundary limit. This supports the developing concept that mixtures can perform satisfactorily as long as the combined gradation of a single sieve size did not retain too large of an amount.

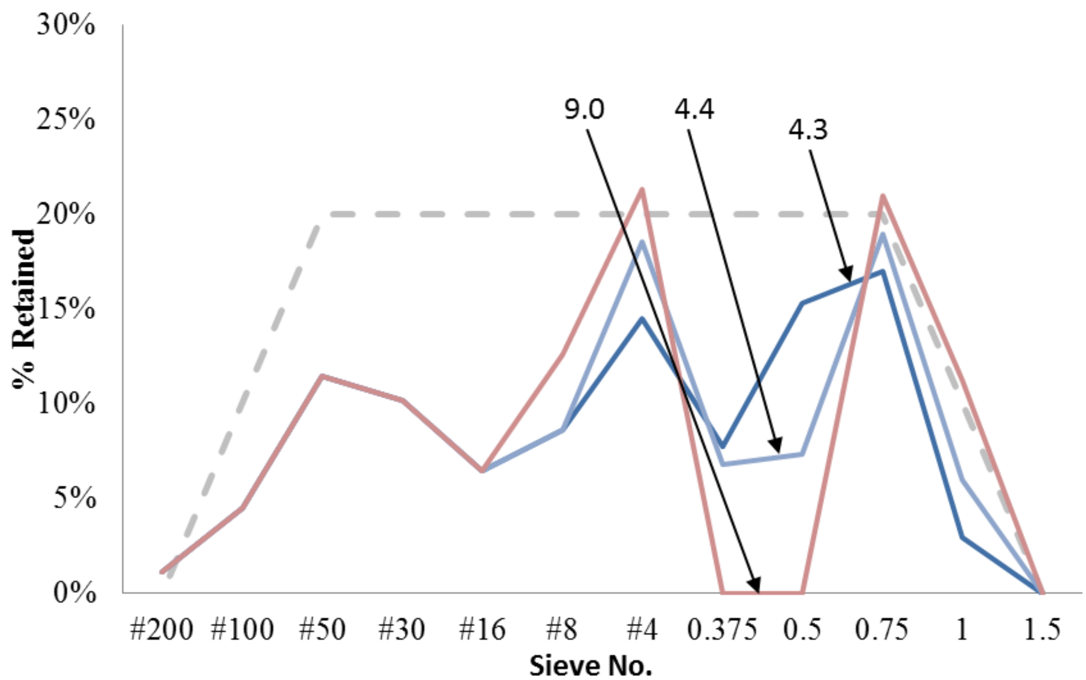

Fig. 4-8. Different degrees of double valley gradations with WR (oz./cwt) required to pass the Box Test.

3.3.1 Developing a minimum boundary

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

3.4 Nominal maximum coarse aggregate size

Multiple mixture design methods and publications claim the nominal maximum size of the coarse aggregate affects the workability of the concrete [4, 5, 6, 11, 12]. This research used three gradations with a 0.75”, 1.0”, and 1.5” nominal maximum sieve sizes. Also, each gradation was designed to have similar sand contents and no sieve size were above 20%. In Fig. 4-9, the results show gradations with various nominal maximum sizes can produce satisfactory mixtures with very little difference in workability. The 1.5” nominal maximum mixture required the lowest WR dosage to pass the box test but this difference was not significant to require a further paste reduction. This data suggests that the guidance of only increasing the aggregate size by itself does not lead to an improvement in the workability of a mixture. However using a larger maximum aggregate size was beneficial because it more easily produces an aggregate gradation that does not have an excessive amount of material on a single sieve size. In other words, it gives the producer a larger number of sieves to distribute their gradation without creating an excessive amount on a single sieve size. More work is needed to better understand the interaction of gradation and the nominal maximum coarse aggregate size.

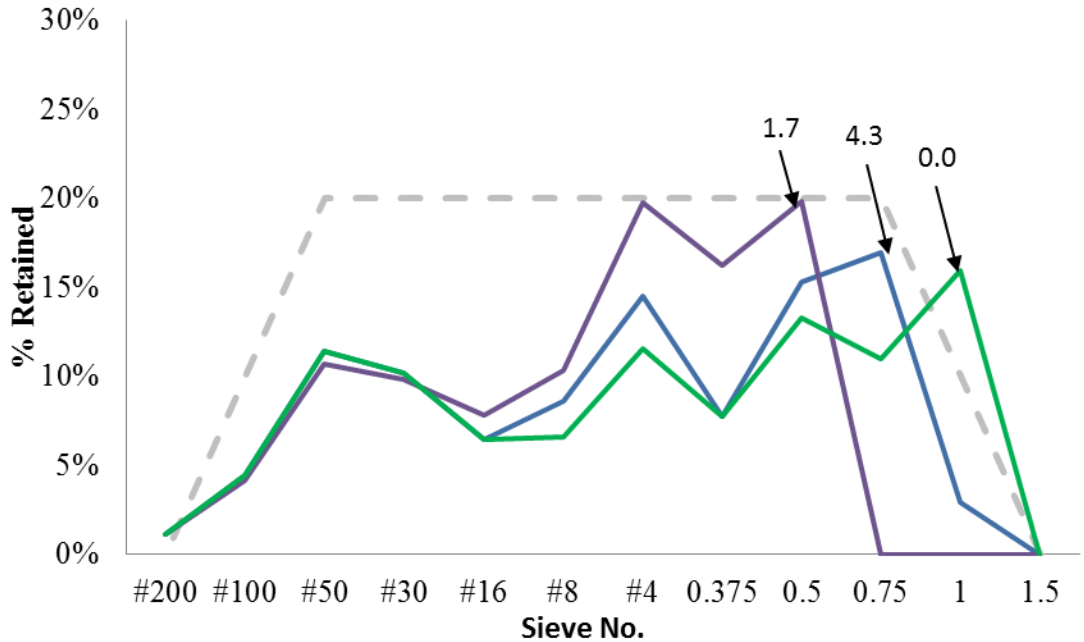

Fig. 4-9. Different nominal maximum sizes with WR (oz./cwt) required to pass the Box Test.

3.5 Gradation Concepts

Popular gradation concepts such as the "perfect gradation", well-graded, or gap-graded topics have been continuously discussed in literature [1, 3, 6, 7, 8]. A continuous trend throughout this research has found gradations can vary largely, but "too" high of a sieve size creates poor workability performance. For example, Fig. 4-2 shows well-graded and gap-graded mixtures could both perform well as long as the gradations did not increase above 20%. The double and single valleys did not affect the workability of the concrete until the sieve size was pushed above 20%. In all likelihood, these gradation concepts were created because people overlooked the importance of high sieve sizes in a combined gradation.

3.6 Practical application and recommendation

The Box Test is a useful and practical workability test for slip formed pavements. Using this test, some basic guidelines were developed for proportioning the coarse aggregates of a concrete mixture. A common trend of coarse aggregate sieve sizes (#4 and larger) retaining amounts above 20% would decrease the workability performance of the mixture. Furthermore, minimum sieve size only effected the WR dosage after pushing other sieve sizes above the 20% boundary. The sieve sizes smaller than (#4) on the combined gradation will be further investigated in the next chapter of this dissertation.

Although the focus has been understanding the effects of a combined gradations with a single reduced paste content, the findings can apply to various concrete mixtures for slip formed pavements. These gradation guidelines will be beneficial to improve construction specifications and practice. Furthermore, the guidelines give the designer the ability to reduce the total binder content and thus decrease the cost of the mixture, while improving the durability and sustainability of the concrete.

4. Conclusion

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

- If a single sieve size of the coarse aggregate (#4 and larger) retained more than 20%, the workability performance of the concrete would decrease.
- Unless a sieve size retains more than 20%, a large range of gradations can be used without drastically affect the workability of the concrete.
- Deficient amounts of a single sieve size or consecutively adjacent sieve sieves did not affect the workability of the concrete until a sieve size retained above 20%.
- Ideal bell shaped curve created surface finishability issues and is not recommended in practice.

- The maximum aggregate size did not have a major effect on the workability. However, the maximum aggregate size can help reduce the high amounts on a single sieve size by increasing the number of sieves used.

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

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CHAPTER V

INVESTIGATION OF FINE AGGREGATE GRADATION ON THE WORKABILITY OF SLIP FORMED CONCRETE PAVEMENTS

1.0 Introduction

One of the most important properties of concrete is workability, which has been commonly described as the ability of a concrete mixture to be mixed, placed, consolidated, and surface finished in desirable manner [1, 2, 3, 4, 5, 6]. One contributor to this property is fine aggregate [3, 5, 6, 7]. A concrete mixture should be proportioned with an adequate volume and gradation consistency of fine aggregate. For surface finishing of concrete, fine aggregate gives the ability of the concrete mixture to be surface finished [3, 5, 6, 7] and also to be cohesive and not edge slump or segregate [1, 3]. People have used the phrases “fine sand” and “coarse sand” to describe the consistency for the particle distribution of the fine aggregate gradation and the relationship to the workability properties of concrete [3, 8, 9]. While fine sand helps contribute to the smooth surface finishability and consolidation of the concrete [2, 3], coarse sand helps to “stiffen up” the concrete mixture to prevent edge slumping [1, 10, 11]. A variety of fine aggregate gradations can be used to adequately proportion a concrete mixture [3, 5], but this gradation should not get “too coarse of sand or “too” fine of sand.

Unfortunately, these relationships have not been well quantified.

1.1 Fineness Modulus of Fine Aggregate

To help further measure and better quantify the coarseness and fineness of a gradation, the fineness modulus was introduced by Duff Abrams in *Design of Concrete Mixtures* [9]. The fineness modulus uses a single number to describe the performance behavior of an aggregate gradation. It has been used to describe any gradation source from a coarse aggregate, intermediate aggregate, fine aggregate, and even a combined gradation [3, 5, 7, 9]. Over time the use of a single number to explain the behavior of aggregate gradation lacked the details to really take into gradation limits [8]. This was especially true for the combined gradation of a mixture. A more useful tool is needed to explain this.

1.2 Specific Surface Area

The specific surface area has been another concept many have used to explain the impacts of sand [2, 3, 5, 7, 8, 12, 13]. This concept revolves around the idea that paste is required to go around every particle size and any extra paste will contribute to the workability of the concrete [2, 5]. When proportioning the amount of fine aggregate in a mixture, slight various in gradation can drastically change the specific surface area of the mixture. In this methodology the volume of extra paste should be a controlling variable on the ability of the concrete to flow [6].

1.3 Objectives

While the previously discussed gradation concepts can be supported by logical reasoning, investigations conducted need additional quantitative research. This investigation attempts to provide a deeper understanding into the effects of the fine aggregate gradation on the workability for a slip formed pavement mixture by examining laboratory mixtures using various aggregate gradations.

2.0 Materials and methods

2.1 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [14] with 20% ASTM C 618 [15] class C fly ash replacement by weight. The water reducer (WR) was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [16]. To measure the gradation effects of fine aggregate, a single coarse aggregate source and fine aggregate source was used. Also, this gradation investigation required the process of sieving to develop various fine aggregate gradations. Obviously, this is not practical for the field, but it gives great insight into the gradation behavior of fine aggregate. Three other coarse aggregate sources and one other fine aggregate source was used to further validate the finding. For more information on the aggregates, it can be found in other publications [17].

2.2 Mixture design

To investigate the impact of the coarse aggregate, all of the mixtures where designed with a water-to-cementitious material ratio (w/cm) of 0.45 and a paste content of 24.2% of the mixture volume. Each mixture had 423 lbs. /yd^3 of cementitious material per cubic yard of concrete and 190.4 lbs. /yd^3 of water. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

2.3 Sieve procedure for creating a gradation

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

2.4 Mixing and testing procedure

Aggregates are collected from outside storage piles, and brought into a temperature-controlled room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun. Then a representative sample was taken for a moisture correction. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure the aggregates were evenly distributed. Next, the cement material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump Test [18] and the Box Test [19].

2.5 Using the Box Test to evaluate the workability of mixtures

The most specificed method to measure the workability of a concrete mixture has been the Slump Test [1, 5, 6], which commonly ranges between 0 to 3 inches for slip formed pavement applications. However, the Slump Test has not been sensetive enough to accurately predict the workability of a slip formed pavement mixture. The construction process of slip formed paving requires the workability of a mixture to be flowable enough under vibration for consolidation, but still able to hold an edge after the vibration has stopped and the side forms were removed.

To better investigate the workability of concrete for slip form paving, the Box Test was developed to evaluate the response of concrete to vibration and then subsequently hold an edge [19]. The Box Test is conducted in the following steps: place freshly mixed concrete into temporary fixed wood forms, using a hand-held vibrator consolidated the concrete in with a controlled entry and exit location over the standard time of six seconds, remove the forms, and visually inspect if the concrete sides were properly consolidated. Then a straight edge can be used to measure edge slumping. Like a slip formed paver, this test requires the concrete to be workable enough to respond to vibration but still have enough cohesion to hold an edge without forms. Also, the Box Test has been used in the field and had similar performance results as a slip formed paver.

The Box Test can be further used to quantitatively compare the workability between mixtures. In the field if a mixture has poor workability, it is common to add water, cement, and/or WR to improve the workability. For this research, the paste volume and w/cm were held constant and discrete dosages of WR was added to the mixture until the mixture achieve satifactory minimal surface voids performance with a ranking of two, which will also be refered as a passing performance in the Box Test. Validations have been published on the Box Test and this WR technique [19]. The single operator repeatability of WR dosage was found to be 2.74 oz/cwt with a 95% confidence interval. In otherwords, if two mixtures are compared and do not differ more than 2.74 oz/cwt, they can be considered the same workability. A more detailed description and validation of this procedure can be further viewed in other publications [17, 19].

2.6 Surface finishability

A very important property of fresh concrete is the ability to finish the surface [2, 3, 10]. On a slip formed paver, the pan profile is used to achieve the initial surface finish [1]. It is essential that the paver and if required the finishers behind the paver are able to provide the necessary surface finish without significant effort. A simple way to evalute surface finishability of concrete is to use a magnesium hand float with a consistent angle and constant downward force on the surface and observe the response. As the hand float passes over the top of the concrete, it will smooth the surface. If a large number of passes with a hand float were required, the mixture was deemed difficult to surface finish. This was an important criteria and was used to investigate each mixture.

3.0 Results and discussion

A concrete mixture must contain a certain volume of sand to accomplish placement, consolidation, and surface finishing in the desirable application. Sand is traditionally defined as the material retained on the #4 through #200 sieve sizes and described as being either fine or coarse depending on where the material was retained on those sieve sizes. To simplify the succeeding discussions, the volume range of #30 through #200 sieve sizes will be referred to as "fine sand" in the document and #8 through #30 sieve sizes as "coarse sand". The sand sieve sizes have not been well understood and currently unpredictable because it can be very impractical to screen the fine aggregate sieve sizes in the field [7]. The goal of the investigation into sand is to better understand the distribution and proportions of fine aggregate sieve sizes. To do this, the following variables were investigated: determining the sieve ranges that make-up coarse sand and fine sand and the volumes required to achieve the preferred workability.

3.1 Coarse Sand

Throughout these investigations, it was very clear to see the coarse sand gives a fresh concrete mixture stiffness and cohesive properties. This coarse sand property has been so important in the field that people have created rules of thumb to ensure enough coarse sand in the mixture to not edge slump and also stay cohesive [8, 10, 11]. However, the field limits and behavior of coarse sand has not been clearly defined. This will help further understand the behavior of coarse sand and better predict workability performance.

3.1.1 #4 Sieve Size

Since fine aggregate has been broadly described as the material retained or passing the #4 sieve size, the investigation of the coarser or larger sand particles should be conducted to determine where the sieve sizes begin to start showing signs the could contribute to the stiffness and cohesive properties previously described. To determine this, Fig. 5-1 shows the performance of mixtures with #16, #8, and #4 sieves removed. The material on the #4 sieve was systematically added ranging to examine the impact on the performance.

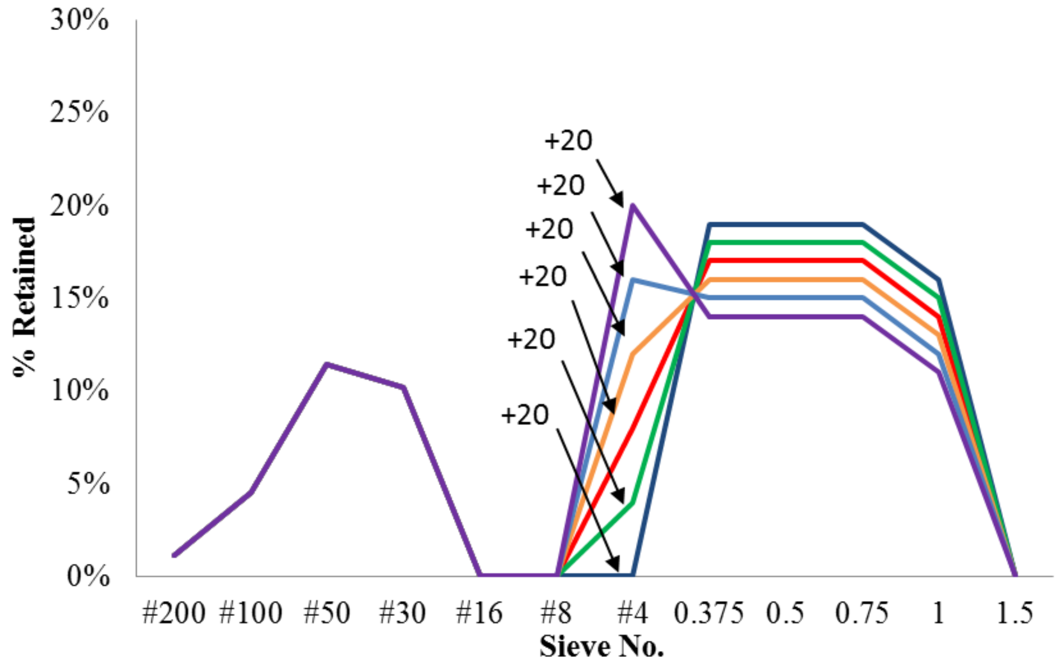


Fig. 5-1. Different amounts of #4 sieve size with WR (oz./cwt) required to pass the Box Test.

Each of the gradations preformed similarly and could not respond to vibration even after 20 oz. /cwt. From visual observations, each mixture had segregation issues where the coarse aggregate and mortar could not stick together. As more WR was added, it lowered the viscosity of the paste, but actually reduced the ability of the paste to cling to the coarse aggregate and become a single homogenous mixture. Furthermore the concrete sample from the Box Test began to start edge slumping because the mortar did not want to stick to the coarse aggregate as shown in Fig. 5-2. Even with 20% of #4, the mortar and coarse aggregate did not act as a single homogenous mixture, which was the previously developed limit for the #4 sieve size. Unlike the traditional classification of fine aggregate [7], this data suggests the material on the #4 sieve does not significantly contribute to the properties associated with mortar and should not be classified as fine aggregate.

Fig. 5-2 shows edge slumping issues due to poor cohesion.

3.1.2 #8 Sieve size

Next, the effects of #8 sieve size were investigated by varying the amount of #8 from 0%, 4%, 8, 12%, and 14% retained as shown in Fig. 5-3. From visual observations, the mixture using only 0% and 4% retained on the #8 had minor segregation issues where the coarse aggregate and mortar could not stick together. The 12% retained on the #8 sieve size required much lower amounts of WR. Also, the coarse aggregate and mortar would cling together and had a good surface finishing. However, 14% retained on the #8 sieve created poor finishability issues as noted with an asterisk in the Figure. These results suggest a range of coarse sand can create satisfactory performance. If these materials were too low, poor cohesion can occur. If these volumes were too high, poor finishability can occur.

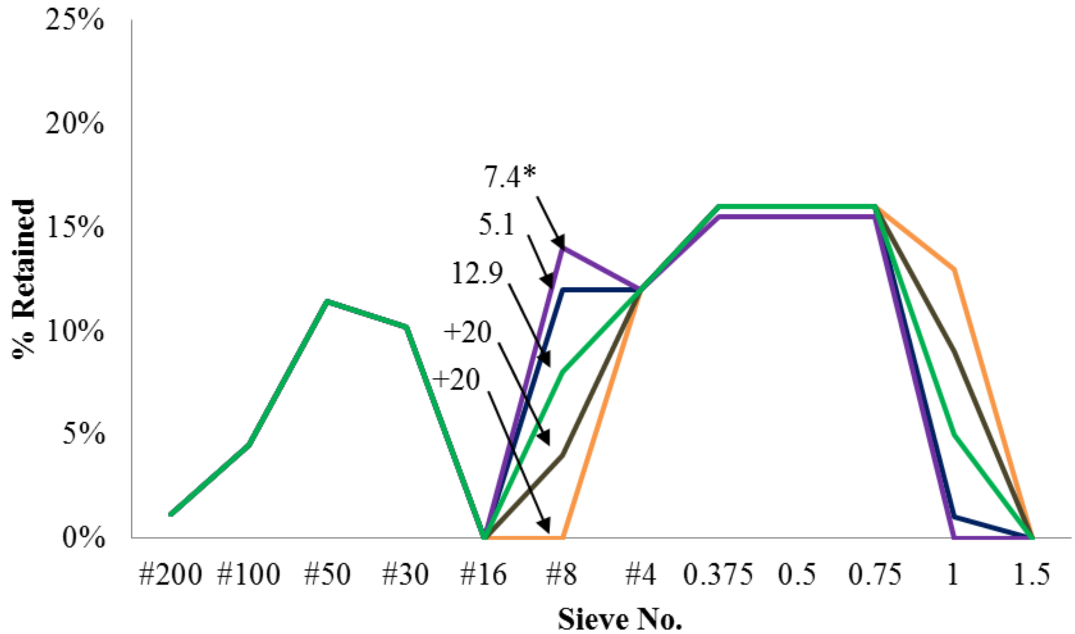


Fig. 5-3. Different amounts of #8 sieve size with WR (oz./cwt) required to pass the Box Test. *note: this gradation had poor finishability.

3.1.3 #16 sieve size

Next, the effects of #16 were investigated by varying the amount of #16 from 0%, 4%, 12%, and 16% retained as shown in Fig. 5-4. The mixture using 4% retained on the #16 performed sufficient enough in the Box Test and was cohesive. The 16% retained on the #16 stayed together, but had poor surface finishability issues as shown in Fig. 5-5. Again, this data continuously suggests a range of these materials are required to help prevent poor cohesion and poor surface finishability.

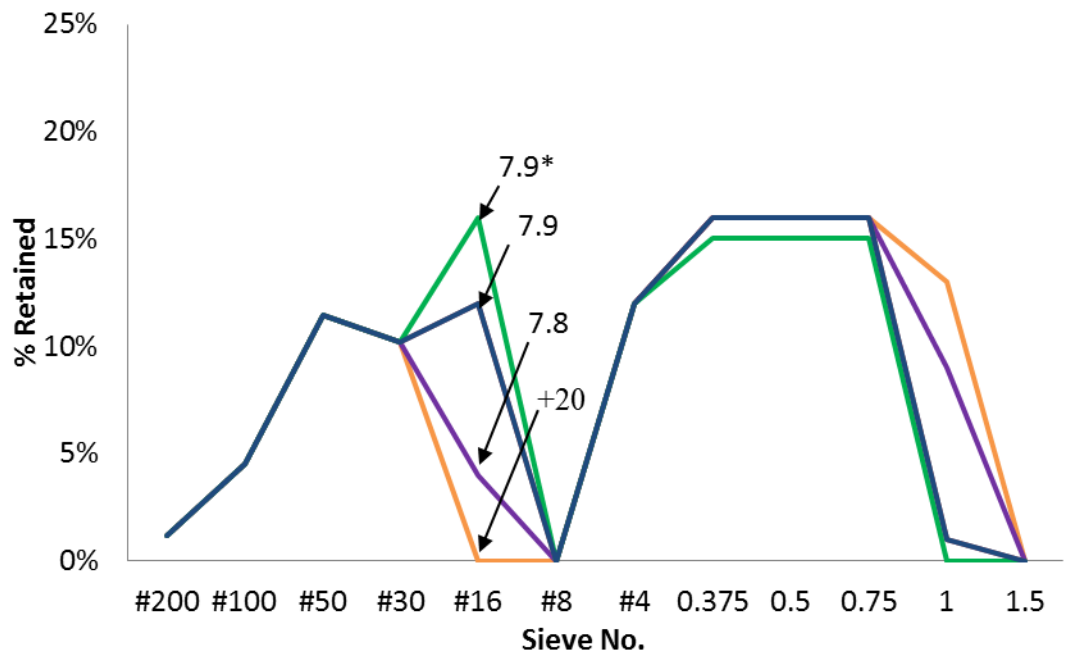


Fig. 5-4. Different amount #16 sieve size with WR (oz./cwt) required to pass the Box Test. *note: this gradation had poor finishability.

Fig. 5-5. Picture of the intense amounts of the #16 sieve size.

3.1.4 Combination of the #8 and #16 Sieve size

To further investigate surface finishability issues, Fig. 5-6 shows various mixture with 0%, 4%, 8% 10%, 12%, and 14% on both the #8 and #16 sieve size. With 4% of #8 and #16, the mixture required a lower amount of WR and obtained proper cohesion. However, 14% on the #8 and #16 proved to create large surface finishability issues.

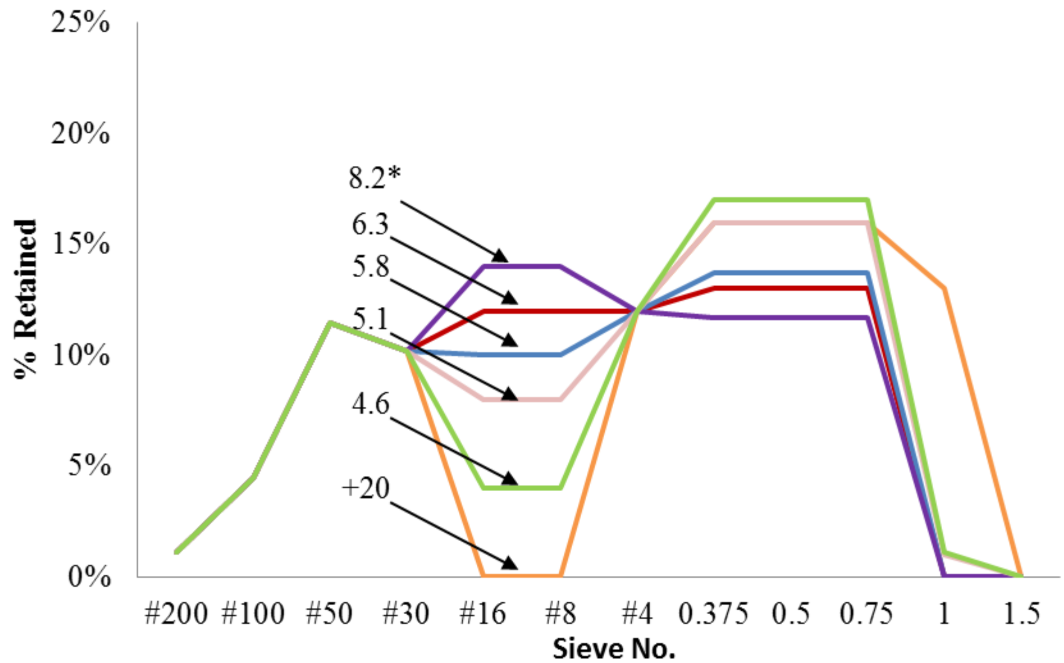


Fig. 5-6. Combination of #8 and #16 with WR (oz./cwt) required to pass the Box Test. *note: this gradation had poor finishability.

3.1.5 #30 sieve size

Also, #30 sieve size was investigated to determine the influences of cohesion on a mixture. In Fig. 5-7, a gradation was used without any #8 and #16, but had almost 15% of #30. The mixture responded favorably to vibration, surface finishing, and ability to hold an edge. From visual observations, #30 created a stiffer mixture that was shown to bring the coarse aggregate and mortar together. The mixture still performed well even when the #8 and #16 sieve sizes were zero. This indicates a mixture does not necessarily need the #8 and #16 sieve sizes for consolidation but higher amounts of #30 may be necessary. However, more research is needed to understand the interaction of #8, #16, and #30 sieve sizes on the workability of concrete. A minimum volume recommendation is made that at least 15% of the aggregate should be on the coarse sand (#8 through #30) sieve sizes. Also, another mixture was investigated with 20% of #30. This created poor surface finishability issues and an individual sieve size limit of 20% on the #30 sieve size was established for this sieve.

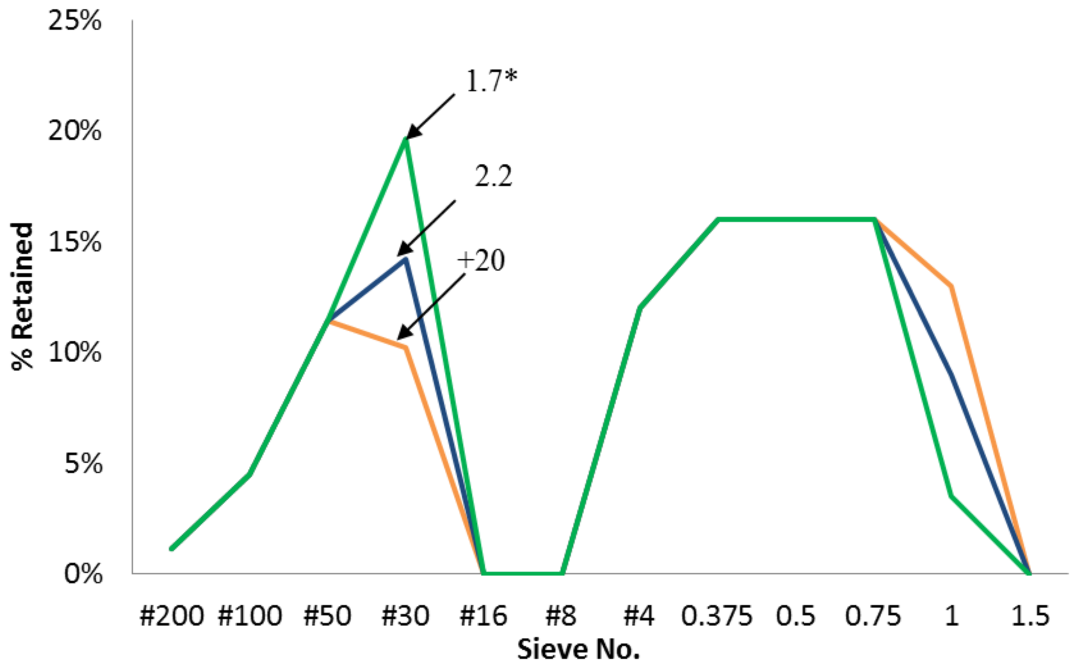


Fig. 5-7 performance of #8, #16, and #30 sieve sizes with WR (oz./cwt) required to pass the Box Test. *note: this gradation had poor finishability.

3.1.6 Coarse Sand Recommendations

Coarse sand was proven to effect the cohesion and surface finishability of the mixture. These workability issues can be very problematic. A minimum volume of coarse sand and individual sieve sizes limits were developed to help prevent these issues. If the mixture was high on a coarse sand sieve size, surface finishability issues occurred. Finishability issues were created at 14% of #8, 16% of #16, 20% of #30, and 14% of both #8 and #16. A conservative maximum sieve size boundary was set at 12% for the #8 and #16. Also, a maximum limit of 20% was set for the #30 sieve size.

If low volumes of coarse sand were present, the mixture tended to segregation and edge slump. Similar findings have been found in the field [8, 10, 11]. From Figures 5-3, 5-4, 5-6 and, 5-7, minimal amounts of coarse sand could create adequate cohesion from the following: 15% of #30, 4% on the #16 with 10% of #30, or 12% on the #8 with 10% of #30. A reasonable minimal volume limit of 15% was recommended for coarse sand value using a natural sand.

3.2 Fine sand

3.2.1 Minor gradation changes of fine sand

To begin understanding the mortar property of concrete, Fig. 5-8 investigates the effects of minor changes in the #30 through #200 sieve sizes on the performance of a mixture. Using a constant gradation on the 1 inch to #16 sieve sizes, three different gradations were evaluated with a constant volume of #30 through #200 sieve sizes, but small changes in the distribution of those four sieve sizes. The results show small amounts of variation do not drastically change the workability.

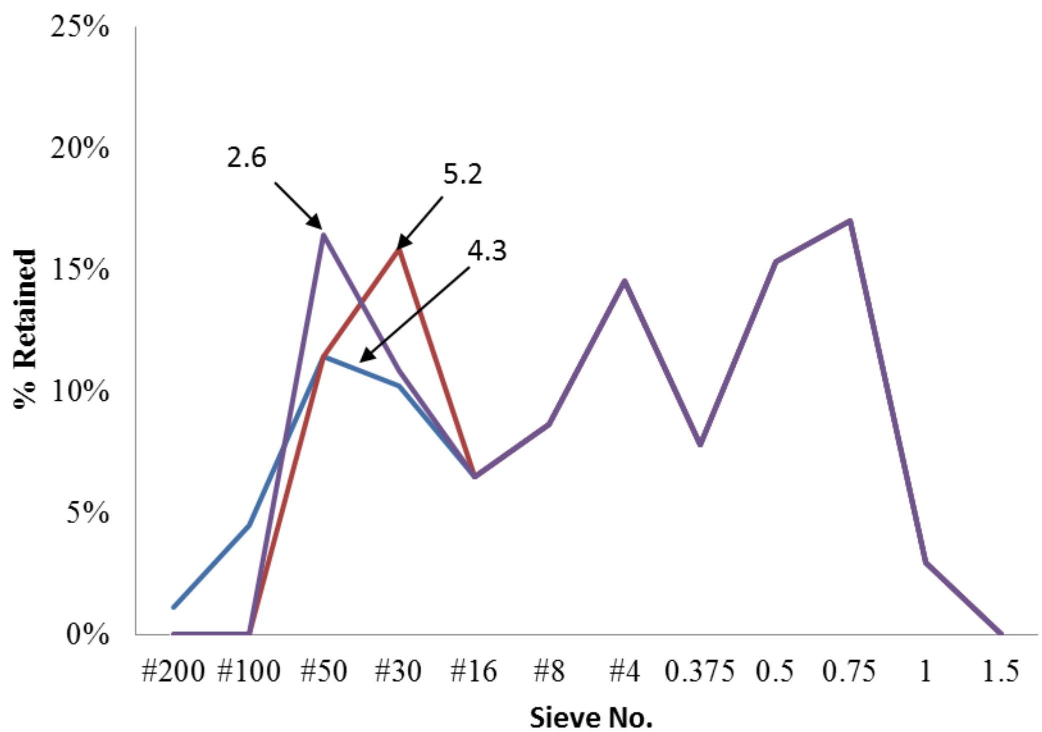


Fig. 5-8 shows minor gradation changes of fine sand with WR (oz./cwt) required to pass the Box Test.

3.2.2 Distribution of #30 sieve size

To determine the effects of different amounts retained on the #30 sieve size, the mixtures in Fig. 5-9 were designed to have a constant gradation on the 1 inch to #16 sieve sizes with varying amounts on the #30 sieve. The gradation close to 20% on the #30 sieve had issues with surface finishing. When a hand float was used on the surface the aggregate retained on the #30 sieve size would create holes on the surface. Furthermore, the gradation requiring 20.4 oz. /cwt not only required high amounts of WR, but it also had poor surface finishing due to the 27% of #30. Again, a 20% limit should be set on the #30 sieve size.

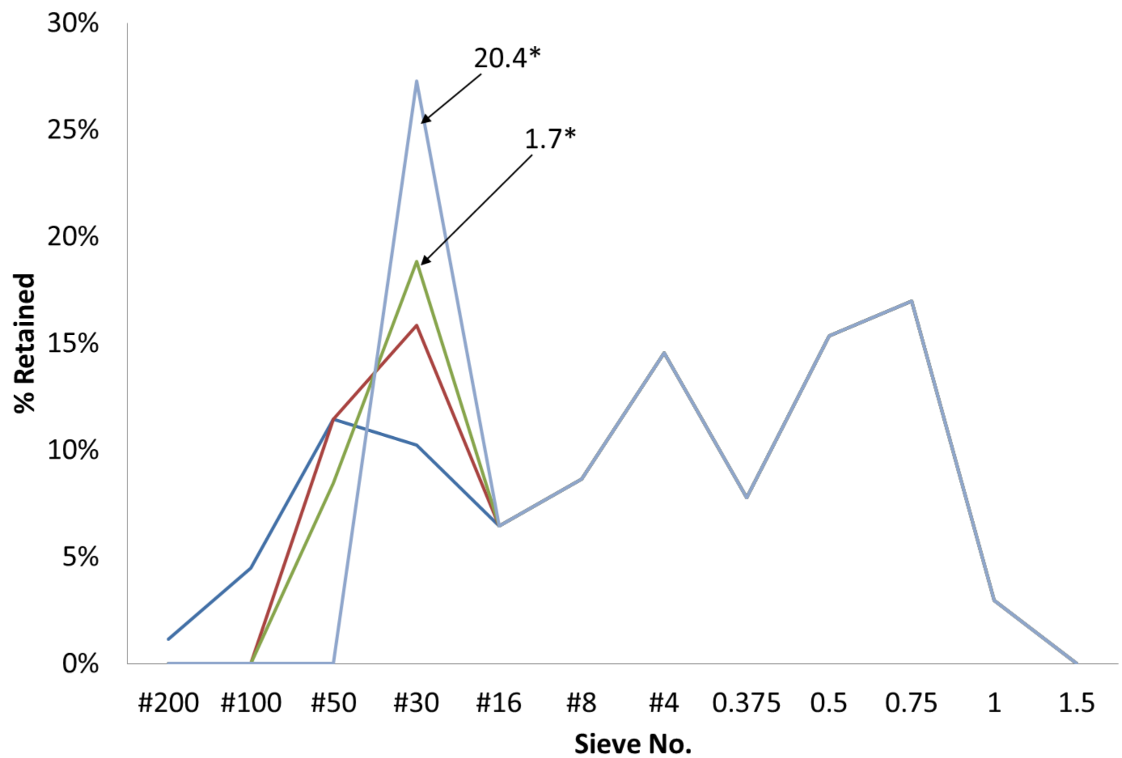


Fig. 5-9 shows the distribution of #30 with WR (oz./cwt) required to pass the Box Test. *note: this gradation had poor finishability.

3.2.3 Distribution of #50 sieve

Similar testing parameters such as those for the distribution of #30 sieve size were conducted except the #50 sieve size was evaluated. Fig. 5-10 was designed to have a constant gradation on the 1 inch to #16 sieve sizes with various amounts on the #50 sieve.

The figure shows a mixture using only #50 did not require high amounts of WR to pass the box test. Additionally, the gradation with 27% retained on the #50 was shown to create a very smooth surface finish with a hand float. This does not match previous findings for the #30, #16, or #8 sieve sizes. Further work is needed to conclude a maximum limit for the #50 sieve size.

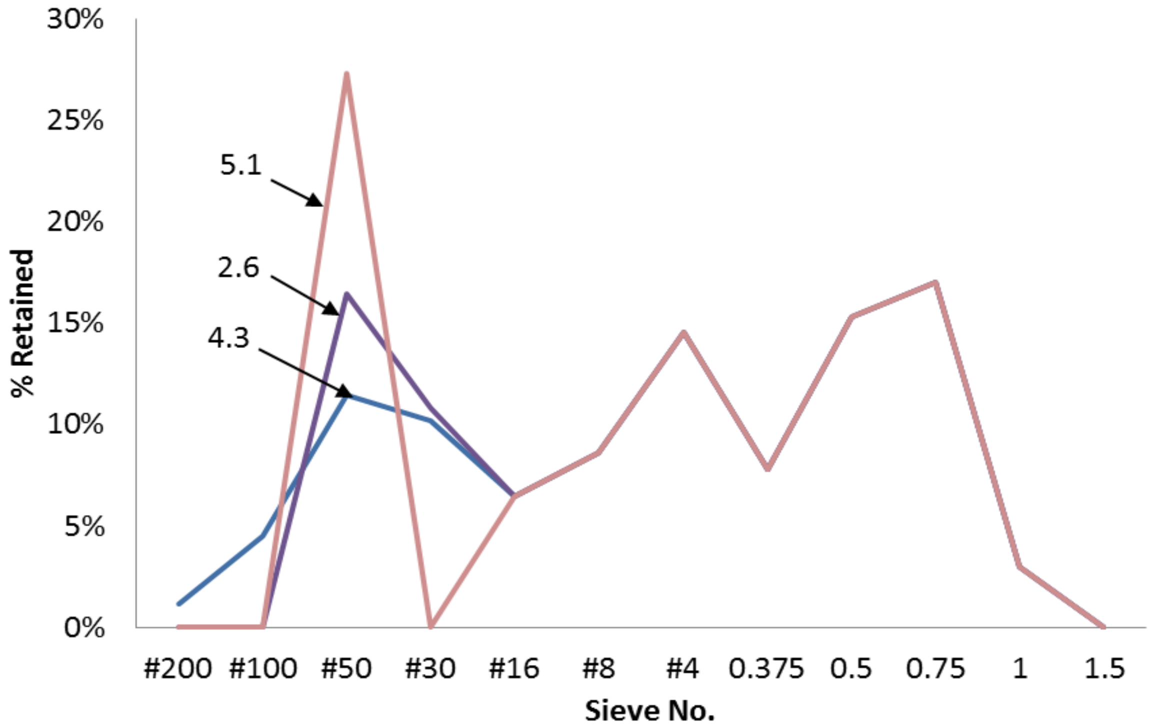


Fig. 5-10 shows the distribution of #50 with WR (oz./cwt) required to pass the Box Test.

3.2.4 Distribution of #100 and #200 sieves

Fig. 5-11 shows a distribution of different amounts of sands with higher amounts of #100 and #200 sieve sizes. It was shown amounts of 15% on the #100 sieve and 4% on the #200 sieve required significantly higher WR dosages to pass the box test. However, reducing the amount retained on the #100 and #200 sieve sizes allowed the mixture to require only a small amount of WR to pass the Box Test. Also, from visual observations the gradations with high amounts of #100 created a very smooth surface finish, but the paste around the coarse aggregate was easily removed with very little paste remaining on the coarse aggregate. The #100 sieve size creates a very smooth surface finishability. Only a limited number of mixtures were investigated due to challenges of obtaining enough material retained on the #100 and #200. Nevertheless, 10% on the #100 and 3% retained on the #200 have been shown to not decrease the workability of the concrete, but more than 10% on the #100 was shown to significantly decrease the workability.

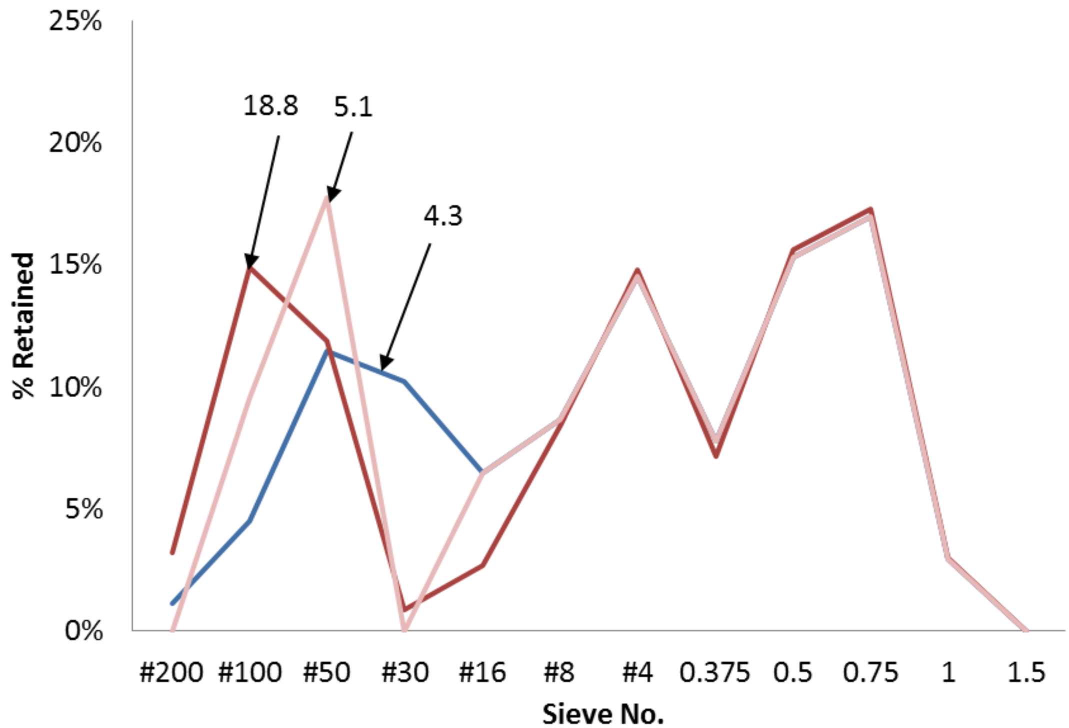


Fig. 5-11 shows the various amounts of #100 and #200 with WR (oz./cwt) required to pass the Box Test.

3.3 Proportioning fine sand

Without exceeded the previous developed sieve size limits, various combined gradations will be investigated to determine adequate volume proportioning ranges for fine aggregate. Fig. 5-12 shows varying amounts of sand with a constant ratio of the coarse to intermediate aggregate. High amounts of WR was caused by inadequate volume amounts of "too much" or "too little" fine sand (#30 through #200). When the volume of fine sand was low in the mixture, the mixture looked like aggregates coated with a small film of paste. This mixture was very difficult to consolidate and surface finish. When higher volumes of fine sand were used, the mixture became “sandy”, which created difficultly in surface finishing and consolidation. A picture and description of a low, medium, and high amount of sand was presented in Table 5-1.

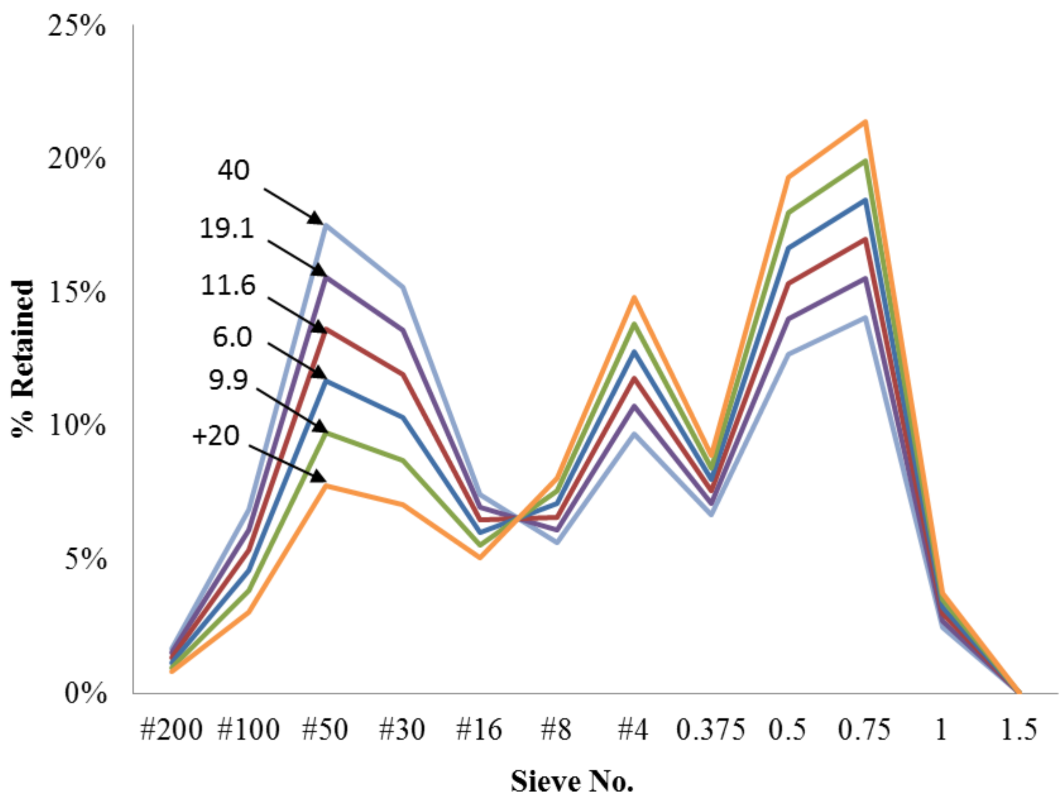
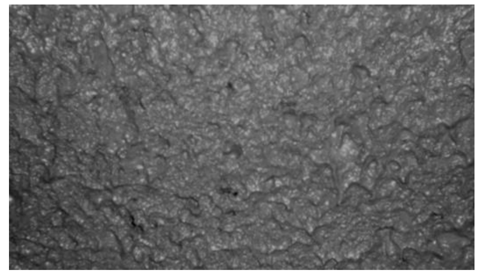
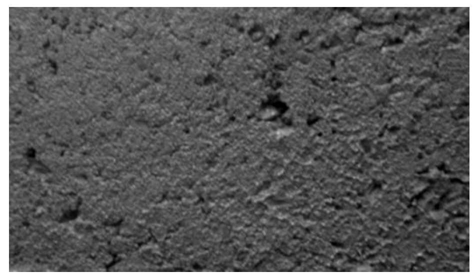
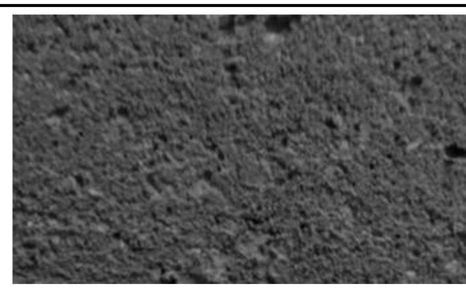


Fig. 5-12 shows varying the proportions of sand and a fixed ratio of coarse to intermediate aggregate with WR (oz./cwt) required to pass the Box Test.

Table 5-1 Concrete Surface with Different Volumes of Fine Sand

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

3.3.1 Distribution effects of fine sand ranges

Even though the sieve size limits were not exceeded, it was important to determine if the distribution of fine sand changes the proportioning amounts. To investigate this mixtures were created with combined gradations of the #16 sieve size and larger held at a constant ratio and the distribution of #30 through #200 were varied. Some of the most common extremes of natural fine sand were created with these different distributions. Fig. 5-13displays the different volumes of fine sand and the WR dosage required in the Box Test. These lines have a basic trend of positive slopping parabolas. When the fine sand volume in the mixture was not within a certain range, the WR dosage required increased dramatically. Using 12 oz. /cwt of WR as the boundary, a general volume range was determined to be 23% to 32% of fine sand (#30 through #200).

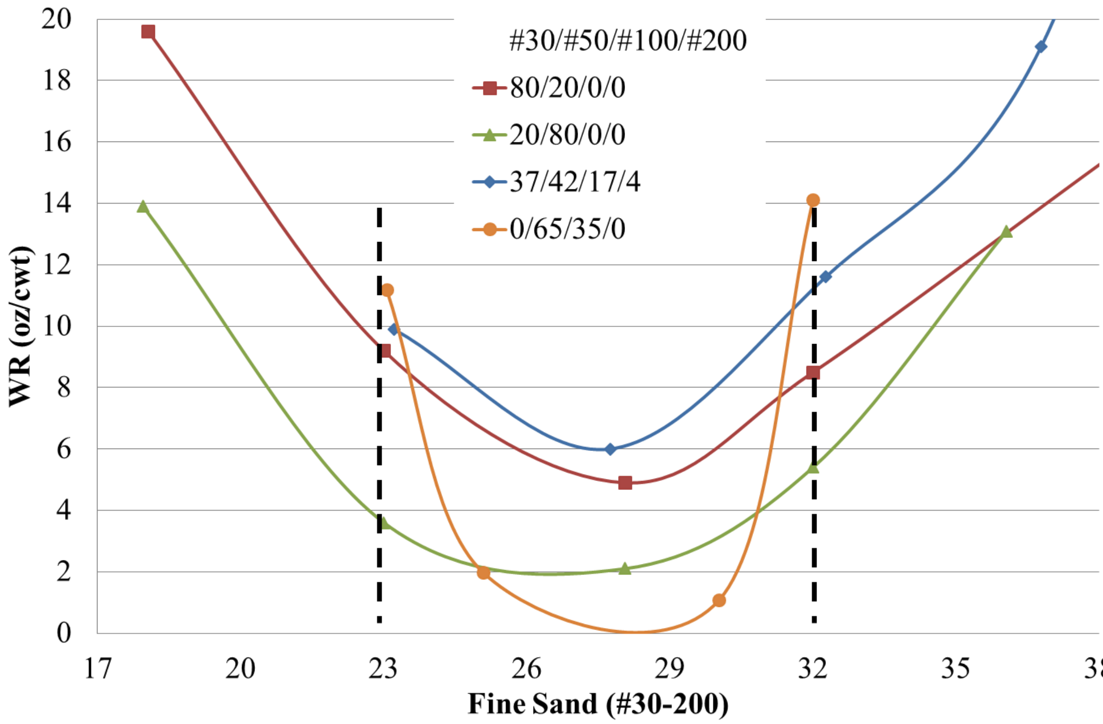


Fig. 5-13 displays various proportions of fine sand distributions verse WR (oz./cwt) required to pass the Box Test.

To further investigate this fine sand range, Fig. 5-14 uses various combinations of crushed limestone A, crushed limestone B, crushed river gravel, natural river sand A, and natural river sand B. These different coarse aggregate and fine aggregate sources had similar results as Fig. 5-13. Each line have a basic trend of positive slopping parabola. When the fine sand volume in the mixture was not within a certain range, the WR dosage required increased dramatically. Fig. 5-14 shows the fine sand (#30 through #200) range being about 24% to 34%.

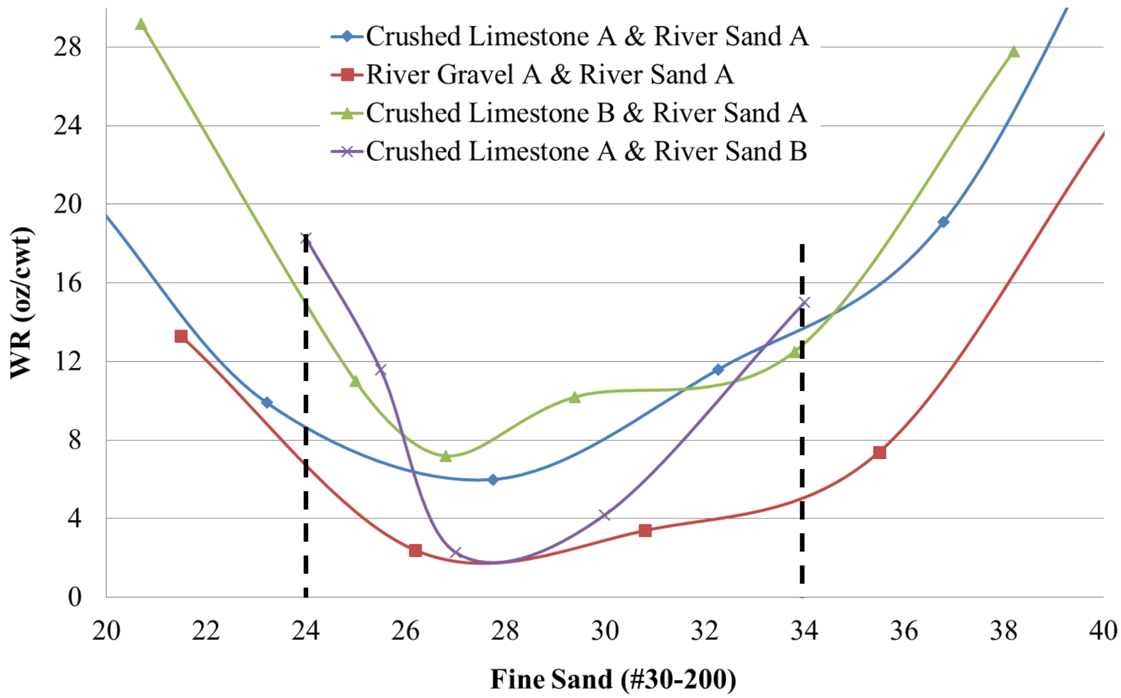


Fig. 5-14 displays various fine sand proportions of aggregate sources verse WR (oz. /cwt) required to pass the Box Test.

3.3.2 Fine Sand Recommendations

Even though Fig. 5-13 and Fig. 5-14 had various gradations and aggregate sources, the fine sand volume ranges were only slightly different by a percentage or two. For practical purposes a volume range of fine sand (#30 to #200) was recommended from 24% to 34%. More research could be conducted into this volume range with additional aggregate sources and gradations.

3.4 Recommended combined gradation limits

In this chapter and also Chapter 4, boundary limits for each individual sieve size were developed from 1 inch through the #100 sieve size. The maximum boundary limits were created due to poor workability performance of the individual sieve size. Surface finishability issues created upper limits of 12% for the #8 and #16 sieve. Minimum values on the #50, #30, #4, 3/8" and ½" sieve sizes were established from these sieves forcing higher values on other sieve sizes. Very little testing was done with 1.5” maximum nominal aggregate sizes and could not be included in this scope of work. A minimal volume on the #8 to #30 was needed to create cohesion in the mixture. Also, a volume range of fine sand (#30 to #200) was needed for satisfactory performance. The summary of the recommendations was given in Fig. 5-15.

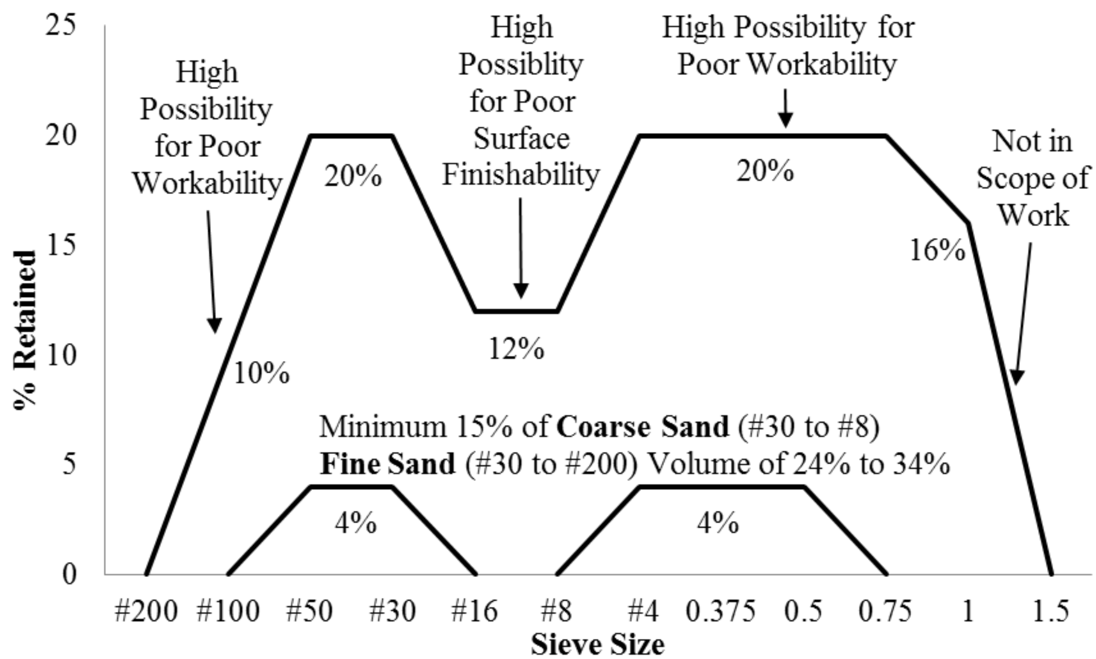


Fig. 5-15 Developed limits with coarse sand and fine sand ranges.

3.5 Practical Applications

This work was able to develop some basic and simple guidelines for proportioning the fine and coarse sand in a combined gradation. These gradation guidelines can be extremely beneficial to improve the construction specifications and practices. Furthermore, the guidelines give the ability of a mixture to reduce the total cementitious material content and thus decreasing the cost of the mixture, improving durability of the concrete, and reducing CO_2 emissions [1, 2, 4, 7, 20, 21].

3.6 Specific surface area mechanism behind gradation

The Surface area mechanism has been a continuous trended through most literature. To compare the specific surface areas and WR required to pass the Box Test, Fig. 5-16 was constructed. This figure and also Chapter 3 of this dissertation shows that surface area alone was not the single indicator for the workability of the concrete. More research needs to be conducted to understand the segregation problems of excessive particle size amounts and the role of fine aggregate into a gradation mechanism.

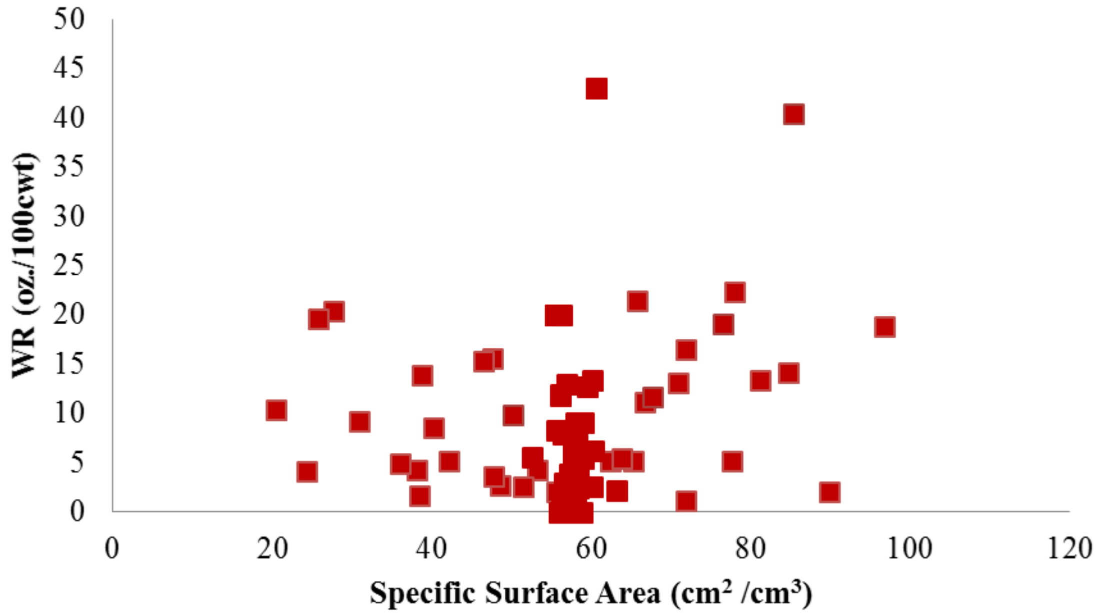


Fig. 5-16 shows the specific surface area versus WR dosage WR (oz./cwt) required to pass the Box Test.

4.0 Conclusion

Various fine aggregate concepts were investigated for a better understanding of the workability of slip formed paving concrete. Using the Box Test, the research shows that gradations have a significant impact on the workability of concrete mixtures for concrete pavements. Proportioning of aggregate can be a very complex issues. Based on the data collected using these specific aggregate sources, the following have been found:

- Coarse sand (#8 through #30) was shown to impact the cohesion of the mixture, which can lead to edge slumping and segregation. A value greater than 15% is suggested to be retained on the coarse sand (#8 through #30).
- Amounts over 12% on the #16 and #8 created surface finishing issues for the mixtures investigated.
- Also, retaining 20% of #30 created surface finishing issues for the mixtures investigated.
- Fine sand (#30 through #200) volume was recommend to range from 24% to 34% of the combined gradation.
- Smaller sieve sizes of #50, #100, and #200 give a smooth surface finish.

Understanding the gradation limits of an individual percent retained chart was a fundamental step into adequately proportioning aggregates. It allows for a better approach to predict workability and reduce the paste content of a mixture. Further research needs to be conducted into the mechanism behind gradation.

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CHAPTER VI

WORKABILITY TESTS FOR FLOWABLE CONCRETE APPLICATIONS

1.0 Introduction

The workability of concrete describes the ability of a concrete mixture to be mixed, placed, consolidated, and surface finished for a specific application [1, 2, 3, 4, 5, 6, 7]. These tasks require a mixture to obtain certain behavior characteristics such as a certain stiffness, flow, cohesiveness, richness, and surface finishability [1, 3, 4, 8]. If a concrete mixture does not obtain the required behavior performance, the workability of the concrete cannot be obtained and therefore the concrete is not suitable for the application [1, 3, 4, 8]. This is why many concrete producers make a trial batch and measure the workability of the designed mixture before using the mixture in production [1, 3, 4, 8].

One of the most sought-after achievements in the concrete industry has been a test to adequately measure the workability of the concrete [6, 8, 9, 10]. Most workability tests measure various properties of fresh concrete [6, 9, 10], but very few tests measure a useful workability property for a certain application [11]. For example, the Slump Test [12] has been the most specified workability test, but it measures the consistently of fresh concrete to fall under its own weight [13]. The ability of a mixture to fall will not dramatically indicate if the mixture will be suitable for building a floor slab or bridge deck. This inability to adequately measure the workability of concrete has created much controversy over the impacts of various mixture components effecting the workability of concrete and the dependability of any workability test to measure the workability of fresh concrete [8].

To complicate the issue further, various applications require completely different workability properties of fresh concrete. For example, a slip formed pavement requires a mixture to be flowable for consolidation, but stiff enough to hold an edge after the vibration has stopped [1, 11]. Yet, pumped concrete applications require higher flow mixtures for placement, which significantly reduces the emphasis on the consolidation behavior of fresh concrete [3]. Some current workability tests may give insights into this performance but they are not specific enough to give direct insights into how the concrete will be used.

1.1 Objectives

For this research, the focus of this work will be on the various workability properties of flowable concrete. The concrete must be flowable enough to be pumped and placed with ease. Also, the surface finishability of the mixture is also important. It is challenging for a test to measure both the flowability and surface finishability of a mixture. This chapter presents four ways to help evaluate the workability of flowable concrete.

2.0 Evaluation techniques for the workability of flowable concrete

The goal of a workability test should be to provide a standard measurement that precisely evaluates the important performance parameters of a mixture in the desired application. Unfortunately, a single workability test may not be able to measure every important workability property for an application. Four different tests were used to help evaluate the behavior of the concrete. These include: i.) Slump Test [12], ii.) visual observations, iii.) the Float Test, and iv.) ICAR Rheometer [14].

2.1 The Slump Test

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

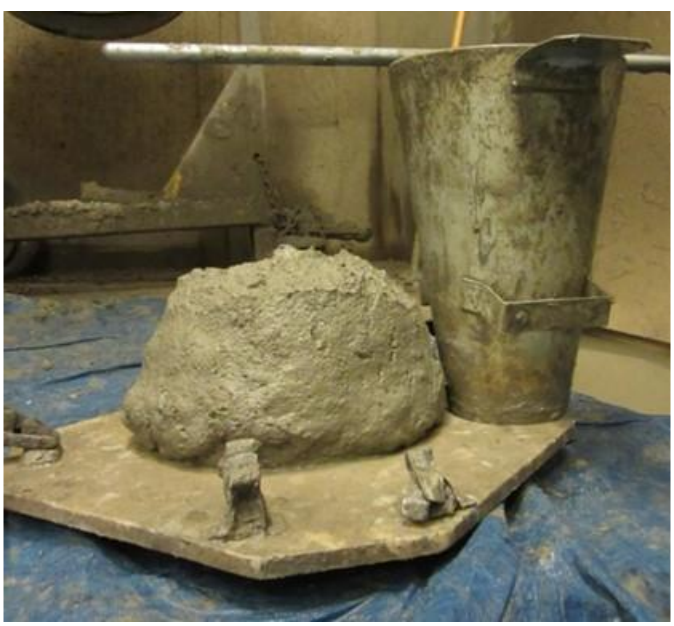


Fig. 6-1 shows the Slump Test being conducted on a flowable concrete mixture.

While the Slump Test has been widely used as a specification to evaluate workability, it has been commonly believed to be inadequate at measuring the workability of concrete in the field [8]. 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.” [13]. While this “sag” property of the concrete may have other uses in the quality control department, this property does not measure the ease at which a mixture can be mixed, placed, consolidated, or surface finished. Other tests are needed to measure the workability of concrete.

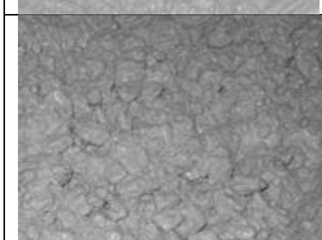
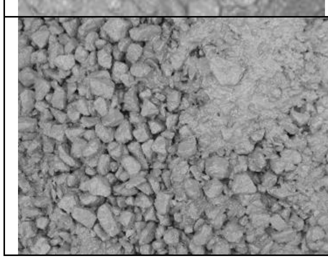
2.2 Visual Observations

Since meaningful workability tests have not be developed, contractors use visual observations to evaluate the workability of a concrete mixture [8, 15, 16]. The observations can be conducted by watching the concrete flow down a concrete chute, dragging the concrete with a come-along, or using a float to smooth the surface of the concrete to evaluate the surface finishability. These tasks require a mixture to obtain certain behavior characteristics such as a certain stiffness, flow, cohesiveness, richness, and surface finishability [1, 3, 4, 8]. While stiffness describes the resistance of concrete to movement, flow describes the ability of the concrete to continuously move [3, 4, 8]. Also, richness describes the amount of sand and paste in the mixture for proper workability [4, 8]. Mixture with poor richness may struggle to meet the desired workability requirements. Another behavior important behavior of concrete is the cohesiveness of the mixture to be homogenous and not segregate [1, 3, 4, 8]. This can have a dramatic impact on stiffness, flow, and surface finishability. The proceeding subsections discuss each performance behavior.

2.2.1 Cohesion

One of the most important properties of concrete is cohesion. This is the ability of the mixture to be a homogenous mixture while moving or at rest. Many times people refer to poorly cohesive mixtures as highly segregated mixtures. To assess the ability of the mixture to stay together, the five following performances were used: a mixture can be cohesive uniformly homogenous mixture (A), close to a homogenous mixture (B), minor amounts of segregation occur at rest, but not during motion (C), major amounts of segregation at rest, but only minor amounts in motion (D), and extreme amounts of segregation at rest or while in motion (F). Table 6-1 contains A, C, and F performance ratings with a visual example and description of the performance rating.

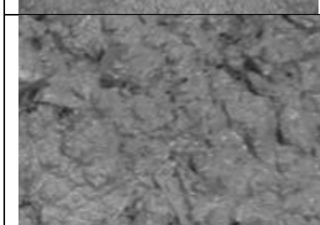
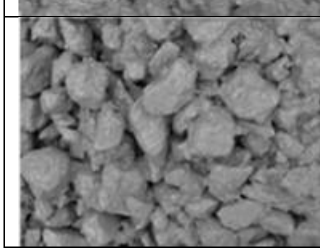
Table 6-1. Different Cohesion Performance Ratings

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

2.2.2 Richness

Another important behavior property of the concrete is richness. This describes the ability of a mixture to property proportion enough sand and paste to achieve the required workability performance of the concrete. Five different performance ratings were used to assesses the richness of a mixture and were as follows: well-proportioned amount of sand and paste (A), sufficiently proportioned amount of sand and paste (B), slightly Inadequately proportioned amount of sand and paste (C), inadequately proportioned amount of sand and paste (D), and impractically proportioned amount of sand and paste (F). Table 6-2 contains A, C, and F performance ratings with a visual example and description of the performance rating.

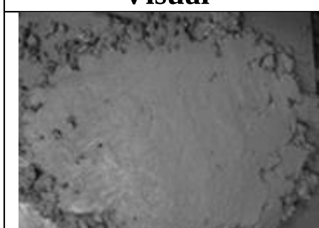
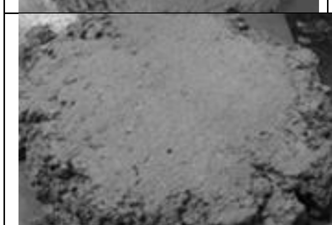
Table 6-2. Different Richness Performance Ratings

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

2.2.3 Finishability

Finishability of a mixture describes the effort required to adequately finish the surface. Five different performance ratings were used to assesses the finishability of a mixture and were as follows: Insignificant effort was required to adequately finish the surface (A), reasonable effort was required to adequately finish the surface (B), significant effect was required to adequately finish the surface (C), excessive effort was required to adequately finish the surface (D), unattainable effort was required to adequately finish the surface (F). Table 6-3 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 6-3. Different Finishability Behavior Performance Ratings

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

2.2.4 Flowability

Flowability of a concrete mixture describes the effort required to continuously move the concrete. Five different performance ratings were used to assesses the flowability of a mixture and were as follows: insignificant effort was required to continuously move the concrete (A), reasonable effort was required to continuously move the concrete (B), significant effect was required to continuously move the concrete (C), excessive effort was required to continuously move the concrete (D), and unattainable effort was required to continuously move the concrete (F). Table 6-4 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 6-4. Different Flowability Performance Ratings

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

2.2.5 Stiffness

Stiffness of a concrete mixtures describes the effort required to initiate movement of the concrete. Five different performance ratings were used to assesses the stiffness of a mixture and were as follows: insignificant effort was required to initiate movement of concrete (A), reasonable effort was required to initiate movement of concrete (B), significant effort was required to initiate movement of concrete (C), excessive effort was required to initiate movement of concrete (D), and unattainable effort was required to initiate movement of concrete (F). Table 6-5 contains A, C, and F performance ratings with a visual example and description of the performance rating.

Table 6-5. Different Stiffness Performance Ratings

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

2.2.6 Procedure for using visual observations

Currently, these visual observation methods are not the most scientific research technique or even consistently comparable between concrete finishers, but it has been very effective for determining the workability of concrete at the jobsite. This work aims to standardize some of the visual observations made by a contractor to assist in evaluating a concrete mixture through visual observations. The evaluation procedure for each behavior should be a simple and quick process. Table 6-6 contains a basic description of each behavior and the laboratory evaluation method question for each behavior properties of fresh concrete. The operator is required to evaluate and give a performance rating on an A through F scale for each of the five behavior characteristics. Like previously discussed, Table 6-1 through Table 6-5 can aid the operator in determining the rating of each behavior. After each performance behavior rating was determined, an average performance rating was calculated for the mixture. This average performance rating will be used as the final rating of the visual observation and described as the following: high workable mixture (A), respectable workable mixture (B), useable mixture (C), inadequate mixture (D), and not practical for the application (F).

Table 6-6 Visual Observation Evaluation Methods for Each Behavior

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

2.3 The Float Test

The workability of concrete not only describes the ability of how a mixture flows, but also to finish the surface. The surface of the concrete can be floated, troweled, straight-edged, broomed, tinned, edged, and jointed depending on the applications [3, 15, 16]. The initial surface process of floating removes voids, decreases texture, and further levels the concrete surface. This floating process is required before any of these other processes can be later accomplished [15]. In other words if the concrete was not adequately floated, it will later affect the other finishing processes.

2.3.1 Concept of the Float Test

A very common way to float the surface of the concrete has been to use a bull-float for removing surface voids and creating a smoother surface texture [3, 15, 16]. As shown in Fig. 6-2, this involves a flat rectangular piece of metal that glides over the surface of the concrete to fill in voids, remove texture, and further level the surface. Multiple passes can be required to glide over the surface of the concrete to achieve the desired surface finish. If a large number of passes was required to achieve the desired surface finish, the mixture had a poor ability to be surface finished. This number of passes required to fill in the surface voids and smooth the concrete surface can measure the ability of a mixture to be surface finished.

Fig. 6-2 shows the bull-float being used.

2.3.2 Developing the Float Test

To further develop the process of bull-floating into a laboratory test, the preparation of concrete samples and the parameters of the bull-float process had to be consistently controlled. As shown in Fig. 6-3, the sample dimensions of 2 ft. by 3 ft. with a thickness of 3.5 in. were chosen to provide enough room to adequately evaluate the surface finishability, to give proper aggregate cover, and to still limit the amount of concrete used. The fresh concrete was slightly overfilled into the sample form. Then any excess concrete can be removed with a strike-off board siting on the top of the forms at one end and being pulled to the other end of the forms with a consistent forward motion as shown in Fig. 6-4. This strike off motion was only a forward motion and not a sawing action due to this sawing action helping to create a smoother surface. If any low spots were created after the strike off, enough concrete was added to fill in the hole. Then using a template three standard holes with a 1 in. diameter and depth of 1 in. were created in the concrete surface of the concrete.

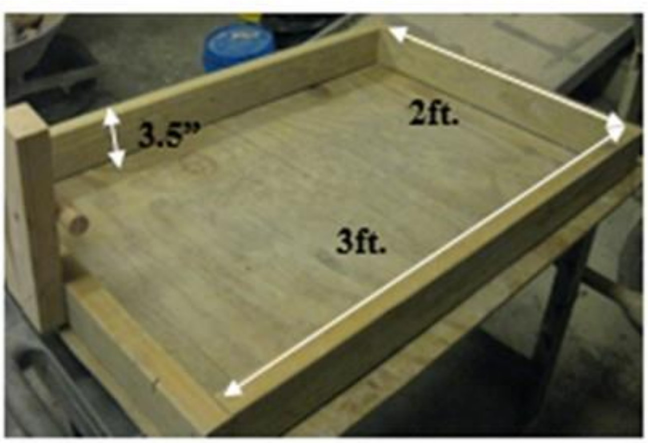


Fig. 6-3 shows the dimensions of the Float Test forms.

Fig. 6-4 shows concrete being striked-off.

Then a modified bull float was placed on the surface. This bull-floated was modified because in the field a bull-float may have a range of angles, weights, and speeds to allow for proper surface finishability of the concrete. However, to create a more consistent and repeatable test, the angle, weight, and speed of the bull-float was fixed to the following parameters: a fixed bull-float angle of the 2 degrees allowed a slight height tilt of less than 0.25 inch as shown in Fig. 6-2, the bull-float self-weight of 7.1 lbs. created a stress of 0.08 psi on the surface of the fresh concrete, and a constant bull-float speed of 0.5 ft. / sec measured with a metronome and marks on the side of the form. These parameters were selected to consistently and adequately allow the bull-float to properly finish the surface [3, 15, 16]. Fig. 6-5 describes the four steps involved in the Float Test.

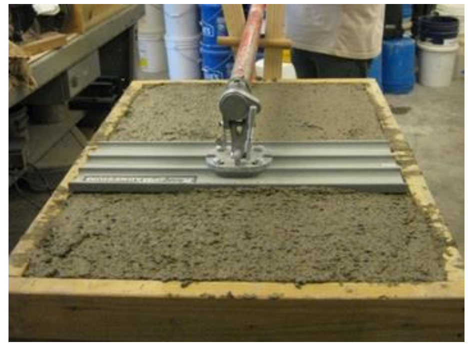
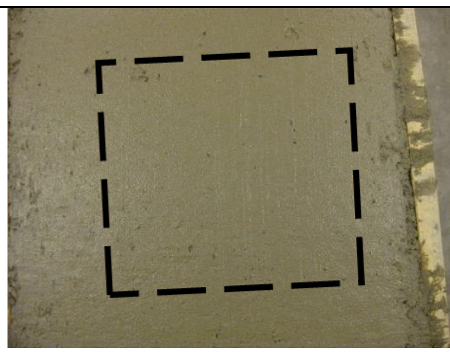
	
Step 1	Step 2
After placing and leveling the concrete with a strike off board, place template on the form and insert the 1” diameter dowel into the concrete to create a hole.	Place bull float on the surface. With a fixed upward tilt of 2 degree, move the bull float at a constant forward motion of 0.5ft/sec until it reaches the form. (This is one pass.)
	
Step 3	Step 4
Using only the middle 1.5 ft. square area, determine the texture scale and closing of the holes with Fig. 6-6 and Fig. 6-7.	If the texture was a 3 or greater or the hole was not removed, the bull float passed back and forth until the texture was 2 or smaller and the hole closed.

Fig. 6-5 displays the four steps of the Float Test**.**

2.3.3 Evaluation of the Float Test

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

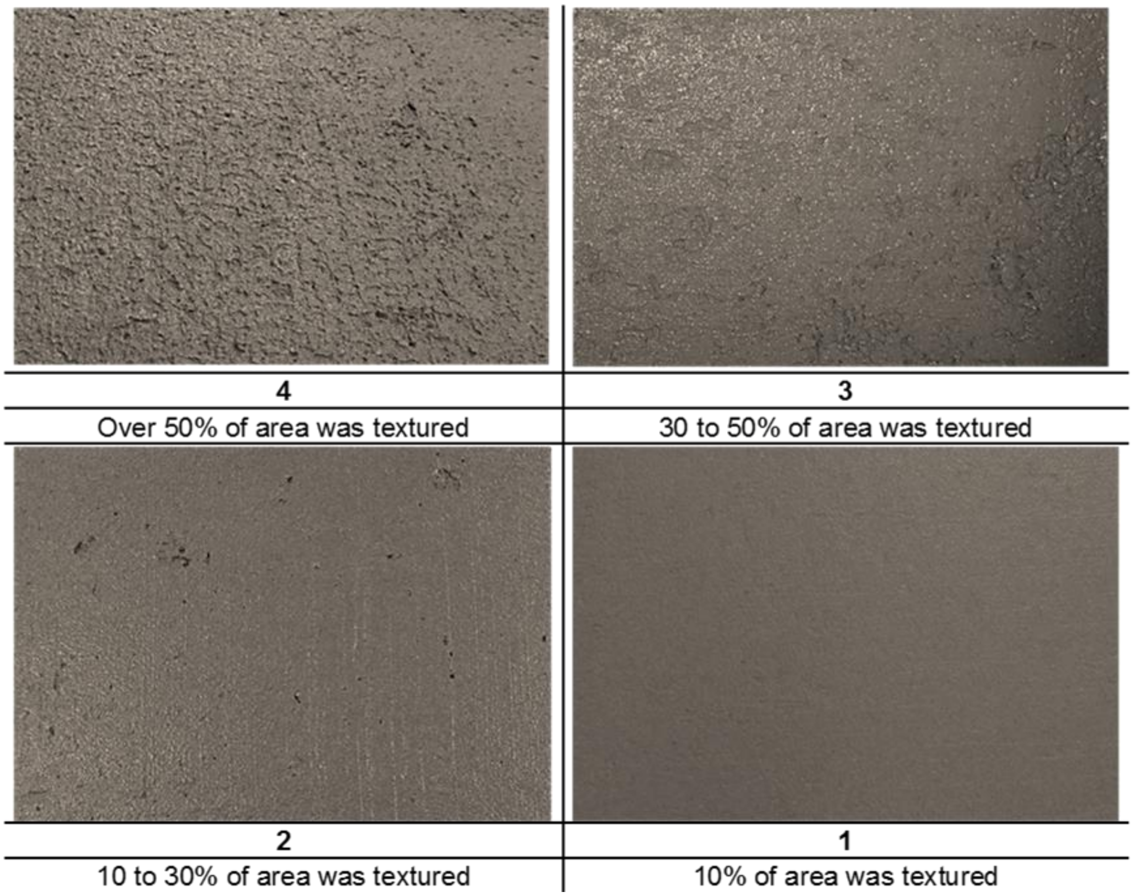


Fig. 6-6 displays the percentage and numerical textured values of Float Test.

Another quantifiable measurement was to determine the ability of the concrete to fill in the created holes. To further measure this behavior, three standard holes with a 1 in. diameter and depth of 1 in. were created in the concrete surface. These holes are supposed to represent holes that are sometimes present from removing large aggregate by strike off of the surface. Fig. 6-7 shows the removal of the holes through the bull-float passing over the surface each time.

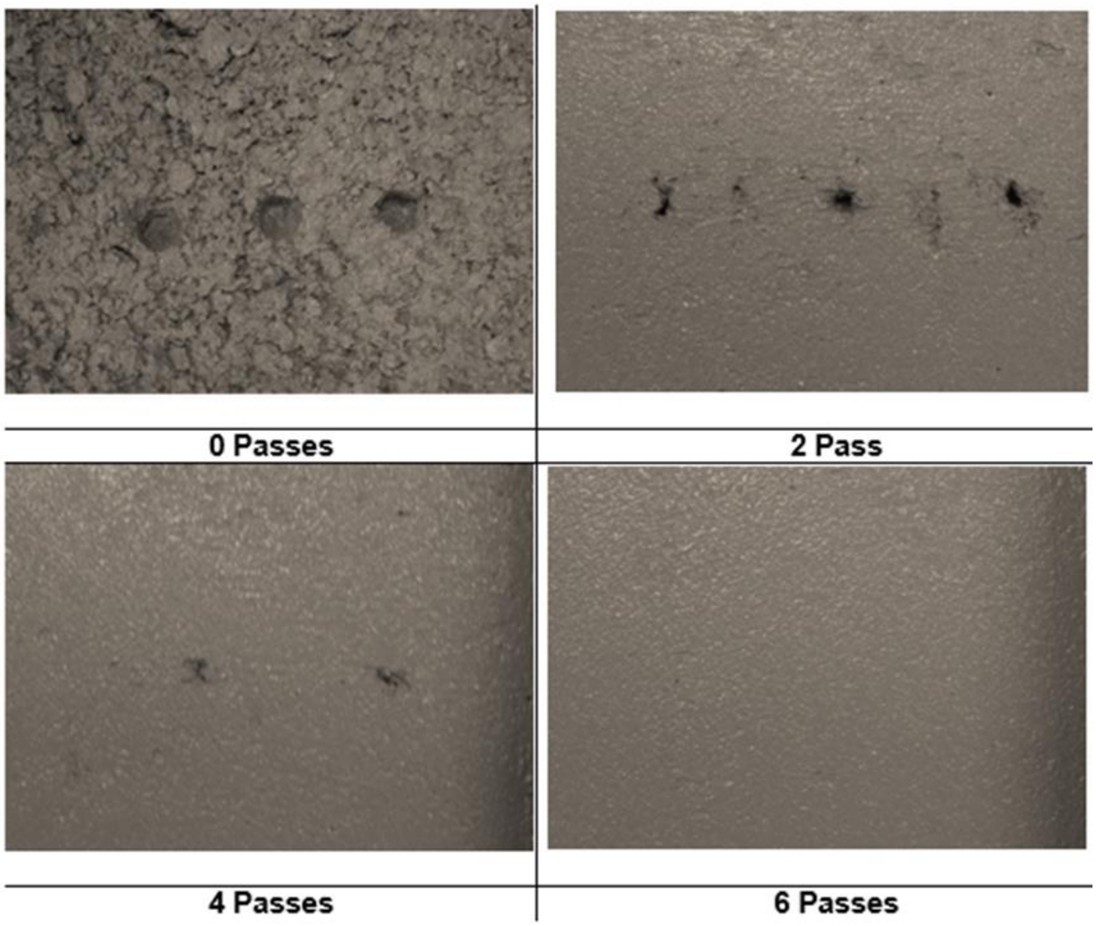


Fig. 6-7 shows an example of the three holes closings from each bull-float pass**.**

2.4 Rheology

Critical workability parameters of fresh concrete has been the flowability properties of a mixture, which are also called the rheological properties of fresh concrete [3, 6, 14, 17. 18]. Since concrete is a thixotropic fluid [17, 18], the rheological measurements can be broken down into the static yield stress, dynamic yield stress, and the plastic viscosity [14, 18]. While the static yield stress measures the minimum stress to initiate flow, the dynamic yield stress is the minimum stress to maintain flow. The plastic viscosity can be described as the ability to resist flow. A description and example of each parameter is described in Table 6-7.

Table 6-7. Rheological Parameters

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

To measure the rheological properties in a concrete mixture, the ICAR rheometer [14] was developed with a four bladed paddle vane as shown in Fig. 6-8. Through other research, validations of the ICAR rheometer was completed on the parameters and standard equipment of the ICAR rheometer such as vane type, dimensions of vane, container dimensions, stress growth test speed, and flow curve test speeds [14]. Test procedure validations for testing a concrete mixture using an ICAR Rheometer were summarized in the following:

1. After mixing, hand scoop the concrete into the rheometer container. (1.5 minutes)
2. Reset the torque on the rheometer in the air.
3. The rheometer was inserted vertically into the container. (At 2 minutes after mixer stopped)

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

Fig. 6-8 shows the rheometer finding the flowability properties of a mixture.

2.5 Developing a performance scale for flowable concrete applications

Four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table

6-8 was developed to represent flowable concrete workability performances. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Table 6-8. Workability Performance Rating System

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

2.6 Quantifying workability assessments

After analyzing the data and comparing each workability test for flowable concrete applications, the quantity of measurements needed to be simplified into a practical manner. In other words, these seven different measurements were quantified into a single overall workability performance rating for a given mixture. This was completed by taking the average workability performance of each measurement as classified in Table 6-5. After the average numerical value was calculated, it was converted back into the following workability scale range: excellent (1), good (1-2), moderate (2-3), poor (3-4), and unusable (4-5). For an example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would mathematically be 1.43 and be classified as a good overall workability.

2.7 Further work

Even though the four different workability test were developed, validations still need to be conducted into the repeatability of each test. It is recommended for an investigation to be conducted using ten different mixtures with various workability performances, paste volumes, water reduce dosages, and even different aggregate proportions. Each test should be repeated three times per mixture. Furthermore, the ten mixtures should be duplicated with another operator. The visual observation rating should have at least four different operators to compare the variability between operators. This is being carried out by another student for their graduate work [19].

3.0 Concluding remarks

The workability of flowable concrete applications was introduced. Also, four different workability tests were introduced to evaluate the workability for flowable concrete applications. These four tests can evaluate the concrete in eleven different ways. The following can be stated about the different workability tests.

- The slump test has been the most commonly specified workability test, but it cannot measure the wide range workability performance criteria of concrete.
- Visual observations is used most often in the field.
- The ICAR Rheometer can measure the rheology parameters of static yield stress, dynamic yield stress, and plastic viscosity.

- The Float Test measures the ability of a concrete mixture to be adequately surface finished.

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CHAPTER VII

INVESTIGATION OF COARSE AGGREGATE GRADATION ON THE WORKABILITY OF FLOWABLE CONCRETE APPLICATIONS

1.0 Introduction

A concrete mixture is commonly composed of only a single coarse aggregate and fine aggregate [1, 2, 3, 4, 5, 6]. While these aggregate gradations typically meet the standards of ASTM C 33[5, 7], the gradations standards were established to be most economically produced and not necessarily the best performance in a concrete mixture [8]. Furthermore, many different approaches and aggregate concepts have been used to guide the design of the proportion and gradation aggregates [2, 3, 5, 6, 7, 10]. Some of these include numerical packing methods [11, 12, 13, 14, 15], surface area estimations [6, 10, 16, 17], and graphical combined gradation techniques based on practical experience [1, 6, 18].

When a concrete mixture was poorly proportioned or obtains a poor gradation, the workability performance of the concrete can be negatively impacted [1, 2, 3, 4, 5, 6]. In some cases adjustments of larger admixture dosages or a higher volume of paste (water and binder) can achieve the desired workability [1, 2, 3, 4, 5, 6, 19]. Higher volumes of paste can cause greater overall cost, decrease in durability, and lower sustainability of the produced structure [2, 4, 18, 20, 21]. Unfortunately, very little published work has systematically quantified this relationship [6, 10, 22, 23, 24, 25].

In Chapters 3, 4, and 5 of this dissertation has been used to quantitatively compare mixtures various aggregate concepts and proportioning techniques and the workability of concrete for slip formed pavements. The combined gradation with the Individual Percent Retained (IPR) chart best predicted the impact of the aggregate gradation and proportioning for the workability of concrete in slip formed pavements.

1.1 Objectives

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

2.0 Materials and methods

2.1 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [26] with 20% ASTM C 618 [27] class C fly ash replacement by weight. To investigate the impact of the aggregate gradation, all of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 564 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 32.2% for the mixture volume. A constant water reducer (WR) of 6 oz. /cwt was used in every mixture to help emphasize the higher flowability properties of each mixture. This WR was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [28]. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

2.2 Mixture design

Again, each mixture had a constant paste volume of 32.2% with w/cm of 0.45, 564 lbs./cy of cement, 20% class C fly ash replacement, and 6 oz. /cwt of WR. Then aggregate gradations and aggregate proportions were change to adequately evaluate the impacts of the workability. Table 7-1 shows the seventy five different batch weights used in this study. Many of the mixtures use a coarse, intermediate, and fine aggregate to proportion the combed gradation. Three crushed limestone sources and three natural sand sources were used to evaluate and validate the aggregate proportioning limits. One coarse aggregate source and one natural sand source were used to evaluate gradation limits, but two different coarse aggregate sources and two different natural sand sources were used to validate these results. Many of the gradations were sieved to evaluate the different gradation limits and cannot be classified according to any standard gradation system.

Table 7-1. Batch Weights

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

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

2.3 Sieve procedure for creating a gradation

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

2.4 Mixing and testing procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken to determine the moisture content to apply the correction. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump Test [29], visual observations, ICAR rheometer, and the Float Test. These Test can be further explained in Chapter 6 of this dissertation.

2.5 Using the workability tests to evaluate flowable concrete

Four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table 7-2 was developed to represent flowable concrete workability performance. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Table 7-2. Workability Performance Rating System

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

2.6 Quantifying workability assessments

After analyzing the data and comparing each workability test for flowable concrete, the quantity of measurements needed to be simplified into a practical manner. In other words, these seven different measurements were quantified into a single overall workability performance rating for a given mixture. This was completed by taking the average workability performance of each measurement as classified in Table 7-2. After the average numerical value was calculated, it was converted back into the following workability scale range: excellent (1), good (1-2), moderate (2-3), poor (3-4), and unusable (4-5). For an example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would mathematically be 1.43 and be classified as a good overall workability.

3. Results and discussion

The purpose of the research was to develop coarse aggregate sieve sizes (#4 and larger) limits for a combined gradation in order to better control the workability of a concrete mixture design. To achieve this, the workability of seventy-five mixtures were evaluated as shown in Table 7-3. This table was color coated with black representing good or excellent workability performance, yellow representing moderate workability performance, and red representing poor or unusable workability performance. Also through the results, the combined gradation of each mixture will be plotted using the individual percent retained chart with the overall workability rating.

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

Table 7-3. Workability Performance Rating System

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

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

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

3.1 Coarse and intermediate gradation

To begin investigating the minimum and maximum gradation limits, Fig. 7-1 shows gradations with a fairly constant sand, but varying coarse to intermediate aggregate volumes with the overall workability performance. The four middle gradations have an overall good workability for flowable concrete. However, when the amount of coarse or intermediate for a given aggregate became excessive on a single sieve or multiple sieves then the workability drastically decreases. This intense amount of intermediate and large coarse aggregate can be further shown visually in Fig. 7-2 and also the Slump Test in Fig. 7-3. The data suggests the coarse aggregate sieve sizes (#4 through ¾”) becomes excessive at 20% retained on a sieve size. This will be a continuous trend throughout this investigation and a maximum limit of 20% should be set at this value.

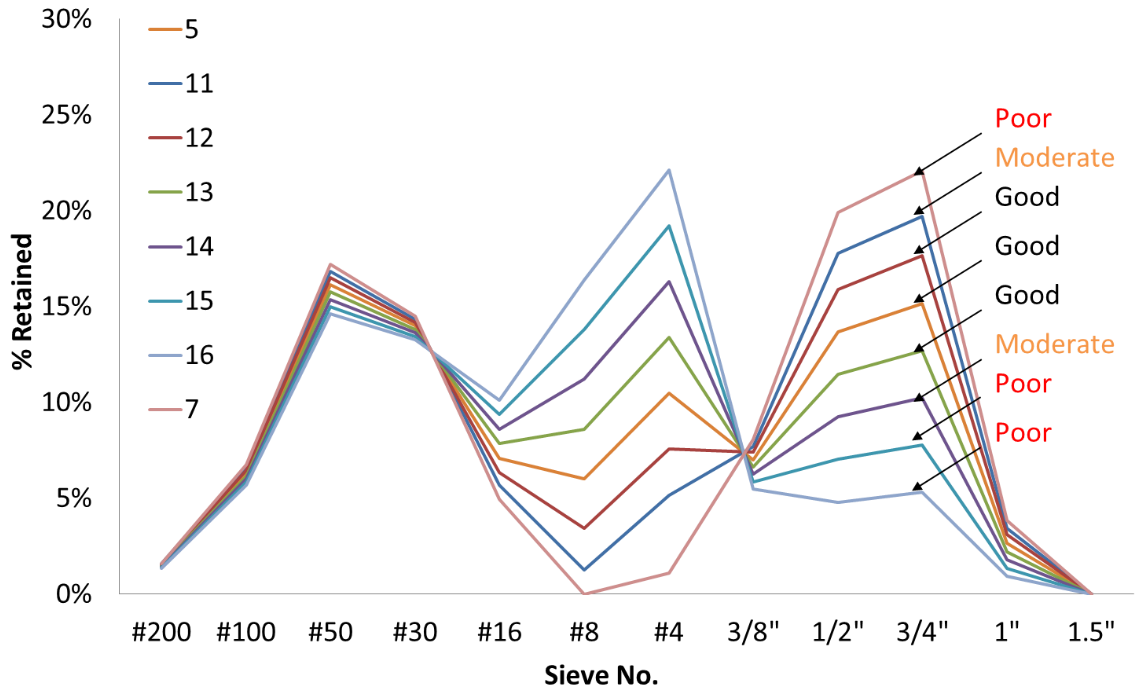


Fig. 7-1. Varies coarse to intermediate gradations with overall workability performance.

Fig. 7-2. Displays the visual observations of excessive amounts of coarse and intermediate sieve sizes**.**

Fig. 7-3. Shows the Slump Test measuring the excessive amounts of coarse and intermediate sieve sizes.

3.1.1 Using other Aggregate Sources

One coarse aggregate source and one sand source was used to investigate many of the gradation concepts. Two more crushed limestone sources and two more natural sand sources were selected to further validate the findings. Fig. 7-4 uses limestone B and sand B and Fig. 7-5 plots limestone C and sand C.

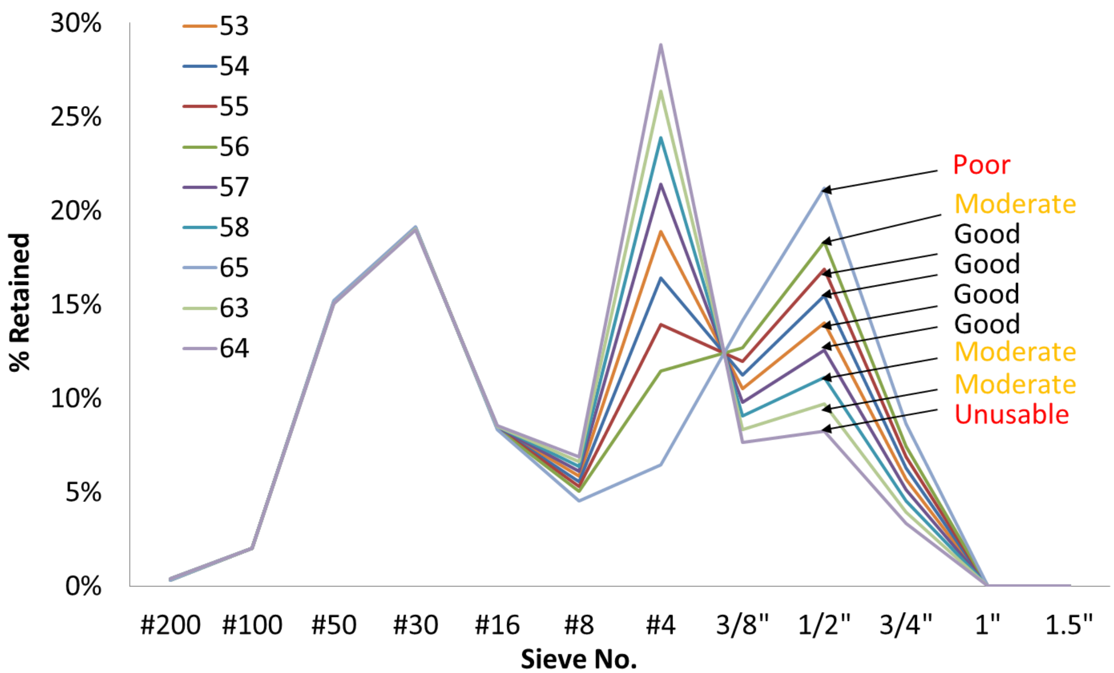


Fig. 7-4. Shows the overall workability of Limestone B.

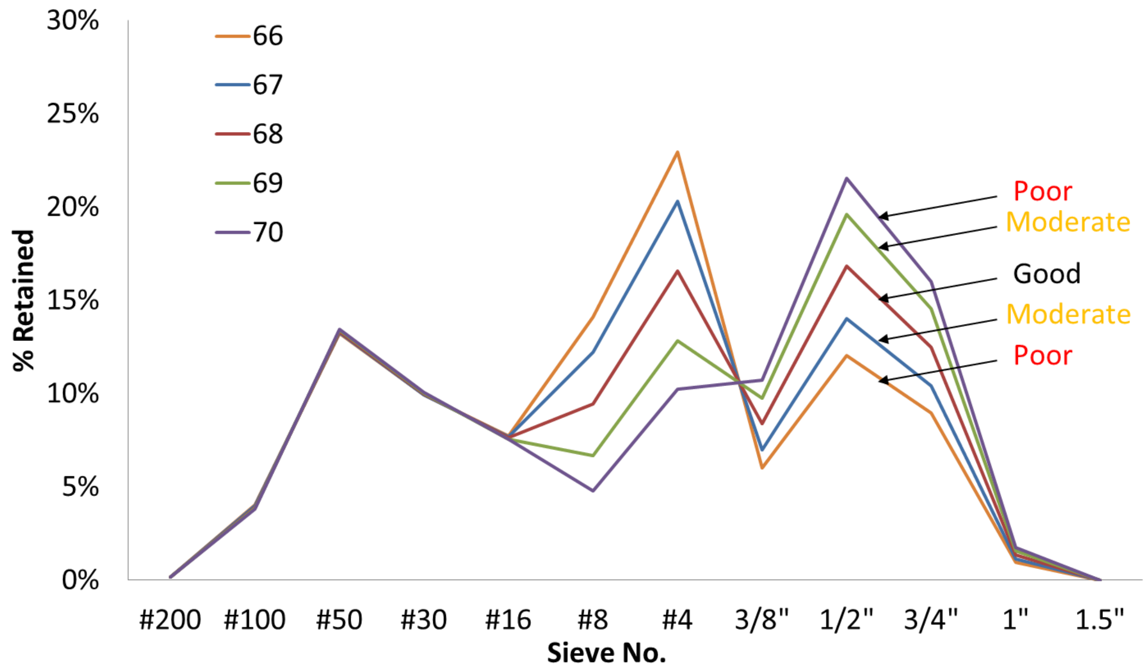


Fig. 7-5 shows the overall workability of Limestone C.

3.1.2 Maximum boundary limit

Due to excessive amounts of a sieve size create workability problems, maximum sieve size limits from the field have been proposed and range from 15 to 22 % for each sieve size [6, 30, 31]. The results of this work showed excessive amounts can create workability issues. Even though the maximum limits did slightly vary, a simple gradation limit of 20% could be set for a single sieve size ranging from #4 to 0.75". The 20% retained on the #4 to 0.75" sieve size range will be a reoccurring trend throughout these results and serve as a key finding of this work. These results also matches the recommendations made for slip formed pavements in Chapter 4 of this dissertation.

3.2 Theoretical bell shaped curve

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

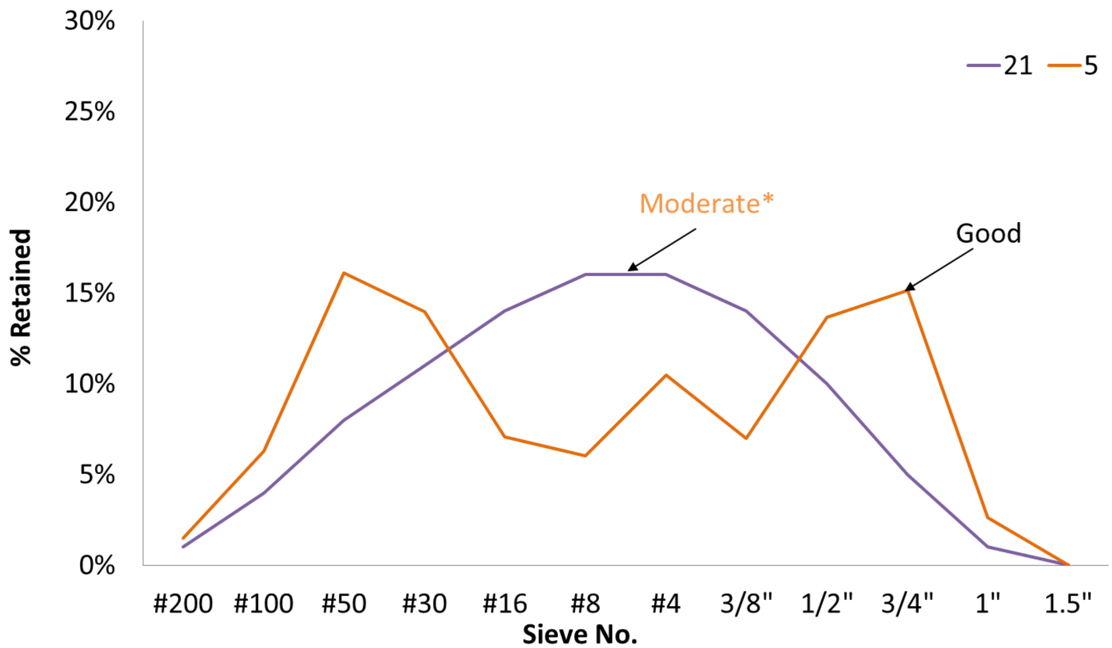
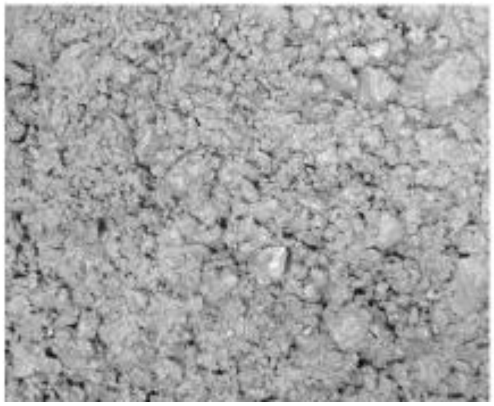


Fig. 7-6 compares the overall workability of the theoretical bell shaped curve with a practical gradation**.** *note: this mixture had surface finishability issues.

Before Finishing



After 8 Passes

Fig. 7-7 compares the visual observation bell shaped curve with a practical gradation.

3.3 Minimum boundary

Several of the gradations in this research have contained “low” values of certain aggregate sizes. These low spots in the gradation have been called “valleys” and are commonly thought to reduce the workability of the mixture and should be avoided. To investigate the impacts of valleys on gradation curves, Fig. 7-8 shows combined gradations containing a valley, a double valley, and a gradation used in the field. The workability performance of the mixture did not drastically change if gradation had a single or a double valley. It should be noted that while changing the gradation of this mixture no single sieve size was greater than 20%.

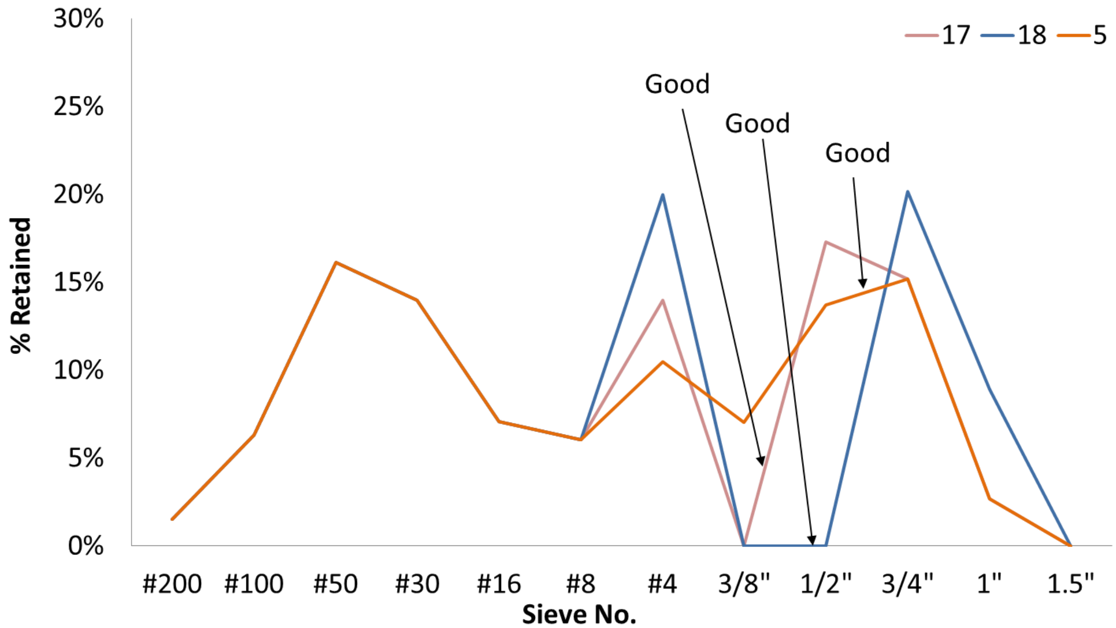


Fig. 7-8 displays the overall workability from a single and double valley.

3.3.1 Developing a minimum boundary

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

3.4 Nominal maximum coarse aggregate size

Multiple mixture design methods and publications claim the maximum size of the coarse aggregate affects the workability of the concrete [1, 2, 3, 4, 32]. To determine the validity of these claims, ½", ¾", and 1" maximum size gradations were evaluated in Fig. 7-9. Each gradation was designed to have similar sand contents and no sieve size above 20%. The results show gradations with various maximum sizes can produce satisfactory mixtures with no significant differences in workability. This data suggests that the guidance of only increasing the aggregate size by itself does not lead to an improvement in the workability of a mixture. However using a larger maximum aggregate size is beneficial because it more easily produces an aggregate gradation that does not have an excessive amount of material on a single sieve size. In other words, it gives the producer a larger number of sieves to distribute their gradation without creating an excessive amount on a single sieve size.

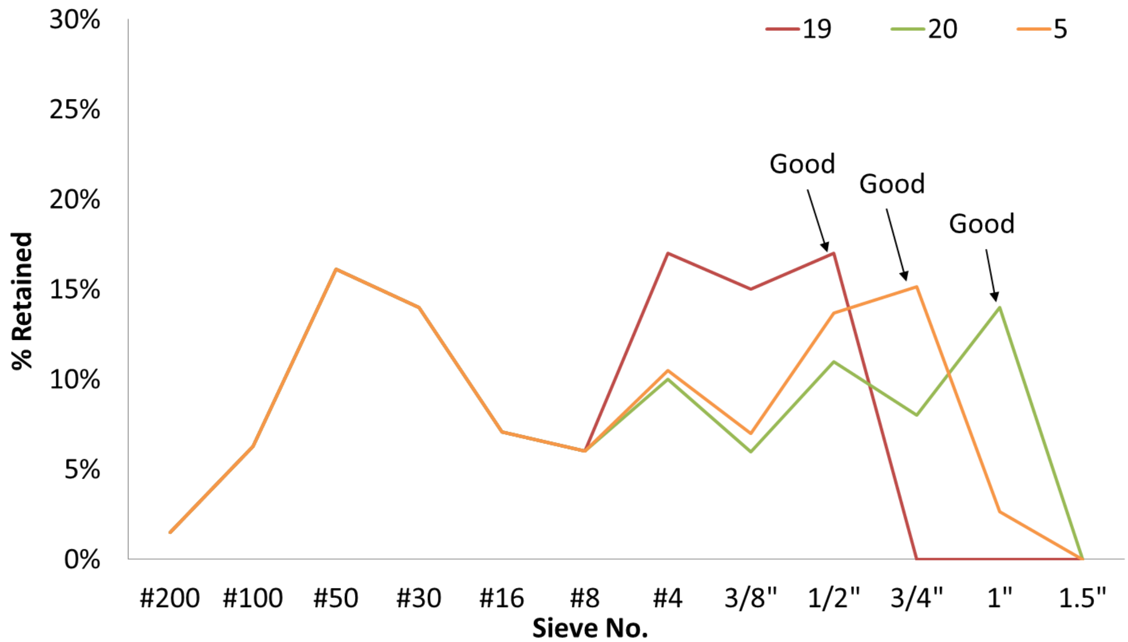


Fig. 7-9 compares the overall workability of the different maximum sieve sizes with closely consistent sand amounts.

3.5 Recommended boundary limits

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

3.6 Well-graded vs. gap-graded

Even though well and gap-graded definitions are broad, Fig. 7-1 shows that more well-graded and gap-graded mixtures could both perform well as long as the gradations did not increase above 20%. The three gradations that were concentrated in the "middle of the chart had similar WR even though the degree of gaps were drastically different. Even in Fig. 7-6, an idea bell shape curve and many other practical gradations had similar workability. This shows a combined gradation does not have to be well-graded or gap-graded. Multiple varieties of gradations will all perform similar.

3.7 Practical applications

This work was able to develop some basic and simple guidelines for proportioning the coarse aggregate sieve sizes in a combined gradation. These gradation guidelines can be extremely beneficial to improve the construction specifications and practices. Furthermore, the guidelines give the ability of a mixture to reduce the total cementitious material content and thus decreasing the cost of the mixture, improving durability of the concrete, and reducing CO_2 emissions [1, 2, 21].

4. Conclusion

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

- If a single sieve size of the coarse aggregate (#4 and larger) retained more than 20%, the workability performance of the concrete would tend to decrease.

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

The gradation and proportioning of fine aggregate is essential to understanding and developing concrete mixtures with the ability to be placed, consolidated, and surface finished. Understanding the gradation limits of an individual percent retained chart is a fundamental step into adequately proportioning aggregates. This will allow for a better approach to predict workability and reduce the paste content of a mixture. These findings were very similar to the results in Chapter 4 and will be discuss more in Chapter 10 of the Conclusions. Also, the impacts of aggregate characteristics needs to be further investigated.

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CHAPTER VIII

INVESTIGATION OF FINE AGGREGATE GRADATION ON THE WORKABILITY OF FLOWABLE CONCRETE APPLICATIONS

1.0 Introduction

One of the most important properties of concrete is workability, which has been commonly described as the ability of a concrete mixture to be mixed, placed, consolidated, and surface finished in desirable manner [1, 2, 3, 4, 5, 6]. One contributor to this property is fine aggregate [3, 5, 6, 7]. A concrete mixture should be proportioned with an adequate volume and gradation consistency of fine aggregate. For surface finishing of concrete, fine aggregate gives the ability of the concrete mixture to be surface finished [3, 5, 6, 7] and also to be cohesive and not edge slump or segregate [1, 3]. People have used the phrases "fine sand" and "coarse sand" to describe the consistency for the particle distribution of the fine aggregate gradation and the relationship to the workability properties of concrete [3, 8, 9]. These two phrases have given powerful meanings. While fine sand helps contribute to the smooth surface finishability and consolidation of the concrete [2, 3], coarse sand helps to "stiffen up" the concrete mixture to prevent segregation [1, 10, 11].

A variety of fine aggregate gradations can be used to adequately proportion a concrete mixture [3, 5], but this gradation should not get “too coarse of sand or “too” fine of sand. Unfortunately, very little published work has systematically quantified this relationship [5, 9, 12, 13, 14, 15].

In Chapters 3, 4, and 5 of this dissertation has been used to quantitatively compare mixtures various aggregate concepts and proportioning techniques and the workability of concrete for slip formed pavements. The findings suggest a combined gradation based on the Individual Percent Retained (IPR) chart best predicted the impact of the aggregate gradation and proportioning for the workability of concrete for slip formed pavements.

1.1 Objectives

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

2.0 Materials and methods

2.1 Materials

All the concrete mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [16] with 20% ASTM C 618 [17] class C fly ash replacement by weight. To investigate the impact of the aggregate gradation, all of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, 564 lbs./cy of cement, 20% class C fly ash replacement, and a paste content of 32.2% for the mixture volume. A constant water reducer (WR) of 6 oz. /cwt was used in every mixture to help emphasis the higher flowability properties of each mixture. This WR was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [18]. However, the aggregate proportions were changed. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

2.2 Mixture design

To investigate the impact of the aggregate gradation, all of the mixtures were designed with the same paste properties: a water-to-cementitious material ratio (w/cm) of 0.45, a paste content of 32.2% of the mixture volume, and 20% class C fly ash replacement. However, the aggregate proportions were changed. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

Table 8-1 shows the seventy five different batch weights used in this study. Many of the mixtures use a coarse, intermediate, and fine aggregate to proportion the combed gradation. Three crushed limestone sources and three natural sand sources were used to evaluate and validate the aggregate proportioning limits. One coarse aggregate source and one natural sand source were used to evaluate gradation limits, but two different coarse aggregate sources and two different natural sand sources were used to validate these results. Many of the gradations were sieved to evaluate the different gradation limits and cannot be classified according to any standard gradation system.

Table 8-1. Batch Weights

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

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

2.3 Sieve procedure for creating a gradation

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

2.4 Mixing and testing procedure

Aggregates were collected from outside stockpiles and brought into a temperature-controlled room at 72°F for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken to determine the moisture content to apply the correction. At the time of mixing all aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregate surface to saturate and ensure the aggregates were evenly distributed. Next, the cement material and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included Slump Test [20], visual observations, ICAR rheometer, and the Float Test. These Test can be further explained in Chapter 6 of this dissertation.

2.5 Using the workability tests to evaluate flowable concrete

The four different workability tests were used to collect seven different workability measurements of fresh concrete. However, a performance scale for any of these tests has not been well-established. For example, even though the Slump Test has been the most well-established of these workability tests, only a broad range of values can be stated to most likely achieve the desired performance. The workability performance scale needs to be constructed for interpreting the data. After communicating with ten different concrete finishers and using visual observations to find performance trends of each parameter, Table 8-2 was developed to represent flowable concrete workability performances. Each workability measurement has a practical performance range for the application. Also, the workability rating scale was developed specifically for this research and should not necessarily be used as a specification for accepting or rejecting a mixture. These five different classifications of excellent through unusable will further give insights into the workability performance.

Table 8-2. Workability Performance Rating System

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

2.6 Quantifying workability assessments

After analyzing the data and comparing each workability test for flowable concrete applications, the quantity of measurements needed to be simplified into a practical manner. In other words, these seven different measurements were quantified into a single overall workability performance rating for a given mixture. This was completed by taking the average workability performance of each measurement as classified in Table 8-2. After the average numerical value was calculated, it was converted back into the following workability scale range: excellent (1), good (1-2), moderate (2-3), poor (3-4), and unusable (4-5). For an example, if a mixture received the following rating: excellent (1) for visual observations, good (2) for Slump Test, excellent (1) for the Float Test in smoothness, excellent (1) for the Float Test in closing holes, good (2) for static yield stress, good (2) for dynamic yield stress, and excellent (1) for plastic viscosity, the average overall workability rating would mathematically be 1.43 and be classified as a good overall workability.

3. Results and discussion

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

Table 8-3. Workability Performance Rating System

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

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

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

3.1 Proportioning Fine Sand

Traditionally fine aggregate has been defined as the material retained on the #8-200 sieve sizes [7]. A concrete mixture must contain a certain amount of fine aggregate to accomplish placement, consolidation, and surface finishing for the desired application. This fine aggregate behavior has been further broken down into coarse sand and fine sand to better understand this behavior. From Chapter 5 of this dissertation, the fine sand sieves were found to be #30 through #200 and the coarse sand sieves were from #8 through #30. Fig. 8-1 shows varying amounts of sand with a constant ratio of the coarse to intermediate aggregate. Without exceeded the developed sieve size limits shown later in the results section, various combined gradations will be investigated to determine adequate volume proportioning ranges for fine aggregate.

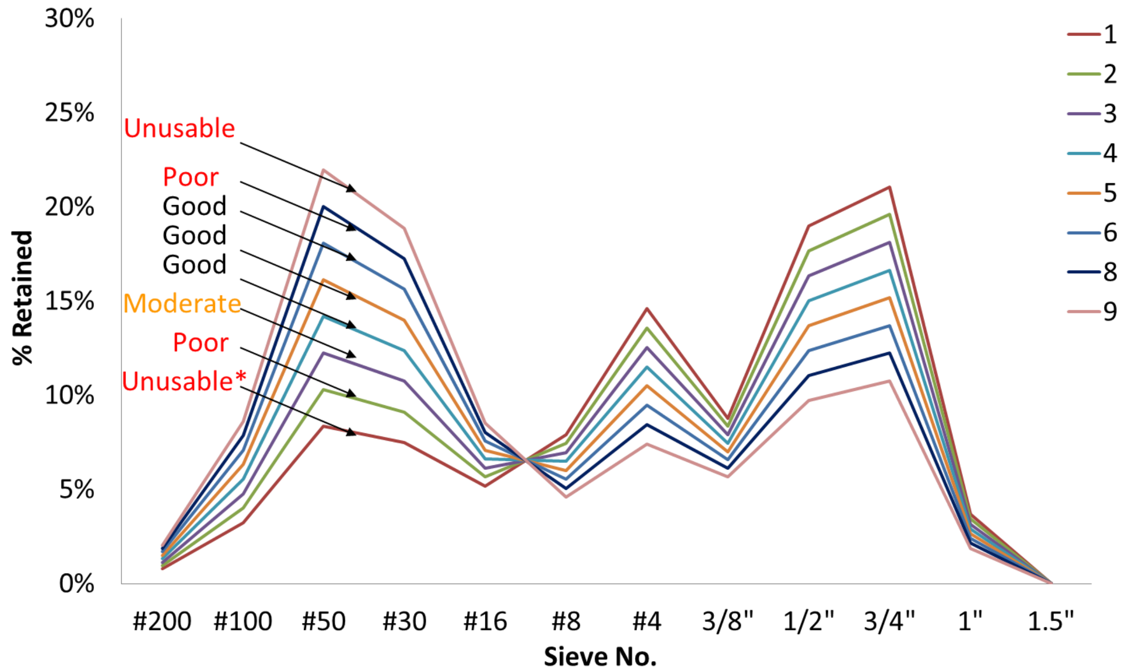

Fig. 8-1 show the overall workability with different amounts of sand and fixed ratio of coarse to intermediate aggregate. *note: this mixture had surface finishability or cohesion issues.

Fig. 8-1 shows a logical trends of workability and fine sand volume. If the gradation was proportioned with inadequate volume amounts of “too much” or “too little” fine sand, the workability was poor. Fig. 8-2 shows the visual pictures of low, sufficient, and high amounts of fine sand. Also in Fig. 8-3, a visual picture of the low, sufficient, and high amounts of fine sand mixtures being conducted with the Slump Test. When the volume of fine sand was low in the mixture, the mixture looked like coarse aggregates coated with a small film of paste as shown in Fig. 8-2 and Fig. 8-3. This low sand volume mixture visually flowed like a coarse aggregate stockpile. Also the low sand mixture was discharged from the mixing and into a wheel barrow. Fig. 8-4 was a picture shows the poor exhibited poor cohesion properties as shown in Fig. 8-3. When excessive volumes of fine sand were used, the mixture became "sandy", which created a very stiff and poor flowability properties.

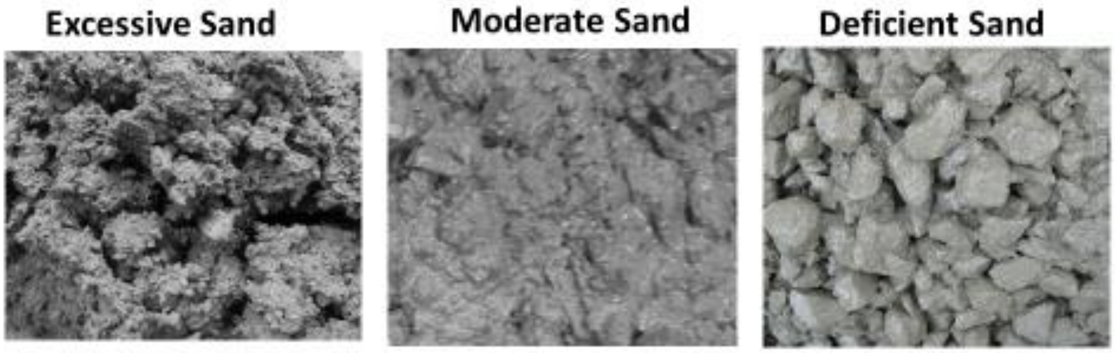

Fig. 8-2 shows from visual observation the excessive and deficient amounts of sand.

Fig. 8-3 shows the Slump Test measuring the excessive and deficient amounts of sand.

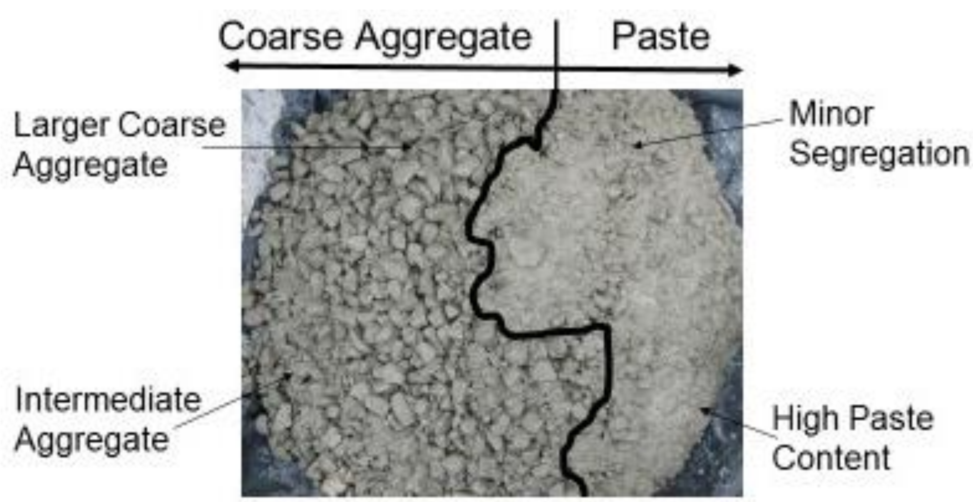

Fig. 8-4 shows from visual observation the deficient amounts of sand had major segregation issues.

3.1.1 Developing proportioning limits for fine sand

Other sources were needed to help develop fine sand volume proportioning limits. Fig. 8-5 and Fig. 8-6 both different aggregate sources with varying amounts of sand with a constant ratio of the coarse to intermediate aggregate. These fine sand volume limits cannot be easily displayed on an individual percent retained chart. Fig. 8-7 plots the mixtures from Fig. 8-4 through 8-6 using the fine sand volume and overall workability performance. A distinct upward parabola trend can be shown and recommended limits were set between 23% to 43% fine sand volume.

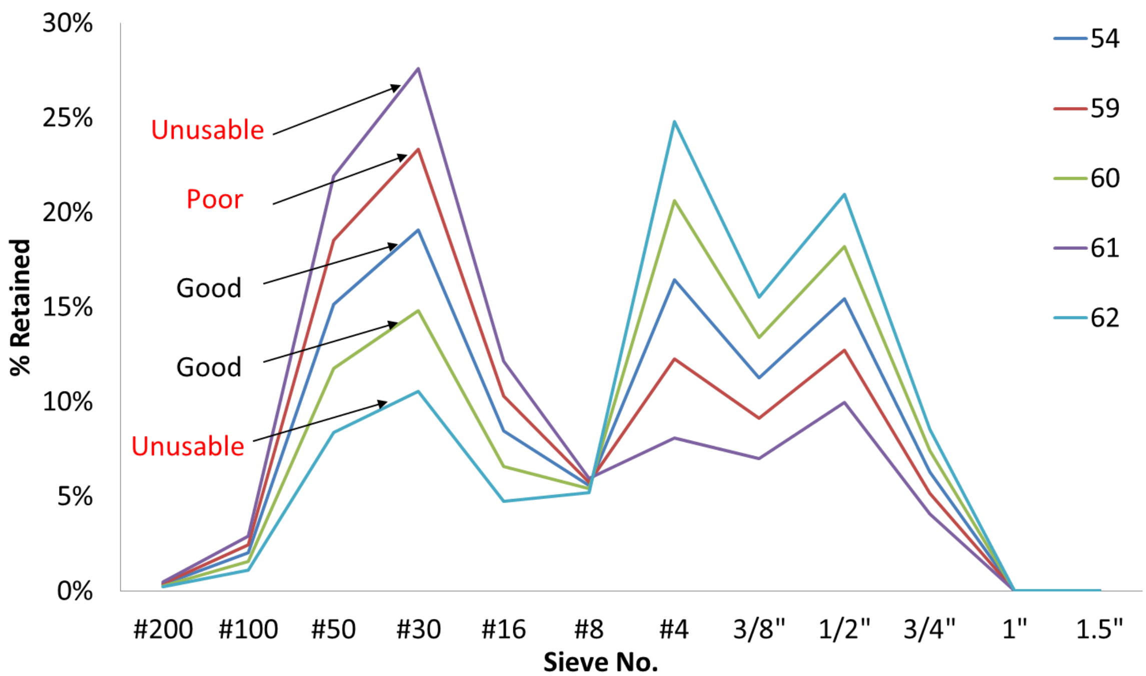

Fig. 8-5 shows the sand proportions for overall workability of limestone B and sand B.

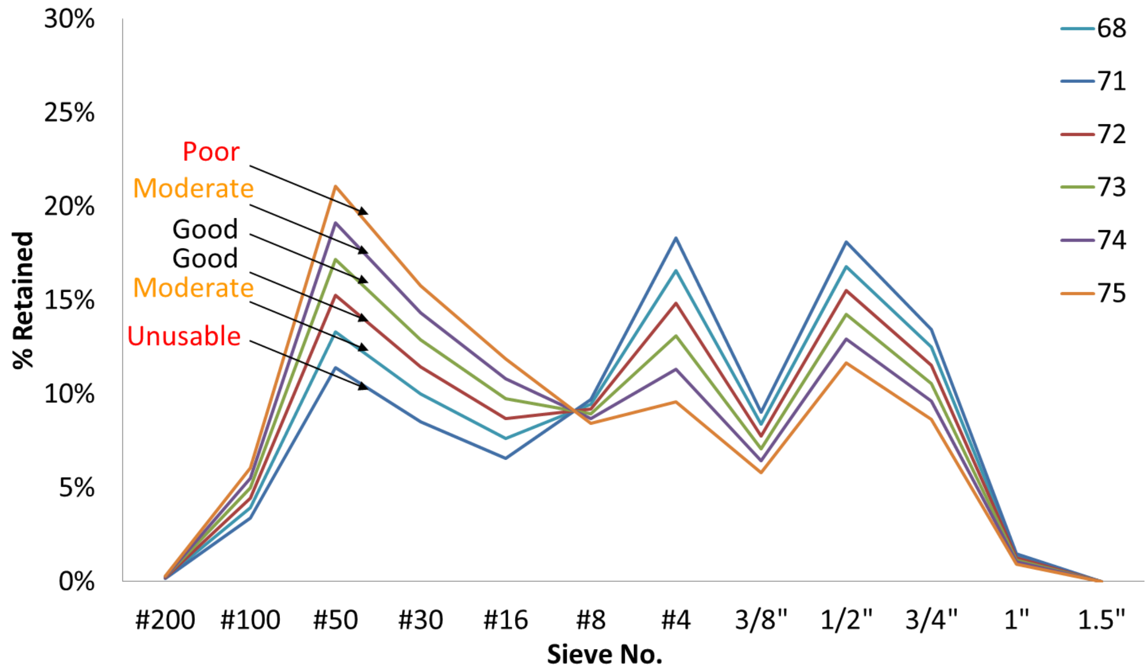

Fig. 8-6 shows the sand proportions for overall workability of limestone C and sand C**.**

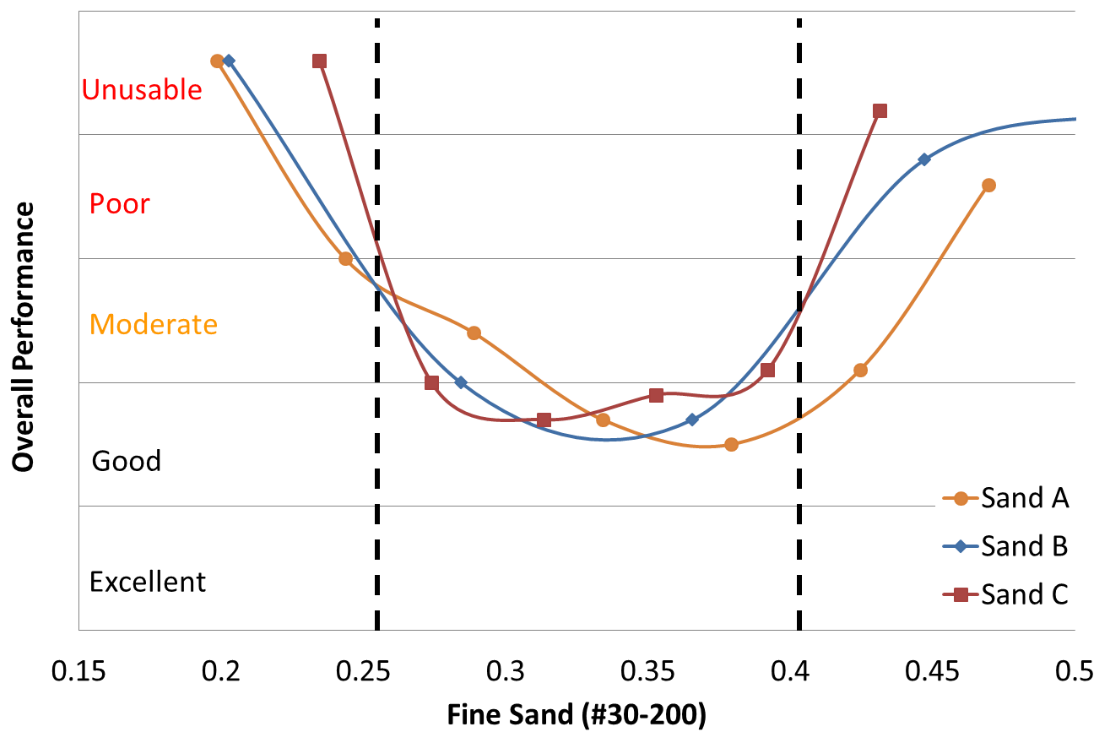

Fig. 8-7 plots the overall workability and different fine sand volumes.

3.1.2 Fine Sand Distribution

Past investigations in Chapter 5 presented similar workabilities with a variety of fine sand distributions. Fig. 8-8 shows various distributions of find sand the distribution of fine sand sieve sizes for flowable applications. The combined gradations stayed constant from #16 and larger with the exception of one very ultra-fine gradation. The purpose of the figure was to compare the workabilities behaviors of different distributions of #30 through #200.

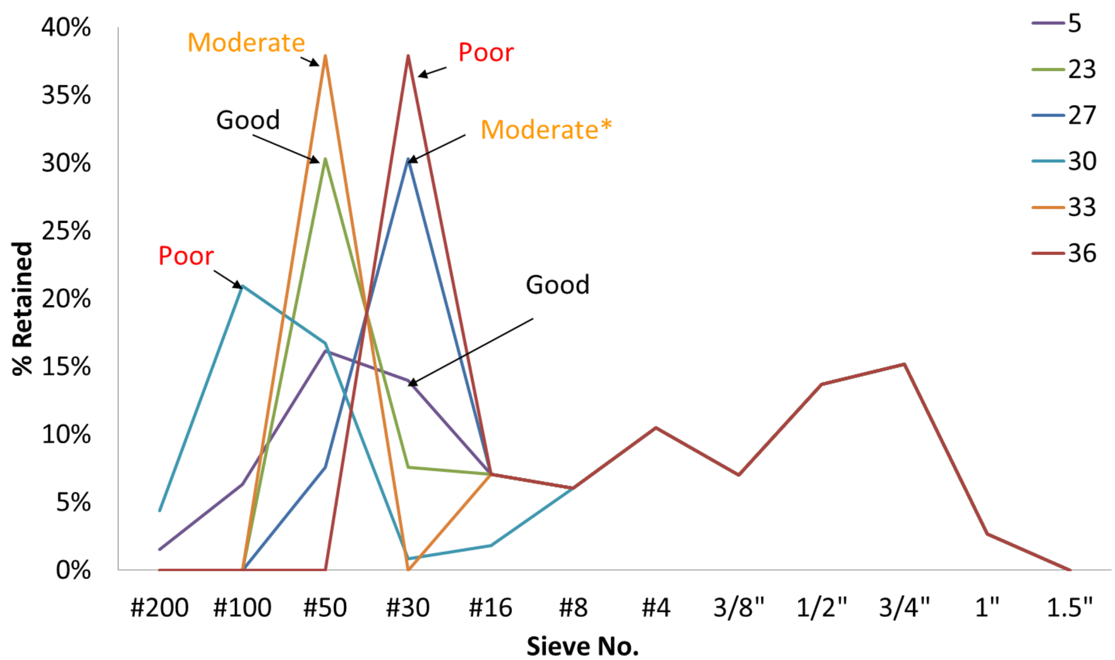

Fig. 8-8 shows various fine sand distributions and the overall workability. *note: this mixture had surface finishability issues.

3.1.2.1 Effects of #30

Mixture 27 had a gradation close to 30% on the #30 sieve and also had issues with surface finishing as shown in Fig. 8-9. The large amount of #30 created a very poor finishability and could be described as gritty. This is not a desirable mixture for mixtures requiring a surface finish, especially with a hard trowel. Chapter 5 has found the same behavior with high amounts of #30 with a boundary limit of 20%. A practical boundary limit of 20% on the #30 was also concluded for the flowable concrete research.

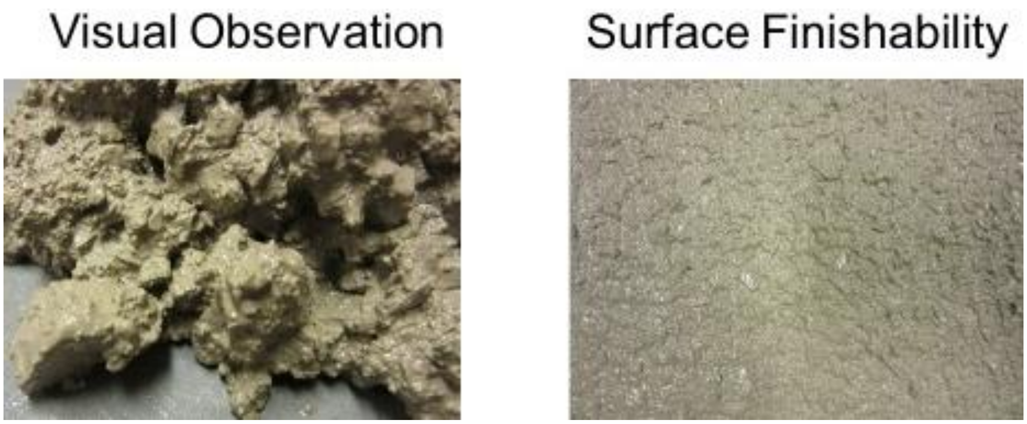

Fig. 8-9 shows visual pictures of the excessive amounts of #30 in mixture 27.

3.1.2.2 Effects of #50

Also, the gradation with 30% retained on the #50 was shown to create a very smooth surface finish. While this mixture was being mixed in a drum mixer, the sides of the drum actually surface finished the mixture as shown Fig. 8-10. In other words, this was almost a self-finishing mixture.

Fig. 8-10 shows visual picture of the 30% of #50 in mixture 23**.**

3.1.2.3 Effects of #100 and #200

Mixture 30 in Fig. 8-8 had very poor workability performance. Fig. 8-11 shows the visual observations of the mixture. The amounts of #100 and #200 sieve sizes created a mixture with sand and paste around the coarse aggregate particles. Obviously, this gradation is not desirable. A similar limit to Chapter 5 will be set of 10% on the #100. More research needs to be conducted into understanding the behavior of #100 and #200.

Fig. 8-11 shows visual pictures of the excessive amounts of #100 and #200 in mixture 30.

3.2 Coarse Sand

Throughout these investigations, it was very clear to see the coarse sand gives a fresh concrete mixture stiffness and cohesive properties. The importance of coarse sand property has pushed the creation rules of thumb from the field. These rules of thumb try to ensure a mixture will have enough coarse sand to help prevent edge slumping and segregation [8, 10, 11]. However, the sieve sizes creating these properties have never been clearly defined and therefore could not be adequately proportioned. Chapter 5 shows the #8, #16, and #30 sieve sizes form the coarse sand. Below are subsections into the investigations of these coarse sand sieve sizes.

3.2.1 Investigating #8 sieve size

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

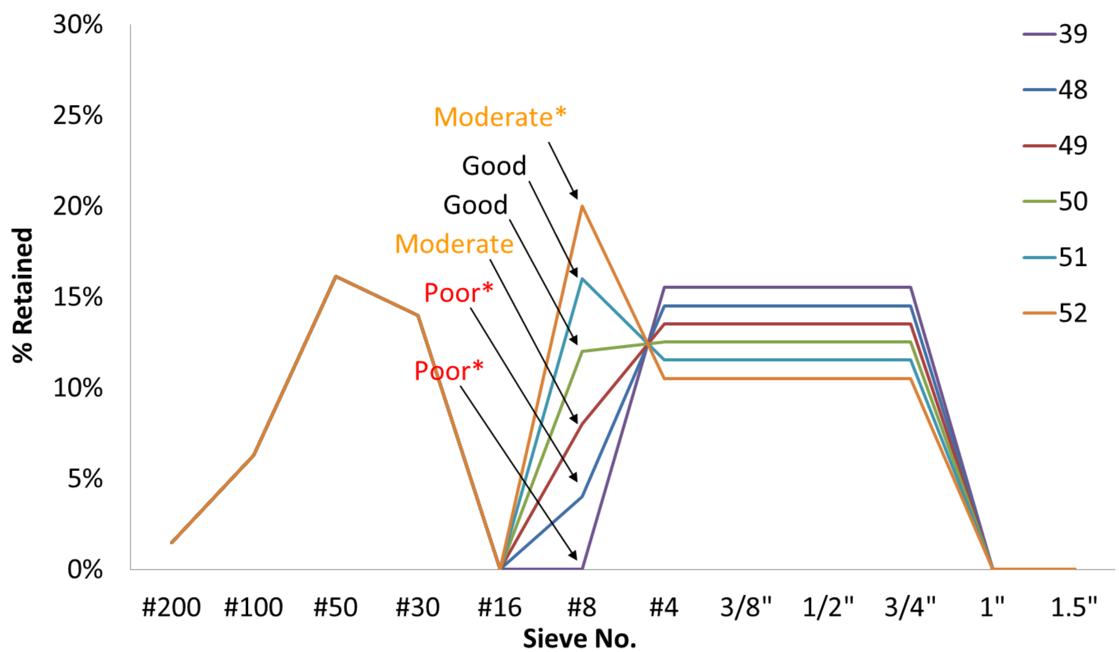

Fig. 8-12 shows the overall workability with various amounts of #8**.** *note: this mixture had surface finishability or cohesion issues.

Fig. 8-13 shows poor cohesion of mixture 39 without #8 and #16.

Fig. 8-14 shows poor finishability of mixture 52 with high amounts of #8.

3.2.2 Investigating #16 Sieve Size

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

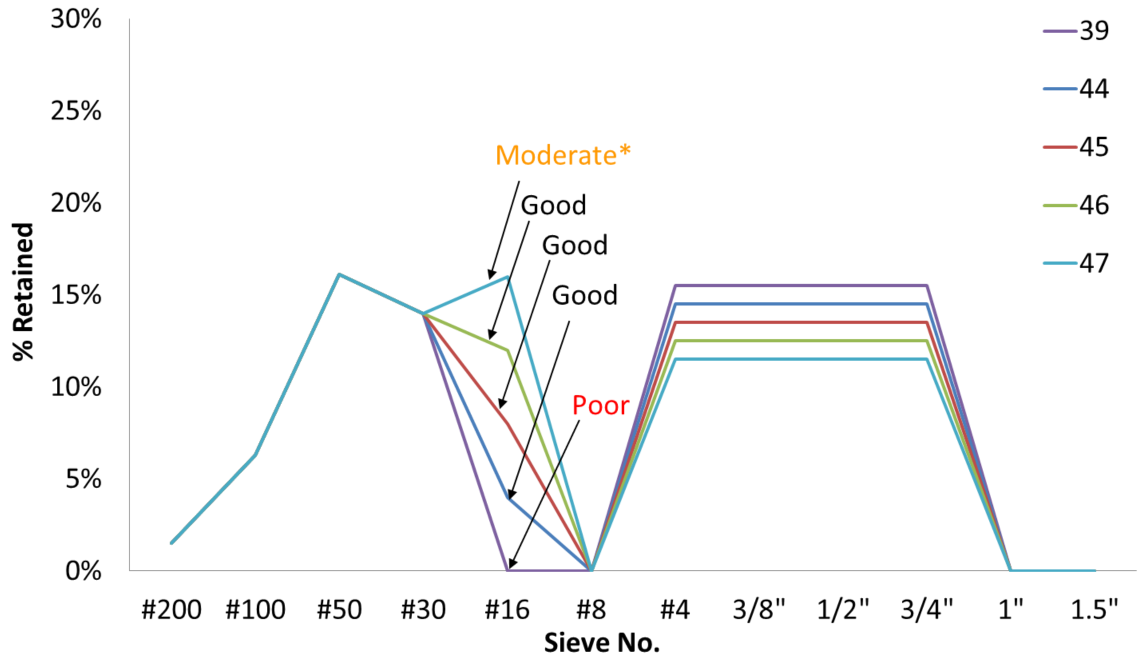

Fig. 8-15 shows the overall workability with various amounts of #16. *note: this mixture had surface finishability or cohesion issues.

Fig. 8-16 shows poor finishability of mixture 47 with high amounts of #16.

3.2.3 Investigating the combination of #8 and #16 sieve sizes

To investigate the #8 and #16 sieve size, the #8 and #16 sieve size was removed and various amounts of both sieve sizes were varied from 0% to 14% as shown in Fig. 8-17. Like previously discussed, mixture 39 with 0% of #8 and #16 had poor cohesion as shown in

Fig. 8-13. However, adding 2% of #8 and #16 allowed the mixture to improve the workability. Poor finishability was created with a gradation using 14% of #8 and #16. Even after 30 passes, the surface could not be adequately floated. A lower maximum sieve limit amount of 12% should be recommended. This recommendation also matches Chapter 5 of this dissertation.

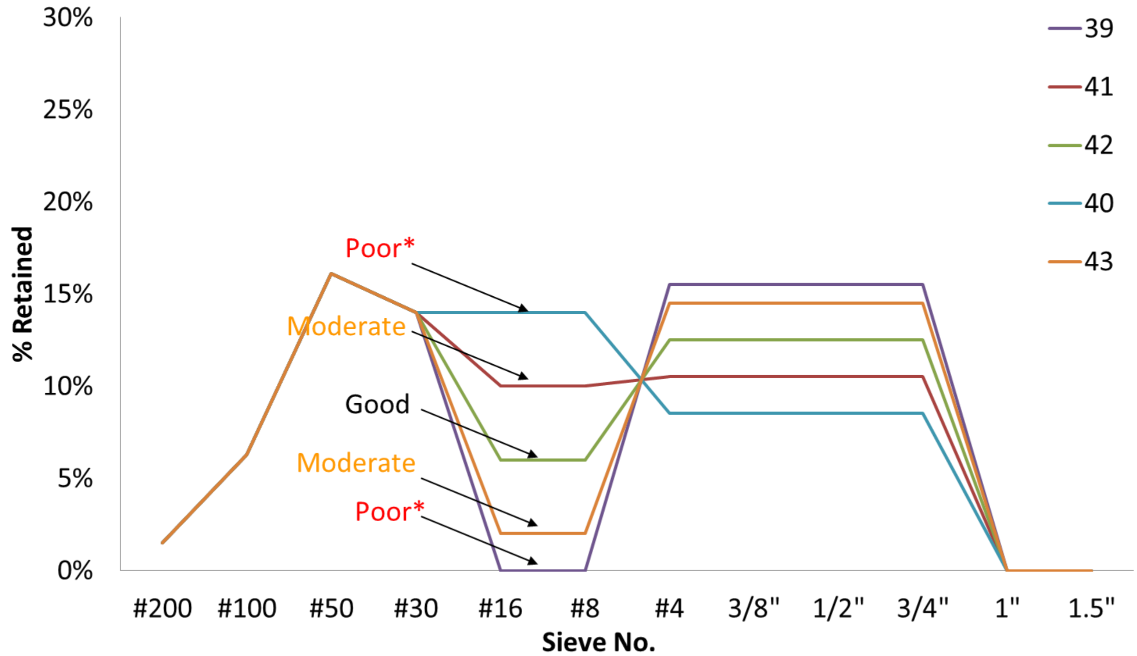

Fig. 8-17 shows the overall workability with various amounts of #8 and #16. *note: this mixture had surface finishability or cohesion issues.

3.3 Recommended Combined Gradation Limits

Throughout this research, a common trend of coarse aggregate sieve sizes retaining over 20% could have a decrease in workability. However, a gradation with low amounts on one or two sieve sizes does not necessarily affect the performance of the concrete. Yet, it becomes difficult to stay within the maximum boundary limits if a gradation was missing or having a small amount on an adjacent sieve sizes. Fig. 8-18 shows the recommended individual sieve size and proportioning limits of a combined gradation.

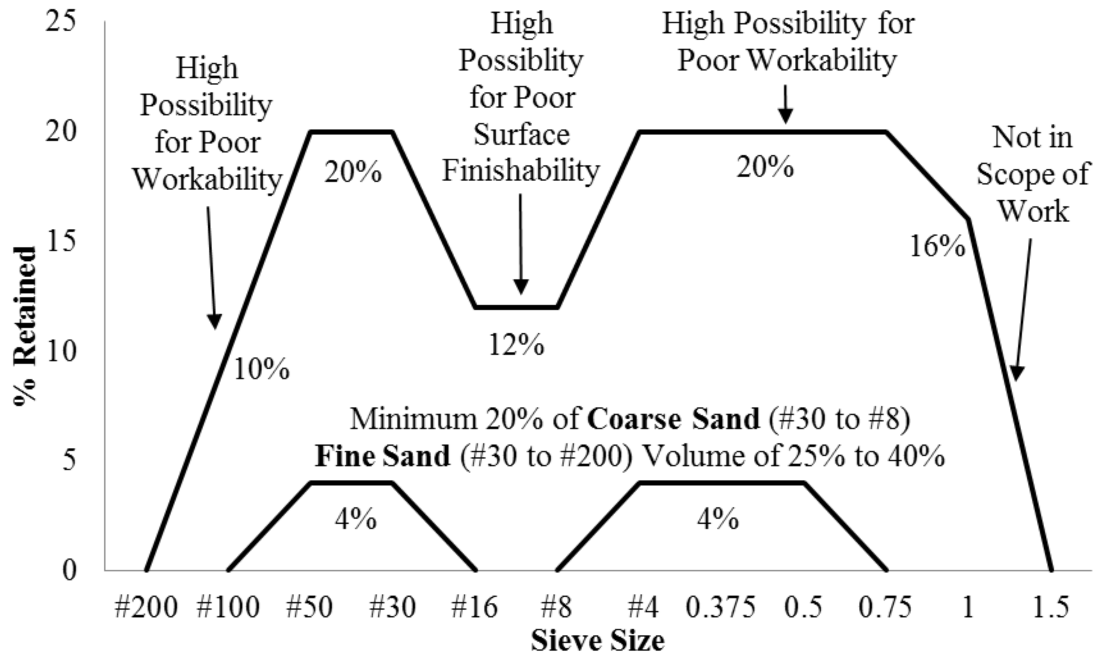

Fig. 8-18 Developed limits with coarse sand and fine sand ranges.

3.3.1 Coarse Sand Limits

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

3.3.1.1 Surface Finishability Issues

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

3.3.1.2 Cohesion

If low amounts of coarse sand (#8 to #30) were present, the mixture tended to segregate. Similar findings were found in Chapter 5 of this dissertation and also other publications [8, 10, 11]. For this investigation, minimal amounts of coarse sand could create adequate cohesion from the following: 4% on the #16 with 15% of #30, 12% on the #8 with 15% of #30, or 2% on the #8 and #16 with 15% of #30. Since natural sands will typically contain both amounts of #8 and #16, this should be taken into account for a practical limit. A reasonable minimal volume limit of 20% was recommended for coarse sand value using a natural sand.

3.3.2 Fine Sand Limits

Fine sand proportioning was shown to be fairly consistent in Fig. 8-7. The practical volume range of fine sand (#30 to #200) for flowable concrete was recommended from 25% to 40%. These proportioning trends of fine sand (#30 to #200) from 24% to 34% were similar to the proportioning trends of Chapter 5 with slip formed pavements. This could be from either different paste content or broader workability range of flowable concrete.

3.4 Practical Applications

This work was able to develop some basic and simple guidelines for proportioning the coarse aggregate sieve sizes in a combined gradation. These gradation guidelines can be extremely beneficial to improve the construction specifications and practices. Furthermore, the guidelines give the ability of a mixture to reduce the total cementitious material content and thus decreasing the cost of the mixture, improving durability of the concrete, and reducing CO_2 emissions [1, 2, 4, 7, 22].

4.0 Conclusion

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

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

Understanding the gradation limits of an individual percent retained chart was a fundamental step into adequately proportioning aggregates. It allows for a better approach to predict workability and reduce the paste content of a mixture. These findings were very similar to the results in Chapter 5 and will be discuss more in Chapter 10 of the Conclusions. Further research needs to be conducted into the mechanism behind gradation.

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CHAPTER IX

AGGREGATE MECHANISM OF PROPORTIONING LIMITS

1.0 Introduction

The workability of concrete describes the ability of a fresh concrete mixture to be mixed, placed, consolidated, and surface finished for a specific application [1, 2, 3 4]. As shown in Fig. 9-1, concrete can be poured using many different applications such as slip formed pavements, bridge decks, foundation footing, floor slabs, and vertical walls. However, a concrete mixture may be excellent for a slip formed pavement applications, but very poor performance in a pumpable mixture for a bridge deck [2, 3]. In other words, the workability requirements of concrete change depending on the application. The workability of the concrete can be adjusted through the paste volume, properties of the paste, or aggregate proportions [1, 2, 3, 4, 5, 6, 7].

Fig. 9-1 shows various workability applications for concrete.

1.1 Workability issues of concrete

A concrete mixture is proportioned using the available materials together to best allow the ability of the concrete to be placed, molded, and surface finished for a specified application [2, 3, 5, 6, 7, 8, 9]. Sometimes workability issues arise in a concrete mixture. As shown in Table 9-1, the following are some of the common workability issues of concrete: flowability, consolidation, cohesion, edge slumping, and surface finishability.

Table 9-1. Workability Issues

Workability Issue	Description
Inadequate Flow	• Difficulty of a mixture to continuously flow [2, 7].
Stiffness	• Inability of a mixture to begin flowing [2, 6, 7].
Harsh Finishability	• Difficulty removing undesirable surface imperfections [2, 6].
Edge Slumping	• Inability of a freshly placed slip formed paving mixture to hold an edge [1].
Segregation	• Behaves as two separate substances due to lack of cohesion [1, 2, 6].
Poor Consolidation	• Inability to remove voids in a mixture [1, 2, 3].

1.2 Workability effects of paste

If a mixture has only coarse and fine aggregates in the total volume, the mixture will not act as a composite material but instead a disorderly mess of two different materials. However, enough paste can be added to create an interconnected and somewhat cohesive mixture for a certain application. As more paste is added, the mixture will tend to become more flowable. Only enough paste should be added to make the mixture adequately flowable for a given application [5, 6, 9, 10].

1.3 Workability effects of rock

The rock, which is coarse and intermediate aggregates, creates the largest amount of filler. This ability of coarse and intermediate aggregate to fill and not drastically impede the workability of fresh concrete is highly dependent on the gradation, shape, and characteristics of the aggregate [2, 3, 5, 10]. Fig. 9-2 shows a mixture with excessive amounts of coarse, excessive amounts of intermediate, and moderate amounts of both. These excessive amounts can drastically effected the workability of the concrete. For example, too much intermediate aggregate will create too stiff of a mixture. Excessive coarse aggregate can create highly variable flow and even segregation [11].

Fig. 9-2 displays the visual observations of excessive amounts of coarse and intermediate sieve sizes.

1.4 Workability effects of sand

One of the most important workability components of fresh concrete is sand [2, 4]. As shown in Fig. 9-3, a moderate volume of sand is required to obtain the desired workability properties of concrete. While this might seem simple, the performance behavior of sand has been misunderstood due to the various intermediate sizes along with finer sand sieve sizes present in most gradations. Through research the sand gradation can be broken down into coarse sand and fine sand. Coarse sand (#8 through #30) contributes to the stiffness consistency of a mixture. Too much of the coarse sand creates undesirable surface finishability issues. The fine sand (#30 through #200) creates a smoother surface finish as shown in Fig. 9-5. Too much of the fine sand creates undesirable workability issues like balling as shown in Fig. 9-6. These properties can be further explained in Chapters 5 and 6.

Fig. 9-3 shows from visual observation the excessive and deficient amounts of sand.

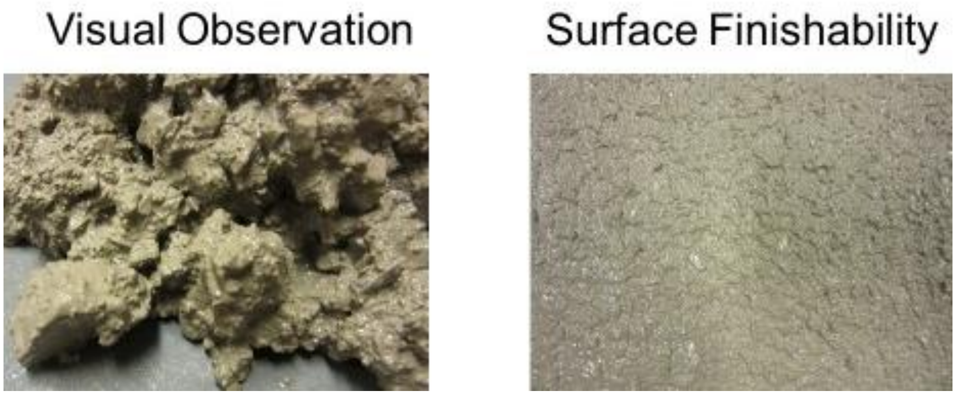

Fig. 9-4 shows impacts of excessive coarse sand amounts.

Fig. 9-5 shows impacts of fine sand.

Fig. 9-6 shows visual pictures of excessive fine sand amounts.

1.5 Proportioning of a concrete mixture

A concrete mixture design is more complex than just randomly blending the components together. The amount of aggregate, cement, and water are proportioned to meet certain specifications such as water-to-cementitious material (w/cm) ratio, compressive strength, durability, sustainability, and workability [1, 2, 3, 4, 5, 6, 7, 9]. While some these specifications of a mixture are commonly met without large difficulties, others can be very complex to meet with the available materials. This workability requirement can be very problematic due to the lack of developed knowledge in concrete aggregate proportioning and concrete workability fields. Through research Table 9-2 and Fig. 9-7 were developed to help properly proportion aggregates with a combined gradation technique. Table 9-2 describes the sieve group behaviors of a combined gradation. Fig. 9-7 shows the limits on an individual percent retained chart.

Table 9-2. Functions of Sieve Sizes for a Combined Gradation

Sieve Group Behavior	Sieve Numbers	Function	Excess	Shortage
Coarse aggregate	**1", ¾", ½", 3/8", #4**	• Acts as a filler to reduce shrinkage	Poor flowability and finishability issues	Could force other sieve sizes to be excessive
Coarse Sand	**#8, #16, #30**	• Creates a stiffer consistency for better cohesion	Finishability issues	Poor cohesion and edge slumping
Fine Sand	**#30, #50, #100**	• Creates a smooth surface finish for floating and troweling	Impedes flow, poor consolidation, Finishability issues	Poor cohesion, poor flowability, harsh finishability issues

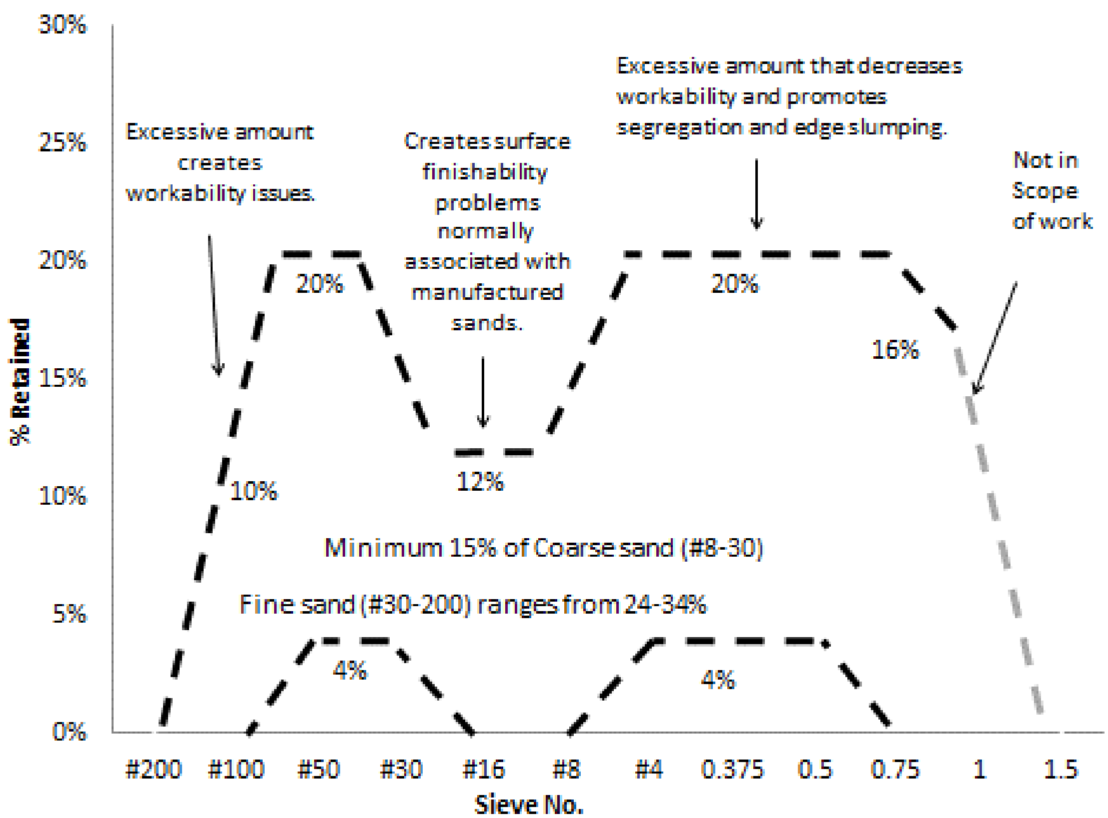

Fig. 9-7 shows recommended sieve limits for slip formed pavements.

1.6 Aggregate mechanism of workability

Multiple theories have been developed over the years to help explain the effects of aggregates on the workability performance of concrete [5, 12, 13]. As shown in Table 9-3, each mechanism is briefly described with a performance indicator measurement technique. Packing and surface area have been the most traditional theories behind proportioning aggregates. But more research needs to be conducted into these mechanisms.

Table 9-3. Workability mechanisms of these gradation limits.

Mechanisms	**Description**	**Performance Indicator**
Packing	Ability of the aggregate to fill a space [5, 14, 15, 16, 17].	Minimum voids or range of voids [22]
Surface Area	Each particle needs to be cover by paste [5, 18, 21].	Lower surface area gradations [5, 17, 18, 19, 20]
Surface Chemistry	The entire concrete mixture behaves through the surface chemistry interaction.	Cohesive mixture
Hybrid Mechanism	The entire concrete mixture behavior is controlled by packing and surface area [5, 6, 9]	Mixture with lower voids contents and lower surface area [5]

1.6.1 Packing

Packing has been one of the most talked about mechanisms to effect the workability of concrete. This ability of the aggregate to pack or fill into a specific volume can be measured based on the voids content. The packing premise suggests minimizing the voids content of the total aggregate component in a mixture and this should in turn require less paste to fill the spaces in-between the aggregate particles. For this research, the dry-rodded unit weight [22] was used to empirically measure the volume of voids for the compacted aggregate of the mixture in a container of a known volume.

1.6.2 Surface area

With the emphasis on sand, surface area has been one of the most traditional talked about mechanisms to effect the workability of the concrete. The surface area concept states each aggregate gradation requires a certain amount of paste to cover each particle [5, 18, 20, 21]. The concept suggests for a fixed paste content and aggregate volume, lower surface area gradations will require more paste to achieve a certain workability over mixtures with lower surface areas [6]. In order to make quantitative comparisons, it is common to divide the surface area by the volume and call this the specific surface area (SSA). Various methods have been used to calculate the specific surface area of a mixture [5, 17, 18, 19, 20, 21]. A subsection in the experimental methods can give more information on how the SSA was calculated for this research.

1.6.3 Hybrid of mechanisms

Another proposed mechanism is a hybrid of multiple mechanisms effecting the workability of the concrete [5, 6, 9]. In other words, two or even possibly all three mechanisms together effect the workability of concrete. However, this research will only evaluate the hypothesis of a hybrid mechanism between the packing and surface area.

1.6.3.1 Hybrid of packing & surface area

One commonly proposed hybrid mechanism has been the concept of packing and surface area actually interact together to change the workability of the concrete. In other words, the surface area could be within adequately range values, but the packing could be very poor. Another possibility would be the packing was within a certain range, but the surface area was “too high”. Either possibility could cause poor workability performance.

1.6.4 Surface chemistry

Another possible mechanism deals with the surface chemistry interaction of the concrete component through surface tension and surface energy. While the surface tension can be described as the physical bonding through water [23, 24, 25], surface energy is the chemical bonding through the surface energy of the substances [23, 24, 25]. These two surface chemistry fields can be shown through poor workability especially. As shown in Fig. 9-8, concrete can become segregated due to the lack of cohesion in the mixture. Through this research segregation has commonly occurred when aggregate gradations obtain either low volumes of fine sand, coarse sand, or high sieve size amounts. These three gradation adjustments can also create the majority of other workability issues, especially surface finishability, poor flowability, and poor consolidation. All of these workability issues could possibility be created due to inadequate proportions not creating adequate surface chemistry. In other words, each concrete component interacts to improve the workability of the concrete in a different manner. Cementitious material and water are mixed together to create paste. Sand can be added to the mixture to create the desired mortar properties of the concrete [2, 4]. Coarse aggregate can be added to the mixture to help reduce shrinkage [2, 4, 6, 10]. Without enough paste or sand, the mixture will not be able to obtain adequate workability [4].

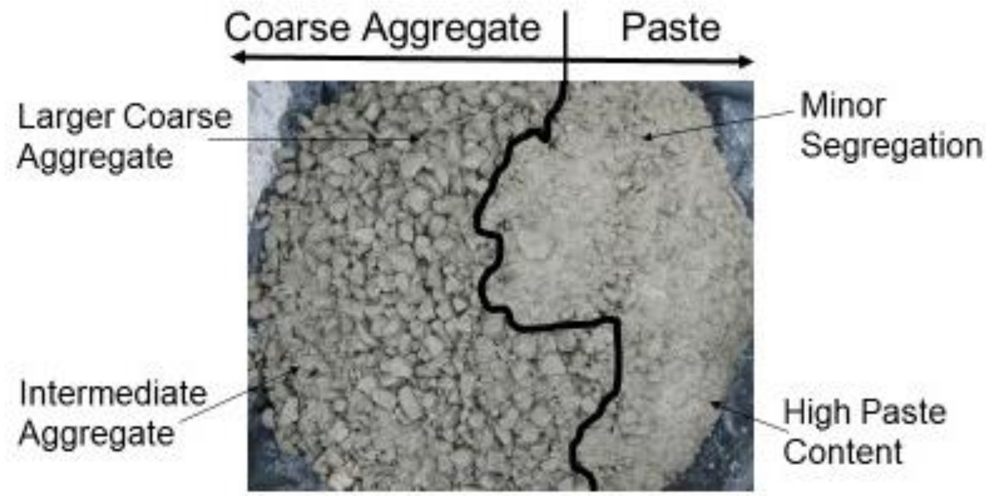

Fig. 9-8 shows from visual observation the deficient amounts of sand had major segregation issues.

To help demonstrate the surface chemistry interaction of sand, an example of a sandcastle will be illustrated. When building a sandcastle, one learns very quickly that dry sand does not have the ability to be molded [26, 27]. However, adding water to the sand will create covalent bonds [5, 24] between the particles to allow the sand to be molded and to stay together [26, 27]. This basic behavior depends on the amount of water in the mixture [26], the gradation of the sand [26], and the chemical properties of the sand [28]. If the sand has too little or too much water, cohesion is very limited [26]. Also, influence cohesion by the finer or coarse size amounts [26]. Just like with the sandcastle illustration, Fig. 9 shows when wet sand is mixed with coarse aggregate, the wet sand will stick to the coarse aggregate.

Fig. 9-9 shows wet sand being attached to coarse aggregate.

When cement is added with water, sand, and coarse aggregate, it creates a more fluid mixture behaviors. These behaviors in concrete are commonly called the mortar properties of fresh concrete [4, 5]. When coarse aggregate is added to the concrete mixture, the mortar attaches to the coarse aggregate. As shown in Fig. 9-10, a piece of coarse aggregate was removed from a rock and sand mixture that was spun in a concrete mixer. It clearly shows various particle sizes attached. In other words, the coarse sand and fine sand bond with the coarse aggregate to create a cohesive mixture. For larger aggregate, the particle sizes become heavier and the covalent bonds around the surface of the particle can be more acceptable to breaking the bond [26, 27]. This is why larger particles do not tend to stick together but the smaller particles tend to be bond better.

Fig. 9-10 shows a piece of coarse aggregate pulled out of good workability concrete.

1.6.4.1 Behavior of fine sand (#30-200)

Fine sand particles interacts largely with the paste to form the mortar property behavior of concrete. This can have a direction relationship with the consistency of the mortar to properly surface finish the concrete. High amounts or too many particles suspended in the mixture creates a higher viscosity concrete and therefore poor workability. Low amounts create a mixture behaving as coarse aggregate covered with paste. A good workable mixture needs to be within the required fine aggregate volume range.

1.6.4.1 Behavior of coarse sand (#8-30)

For coarse aggregate the particle sizes become heavier and the covalent bonds around the surface of the particle are easier to break. This could cause the fine sand and paste to not stay bond with the coarse aggregate. But the coarse sand particles have been known to create stiffness in the concrete. Fig. 9-11 shows the easy at which the #16 sieve size can bond to the coarse aggregate. Since these intermediate particles can easily bond to the coarse aggregate or the fine sand and paste, the coarse sand can bridge the coarse aggregate, fine sand, and paste together into a single cohesive mixture. This can have a direct relationship with problematic mixture design issues such as segregation and edge slumping. Low volume amounts of a coarse sand in the mixture cannot hold itself together and will cause segregation, edge slumping, and finishability problems. Also, high volume amounts of coarse sand can also create too stiff of a mixture that does not allow the paste, fine sand, and coarse aggregate to flow properly.

Fig. 9-11 shows wet sand being attached to coarse aggregate.

1.6.4.1 Behavior of high amounts sieve sizes

Traditionally, high amounts of an individual sieve size was theoretically explained through poor packing concepts. However, the surface chemistry concept could be used to explain the behavior also. Since all of the particles are held together through the interaction of surface chemistry, excessive amounts of any particle sieve size can become overwhelming for the mixture to keep the bonds. Then particles can be more prone to come out of the mixture and create workability issues. This concept needs to be further developed and investigated to determine the validity.

1.7 Objectives

Quantitative comparisons are needed to begin understanding the mechanisms behind the gradation and proportioning limits impacting the workability of fresh concrete. This work aims to provide a deeper understanding by comparing the effectiveness of different mechanisms and how they relate to the workability of concrete.

2.0 Experiential methods

2.1 Materials

All the concrete and mortar mixtures described in this paper were prepared using a Type I cement that meets the requirements of ASTM C 150 [29] with 20% ASTM C 618 [30] class C fly ash replacement by weight. The water reducer (WR) was a lignosulfonate mid-range WR with a type A/F classification according to ASTM C 494 [31]. To determine the mechanisms between the workability of concrete and the gradation, a single natural sand and a single coarse aggregate source was used. For more information on the aggregate, it can be found in another publication [11].

2.2 Mixture design

2.2.1 Concrete mixture design

To investigate the impact of the coarse aggregate, all of the mixtures where designed with a water-to-cementitious material ratio (w/cm) of 0.45 and a paste content of 24.2% of the mixture volume. With 20% class C fly ash replacement, each mixture had 423 lbs. /yd^3 of cementitious material per cubic yard of concrete and 190.4 lbs. /yd^3 of water. By holding these paste parameters constant, this allowed comparisons between the workability of the mixtures with the various combined gradations.

2.2.2 Mortar mixture design

The mixtures were design to be the same mixture design as the concrete mixture, but just remove the coarse aggregate in the mixture. This was to evaluate the interaction of coarse aggregate and the sand.

2.3 Testing procedure

Multiple evaluation procedures were used to investigate the mechanisms. Each mechanism required different set of tests. The packing mechanism used dry-rodded unit weights [22]. The surface area mechanism was calculated using the specific surface area. The surface chemistry mechanism used multiple testing procedures with an emphasis on the mortar testing and visual observations.

2.3.1 Dry-rodded unit weight

Similar to ASTM C 29 procedure [22], below is a description of the dry-rodded unit weight process used in this research. The procedure was changed to more easily allow the aggregate to be a homogenous mixture. A single operator for coarse or fine aggregate has a standard deviation of 0.88 lbs. / ft^3 and should not different more than 2.5 lbs. / ft^3 [22]. In other words, if the aggregate has a specific gravity of 2.65 and the aggregate unit weight was measured at 100 lbs. / ft^3 and 102.5 lbs. / ft^3, the voids content could have a difference of 1.5%.

The dry-rodded unit weight steps:

1. Dried aggregate in oven for 24 hours.
2. Designed batch weight to slightly overfill unit weight bucket.
3. Weigh out the coarse, intermediate, and fine aggregate and combine them into a 5 gallon bucket.
4. Bucket was shook for 3 minutes for the aggregates to mix together.
5. The unit weight bucket was filled in 3 layers with 25 rods per layer.
6. The top of the unit weight bucket was struck off.
7. Unit weight bucket was placed on scale and weighed.

2.3.1 Specific surface area calculations

Various methods have been used to calculate the specific surface area of a mixture [5, 18, 21]. For this research, an estimated specific surface area was calculated for each sieve size by counting the number of particles per a given volume, assuming spherical particles with angularity factors [5], and assuming a diameter of the middle distance between the passing and retained sieve size. The 1" through #4 sieve size uses the coarse aggregate with an angularity factor of 1.5 [5] and the #8 through #100 uses the natural sand with an angularity factor of 1.1 [5]. Similar methods have been used in other publications [6, 14, 15]. Table 4 shows the calculated numbers using the aggregates in this research and compares those numbers to previous publications [5, 19, 20]. This research, Loudon, and Shacklock and Walker used slightly dissimilar standard of sieve sizes, different aggregate sources, and slightly altered methods for calculating the SSA. Many of the sieve sizes still have similar values, but the smaller sieve sizes can vary especially with the #30, #50, and #100.

Table 9-4. SSA Values

Sieve Size	Research Aggregates (cm^2/cm^3)	Loudon (cm^2/cm^3)*	Shacklock & Walker (cm^2/cm^3)*
1"	2.4	n/a	n/a
3/4"	2.2	2.2	n/a
1/2"	2.9	n/a	6.6
3/8"	3.9	4.4	8.0
#4	4.3	8.9	10
#8	20	18	48
#16	24	35	99
#30	83	71	149
#50	210	143	260
#100	370	284	n/a

*Please note that Loudon and Shacklock & Walker used slightly different sieve sizes, methods, and aggregate sources.

2.3.3 The Box Test

The construction process of slip formed paving requires theworkability of a mixture to be flowable enough under vibration for consolidation, but still able to maintain an edge after the vibration has stopped and the side forms were removed. To better investigate the workability of concrete for slip form paving, the Box Test was developed to evaluate the response of concrete to vibration and then subsequently hold an edge [3]. The Box Test was conducted as follows: 1) freshly mixed concrete was place into temporary fixed wood forms, 2) a hand-held vibrator with a specified size and speed was used to consolidated the concrete at a fixed time with a controlled entry and exit location, 3) the forms were removed, 5) the concrete was visually inspected to assess if the sides were properly consolidated, and 6) a straight edge can be used to measure edge slumping. Like a slip formed paver, this test requires the concrete to be workable enough to consolidate under vibration but still have enough cohesion to hold an edge when the forms were removed. The Box Test has shown similar performance results as a slip formed paver in the field.

For this research, the paste volume and w/cm were held constant and discrete dosages of WR was added to the mixture until the mixture achieved satifactory performance in the Box Test. The single operator repeatability of WR dosage was found to be 2.74 oz/cwt with a 95% confidence interval. In otherwords, if two mixtures are compared and do not differ more than 2.74 oz/cwt, they can be considered to have the same workability as measured by the Box Test. See Chapter 2 for validations and more information on this test.

2.3.3 Mortar testing

The purpose of the mortar testing was determining if similar workability performances could be seen with concrete and mortar mixtures. All sand was oven dried and cooled to room temperature to ensure proper moisture content. Then ASTM C 305 [32] was used as the mortar mixing procedure. Even though these mixtures were mortar mixtures, the basic consistency of fine sand requirement should still be observed [33]. As shown in Fig. 9-12, every mixture was hand floated for surface finishability. Also, each mixture was evaluated using visual observations similar to Chapter 6 of this document. The visual inspections included flow, stiffness, richness, and cohesion of the mortar.

Fig. 9-12 shows a mortar mixture being evaluated for smoothness.

3.0 Results and discussion

The possible mechanisms behind the proportioning limits was further investigated. The basic proportioning chart showing various proportions of coarse and intermediate gradation was used to compare the performance differences in WR to the possible mechanisms. WR dosage higher than 10 oz. /cwt was considered a poorly performing mixture. In other words, the performance trend of a possible mechanism should be similar to the WR dosage. If a trend was not shown, the possible mechanism did not explain the proportioning limits.

3.1 Packing

To adequately investigate the possibility of a packing mechanism, dry-rodded unit weights were conducted on a combined gradation, sieve sizes larger than the #30, and the #4 sieve size and larger. These dry-rods are largely different and the combined gradation and the #4 sieve size and larger can be visually shown in Fig. 9-13. If packing controls the workability of the concrete, a distinct trend should form between the voids content and the amount of WR required to pass the Box Test. If the voids content does not change drastically with the amount of WR dosage, the packing technique measured through dry-rodded unit weights does not adequately show a performance trend.

Combined Gradation

#4 & Larger Sieve Sizes

Fig. 9-13 shows different dry-rodded unit weights.

3.1.1 Combined gradation packing

To further understand the workability of concrete through measuring the void content of a combined dry-rodded unit weight, Fig. 9-14 present various proportions of coarse and intermediate aggregate with a fairly constant sand volume. Each gradation has the amount of WR to pass the Box Test and the voids content from a combined dry-rodded unit weight. If the WR dosage and voids content was compared While the WR dosage changes drastically from 2.9 oz. /cwt to +40 oz. /cwt, the voids content only slightly varies from 23.8% to 25.3%. These results showed the voids content did not have an effect on the workability of a mixture. Furthermore from their own personal experiences in research, T.C. Powers and Duff Abrams both believed the aggregate combination that gives the lowest percentage of voids is not necessarily the best mixture design [6, 9]. Other obstacles were possibly effecting the workability.

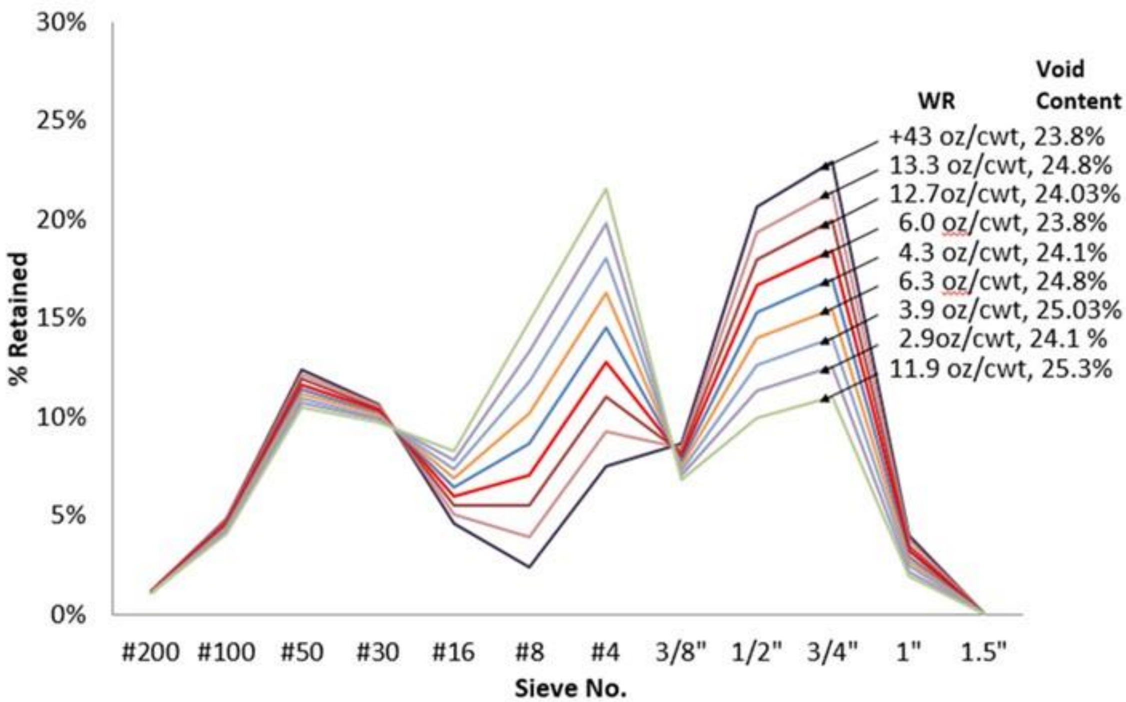

Fig. 9-14 shows dry-rodded unit weight of a combined gradation

3.1.2 Effects with #16 and larger

To further understand the workability of concrete through measuring the void content of a combined dry-rodded unit weight, Fig. 9-15 presents various proportions of coarse and intermediate aggregate with a fairly constant sand volume. Each gradation has the amount of WR to pass the Box Test and the voids content from a combined dry-rodded unit weight. While the WR dosage changes drastically from 2.9 oz. /cwt to +40 oz. /cwt, the voids content varied from 33.5% to 37.9%. This roughly 4% range of voids content did not seem relate extremely well to WR dosage. The transitions from lower WR dosages of less than 6 oz. /cwt to higher WR dosages more than 10 oz. /cwt did not drastically change, especially at the higher intermediate gradations.

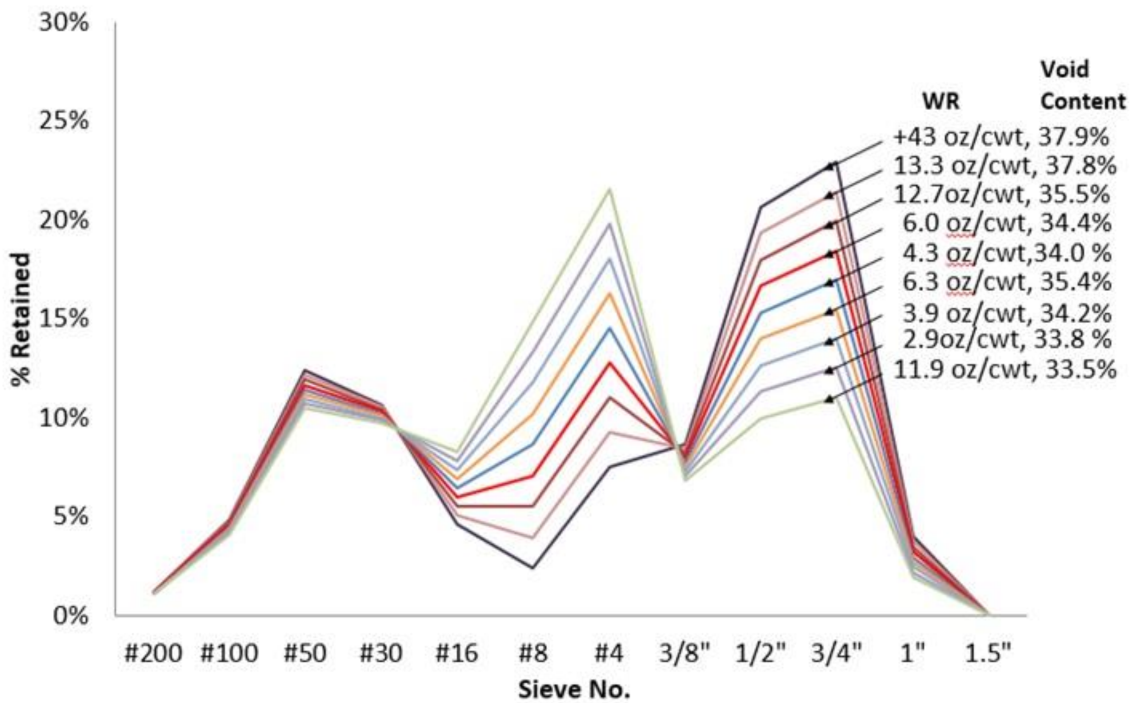

Fig. 9-15 shows dry-rodded unit weight of #16 and Larger

3.1.3 Effects with #4 and larger

The research behind the ACI 211 mixture design procedure used the #4 sieve size and larger to develop proportioning of coarse aggregate [34, 35]. Since dry-rodded unit weights of the combined gradation and #16 and larger sieve size were not shown to have performance trends, the #4 sieve size and larger had dry-rodded unit weights conducted as shown in Fig. 9-16. Each gradation has the amount of WR to pass the Box Test and the voids content from a combined dry-rodded unit weight. While the WR dosage changes drastically from 2.9 oz. /cwt to +40 oz. /cwt, the voids content only slightly varies from

38.5% to 40.7%. Unfortunately, these results showed the voids content did not have an effect on the workability of a mixture.

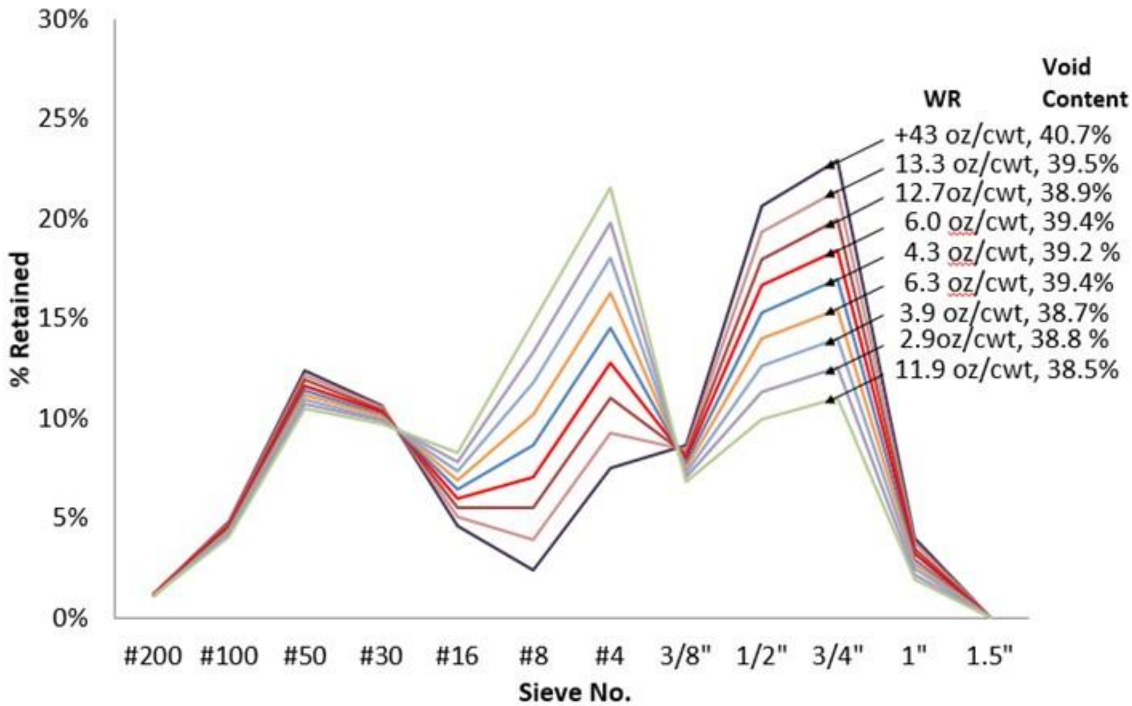

Fig. 9-16 shows dry-rodded unit weight of #4 and Larger

3.2 Surface area

To investigate the SSA of Fig. 9-14, the SSA was calculated for each combined gradation and plotted in Fig. 9-17. No trend could necessarily been seen. Five different mixtures performed ranging from 55 to 59 cm^2/cm^3, but other gradations meet the same range criteria and required a higher WR value. To further strengthen this statement, Fig. 18 plots the SSA for all the slip formed pavement mixtures described in Chapters 4 and 5. This shows the same results that SSA does not directly change the performance of the concrete.

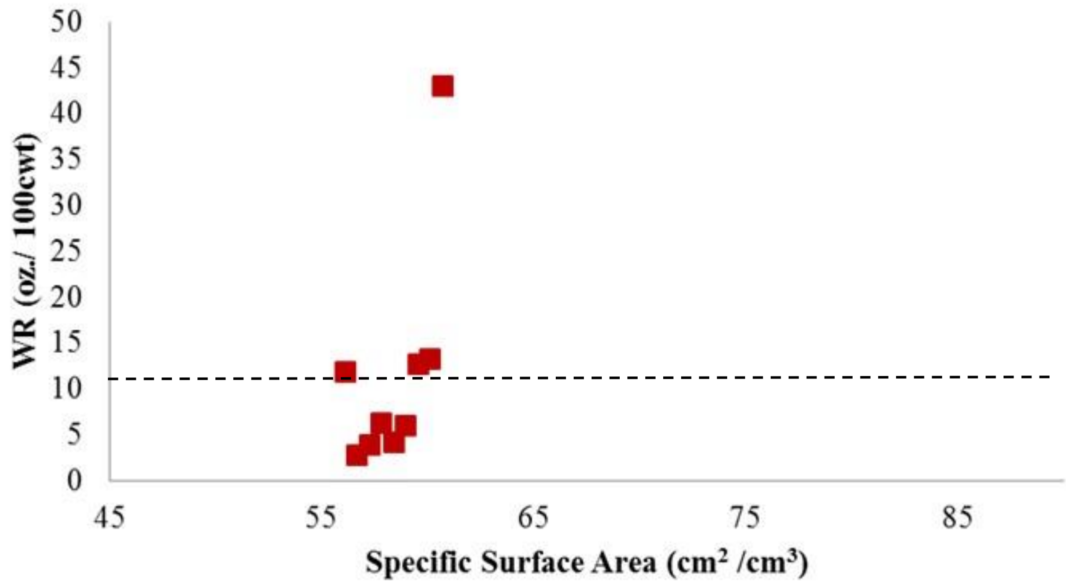

Fig. 9-17 shows SSA and WR required to pass the Box Test of Fig. 9-14.

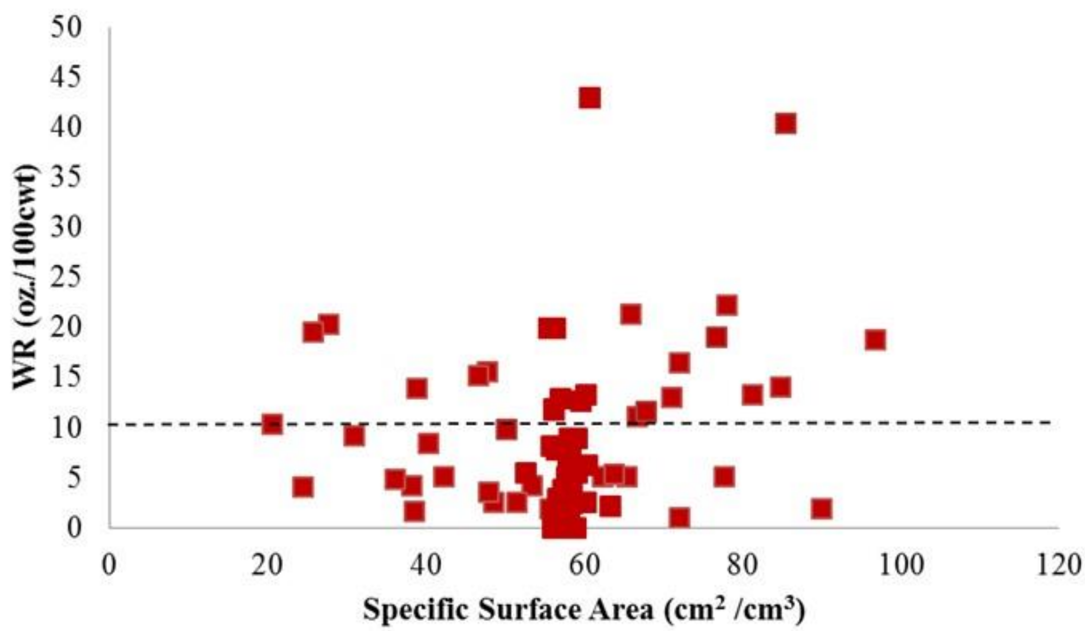

Fig. 9-18 shows SSA and WR required to pass the Box Test of several slip formed pavement mixtures.

3.3 Hybrid of dry rod and SSA

To determine the possibility of a relationship between packing and SSA, Fig. 9-19 plots SSA versus voids content of the combined dry-rodded unit, #16 and larger sieve sizes, and

#4 and larger sieve sizes. The data markers in red colors were WR dosage over 10 oz. /cwt. Good WR dosage had black markers. If a possible relationship between the voids content and surface area was occurring, the data should have a trend. However, the data points do not. The voids content is rather flat and the SSA values range only 4 cm^2/cm^3. Even though this data may begin suggesting a range of SSA, Fig. 9-18 reinforces the SSA inconsistency of performance. The data did not show a performance trend between packing and surface area.

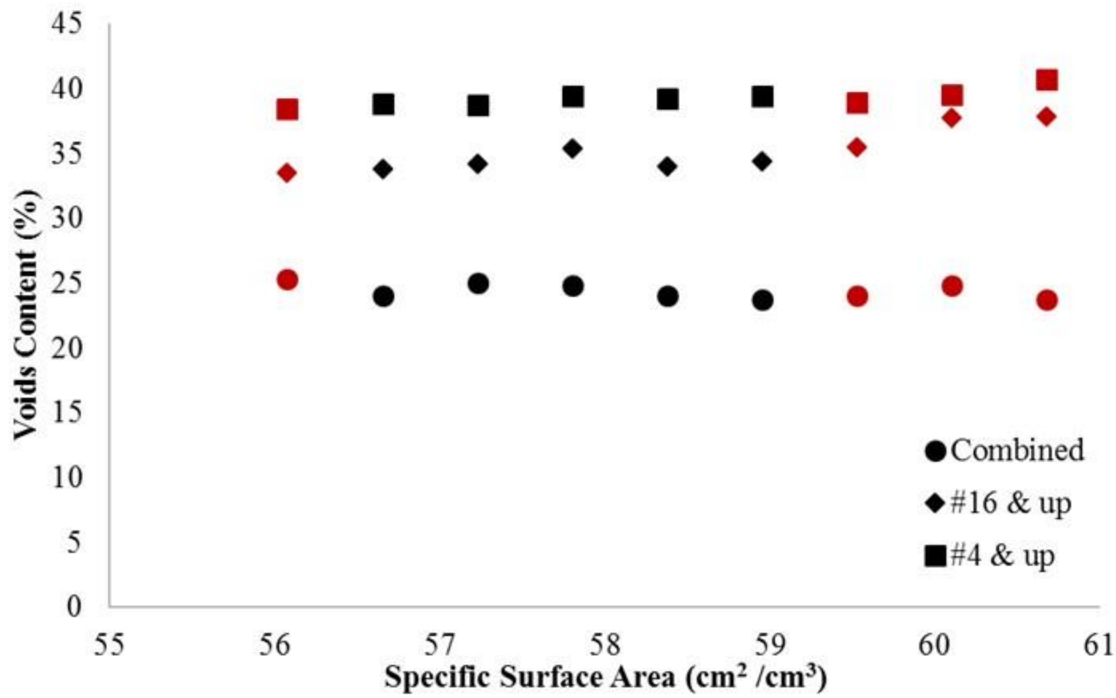

Fig. 9-19 compares the SSA and voids content of Fig. 9-14 through 9-16.
*note: red data markers required WR dosage over 10 oz. /cwt and black data markers required lower than 10 oz./cwt.

3.4 Surface chemistry

Unfortunately, the surface chemistry theory could not be developed enough to compare a performance indications of the previously investigated gradations. The investigation of a surface chemistry mechanism was conducted to establish the possibility of basic interactions between the different components in a concrete mixture.

3.4.1 Interaction of mortar and coarse aggregate

To determine if wet sand does actually attach to the coarse aggregate, an investigation was conducted into the amount of fine sand volume was required for mortar and concrete. The mortar mixtures were produced by taking a concrete mixture design and removing all of the coarse aggregate. This was to examine the interaction between the coarse and fine aggregate. In other words, if you remove the coarse aggregate, how does that change the workability of the mortar mixture? If the mortar and concrete proportion volume of fine sand are very similar, then there is no interaction between the coarse aggregate and fine aggregate. If the mortar mixtures have lower proportions amounts than the concrete mixtures, then this means there is an interaction between the sand and coarse aggregate.

The workability performances of different fine sand volumes were investigated for the concrete and mortar mixtures. The mortar mixtures used the visual observations as the performance rating. But for the concrete mixtures, the WR dosage was convert in the following scale: excellent is 5 oz./cwt, good is between 5 and 10 oz. /cwt, moderate is 10 to 15 oz./cwt, poor is 15 to 20 oz./cwt, and unusable is over 20 oz./cwt. This scale was very reasonable for this research, but not practical for field applications. As shown in Fig. 20, the concrete mixture and the mortar mixture differ largely. The mortar required roughly 10% less fine sand volume to achieve a similar workability. This data suggests sand does interact with coarse aggregate in the mixture.

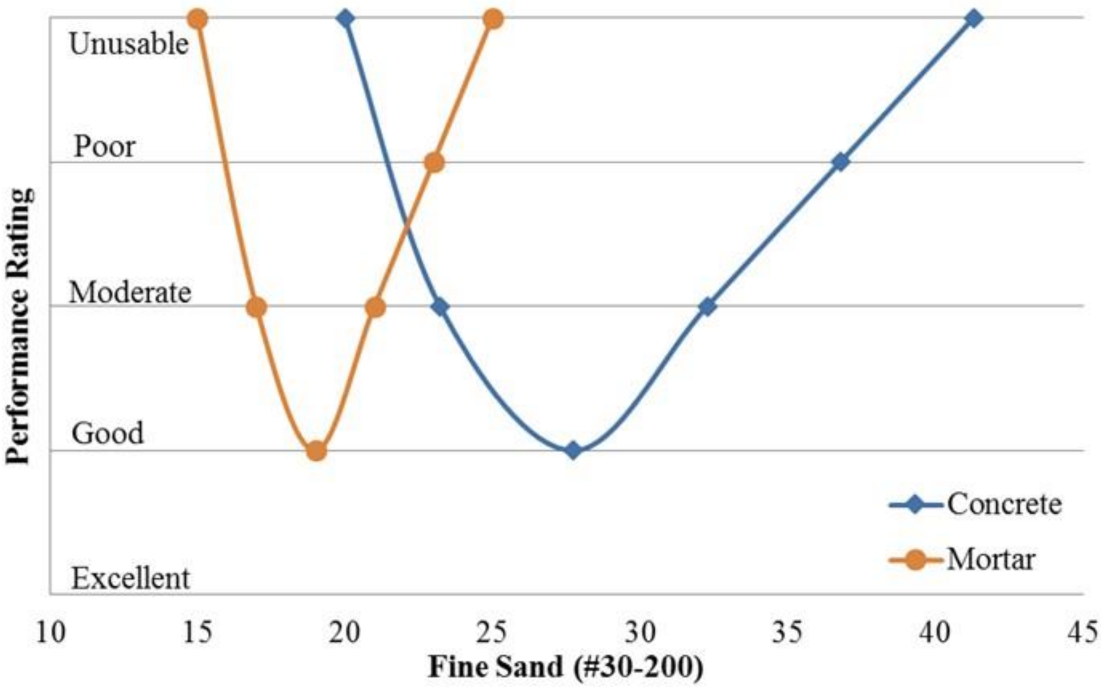

Fig. 9-20 compares the fine sand volumes of concrete and mortar mixtures.

3.4.3.1 Surface tension

The next step was to determine how the sand and coarse aggregate interact. Sand and coarse aggregate was over dried to remove the water. A dry ¾" rock particle was placed into a bottle with dry sand and the lid was placed on the container. This bottle was shook vigorously for 3 minutes and poured onto a counter. From visual observations, the dry sand could not stick to the rock as shown in Fig. 9-21. The material was added back into the container and also enough water to saturate the sand. Again, the bottle was shook vigorously for 3 minutes and poured onto a counter. From visual observations, the sand and coarse aggregate now attached to each other as shown in Fig. 9-22. This plainly shows the surface tension of the water causes the fine aggregates to stick to the coarse aggregates. Similar results have been found with the interaction of fine aggregate and water in other publications [26, 27].

Fig. 9-21 shows dry sand not attaching to coarse aggregate.

Fig. 9-22 shows wet sand attached to coarse aggregate.

3.4.3.2 Surface energy

Since the surface tension of water was shown to physically bond the coarse aggregate and fine aggregate together, an investigation was conducted to determine if only surface tension was responsible for this bond. To investigate this, a coarse aggregate was cover with wet sand and placed into a temperature controlled drying chamber at 72 degrees F and 40% RH. After the sample had dried for seven days, the fine aggregate still attached to the coarse aggregate as shown in Fig. 9-23. In reality this testing process could not get the sample down to 0% moisture, but the sample was visually dry. With very little moisture still remaining, this result suggests the sand particles had strong bonds on the coarse aggregate particle and significant effort was required to remove the fine aggregate particles. This could be due to either the very small amount of moisture in surface tension kept the bond together, or the surface energy of the particle was played into this silica and calcium bond [24, 28]. More work is required into understanding this and other possible surface energy effects.

Fig. 9-23 shows dried fine aggregate still attached to coarse aggregate.

3.5 Applying mechanism to limits

Unfortunately, the surface chemistry mechanism could not be further evaluated like the packing and surface area theories. More investigations need to be conducted into the basic mechanism. However, the following subsections will help explain the interaction of the surface chemistry on the fine sand, coarse sand, and maximum limits.

3.5.1 Maximum limits

Excessive particle sieve sizes will not be able to stay cohesive in the mixture because too many particles were present and could not bond to particles. Since all of the particles are held together through the interaction of surface chemistry, excessive amounts of any particle sieve can become overwhelming for the mixture to keep the bonds. This causes excessive sieve particles break the bonds and come out of the mixture. More research needs to be conducted into understanding the validity of this interaction.

3.5.2 Fine sand volume

Fine sand particles interacts largely with the paste to form the mortar property behavior of concrete. This can have a direct relationship with the consistency of the mortar to properly surface finish the concrete. High amounts or too many particles in the mixture creates a higher viscosity mixture due to the particles were now becoming less suspended and therefore poor workability. Low amounts of fine sand create a mixture behaving as a stockpile of coarse aggregate covered with paste and therefore overall poor workability. A good workable mixture needs to be within the required fine aggregate volume range.

3.5.3 Coarse sand volume

For coarse aggregate the particle sizes become heavier and the covalent bonds [5, 26, 27] around the surface of the particle are easily broken break. This causes the fine sand and paste to not easily bond with the coarse aggregate. However, the coarse sand particles can act as a transitional link between the fine sand, paste, and coarse aggregate. This can have a direct relationship with problematic mixture design issues such as segregation and edge slumping. Low volume amounts of a mixture cannot hold itself together and will cause segregation, edge slumping, and finishability problems as shown in Fig. 9-24. More coarse sand needs to be added to create the stiffness to bridge between the fine sand, paste, and coarse aggregate. Also, high volume amounts of coarse sand could create a stiff mixture that does not allow the paste, fine sand, and coarse aggregate to flow properly. The consistency of a high coarse sand mixture is very stiff with less suspension of particles and more tendency to come out of the mixture. Similar to high amounts of fine sand or maximum sieve size limits.

Fig. 9-24 shows low flow concrete being placed with a slip formed paver.

3.8 Further work

More work is needed to further understand the mechanism behind the aggregate limits and the workability of concrete. The surface chemistry mechanism theory has some potential to give a deeper understanding into the workability of concrete. Further research efforts should be focused to better understand the gradation effects of the surface chemistry interaction to produce different workability performances. Mixtures with different performances should be analyzed to better determine the relationship between the maximum limits, coarse sand, and fine sand. First, each of these relationships could be analyzed using a micro X-ray CT scanner to provide more understanding into the surface chemistry mechanism. Second, these relationships create a partially suspended mixture. The aggregate distribution in good and poor mixtures could be examined in 3-D. The flowability, finishability, consolidation, and stiffness could each be used to further understanding the behavior of concrete. Third, the effects of paste properties on these mechanisms needs be further investigated. The w/cm, paste volume, and WR dosage each drastically change the workability of the concrete. Different paste properties should be changed in the mixture. The workability performance should be measured and sample taken. The micro X-ray CT scanner could look at the interaction relationship. Then a 3-D simulation could help further explain this relationship.

4. Concluding remarks

Some possible mechanisms behind the proportioning limits was further investigated. Even though a relationship between the workability performance and a possible mechanism was not found, the data did reveal neither surface area nor packing mechanism through a dry-rodded unit weight directly created a performance pattern. Similar findings were found of surface area and three popular packing techniques in Chapter 3. The surface chemistry interaction did show some insight to a plausible mechanism, but more research needs to be conducted into understanding the interaction and relating the mechanism directly to the proportioning limits.

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CHAPTER X

CONCLUSIONS

1.0 Overview

The main goal of this research was to further advance the knowledge of aggregate proportioning and also develop practical aggregate specifications for concrete producers. This was completed through a series of empirical iterations looking into the relationship between aggregate and the workability of concrete. Workability tests for slip formed pavements and flowable concrete applications were developed and used to evaluate more than eight hundred different concrete mixtures. The conclusions of each chapter will be provided along with practical aggregate recommendations, significance of this work, and further research needs.

1.1 A workability test for slip formed pavements

- This work shows the Box Test provides a simple and quantitative tool to evaluate the impact of different mixture variables for slip formed pavement mixtures.
- The consistency of multiple evaluators to visually measure surface voids was shown to be over 90%.

- In two different field comparisons, the Box Test performed comparably the same as a slip formed paving machine.
- No difference was found between mixtures evaluated with a single or multiple dosage of water reducer for the Box Test.
- The repeatability of a single operator adding WR dosage had a maximum expected difference of 2.5 oz. /cwt and an average absolute difference of 1.2 oz. /cwt.
- Multiple operators adding WR dosage had an average absolute difference of 1.7 oz. /cwt and a maximum expected difference of 3.9 oz. /cwt.
- The procedure using the Box Test was able to provide a quantitative comparison of the mixture proportions for coarse, intermediate, and fine aggregate on the response to vibration.

1.2 The effects of coarse aggregate on the workability of slip formed concrete pavements

- The coarseness factor chart, specific surface area, minimum voids content using the dry-rodded unit weight, modified Toufar method, and the compressible packing model were not helpful tools in understanding the workability behavior of concrete for slip formed pavements.
- Both the power 45 and IPR Chart showed the best insight to how a gradation would impact the workability of the concrete. However, the IPR Chart was easier to use than the power 45 Chart and so is recommended to investigate if the aggregate gradation has too high a value on a single sieve.

- Proportioning aggregate to a best fit line on the power 45 chart or an estimated minimum voids content of the modified Toufar method tended to produce harsher mixtures.
- Mixtures using larger nominal maximum coarse aggregate sizes did not necessarily improve the workability.
- The angularity and shape of the aggregates used did play a role in the workability of the mixture but were not as significant as the gradation.

1.3 Investigation of coarse aggregate gradation on the workability of slip formed concrete pavements

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

1.4 Investigation of fine aggregate gradation on the workability of slip formed concrete pavements

- Coarse sand (#8 through #30) was shown to impact the cohesion of the mixture, which can lead to edge slumping and segregation. A value greater than 15% is suggested to be retained on the coarse sand (#8 through #30).
- Amounts over 12% on the #16 and #8 created surface finishing issues for the mixtures investigated.
- Also, retaining 20% of #30 created surface finishing issues for the mixtures investigated.
- Fine sand (#30 through #200) volume was recommend to range from 24% to 34% of the combined gradation.
- Smaller sieve sizes of #50, #100, and #200 give a smooth surface finish.

1.5 Workability tests for flowable concrete applications

- The slump test has been the most commonly specified workability test, but it cannot measure the wide range workability performance criteria of concrete.
- Visual observations is used most often in the field.
- The ICAR Rheometer can measure the rheology parameters of static yield stress, dynamic yield stress, and plastic viscosity.
- The Float Test measures the ability of a concrete mixture to be adequately surface finished.
- An overall ranking scheme for flowable concrete mixtures was developed.

1.6 Investigation of coarse aggregate gradation on the workability of flowable concrete

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

1.7 Investigation of fine aggregate gradation on the workability of flowable concrete

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

1.8 Practical recommendations for slip formed and flowable concrete

Fig. 10-1 shows the recommended sieve limits for slip formed pavements. Fig. 10-2 shows the recommended sieve limits for flowable concrete applications. A coarse sand range and a fine sand range were also developed for each figure. Both of these figures have the same maximum and minimum boundary limits for each sieve size, but have slight different coarse and fine sand ranges. Proceeding sections will further discuss each of these differences.

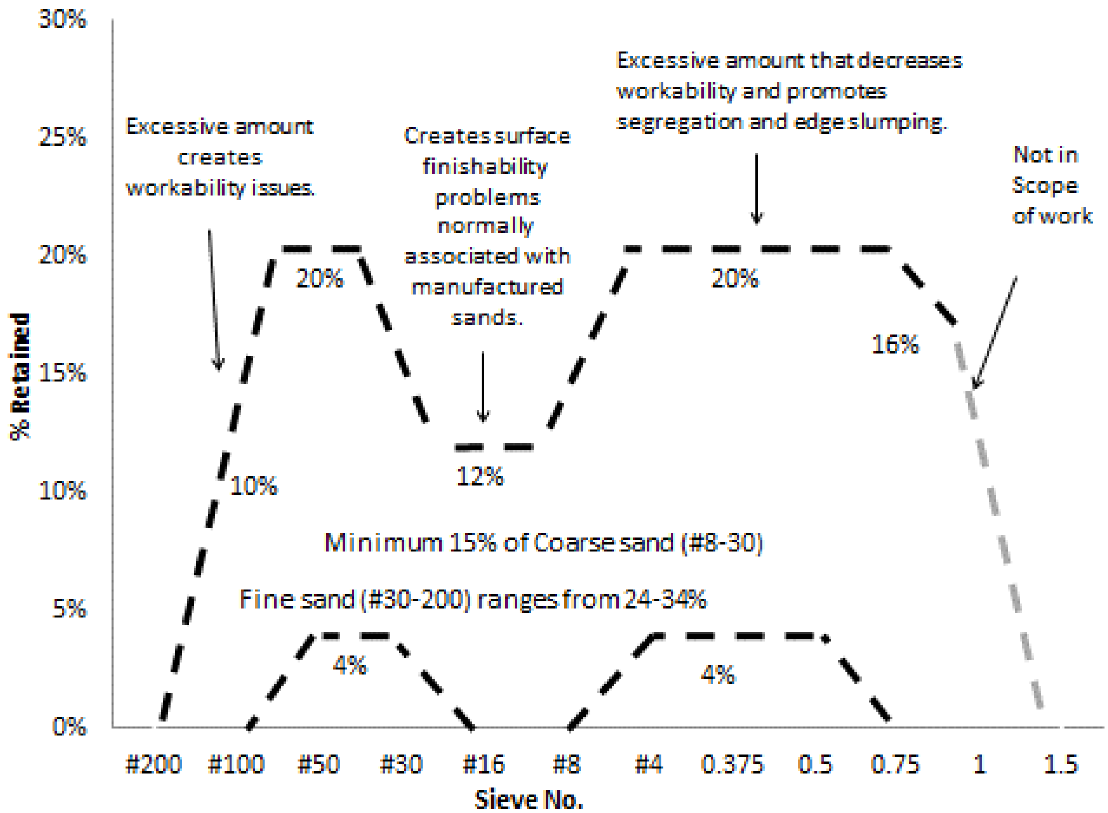

Fig. 10-1 shows recommended sieve limits for slip formed pavements.

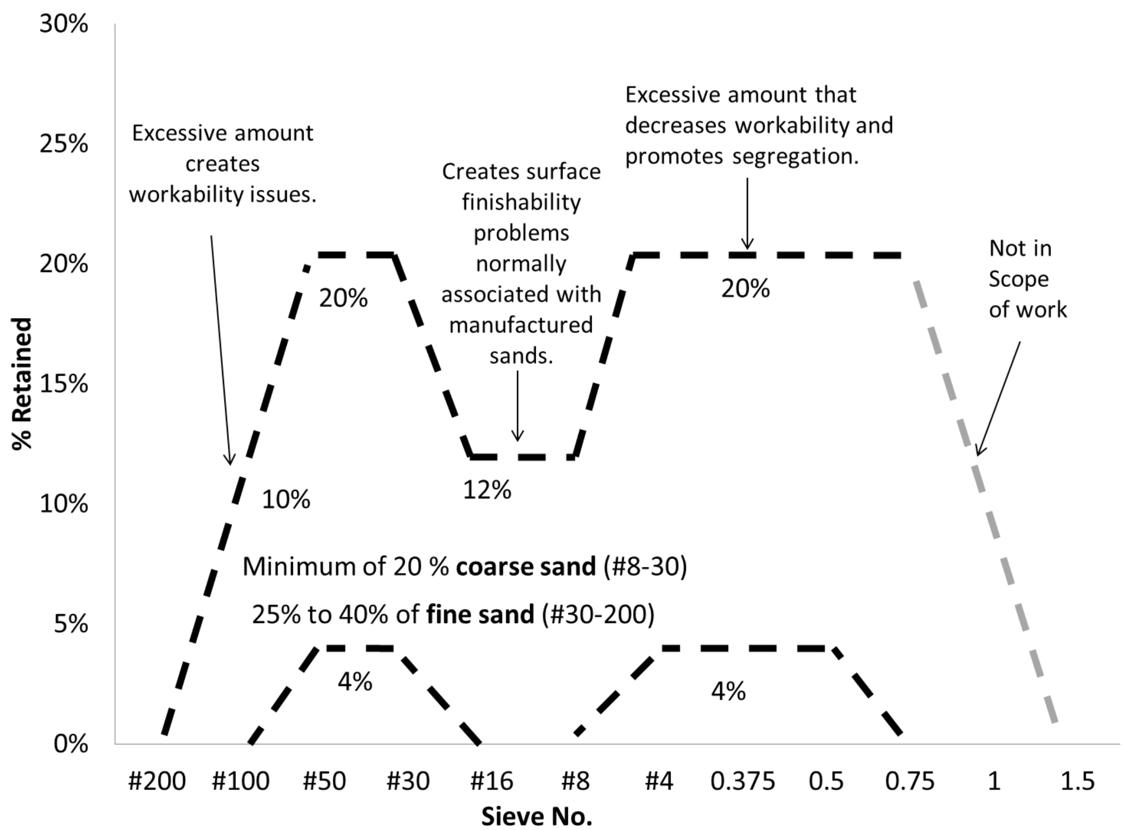

Fig. 10-2 shows recommended sieve limits for flowable concrete applications.

1.8.1 Comparing fine sand recommendations

The practical volume range of fine sand (#30 to #200) for flowable concrete applications was recommended from 25% to 40%. These proportioning trends of fine sand (#30 to #200) from 24% to 34% were similar to the proportioning trends of Chapter 5 with slip formed pavements. This could be from either different paste content or broader workability range of flowable concrete.

1.8.2 Comparing coarse sand recommendations

Coarse sand was proven to effect the cohesion and surface finishability of the mixture. These workability issues can be very problematic. A minimum volume of coarse sand and individual sieve sizes limits were developed to help prevent these issues. If the mixture was high on a coarse sand sieve size, surface finishability issues occurred. Finishability issues were created at 14% of #8, 16% of #16, 20% of #30, and 14% of both #8 and #16. A conservative maximum sieve size boundary was set at 12% for the #8 and #16. Also, a maximum limit of 20% was set for the #30 sieve size. Similar results were found for flowable concrete applications and the same maximum boundaries were recommended.

If low amounts of coarse sand were present, the mixture tended to segregation and edge slump. Similar findings have been found in the field [8, 10, 11]. From Figures 5-3, 5-4, 5-6 and, 5-7, minimal amounts of coarse sand could create adequate cohesion from the following: 15% of #30, 4% on the #16 with 10% of #30, or 12% on the #8 with 10% of #30. A reasonable minimal volume limit of 15% was recommended for coarse sand value using a natural sand. Similar results were found in flowable concrete applications, but instead of 15%, a volume limit of 20% was recommended. This difference could be dependent on the amount of paste used in the mixture.

1.9 Aggregate mechanism on aggregate proportioning

Some possible mechanisms behind the aggregate proportioning limits was further investigated. Even though a relationship between the workability performance and a possible mechanism was not found, the data did reveal neither surface area nor packing mechanism through a dry-rodded unit weight directly created a performance pattern. Similar findings were found of surface area and three popular packing techniques in Chapter 3. The surface chemistry interaction did show some insight to a plausible mechanism, but more research needs to be conducted into understanding the interaction and relating the mechanism directly to the proportioning limits.

1.10 Significance of this research

A more quantifiable method of aggregate proportioning and predicting the aggregate performance of a mixture was developed. Practical aggregate gradation and proportioning limits were created for slip formed pavement and flowable concrete applications. Table 10-1, Fig 10-1, and Fig. 10-2 summarized these aggregate research finding. Sieve sizes were grouped by behavior to better predict performance. Maximum boundary of each sieve size was established for a combined gradation. These findings can give great insights into the performance of a concrete mixture and adjustments can be made on poorly proportioned aggregate.

Also, multiple workability tests were developed to help better measure the workability of a concrete mixture for slip formed pavements and flowable concrete applications. These tests were not developed with the purpose of creating more workability performance specifications, but rather to help researchers, contractors, and concrete producers better measure the workability of the concrete.

1.11 Further research needs

Additional work is needed to further validate and understand aggregate gradation. The interaction between coarse aggregate, coarse sand, and fine sand should be further examined to better understand the impacts on workability. The 1" and larger sieve size limits could be developed and understanding the potential impacts of creating a less cohesive mixture. Also, larger aggregate sieve sizes could affect the cohesion of the mixture and a more in-depth investigate could be conducted into large coarse aggregate and coarse sand impacts. Both coarse sand and fine sand could also be further examined and develop better techniques to predict behavior performance.

The aggregate shape, texture, and angularity should be explored with altered percentages of each aggregate characteristic to determine the degree of significance. Gradation cannot solely taken into account these aggregate characteristics. Further investigations could possibly help create better and more effective aggregate specifications.

Aggregate mechanism behind these gradation limits should be further investigated. Even though the packing techniques and specific surface area was not related to the workability performance trends, these investigated techniques could be slightly flawed conceptually and an adjusted technique could possibly be developed. This could be linked to some basic use of surface chemistry to partially suspend the aggregate particles.

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APPENDICES

1.0 Mixture Design Process

The dissertation investigated aggregate proportioning and developed aggregate gradation recommendations. This is a very important step into developing a more practical mixture design procedure. However, the workability impacts of paste volume and paste properties in concrete have yet to be established. Hopefully, these paste relationships will be eventually developed.

This appendix has been developed in order to help develop an iterative mixture design process and also present practical advice to practitioners, specifiers, and inspectors. Fig. A-1 shows the basic process of developing a mixture design using the aggregate gradation recommendations. 1.) Design the local aggregates into a combined gradation and check coarse aggregate shape. 2.) Design the paste properties such as water-to-cementitious material (w/cm), secondary cementitious material (SCM) replace percentage, amount of water reducer (WR) dosage, air-entrainment, etc. 3.) Develop an initial estimate of paste volume to meet the workability for your application. This will also depend on the combined gradation, paste volume, and paste properties previously designed. The paste volume is typically between 4.5 sacks and 7 sacks, depending on the applications.

4.) Conduct a trial batch to determine if the mixture meets the proper workability. If not, adjust the paste volume, paste properties, and aggregate gradation to achieve the desired workability.

The difficultly of this process depends on many factors such as the skillset of the mix designer, the local materials, and complexity of the mixture specification. The reader should realize the local materials may not be optimal for these guidelines, but the designer should still use the guidelines to understand the possible problems with the mixture. .. These poor gradations may require higher amounts of binder, w/cm ratios, and WR dosages. This may increase the cost and decrease the sustainability of the concrete structure, but the desired workability performance can usually still be obtained.

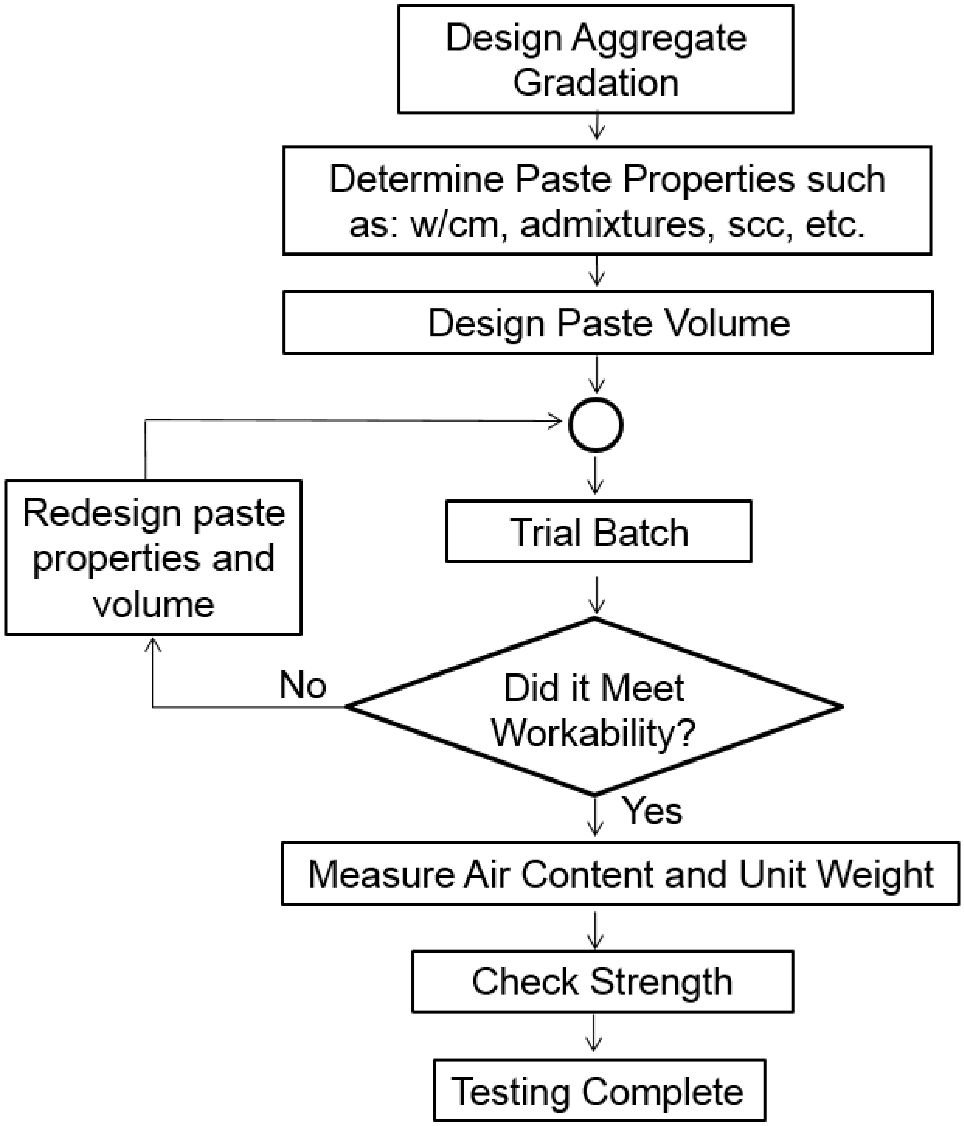

Fig. A-1. Overview of the design process for a concrete mixture design.

2.0 Aggregate Proportioning

Aggregate makes up roughly 60% to 80% of the overall concrete volume. This aggregate volume is the majority of the concrete and a great emphasizes should be placed on the importance to the performance of the concrete mixture. Typically, aggregate specifications require the local aggregate sources to produce an ASTM C 33 fine aggregate gradation and #57 coarse aggregate gradation. These individual gradation limits were not necessarily designed for concrete, but rather aggregate production. The combined gradation guidelines come into play to help proportion the individual aggregate sources together into a combined gradation.

2.1 Combined Gradation Guidelines

While many specifications often require that the designer uses an ASTM C 33 aggregate gradation, this does not seem necessary to produce quality concrete. Instead of worrying about individual sieve sizes, it is better to worry about the combined gradation. A concrete mixture should have sufficient amounts of coarse sand, fine sand, and ideally would not have too much retained on a given sieve size. These combined gradation guidelines will show possible performance trends in the mixture.

2.1.2 Recommended Guidelines for Aggregate Proportioning

A combined aggregate gradation should meet the following requirements:

- Combined gradation should be within the boundary sieve limits in Fig A-2.
- The total volume of fine sand (#30-200) must be within 24% and 34% of the aggregate content used for low flow concrete and within 25% and 40% for high flow concrete.
- The total volume of coarse sand (#8-#30) should be at least 15% for low flow concrete and 20% for high flow concrete.
- Limit the flat or elongated coarse aggregate (#4 and larger) to 15% or less at a ratio of 1:3 according to ASTM 4791.

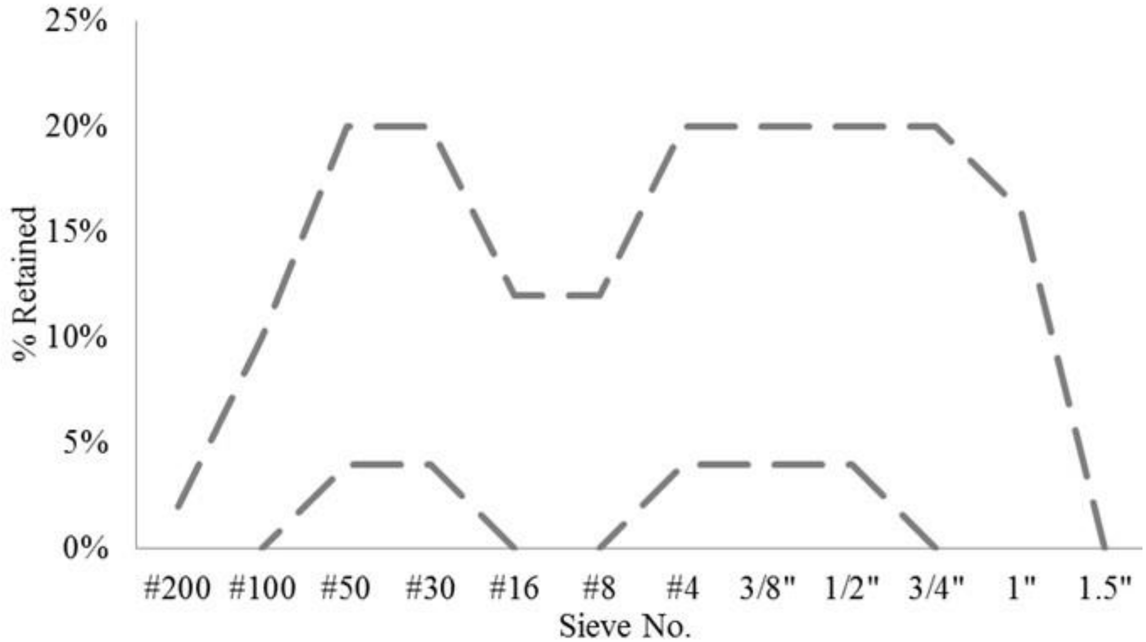

Fig. A-2 – The limits for the minimum and maximum boundary limits.

2.2 Gradations Not Within Combined Gradation Guidelines

Sometimes it is either not possible, or economical to produce gradations within the recommended limits. In these cases it may be possible to develop concrete mixtures with satisfactory performance. However, it is possible that in these cases this may make the concrete more susceptible to segregation, finishing issues, or poor flow. The paste volume or paste properties can sometimes be altered to help compensation for a poor aggregate gradation. Unfortunately, these changes in paste may only slight reduce the poor workability performance in the mixture, but additional amount of paste or water can hurt the long term durability of the concrete and also the strength. Care should be taken to evaluate the performance of the concrete in production and to truly see how the material performs in field applications.

2.3 Individual Stockpile Gradations

Recommendations for individual stockpiles can be a very complex topic due to the number of bins and the aggregate stockpile gradations used. A combined gradation system commonly uses two to seven bins of different stockpiles. Developing recommendation for individual stockpiles according to bin number could possibly be completed, but this dissertation will not attempt to calculate these individual gradation requirements.

2.4 Aggregate Volume

The aggregate volume of each individual aggregate source is determined by three steps. First, use a ratio of the total aggregate volume to determine the percentage of each individual aggregate source. When multiple choices can meet the guidelines, a cost analysis of the aggregates should be completed to determine the economical choice. Second, the paste content should be chosen based off the paste properties and combined aggregate gradation performance indications. The mixture can be adjusted through iterations by changing paste properties and paste volume to achieve the desire workability. This will be further discussed in later sections. Third, the total aggregate volume can be determined by subtracting the paste volume from a cubic yard of concrete. This will allow the percentage of each aggregate source to be calculated based off this total aggregate volume.

3.0 Paste Requirements

3.1 Paste Properties

The paste properties can drastically impact the volume of paste required to meet the workability of concrete. These paste properties include water-to-cementitious material (w/cm), secondary cementitious material (SCM) replace percentage, amount of water reducer (WR) dosage, air-entrainment, etc. These components of the paste properties can affect the workability, set time, strength, durability, and permeability of the concrete. This is especially true for w/cm.

3.2 Paste Volume

Another important component of a concrete mixture is the volume amount used. An initial estimate of paste volume can be difficult to select due to the dependent variables of paste properties and combined gradation. A mixture requires enough paste volume to meet the workability requires in the mixture, but excessive amounts of paste volume may create shrinkage cracking, too flowable of a mixture, and a more expensive product. Typically, the cementitious material content will range between 4.5 sacks (423 lbs.) and 7 sacks (658 lbs.), depending on the applications. For low flow mixtures in slip formed applications, this content can be commonly at 5 sacks (470) and flowable concrete mixture for pumpable applications may be at 5.5 sacks (517 lbs.) to 6 sacks (564 lbs.). Again, this drastically depends on the paste properties, combined gradation, and aggregate characteristics. The paste content may be increased by 50 to 100 lbs. for compensations in poor combined gradations, irregular shaped particles, and lower w/cm requirements.

4.0 Trial Batch Mixing

After determining the initial mixture proportions, it is suggested to complete trial batches. This process is very important to achieve the concrete mixture specifications and sadly this step is sometimes overlooked. Fig. A-4 is a flowchart of the trial batching process to design a mixture to meet the required mixture design specifications. 1.) The initial mixture design is trial batched. 2.) The mixture is evaluated initially for meeting workability requirements. 3.) If the mixture cannot meet the workability requirements, the mixture can be adjusted through iterations by changing paste properties and paste volume to achieve the desire workability. 4.) After the mixture meets the workability requirements, the unit weight, air content, and compression strength should be measured and adjusted if necessary.

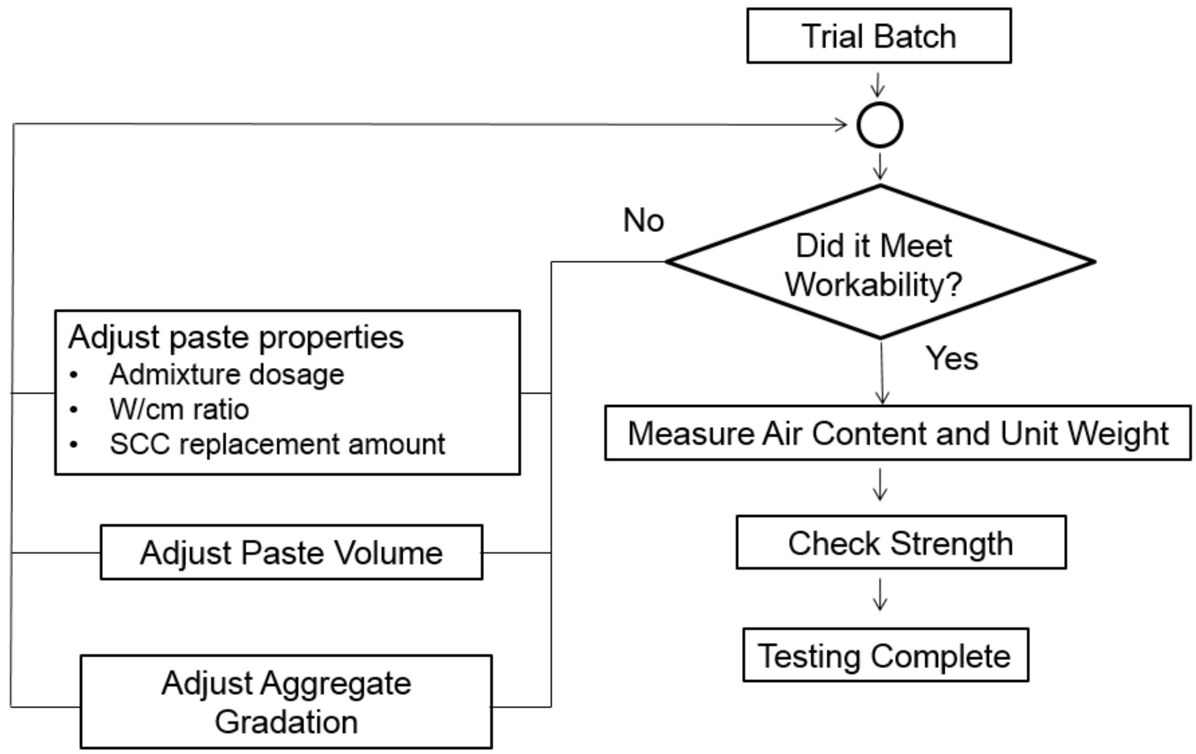

Fig. A-4. Trial batch process for iterating to a mixture design.

4.1 Trial Batch Testing

The evaluation process for determining if a mixture can obtain a certain workability can be very difficult. Typically, people will begin with the slump test and continue to evaluate the mixture with visual observations. But unfortunately, the workability will be really only known as it is being placed. Also, other AASHTO or ASTM test methods can also be used at this same time such as unit weight, air, compressive strength, and flexure strength.

5.0 Quality Control (QC) Testing in the Field

As concrete is being produced in the field, different quality control procedures and test methods can be used to not only meet specifications, but also monitor the consistency between mixtures. Measurements should be taken for slump, unit weight, air, and compressive strength. Other tests such as flexure strength, permeability, and calorimetry may be required for a specific job site. Also, quality control testing can be conducted on the coarse aggregate, fine aggregate, cementitious materials, and admixtures. While the cement and admixture supplies conduct sufficient in house quality assurance testing, the aggregate suppliers must have quality testing of gradation at the concrete plant to ensure accurate gradations.

5.1 Aggregate QC Testing

Aggregate gradations should be monitored daily to ensure accurate gradations. Samples for a sieve analysis should be taken at the last transportation stage before being used, such as on a conveyor belt, in the bins, or in a stockpile. Concrete plants should have quality control practices to reduce stockpile segregation and try to obtain consistent gradation as possible. Also, stockpile replacements should check for consistent gradations. If a stockpile is segregated or drastic variation between gradations of the aggregate stockpile replacements, a concrete mixture can have drastic changes in workability. This is why it is important to complete a sieve analysis regularly to ensure proper consistency between stockpile gradations.

5.2 Consistency of Workability QC Testing

The consistency of producing workable mixtures should be monitored closely. If a concrete producer cannot produce a consistent workability, it will drastically effect the construction process of placing, surface finishing, and curing the concrete. This can create cold joints and even cracking. The Slump Test can be a very powerful tool for measuring the consistency of the workability. Samples can be taken from each truck and the Slump Test can be conducted to ensure consistency due to the slump value not varying more than ±1.0”.

PROPOSED OKLAHOMA DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISIONS
FOR
OPTIMIZED GRADED CONCRETE PAVEMENT

MIX DESIGN AND PROPORTIONING

If the contractor provides a concrete mixture meeting the specifications for optimized graded concrete pavement (OGCP), the minimum cementitious content may be reduced to 470 lbs./yd^3 [279 kg/m^3].

Specification

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

- The combined gradation must be within the boundary limits for each sieve size.
- The total volume of fine sand (#30-200) must be within 24% and 34% of the aggregate content used.
- The total volume of coarse sand (#8-#30) must be 15% or greater.
- Limit the flat or elongated coarse aggregate to 15% or less at a ratio of 1:3 according to ASTM 4791.

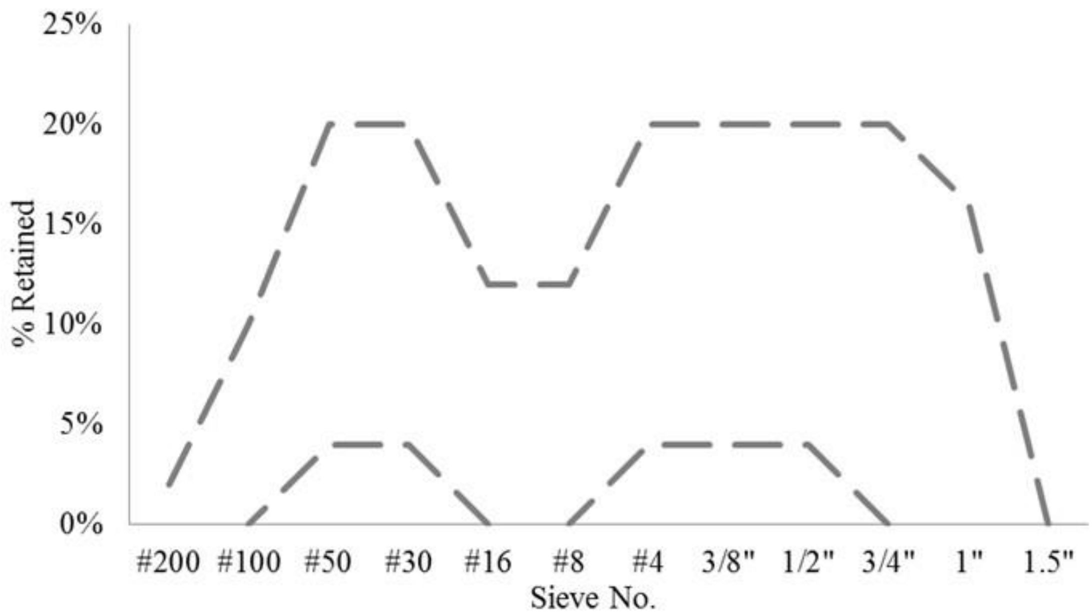

Figure A1 – The limits for the minimum and maximum boundary limits.

Gradation Tolerance

Make necessary adjustments to individual aggregate stockpile proportions during the concrete production to ensure the gradation stays within ODOT requirements. If this is not possible then the minimum cementitious content in the mixture shall be increased to 517 lbs./yd^3 (307 kg/m^3).

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

MIX DESIGN AND PROPORTIONING

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

Specification

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

- The combined gradation must be within the boundary limits for each sieve size.
- The total volume of fine sand (#30-200) must be within 25% and 40% of the aggregate content used.
- The total volume of coarse sand (#8-#30) must be 20% or greater.
- Limit the flat or elongated coarse aggregate to 15% or less at a ratio of 1:3 according to ASTM 4791.

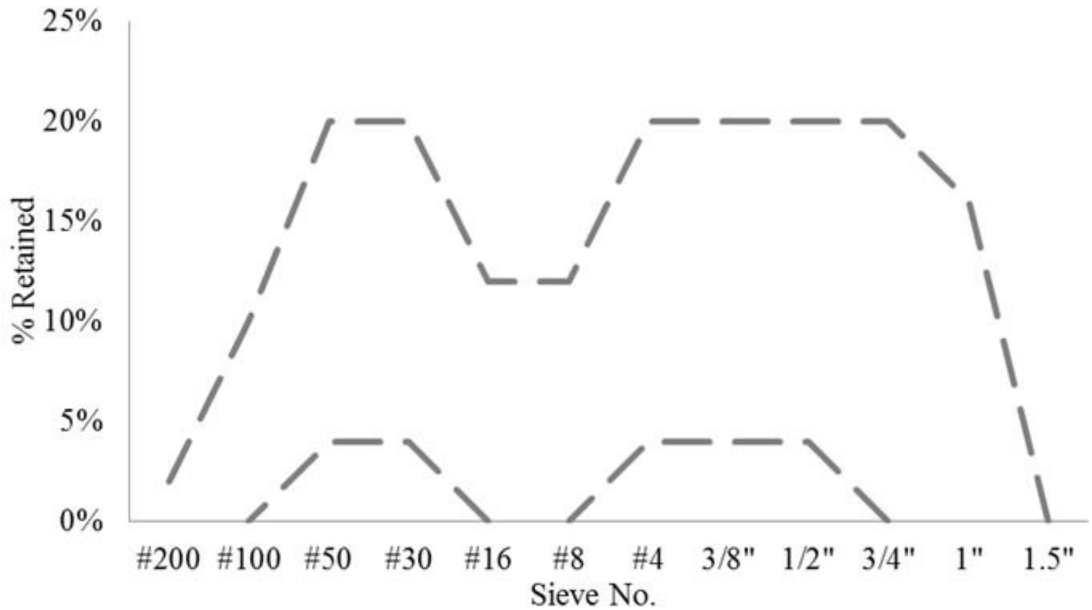

Figure A1 – The limits for the minimum and maximum boundary limits.

Gradation Tolerance

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

VITA

Marllon Daniel Cook

Candidate for the Degree of

Doctor of Philosophy

Thesis: AGGREGATE PROPORTIONING FOR SLIP FORMED PAVEMENTS AND FLOWABLE CONCRETE

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2015.

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2013.

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2012.

Experience:

Concrete finisher for Cook Concrete, LLC.

Professional Memberships:

American Concrete Institute (ACI)