AGGREGATE ASSESMENT AND DURABILITY

EVALUATION OF OPTIMIZED GRADED CONCRETE

IN THE STATE OF OKLAHOMA

By

ASHKAN GHAEEZADEH

Bachelor of Science in Civil Engineering

Islamic Azad University of Najafabad

Isfahan, Iran

2011

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2014

AGGREGATE ASSESMENT AND DURABILITY

EVALUATION OF OPTIMIZED GRADED CONCRETE

IN THE STATE OF OKLAHOMA

Thesis Approved:

M. Tyler Ley, Ph.D., P.E.

Thesis Adviser

Stephen A. Cross, Ph.D., P.E.

Bruce W. Russell, Ph.D., P.E.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. M. Tyler Ley for providing me with the opportunity of furthering my education and guiding and supporting me over the years. You have set an example of excellence as a researcher, mentor, instructor, and role model. Dr. Ley thank you so much.

I would like to thank my committee members, professor Stephen A. Cross and Bruce W. Russell for guiding my research and helping me in better understanding of my thesis for the past two years.

I would also like to thank my wonderful parents, Hossein and Ferdos Ghaeezadeh, and my inspiring brother, Maziar Ghaeezadeh, who have been constantly encouraging and supporting me throughout my entire life. You know that I could not have done this without you.

I would specially like to thank my dearest aunt Ghodsi who have been like a mother to me and supported me with her unconditional love.

I would like to thank Daniel Cook, who as a friend and colleague was always willing to help and give his best suggestions.

Name: ASHKAN GHAEEZADEH

Date of Degree: MAY, 2014

Title of Study: AGGREGATE ASSESMENT AND DURABILITY EVALUATION OF OPTIMIZED GRADED CONCRETE IN THE STATE OF OKLAHOMA

Major Field: CIVIL ENGINEERING

This research is a part of a larger project that emphasizes on creating a more scientific approach to designing concrete mixtures for concrete pavements that use less cement and more aggregate which is called optimized graded concrete. The most challenging obstacle in optimized mixtures is reaching enough workability so that one doesn't have to add more cement or super-plasticizer to reach the desired level of flowability. Aggregate gradation and characteristics have found to be very important when it comes to the workabaility of optimized graded concrete. In this research a new automated method of aggregate assessment was used to compare the shape and the surface of different aggregates as well as their influence on the concrete flowability.
At the end, the performance of optimized graded concrete against drying shrinkage and freezing and thawing condition were investigated.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

II. INVESTIGATION OF AGGREGATE CHARACTRISTICS FOR CONCRETE WITH THE AIMS II 1

Introduction 1
Materials 1
Apparatus 1
Methodology 1
Results 11
Discussion 11

III. DURABILITY PERFORMANCE OF OPTIMIZED GRADED CONCRETE 21

Introduction 21
Materials 21
Methodology 21
Discussion 21

V. CONCLUSION 31

Aggregate characteristics 31
Durability performance of optimized graded concrete 31

REFERENCES 41

APPENDICES 41

LIST OF TABLES

Table Page

1 Source Type and name of each aggregate investigated 5
2 The Oxide Analysis for the Cement Used In the Study..21
3 Mixture Design for Limestone A..22
4 Mixture Design for Limestone B 22
5 Fresh Properties, Paste, and Air Values of the Mixtures 26

LIST OF FIGURES

Figure Page

1 Sieve analysis of each aggregate being analyzed by the AIMS II. 6
2 Gradient vector for smooth vs. angular particle..8
3 Fine and coarse aggregate angularity ranges 8
4 Coarse aggregate texture range..10
5 Cluster classification charts for different aggregate properties 10
6 Fine aggregate form 2D ranges..13
7 AIMS measuring texture index of coarse aggregate...14
8 AIMS measuring angularity of coarse aggregate...15
9 AIMS measuring the sphericity index of coarse aggregate 15
10 AIMS measuring flat and elongated of coarse aggregate 16
11 AIMS measuring the angularity of fine aggregates 16
12 AIMS measuring the form 2D index of fine aggregate 17
13 Satisfactory lapped sample 25
14 Finished sample 25
15 Compares the durability factor of the mixtures throughout the number of cycles 28
16 Compares the length change of the mixtures throughout the number of cycles 28
17 Compares the mass change of the mixtures throughout the number of cycles 29
18 Compares the expansion of Limestone A overtime...30
19 Compares the percent weight change of Limestone A overtime................................30

CHAPTER I

INTRODUCTION

Concrete is the most widely used materials in the planet after water. Durability and its ability to form any shapes make it superior to other materials in the construction world. Concrete is used for many different applications; buildings, power plants, dams, water treatments, pavements and more. Its main ingredients are aggregate, cement, and water. Aggregates fill about two third of the space. Water, cement and any other additives take up the remaining. Among these different elements in concrete, cement costs about 60% of its total cost and produces more carbon dioxide and embodied energy than any other ingredients. Therefore, the idea of lowering the amount of cement consumption per cubic yard of concrete is intriguing. This would result in more cost-effective product with less carbon dioxide emission that can change the paving industry when miles and miles of concrete are placed. This research is a part of a bigger project that emphasizes on creating a more scientific approach in designing concrete mixtures that uses less cement and more aggregate which is called optimized graded concrete. The most challenging obstacle in optimized mixtures is reaching enough workability so that one doesn't have to add more cement or super-plasticizer to reach the desired level of flowability. Aggregate gradation is the most important factor in this regard that is discussed in Cook, et al. (2014). However, one thing that was perceived in this research was that identical optimized concrete mixtures with the same gradation performed different in workability test. This fact raised the question of whether aggregate characteristics such as shape, angularity, texture, flatness/elongation and so forth have any impact on the workability of optimized graded mixtures. In this research a new automated method of aggregate assessment was used to compare the shape and the surface of different aggregates. Aggregate Imaging Measurement System II is an instrument that was developed by Masad (2003). This piece of equipment has the capability to take pictures of aggregate divided in different sizes and produce data that can explain various aggregate's characters. The information will be used to explain the difference in workability in mixtures with identical gradations.

Also of importance to optimized graded mixture is durability. One needs to make sure that lowering the amount of cement and the cost of the concrete does not sacrifice the service life of this new product. Therefore, drying shrinkage and freeze and thaw cycle that are two most important phenomena in reducing the serviceability of concrete in the state of Oklahoma were investigated. In this study, specimens were made with different cement content to explore the effects and limitations of different cement content on the optimized mixtures.

CHAPTER II

INVESTIGATION OF AGGREGATE CHARACTRISTICS FOR CONCRETE WITH AN AUTOMATED TECHNIQUE

Introduction

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

Numerous claims have been made about different aggregate characteristics impacting the workability concrete. The majority of the aggregate claims revolve around the angularity, texture, and shape variation influences the workability of the concrete. The mechanisms of packing and frictional resistance have been the two leading believes behind the workability effects on aggregates. Typically the packing mechanism of aggregates is explained using a dry packing model. It is an approach to determine the ability of an aggregate's gradation, shape, and angularity to fill a volume by measuring the amount of voids. For example, a very flat and elongated shape will take up less space than a cubical or spherical shape. However, the frictional resistance focuses on the different aggregate variables that impede the flow of a concrete mixture. These aggregate variables contributing to frictional resistance include the shape, angularity, and gradation of the aggregate. For example, a river rock with low angularity, well-shaped, and low textured aggregate will have less frictional resistances causing a better workability than a crushed limestone with high angularity, high texture, and extreme flatness and elongation. Therefore using a river rock should require less paste to achieve a certain workability than a crushed limestone and will be more cost effectiveness of the concrete. Unfortunately, no known research has been conducted on these mechanisms for normal concrete mixtures. Other aggregate impacts besides the workability can impact the concrete. For concrete pavements with transverse cracking, faulting of joints and cracks, punch outs, and spalling at joints and cracks have been attributed to coarse aggregate particle shape and angularity (Al-Rousan, 2005) This mechanism has been contributed to the bond strength between cement paste and the aggregate's shape, angularity, and surface texture (Mindness, et al. 1981). In other words, the bond strength increases as aggregates become rougher and more angular (Kosmatka, et al. 2002). Weak bonding of aggregates in concrete pavements has been attributed to longitudinal and transverse cracking, joint cracks, spalling, and punch outs (Folliard, 1999).A necessitate into understanding the workability of concrete and other factors creating problems in concrete is to classify aggregate characteristic. A basic classification has been to measure angularity, texture, and different variations of shape. In the past, only a human eye with some basic measuring tool could only classify the aggregate characteristics. However recently, computer imaging systems are starting to be incorporated into classifying aggregate characteristics. One of the more advanced systems this research will be using is the AIMS II. The main goal of this chapter is to evaluate various aggregate characteristics using the **A**ggregate **I**maging **M**easurement **S**ystem **2** or **AIMS II**.

Materials

Eleven coarse aggregate and three fine aggregate were analyzed using the AIMS II. As shown in Table 1, the aggregates types used are: nine limestones, one sandstone, two river gravels, one manufactured sand, and two river sands. The majority of the aggregate sources are from the state of Oklahoma with the exception of Lamar from Colorado and Cleburne and Wright from Texas. The aggregate sources are commonly used in concrete. Other than Cleburne and Wright, all of the aggregates studied are approved by Oklahoma Department of Transportation. A sieve analysis of each aggregate type can be shown in Figure 17.

Table 1 – Source Type and name of each aggregate investigated.

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

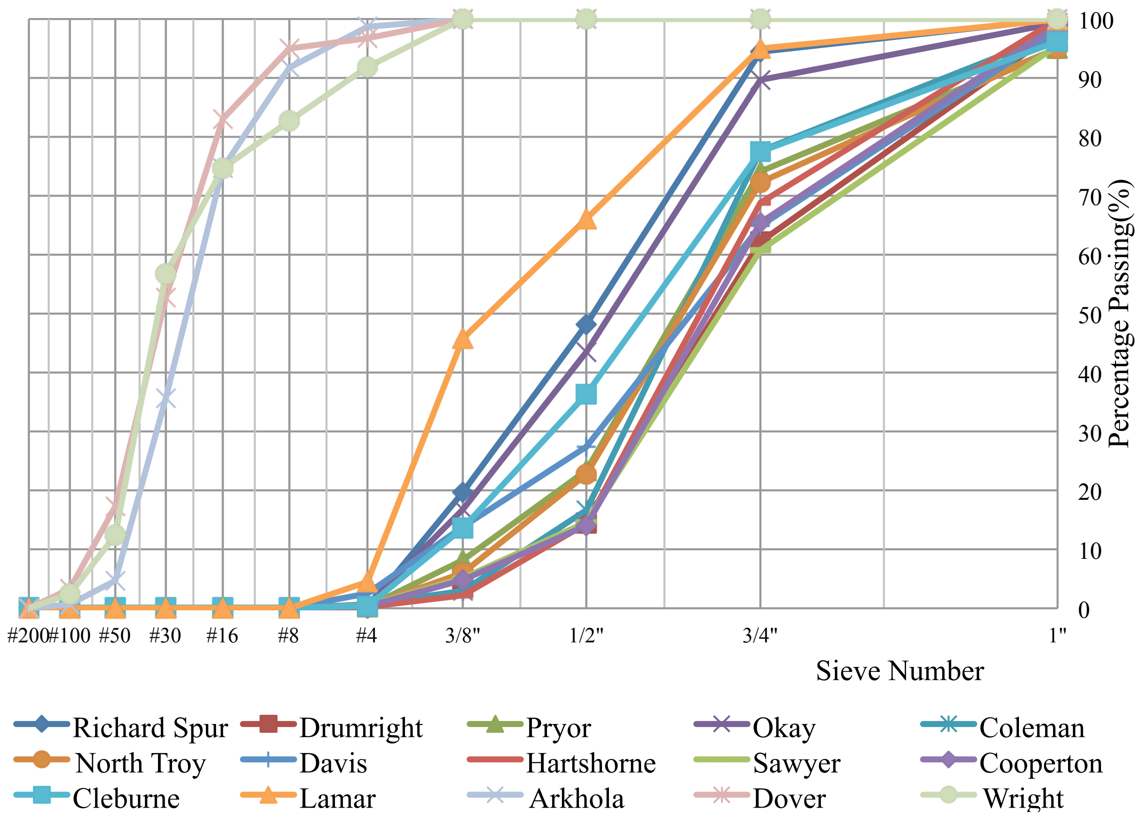

Figure 1- Sieve analysis of each aggregate being analyzed by the AIMS II.

Testing Procedure using the AIMS II

According to past work, the AIMS II has been proved to be relatively good repeatability, reproducibility, and sensitivity (Mahmoud et al, 2009). The development of the method can be found by Masad (2003). The specific objective of this project was to quantify aggregate characteristics from different quarries and sand sources. Each aggregate source was sieved into individual sieve sizes, washed, and analyzed using the automated AIMS II system. The AIMS II measures coarse and fine aggregate differently. Any sieve size at or above 4.75mm (no.4) will be measured for angularity, sphericity, surface texture, three-dimensional shape and flat and elongated. However, the aggregate characteristics differ in that anything below the 4.75mm (no.4) will only have angularity and a form 2D measurement.

Coarse Aggregate Specific Measurements

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

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

These measurements will be discussed in further detail in the coming sections. However, more details on the system design and how it operates can be found in reference (Masad, 2003).

Gradient Angularity

Gradient Angularity applies to both fine and coarse aggregate sizes and describes variations at the edge of the particle that impact the overall shape. The gradient angularity quantifies changes along a particle boundary with higher gradient values indicating a more angular shape. Gradient angularity has a relative scale of 0 to 10000 with a perfect circle having a small non-zero value. It is analyzed by quantifying the change in the gradient on a particle boundary (Chandan, et al. 2004) and is related to the sharpness of the corners of 2-dimensional images of aggregate particles. Shown in Figure 18 below, the gradient method starts by calculating the inclination of gradient vectors on particle boundary points from the x-axis (horizontal axis in an image). The average change in the inclination of the gradient vectors is taken as an indication of angularity. Figure 19 shows the AIMS II measurement for angularity.

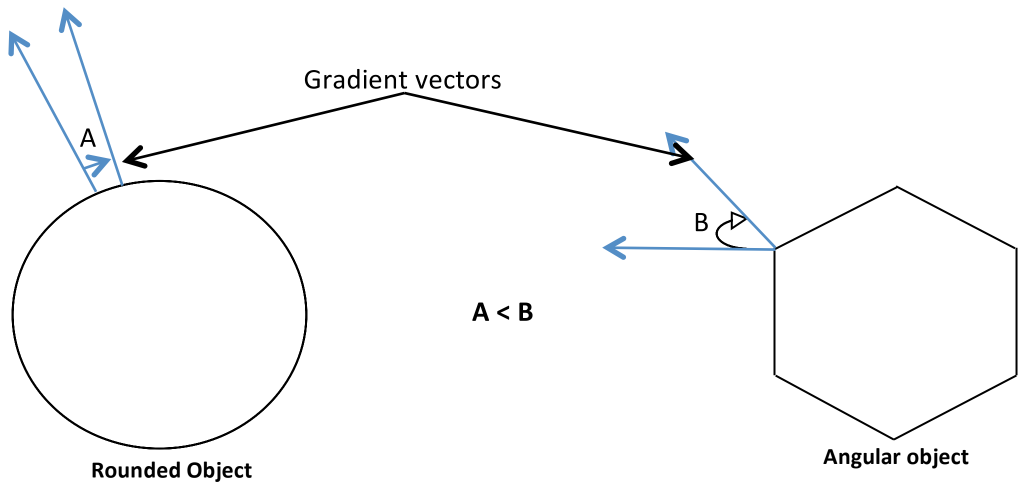

Figure 2 - Gradient Vector for Smooth vs. Angular Particle (Chandan, et al. 2004)

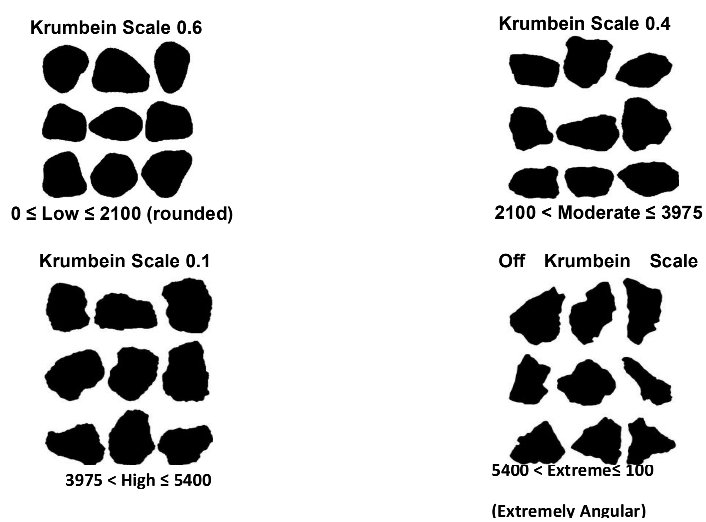

Figure 3- Fine and Coarse Aggregate Angularity Ranges (Krumbein, 1941)

Texture

Texture describes the relative smoothness or roughness of aggregate particles' surfaces. AIMS Texture applies to coarse aggregate sizes only and describes surface micro-texture, features less than approximately 0.5 mm in size which are too small to affect the overall shape. Texture has a relative scale of 0 to 1000 with a smooth polished surface approaching a value of 0. The AIMS Texture analysis uses the wavelet method to quantify texture (Fletcher, et al. 2002),(Al-Rousan, 2004),(Fletcher, et al. 2003). The wavelet analysis gives the texture details in the horizontal, vertical, and diagonal directions in three separate images. The texture index at a given decomposition level is the arithmetic mean of the squared values of the wavelet coefficients for all three directions. The texture index is expressed mathematically as follows:

$$TextureIndex = \frac{1}{3N}\sum_{i=1}^{3}\sum_{j=1}^{N}[\, D_{i,j}(x,y)]^2 \tag{1.1}$$

where n refers to the decomposition level, N denotes the total number of coefficients in a detailed image of texture; i takes values 1, 2, or 3, for the three detailed images of texture; j is the wavelet coefficient index; and (x, y) is the location of the coefficients in the transformed domain. Fletcher (2003) found that texture can be least affected by color or dust particles on the surface of the particles by using a certain level of low resolution and detailed images. In Figure 20, a texture scaled was developed with images and a range of numbers.

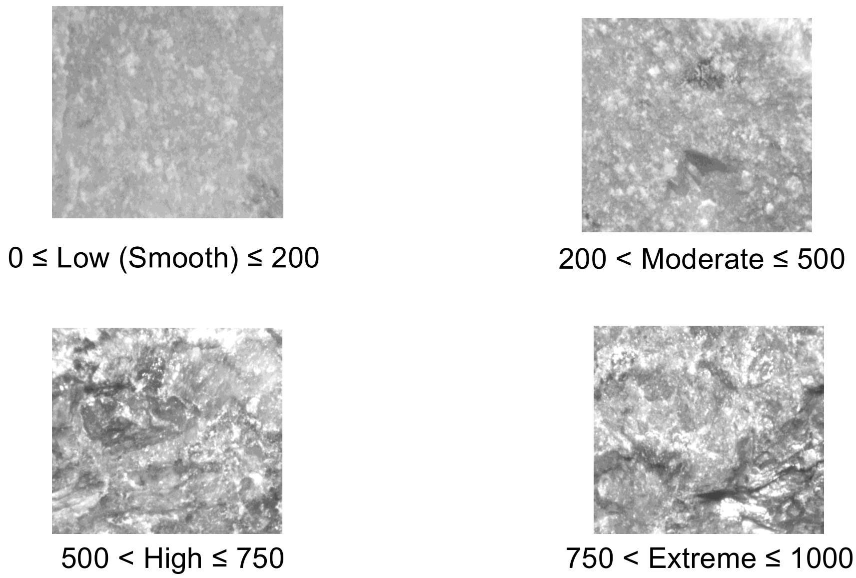

Figure 4 - Coarse Aggregate Texture Range

Sphericity

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

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

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

Figure 5 - Cluster Classification Charts for Different Aggregate Properties (Masad, 2005)

Flat & Elongated, Flat or Elongated

The flat and elongated test measures the percentage of particles above a specified dimension ratio, rather than distribution of relative sizes (Fletcher, et al. 2002). Flat & Elongated represents the ratio of the particle dimensions as described in Equations below:

Flatness Ratio: $$\text{Flatness} = \frac{d_S}{d_I} \qquad (1.3)$$

Elongation Ratio: $$\text{Elongation} = \frac{d_I}{d_L} \qquad (1.4)$$

Flat & Elongated Value: $$L/S = \frac{d_L}{d_S} \qquad (1.5)$$

where: dS = particle thickness (shortest dimension)

dI = particle width (intermediate dimension)

dL = particle length (longest dimension)

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

Flat or Elongated Value (ForE): $$\frac{d_I}{S} \text{ or } \frac{d_L}{d_I} \geq \text{Ratio (i.e.: 1, 2, 3…)} \qquad (1.6)$$

Coarse Aggregate Angularity Texture Value (CAAT)

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

$$\text{CAAT} = 10 \times \text{TX} + 0.5 \times \text{GA} \qquad (1.7)$$

Fine Aggregate Specific Measurements

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

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

Form 2D

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

$$Form2D = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{R_{\theta+\Delta\theta} - R_{\theta}}{R_{\theta}} \tag{1.8}$$

Where: R_{θ} is the radius of the particle at an angle of θ

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

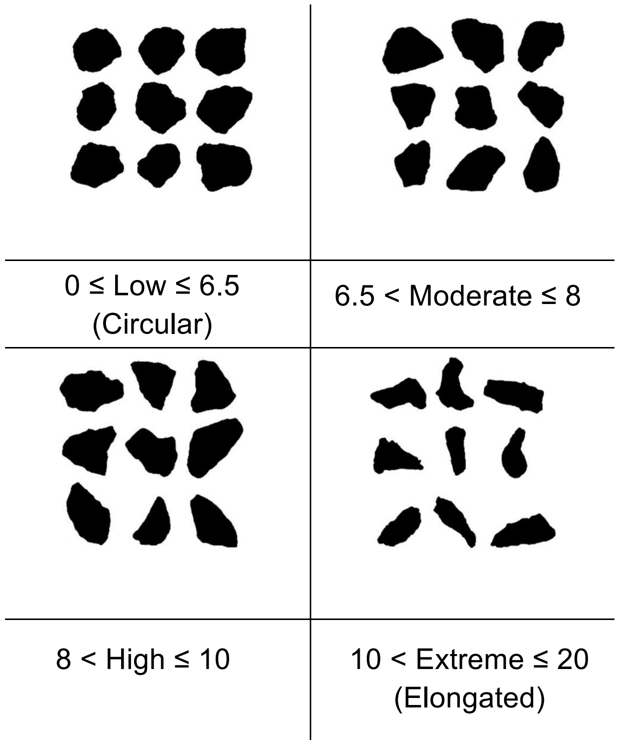

Figure 6 - Fine aggregate form 2D ranges.

Results

Each aggregate source was analyzed using the AIMS II. After analyzing each sieve size, similar to what currently is being done for aggregate gradation, each of the shape characteristics from each sieve size is presented by cumulative distribution instead of single average value for each property. Dealing with the distribution of aggregate characteristics rather than average indices is advantageous for the development of reliable specifications given the high variability in shape characteristics within an aggregate sample (Al-Rousan, 2004). The next step is to statistically analyze the data and assign or identify aggregate groups based on distribution of data acquired. Analyzing the data based on their distribution suggests much more reliable approach to data interpretation (Al-Rousan, 2004). Note: characteristics acquire using AIMS has been compared to, laboratory performance tests and field test (Al-Rousan, 2004)

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

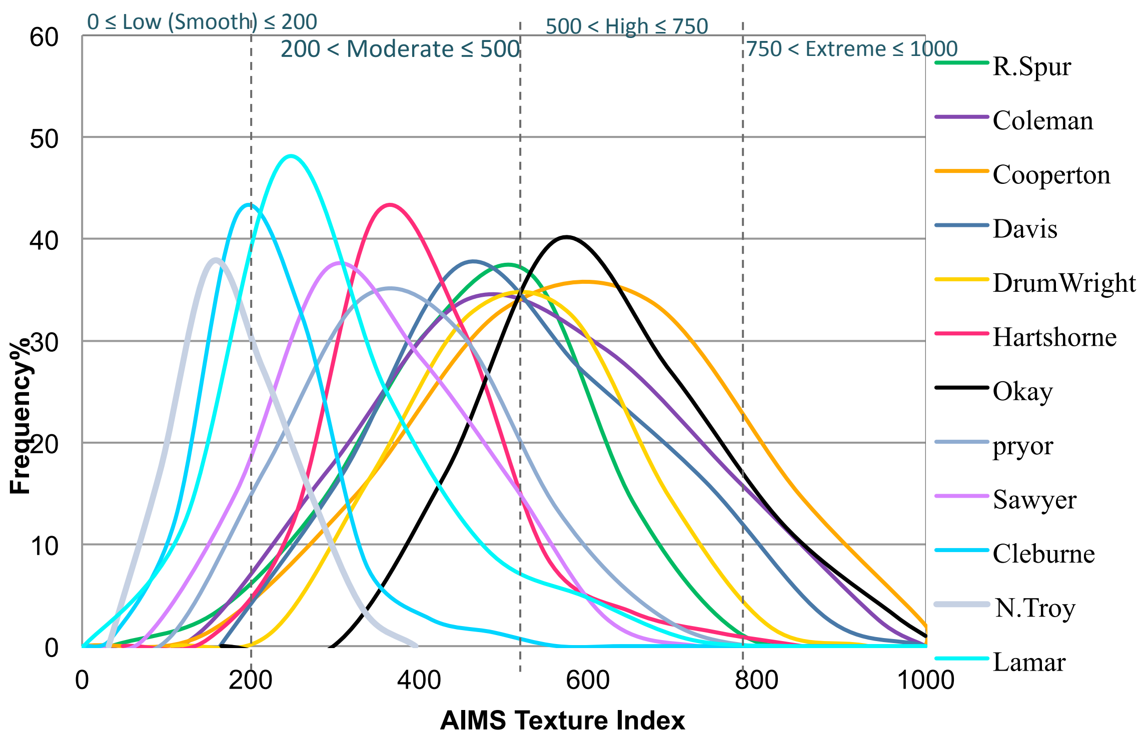

Figure 7 – AIMS measuring texture index of coarse aggregate.

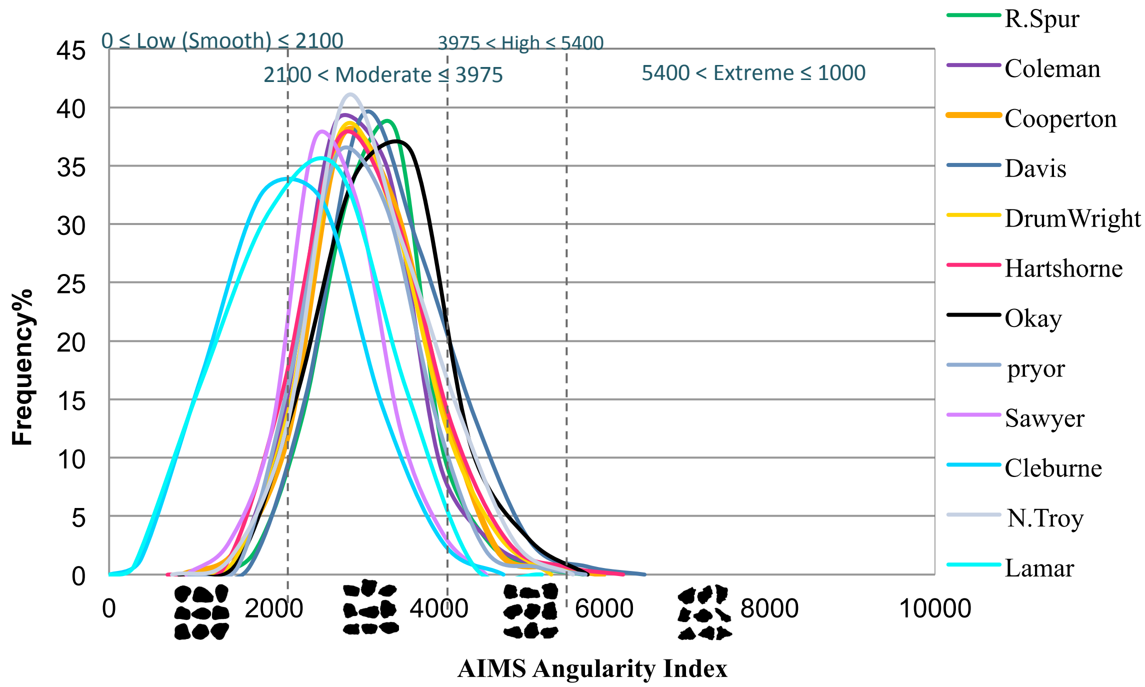

Figure 8- AIMS measuring angularity of coarse aggregate.

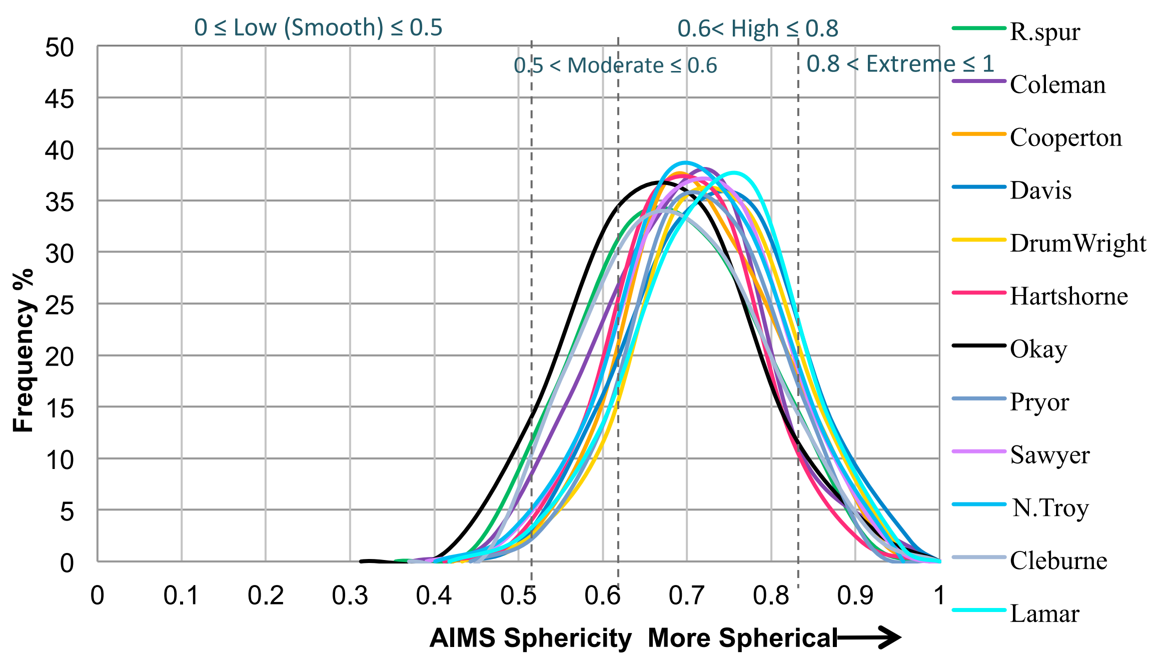

Figure 9 –AIMS measuring the sphericity index of coarse aggregate.

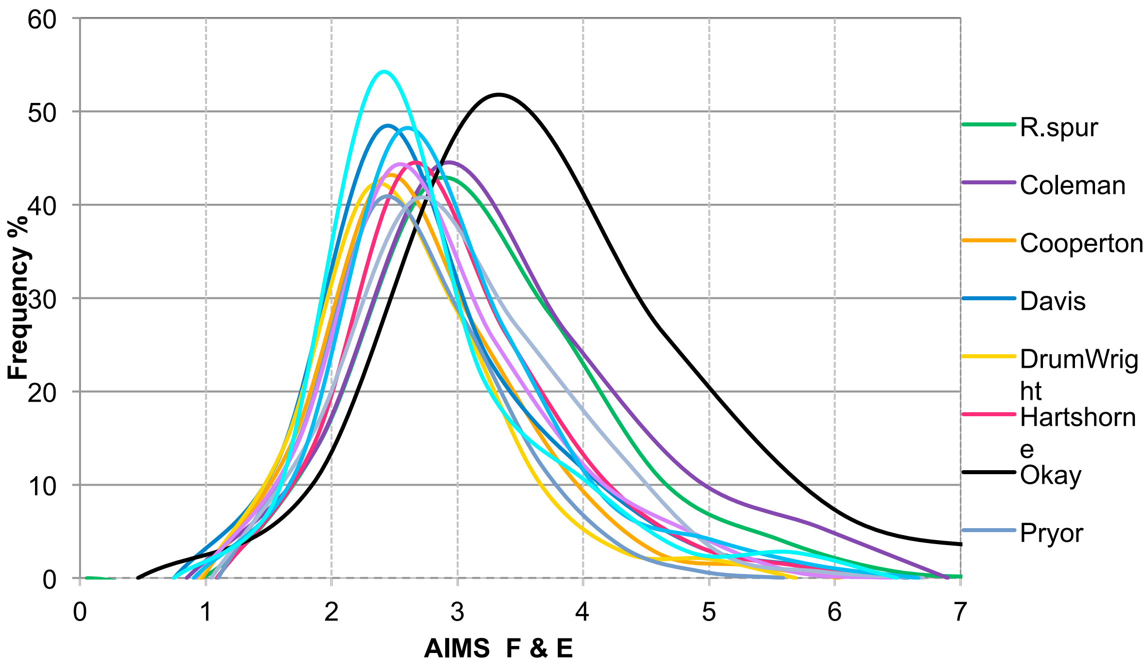

Figure 10 - AIMS measuring flat and elongated of coarse aggregate

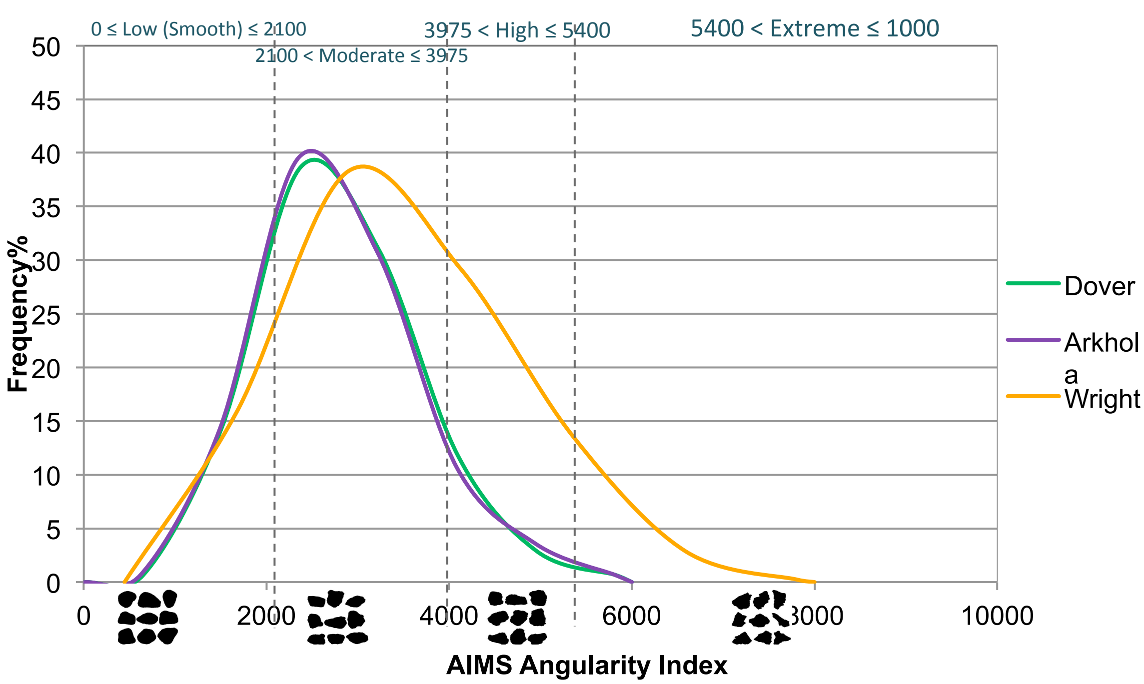

Figure 11 - AIMS measuring the angularity of fine aggregates.

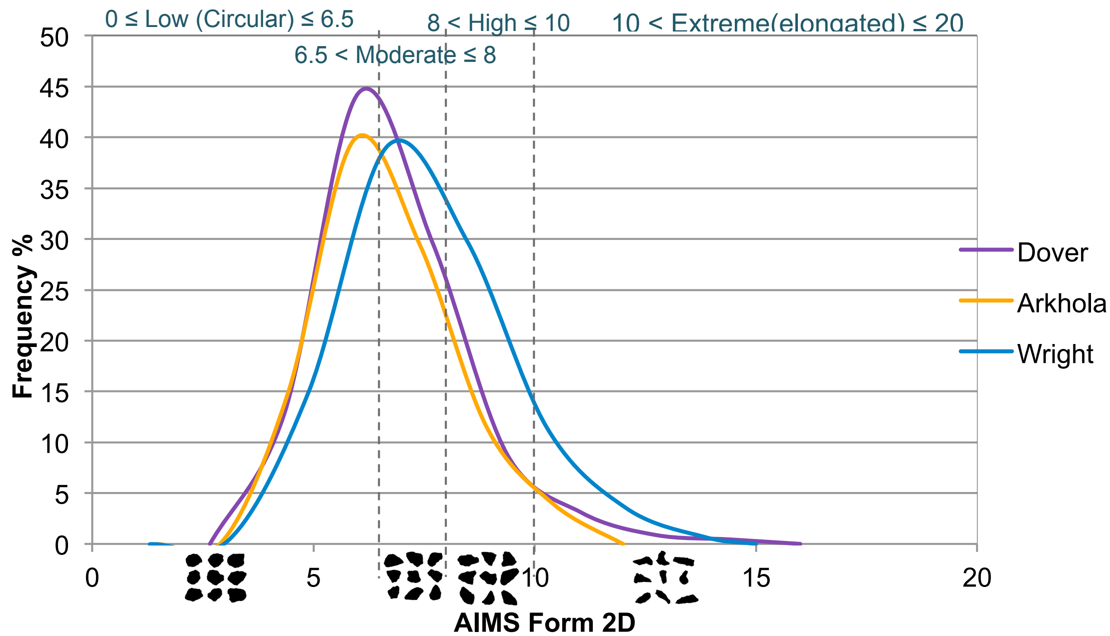

Figure 12 – AIMS measuring the form 2D index of fine aggregate.

Discussion

Texture

Figure 7 shows texture index vs. aggregate percent frequency. As one can see, coarse aggregate image analysis results show that North Troy, Cleburne, and Lamar have relatively low texture in comparing to other aggregates. Likewise, these 11 aggregates can be divided into three zones with low, moderate, and high texture. Aggregate with moderate texture are Sawyer, Hartshorne, and Pryor. On the other hand, because of the fact that aggregates from a quarry come with a wide range of texture rather than a single specific number that can be assigned to the aggregates, some of these aggregate such as Richard Spur, Davis, Drum Wright, Coleman, Okay, and Cooperton are located in the graph where their texture range vary from moderate all way through high and extreme zone. So in order to separate the aggregates from one another it was preferred to use peak of each line which is an indication of where most of particles fall into. According to this fact, Cooperton is an aggregate with high and extreme texture while Richard Spur, Davis, Drum Wright, and Coleman are considered to have high texture. As for Okay, despite of having higher texture than other aggregates that fell into high texture zone, it is still identified as high texture.

Angularity

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

Sphericity

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

Flat & Elongated

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

Angularity of Fine Aggregate

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

Form 2D

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

Conclusion

The AIMS II provides good information on the following aggregate characteristic: angularity, spherecity, texture, and flat and elongated for coarse aggregate in different sieve sizes. In this research weighted average of all the data from different sieve sizes were used to evaluate overall features of a single aggregate. The same concept was used for fine aggregate angularity and form 2D of fine aggregates. The data can be used in comparing different aggregates and their effects on different concrete properties.

- AIMS II has the ability to measure slight differences in the texture of aggregates
- AIMS II gives you good comparison in angularity, spherecity and flat and elongated of aggregates if the they are drastically different.

- Texture varied considerably among aggregate samples. North Troy, Cleburne, and Lamar had relatively low texture in comparison to others. Aggregates with moderate texture are Sawyer, Hartshorne, and Pryor. Cooperton is an aggregate with high and extreme texture while Richard Spur, Davis, Drumwright, Okay, and Coleman are considered to have high texture.
- Angularity data shows Cleburne and Lamar have the least angularity among all the aggregates which is in accordance to what we expected considering they are both river rock. All the other aggregates, despite of having minor differences fall within the moderate zone.
- Flat and elongated is another characteristics of aggregates that was measured using this method. Okay is one aggregate that stands out among all the others for being extremely flat and elongated. Coleman and Richard spur contain more flat and elongated particles after Okay. The rest of the aggregates have relatively the same amount of flat and elongated particle.

- Okay has the least amount of spherical particle among all the other aggregates and it follows by Richard spur, Pryor, and Coleman. Lamar and Davis on the other hand; have the most amount of spherical particle. All the other aggregates have relatively the same amount of spherical particle.

Angularity and form 2D are two characteristics of fine aggregates that was measured using AIMS II. Fine aggregates that were tested through this method are Dover and Arkhola as an example of natural sand and Wright which is manufactured sand.

- Dover and Arkhola have relatively the same amount of angularity and they fell into the category of aggregate with moderate angularity. Wright on the other hand, has a wider range of angularity that varies from moderate range to high.
- When it comes to form2D, Dover and Arkhola particles belong to low zone which is a circular range. Wright on the other hand, is manufactured sand and it contains more moderate

and high range particles. This indicates that Wright particles are less circular comparing to Dover and Arkhola, which are natural sand.

CHAPTER IV

DURABILITY PERFORMANCE OF OPTIMIZED GRADED CONCRETE

Introduction

Durability is of importance when it comes to concrete mixtures. Since optimized graded concrete that is introduced in Cook, et al. 2014 reduces the paste content and increases the amount of aggregate in the mixture, a durability investigated is needed. Many different durability mechanisms could be investigated here. However, drying shrinkage and freeze thaw durability will be the focus of the research due to the primary application of concrete pavements. Drying shrinkage is defined as the contraction of a hardened concrete paste due to the loss of capillary water. A concrete mixture containing a lower paste content and therefore higher aggregate volume should restrain the mixture and have less drying shrinkage issues. When the pores of the concrete become saturated and exposed to freezing temperature, it can cause damage to the microstructure. Over multiple freeze thaw cycles the concrete can be damaged and have widespread cracking. However, air-entrainment agents can be added to create an air void system inside the concrete that can drastically reduce the effects of concrete from freeze-thaw cycles. This air void system is distributed throughout the paste and it actually protects paste from freeze and thaw damage. An optimized graded concrete reduces the paste content and therefore should require less air volume to provide frost durability.

Materials

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

Table 2- The Oxide Analysis for the Cement Used In the Study

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

Mixture Design

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

Table 3- Mixture Design for Limestone A

	4.5 sack	4.75 sack	5 sack
Percent Paste	19.7	20.8	21.9
Cement (lbs/cy)	338.4	357.2	376
Fly Ash (lbs/cy)	84.6	89.3	94
Coarse (lbs/cy)	2034.4	2023.4	2011.8
Intermediate (lbs/cy)	394.5	392.8	391
Fine (lbs/cy)	1004.3	968	932.3
Water(lbs/cy)	190.4	200.9	211.5
W/C	0.45	0.45	0.45

Table 4- Mixture Design For Limestone B

	4.5 sack	4.75 sack	5 sack
Percent Paste	19.7	20.8	21.9
Cement (lbs/cy)	338.4	357.2	376
Fly Ash (lbs/cy)	84.6	89.3	94
Coarse (lbs/cy)	1505.3	1497.1	1488.6
Intermediate (lbs/cy)	1004.4	999.5	994.2
Fine (lbs/cy)	1019.3	982.8	946.9
Water(lbs/cy)	190.4	200.9	211.5
W/C	0.45	0.45	0.45

Mixing Procedure

Aggregates are collected from outside storage piles, and brought into a temperature-controlled laboratory room at 72°F (22°C) for at least 24-hours before mixing. Aggregates were placed in a mixing drum and spun and a representative sample was taken for a moisture correction. Starting the premixing stage, aggregates were loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed. Next, the cement, fly ash, and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixer were scraped. After the rest period, the mixer was turned on and mixed for three minutes. During this final mixing period the air entrainment agent was introduced to the mixture.

Sample Preparation

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

Freeze and Thaw

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

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

Hardened Air Sample Preparation:

The hardened air samples were cut into ¾" thick slices using a self-propelled concrete saw with an 18" diameter continuous rim blade with oil based cutting fluid. The sample was cleaned with water and then dried under a fan. An equal parts mixture of lacquer and acetone was applied to harden the surface and protect the rims of the air voids. An 18 in concrete lapper with magnetically bonded diamond discs of decreasing grit size were used to prepare the samples for testing. The samples were prepared as per ASTM C 457.

After the lapping was complete each sample was inspected under a stereomicroscope to ensure aggregates and paste had been lapped to the same elevation and there was a high quality finish on the specimen. After the specimen had received an acceptable polish, then they were soaked in acetone to remove the lacquer. After soaking in acetone, the prepared sample surface was colored solid with a black permanent marker then dried for 3 hours. A second coat of black marker was then applied in the perpendicular direction to the first coat and the sample dried for 8 hours. A thin layer of barium sulfate, a white powder with a particle size less than 3.94×10^{-5} in (< 1 um), was pressed on the colored surface twice with a rubber stopper to force the white powder into the voids. This technique is described in EN 480-11. This left the surface of the concrete black and the voids stained white. Since the analysis is concerned with the voids in the paste, the voids in the aggregate must be masked. To do this the voids within the aggregate were colored with a fine permanent ink pen under a stereomicroscope. Once completed a final inspection was made of the surface to ensure that voids in the paste are white and all other areas in the sample are black. A sufficiently polished sample and a finished sample can be seen in Figures 13 and 14. This technique is outlined in detail in Ley (2007) and has been used by several other researchers (Jakobsen et al 2006, Sutter 2002, Carlson 2005, Peterson et al 2007).

Once the voids in the paste had been preferentially marked it is possible to use this contrast to determine the air void parameters of the mixture. The research team used the Rapid Air 457 from Concrete Experts, Inc. This machine completes an automated linear traverse analysis on the sample by using a CCD camera to image the surface and an automated stage for precise movement. Image analysis is then used to discern voids (white) from other portions of the sample (dark). A single threshold value of 145 was used for all of the samples that has been shown to be satisfactory with the sample preparation materials and processes used (Ley 2007). This technique requires that the volume of paste be given. This was determined from the batch weights for each concrete mixture design. For the results of the hardened air void analysis reported in this thesis chords smaller than 30 µm were not included in the analysis as they are not easily detected by a human during an ASTM C 457 analysis. By excluding these chords the air void parameters determined by the hardened air void analysis are better comparable to previously reported values of ASTM C 457 results. This has been done previously by many researchers (Jakobsen et al 2006, Ley 2007, Peterson et al 2009, Ramezanianpour & Hooton 2010).

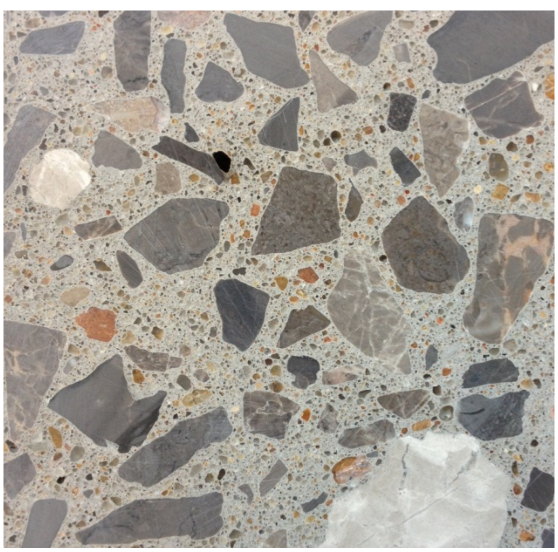

Figure 13- Satisfactory lapped sample

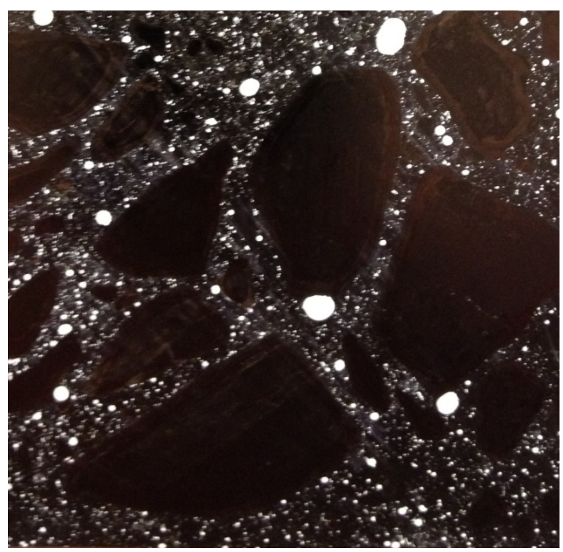

Figure 14- Finished sample

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

Source	Binder/CY	Air %	% Air in the paste	Spacing Factor (in)	Specific Surface (in^2/in^3)	Durability Factor	Unit Weight (lb/ft^3)	Slump (in)
Limestone A	4.5	2.2	10.1	0.011	558	34%	152.9	-
		3.1	13.6	0.013	447	93%	152.2	-
		4.3	17.9	0.009	644	98%	151	-
Limestone A	4.75	2.5	10.7	0.013	542	41%	152.8	0.25
		3.6	14.8	0.01	649	100%	150.3	0.25
		4.6	18.1	0.006	872	95%	149.9	-
Limestone A	5	2	8.4	0.016	451	53%	152.4	0.5
		3.6	14.1	0.007	681	96%	147	0.5
		4	15.5	0.006	647	99%	149.2	0.5
Limestone B	4.5	2.6	11.7	0.011	446	34%	154	0.75
		3.5	15.1	0.006	728	91%	152.8	0.75
		4.05	17.1	0.004	730	94%	152	0.25
Limestone B	4.75	2.48	10.7	0.009	494	36%	154.3	0.25
		3.05	12.8	0.008	584	70%	153.5	0.75
		4.49	17.8	0.004	626	94%	152.3	1.25
Limestone B	5	2.12	8.9	0.011	448	65%	153.8	1
		3.23	12.9	0.009	508	92%	152.5	1.5
		4.54	17.2	0.007	715	95%	150.4	1.75

Shrinkage

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

Results

Hardened Air Void Analysis

Spacing factors were determined for all mixtures and can be found in Table 5 relative to C 231 concrete air contents and calculated paste air contents. CSA recommends a limit of 0.010 in as an individual spacing factor for any given lot of concrete. The ACI 201 limit on spacing factor is shown as a long dashed line at 0.008 in. Lines connect the spacing factors measured at the different fresh air contents observed.

Specific surface values were measured for all mixtures and can be found in Table 5 relative to C 231 concrete air contents and calculated paste air contents. ACI 201 recommends specific surface to be greater than or equal to 600 in2/in3.

Freeze Thaw

With accordance to ASTM C666, the samples were continuously measured at or before the 36 cycle intervals throughout the three hundred freezing and thawing cycles. The average durability factor, length change, and mass change of each mixture throughout the three hundred cycles is shown in Figure 15, 16, 1nd 17, respectively.

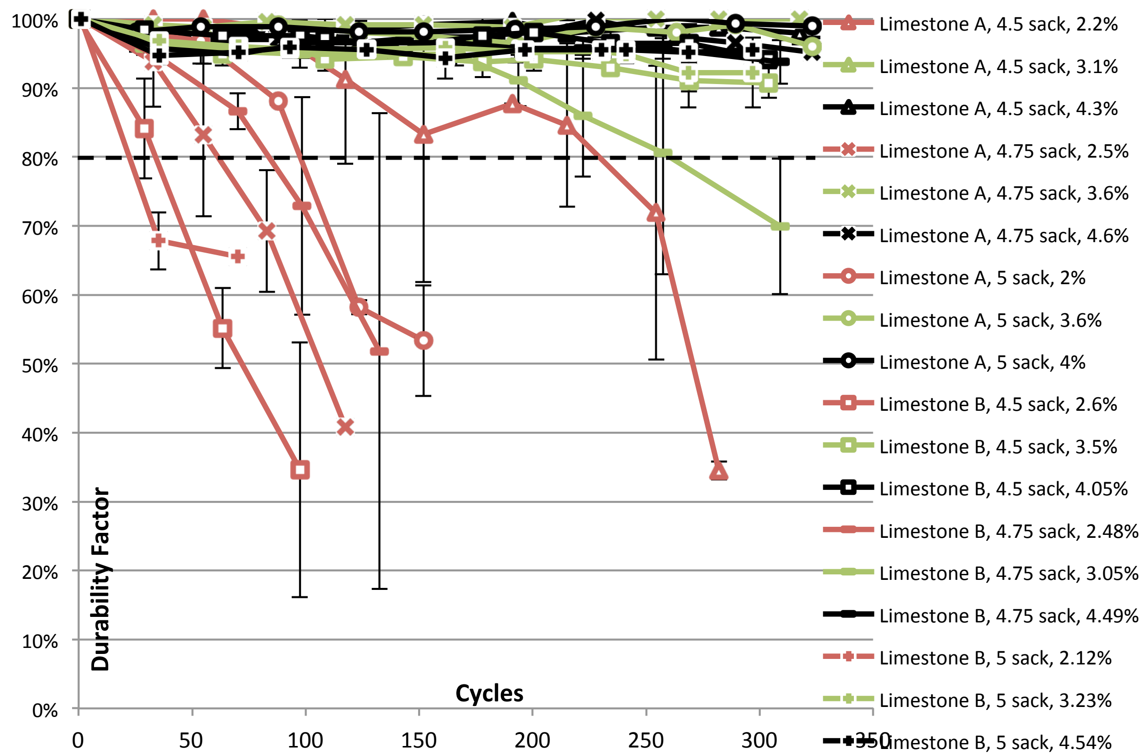

Figure 15- compares the durability factor of the mixtures throughout the number of cycles.

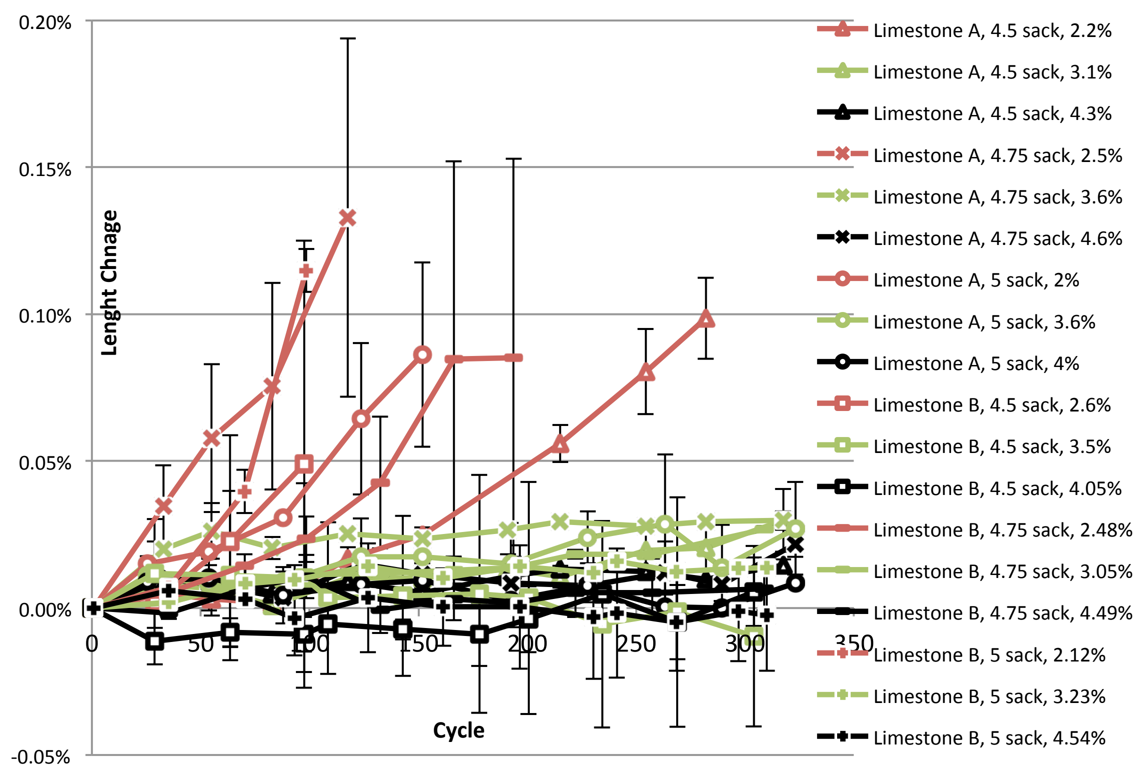

Figure 16- compares the length change of the mixtures throughout the number of cycles.

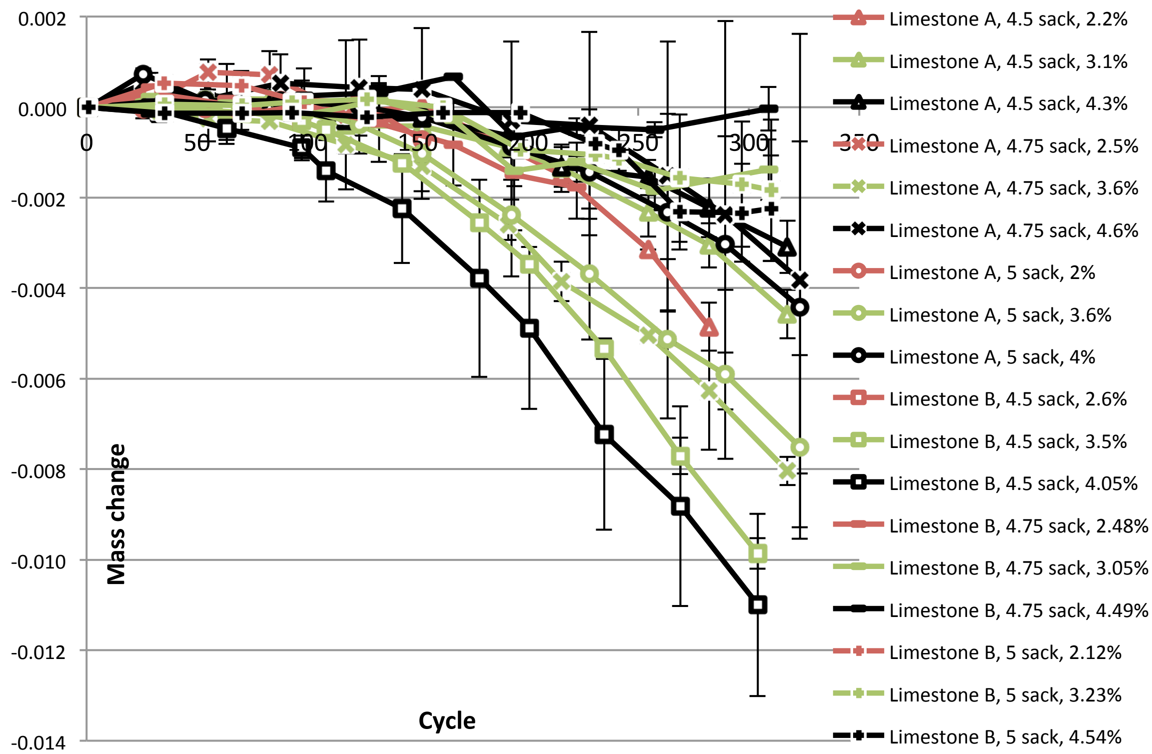

Figure 17- compares the mass change of the mixtures throughout the number of cycles**.**

Shrinkage

Figure 18 and 19 compares the effects of shrinkage over time. While Figure 18 shows the expansion of the specimen throughout time, Figure 19 compares the weight loss percentage due to time.

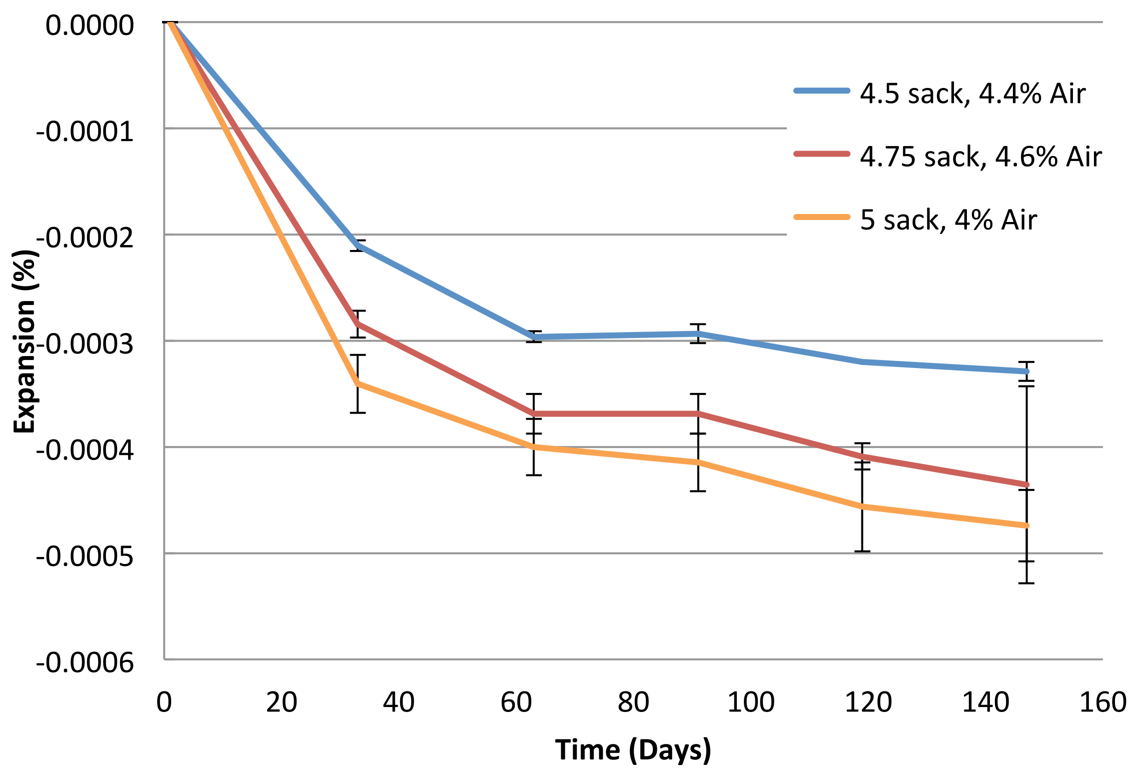

Figure 18- compares the expansion of Limestone A over time.

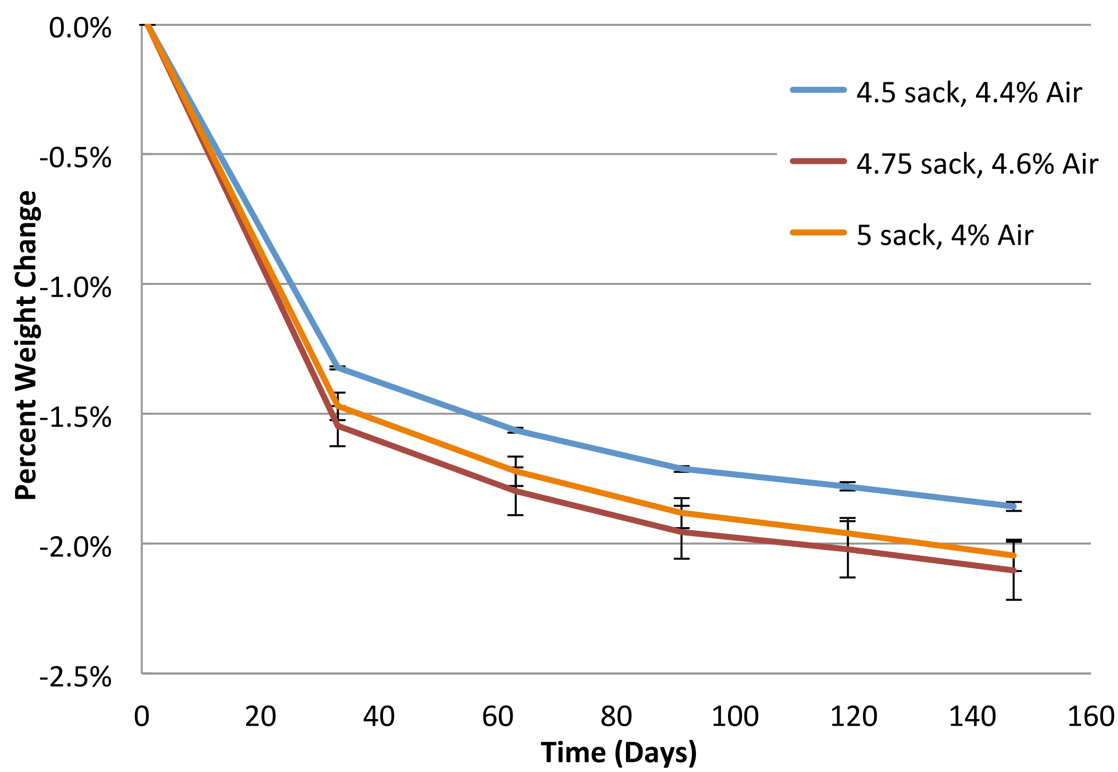

Figure 19- compares the percent weight change of Limestone A over time.

5.4 Discussion

The optimized graded concrete mixtures performed similar to higher paste content mixtures in freeze thaw durability. Figure 15 shows mixtures containing 2.5% air experienced a durability factor lower than 80% after approximately one hundred and ten cycles. However, mixtures containing at least 3.5% air, successfully kept a durability factor above 90% through the required three hundred cycles except for one. The mixtures investigated suggest the existing specifications for freeze thaw durability of concrete pavements do not need to be modified.

As more aggregate and less paste is used, the shrinkage measurements of elongation and weight loss are also reduced. Figure 18 shows decreasing the paste content from 5 to 4.5 sacks with a constant 0.45 w/cm will decrease the shrinkage by 130×10^{-6}. A concrete pavement having an expansion reduction of 130×10^{-6} is a significant reduction in shrinkage. Similarly, Figure 19 shows the percent weight loss of the specimens follows the same trend as percent expansion. The elongation and weight loss measurements confirm reducing the cement content and adding aggregate to the mixture can reduce the shrinkage of the mixture and therefore improve the durability.

Conclusion

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

- The freeze thaw durability performances of optimized graded concrete mixtures showed similar results to mixtures with higher paste contents that were not optimized.
- The mixtures investigated showed the existing specifications for freeze thaw durability of paving concrete do not need to be modified.

- As the shrinkage measurements of weight loss and elongation differences decrease, paste content is decreased in a mixture, it decreases the weight loss and the subsequent shrinkage of the concrete specimens.
- The durability measurements confirm reducing the cement content of a mixture can make improvements in the durability of a mixture.

CHAPTER V

CONCLUSION

This thesis is consisted of two separate research efforts. The second chapter evaluates different characteristics of different aggregates in the state of Oklahoma through an automated technique. The information obtained will be used to better understand the aggregate gradation impacts on the workability of concrete. The third chapter involved investigating the durability of optimized graded concrete mixtures that have the same gradation with different cement content. Based on the data obtained from these studies the following conclusions were made:

- AIMS II has the ability to measure slight differences in the texture of aggregates
- AIMS II gives you good comparison in angularity, spherecity and flat and elongated of aggregates if the they are drastically different.
- Texture varied considerably among aggregate samples. North Troy, Cleburne, and Lamar had relatively low texture in comparison to others. Aggregates with moderate texture are Sawyer, Hartshorne, and Pryor. Cooperton is an aggregate with high and extreme texture while Richard Spur, Davis, Drumwright, Okay, and Coleman are considered to have high texture.
- Angularity data shows Cleburne and Lamar have the least angularity among all the aggregates which is in accordance to what we expected considering they are both river rock. All the other aggregates, despite of having minor differences fall within the moderate zone.

- Flat and elongated is another characteristics of aggregates that was measured using this method. Okay is one aggregate that stands out among all the others for being extremely flat and elongated. Coleman and Richard spur contain more flat and elongated particles after Okay. The rest of the aggregates have relatively the same amount of flat and elongated particle.
- Okay has the least amount of spherical particle among all the other aggregates and it follows by Richard spur, Pryor, and Coleman. Lamar and Davis on the other hand; have the most amount of spherical particle. All the other aggregates have relatively the same amount of spherical particle.

Angularity and form 2D are two characteristics of fine aggregates that was measured using AIMS II. Fine aggregates that were tested through this method are Dover and Arkhola as an example of natural sand and Wright which is manufactured sand.

- Dover and Arkhola have relatively the same amount of angularity and they fell into the category of aggregate with moderate angularity. Wright on the other hand, has a wider range of angularity that varies from moderate range to high.
- When it comes to form2D, Dover and Arkhola particles belong to low zone which is a circular range. Wright on the other hand, is manufactured sand and it contains more moderate and high range particles. This indicates that Wright particles are less circular comparing to Dover and Arkhola, which are natural sand.

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

- The freeze thaw durability performances of optimized graded concrete mixtures showed similar results to mixtures with higher paste contents that were not optimized.
- The mixtures investigated showed the existing specifications for freeze thaw durability of paving concrete do not need to be modified.

- As the shrinkage measurements of weight loss and elongation differences decrease, paste content is decreased in a mixture, it decreases the weight loss and the subsequent shrinkage of the concrete specimens.
- Decreasing the paste content from 5 to 4.5 sacks with a constant 0.45 w/cm will decrease the shrinkage by 130×10^{-6}
- The durability measurements confirm reducing the cement content of a mixture can make improvements in the durability of a mixture.

REFERENCES

ASTM Standard C33, 2003, "Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA

ASTM C138, Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C143/C143M-03, Standard Test Method for Slump of Hydraulic Cement Concrete, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C150, Standard Specification for Portland Cement", American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C157, Standard Test Method for Length Change of Hardened Hydraulic- Cement Mortar and Concrete, American Society for Testing and Materials, West Conshohocken, Pennsylvania 2008).

ASTM C231-04, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method, American Society for Testing and Materials, West Conshohocken, Pennsylvania

ASTM C260, Standard Specification for Air-Entraining Admixtures for Concrete (ASTM, West Conshohocken, Pennsylvania 2010).

ASTM C457 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. ASTM, West Conshohocken, PA., 2012.

ASTM C494-05, Standard Specification for Chemical Admixtures for Concrete, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C618-12a Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM, West Conshohocken, PA., 2012.

ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. ASTM, West Conshohocken, Pennsylvania 2008).

ASTM C1017/C1017M–07, ‘’Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete’’, West Conshohocken, PA

Al-Rousan, T.M. (2004). “Characterization of Aggregate Shape Properties using aComputer Automated System.” PhD Dissertation, Dept. of Civil Engineering, Texas A&M University, College Station, Texas.

Al-Rousan, T., Button, J., Little, D., Tutumluer, E., & Urbana, I. (2005).Appendixes to NCHRP report 555: Test methods for characterizing aggregate shape, texture, and angularity (pp. 1-131). Transportation Research Board.

Carlson, J., Sutter, L., Peterson, K., Van Dam, T. "An update on application of a flat-bed scanner for performing ASTM C 457", Proceedings of the 27th International Conference on Cement Microscopy, Victoria, British Columbia, Canada, 2005.

Cook, M. D., Ghaeezadah, A., & Ley, T. (2014). A Workability Test for Slip Formed Concrete Pavements. In *Transportation Research Board 93rd Annual Meeting* (No. 14-2115).

Concrete pavement.” Final Report, National Cooperative Highway Research Program Project 4-20A. Transportation Research Board, National Research Council, Washington, D.C.

Chandan, C., Sivakumar, K., Fletcher, T., and Masad, E. (2004). “Geometry Analysis of Aggregate Particles using Imaging Techniques.” Journal of Computing in Civil Engineering, ASCE, 18 (1), 75-82.

European Standard, EN 480-11,’’Admixtures for concrete, Mortar and Grout – Test Methods – Part 11: Determination of Air Void Characteristics in Hardened Concrete’’.

Folliard, K. J. (1999). “Aggregate tests related to performance of Portland cement concrete pavements.” Phase 1 Interim Report, Project 4-20B, National Cooperative Highway Research Program, Austin, Texas.

Fletcher, T., Chandan, C., Masad, E., and Siva Kumar, K. (2002). “Measurements of aggregate texture and its influence on HMA permanent deformation.” Journal ofTesting and Evaluation, American Society for Testing and Materials, ASTM,30(6), 524-531

Fletcher, T., Chandan, C., Masad, E., and Siva Kumar, K. (2003). “Aggregate Imaging System (AIMS) for characterizing the shape of fine and coarse aggregates.” Transportation Research Record 1832, Transportation Research Board, Washington D.C., 67-77.

Jakobsen, U.H., Pade, C., Thaulow, N., Brown, D., Sahu, S., Magnusson, O., De Buck, S., and De Schutter, G., “Automated air void analysis of hardened concrete - a round robin study”, Cement and Concrete Research, Vol. 36, pp. 1444-1452, 2006.

Kosmatka, S. H., Kerkhoff, B., and Panarese, W. C. (2002). “Design and control ofconcrete mixtures.” 14th Ed., Portland Cement Association, Skokie, Ill.

Krumbein, W. C. (1941). “Measurement and Geological Significance of Shape andRoundness of Sedimentary Particles.” Journal of Sedimentary Petrology, 11(2), 64-72

Ley, M. T., The Effects of Fly Ash on the Ability to Entrain and Stabilize Air in Concrete, Dissertation, University of Texas at Austin, August 2007.

Mahmoud, E., Gates, L., Masad, E., Erdoğan, S., & Garboczi, E. (2009). Comprehensive evaluation of AIMS texture, angularity, and dimension measurements. *Journal of Materials in Civil Engineering*, *22*(4), 369-379.

Masad, E. The Development of A Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties. NCHRP-IDEA Project 77 Final Report, Transportation Research Board,Washington, D.C., 2003

Masad, E. (2005). “A Progress Repoort Submitted to the Pavement Engineering Program of the Federal Hightway Administration.” Department of Civil Engineering, Texas Transportation Institute.

Mindness, S., and Young, J. F., (1981) Concrete. Prentice Hall Inc., Englewood Cliffs, New Jersey.

Peterson, K. W., Thaulow, N., Baumgart, C. W., Furuichi, H., & Jana, D., “A Round Robin Test on Measurements of Air Void Parameters in Hardened Concrete by Various Automated Image Analyses and ASTM C 457 Methods”, Proceedings of the twenty-ninth conference on cement microscopy, Quebec City, PQ, Canada, 2007.

Peterson, K., Sutter, L. and Radlinski, M., ‘‘The Practical Application of a Flatbed Scanner for Air-Void Characterization of Hardened Concrete,’’ J. ASTM Intl.,Vol. 6, No. 9. doi:10.1520/JAI102446.

Ramezanianpour, A. M., & Hooton, R. D. (2010). “Evaluation of Two Automated Methods for Air-Void Analysis of Hardened Concrete. Journal of ASTM International, 7(2)

VITA

Ashkan Ghaeezadeh

Candidate for the Degree of

Master of Science

Thesis: AGGREGATE ASSEMENT AND DURABILITY EVALUATION OF OPTIMIZED GRADED CONCRETE IN THE STATE OF OKLAHOMA

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science/Arts in your major at Oklahoma State University, Stillwater, Oklahoma in May, 2014

Completed the requirements for the Bachelor of Science in Civil Engineering at Islamic Azad University of Najafabad, Isfahan, Iran in December, 2011.

Experience:

Professional Memberships:

American Institute of Steel Construction
American Concrete Institute