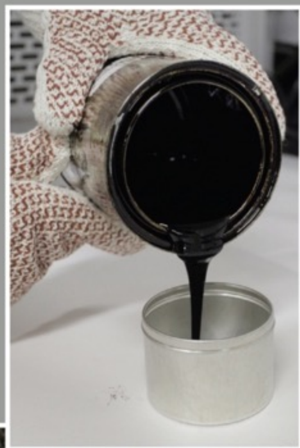
NCAT Report 17-02

EVALUATION OF THE AIMS2 AND MICRO-DEVAL TO CHARACTERIZE AGGREGATE FRICTION PROPERTIES



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April 2017

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ABSTRACT

This National Center for Asphalt Technology (NCAT) report is a summary of a study performed at NCAT by Auburn University Civil Engineering graduate student Mary Greer. Details of the study are reported in her Master's Thesis as part of her qualifications for a Master of Science Degree in May 2015.

There is a need for a laboratory protocol to rapidly evaluate the quality of aggregate friction properties for use in an asphalt surface. Aggregates with good friction resist polishing and retain their shape characteristics. An asphalt surface needs to maintain adequate friction as it is polished by traffic to ensure motorists' safety on the roadway. Some current laboratory procedures used to evaluate the friction properties of aggregates are time consuming and subjective. The purpose of this research study was to evaluate the correlation of aggregate field friction performance to aggregate properties using a laboratory protocol consisting of the second generation Aggregate Imaging Measurement System Model AFA2A (AIMS2) and Micro-Deval.

The test protocol used the AIMS2 device to quantify aggregate shape characteristics (angularity, texture, and form) before and after polishing in the Micro-Deval. The aggregates were selected for their friction performance in asphalt surfaces at the NCAT Test Track. Field friction performance was measured with the locked-wheel skid trailer. Aggregate angularity and texture indexes were compared with the skid trailer field measurements to determine if a correlation could be established.

The AIMS2 device detected changes in aggregate shape after conditioning in the Micro-Deval. However, the analysis did not establish good correlation between the AIMS2 indexes and the field friction data using the test protocol developed in this research study. Additional studies are needed to expand the aggregate types and enhance the laboratory test protocol to verify these conclusions or improve the ability of the test to correlate to field friction performance.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Transportation Officials
AIMS2	Aggregate Imaging Measurement System Model AFA2A
AIMS-II	alternate abbreviation for AIMS2
ASTM	American Society for Testing and Materials
BMD	before Micro-Deval conditioning
CA	coarse aggregate
CAA	coarse aggregate angularity
DFT	Dynamic Friction Tester
ESALs	equivalent single axle loads
F&E	flat and elongated
FA	fine aggregate
FAA	fine aggregate angularity
FDG	fine-dense graded
Form2D	two-dimensional form
Gsa	apparent specific gravity
Gsb	bulk specific gravity
HFST	high friction surface treatment
K-S test	Kolmogorov-Smirnov test
L.A. Abrasion	Los Angeles Abrasion
NCAT	National Center for Asphalt Technology
NMAS	nominal maximum aggregate size
OGFC	open graded friction course
RAP	reclaimed asphalt pavement
SMA	stone matrix asphalt
SN	skid number
SN40R	locked-wheel skid trailer skid number at a test speed of 40 mph with a ribbed tire
SN40S	locked-wheel skid trailer skid number at a test speed of 40 mph with a smooth tire
TWPD	Three Wheel Polishing Device

CHAPTER 1 INTRODUCTION

1.1 Background

Roadway safety is a high priority for highway agencies. Pavement friction, also referred to as skid resistance, is an essential component of an asphalt pavement surface to optimize roadway safety. Heavy traffic polishes the asphalt pavement surface and decreases skid resistance. State agencies set minimum pavement surface friction thresholds to reduce the risk of crashes caused by inadequate friction on the roadway surface, especially in wet weather conditions.

A locked-wheel skid trailer, equipped with either a ribbed or smooth testing tire, is a common method for measuring pavement friction in the field (*1*). If a pavement's friction value falls below the minimum threshold, corrective measures are needed, which can be costly and time consuming. Therefore, laboratory test protocols are needed to rapidly evaluate a surface mixture's ability to maintain acceptable friction prior to placing the mixture in the field.

Aggregate is a major component of an asphalt pavement mixture, and surface mixtures should use good quality aggregates. Shape characteristics of an aggregate may determine its quality. Aggregate texture and angularity influence a mixture's ability to provide a sufficient amount of friction between the pavement surface and vehicle tire (*1*). Understanding the role aggregate texture and angularity play in pavement friction over the performance period of the surface layer is essential to achieving a safe pavement surface.

There are several test methods to evaluate aggregate shape characteristics in the laboratory before and after the aggregates are subjected to conditioning (polishing). Some of these tests are subjective and time consuming (*1*). Researchers continue to develop aggregate imaging systems to quantify aggregate shape characteristics. This research study examines the use of the AIMS2. The AIMS2 device was used to quantify aggregate shape characteristics before and after conditioning the aggregates using the Micro-Deval device. The study will evaluate the AIMS2 measurements as a means of detecting changes in aggregate shape characteristics when aggregates were subjected to conditioning.

1.2 Objectives and Scope

The first objective of this study was to evaluate the feasibility of using the AIMS2 device in conjunction with the Micro-Deval as an aggregate testing protocol in the laboratory for qualifying pavement friction performance in the field. The second objective was to determine if a correlation could be established between the AIMS2 lab results and the locked-wheel skid trailer field friction data.

Five different aggregate sources were selected for testing based on their availability and use in surface mixtures of different test sections on the NCAT Test Track. The aggregate sources were two limestone, two granite, and one bauxite, a high friction aggregate. No. 4 sieve particles (passing the 3/8 inch sieve and retained on the No. 4 sieve) and No. 16 sieve particles (passing the No. 8 sieve and retained on the No. 16 sieve) were extracted from each aggregate source; however, only No. 16 sieve particles were available from the bauxite source. The shape characteristics of each aggregate sample were quantified using the AIMS2 device prior to conditioning. The No. 4 aggregates were then conditioned in the Micro-Deval at 20 minute intervals up to a total of 100 minutes, and the No. 16 aggregates were conditioned at 10 minute intervals up to 30 minutes. The AIMS2 device was used to measure changes in aggregate shape characteristics after each Micro-Deval conditioning interval.

Field friction measurement records using the locked-wheel skid trailer at 40 miles per hour and equipped with a ribbed testing tire were obtained from the selected NCAT Test Track sections. The AIMS2 lab results were compared with the locked-wheel skid trailer field friction data to determine any correlation. Field conditioning intervals and laboratory conditioning intervals were matched based on terminal friction, which refers to the point at which friction values (and AIMS2 indexes) tend to remain constant or decrease at a steady rate. Although friction numbers may decrease, the slope of friction loss remains constant with increased conditioning (*2*).

CHAPTER 2 LITERATURE REVIEW

2.1 Measuring Friction

A number of different methods are currently used for measuring pavement surface friction. The British Pendulum Tester is one tool used to quantify friction at low speeds for aggregates and pavement mixtures following American Society for Testing and Materials (ASTM) E303 standard testing procedure. The Dynamic Friction Tester (DFT) is another device used to measure pavement friction of mixtures in the field or laboratory following ASTM E1911. The locked-wheel skid trailer (ASTM E274) is one of the most commonly used devices to obtain field friction data.

2.1.1 Locked-Wheel Skid Trailer

The locked-wheel skid trailer test involves a specifically designed trailer with a test wheel to measure the skid resistance of pavement. Once a tow vehicle brings the trailer to the desired speed, water is sprayed in front of the test wheel then the braking system locks the test wheel. The measured torque from the interaction between the tire and pavement surface is recorded along with the test speed to calculate a skid resistance value. This is reported as a skid number (SN).

The test wheel can either be ribbed (ASTM E501) or smooth (ASTM E524). The ribbed tire is currently the most common test tire used in the United States (*1*). Figure 1 shows a ribbed test tire (left) compared to a smooth test tire (right).

Figure 1 Ribbed (ASTM E501) versus Smooth Test Tire (ASTM E524) (*3*)

The ribbed tire is sensitive to pavement micro-texture and tends to generate higher skid numbers, and the smooth tire is more sensitive to pavement macro-texture (*4*). As part of the Federal Highway Administration's Long Term Pavement Performance study, six test sections in Connecticut were tested with the skid trailer using the smooth tire and ribbed tire at 40 mph. When the smooth tire test values (SN40S) were compared with the ribbed tire test values (SN40R), the results yielded no correlation (Figure 2). This study verified that the two tires were sensitive to different aspects of pavement texture (*4*). Therefore, it is important to understand the implications of tire type on friction test comparisons.

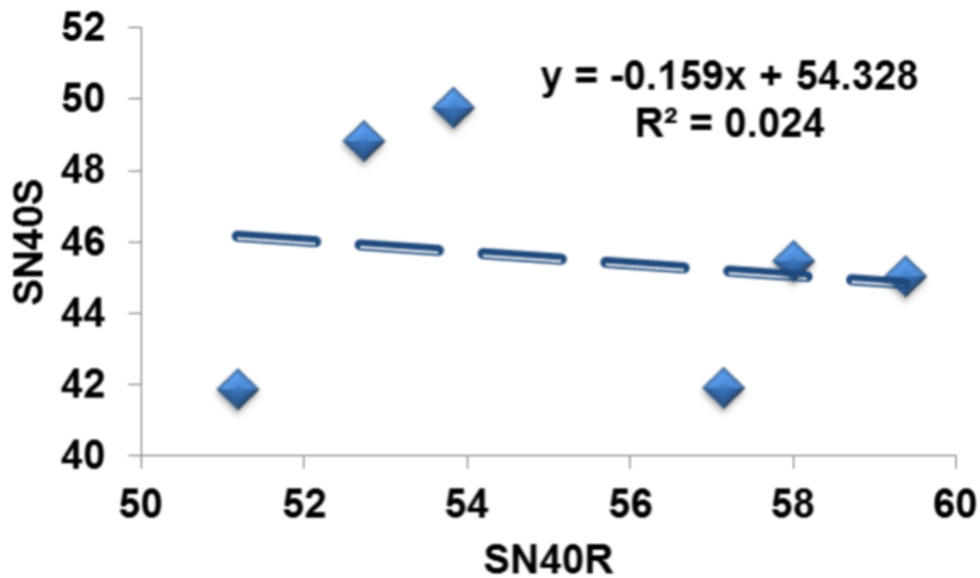

Figure 2 Smooth Tire SNs versus Ribbed Tire SNs Correlation Plot (*4*)

2.1.2 Lab Test Correlations with Locked-Wheel Skid Trailer

A 2010 NCAT study examined the correlation between the DFT testing of laboratory slabs with the ribbed tire skid trailer testing of field pavement sections at the NCAT Test Track (*5*). The study selected four different asphalt surface mixtures from the 2003 Test Track research cycle and prepared slabs for laboratory testing from the 2003 surface mix designs. The slabs were tested using the DFT after increments of polishing applied by the Three Wheel Polishing Device (TWPD). The TWPD was developed by NCAT to polish slabs in order to measure the change in surface texture and friction, as discussed later.

The Test Track sections were tested using the skid trailer to obtain SN40R skid numbers. To clarify, the study refers to the SN40R (mph) as a metric equivalent SN64R (km/h) (*5*). Testing was completed at different trafficking intervals, documented as equivalent single axle loads (ESALs). As expected, the friction coefficients obtained from the DFT at varying speeds and the SN64Rs obtained from the skid trailer decreased with increased polishing and trafficking, respectively. The laboratory DFT values at 60 km/h (DFT_{60}) were used to examine the correlation to skid trailer field data (SN64R). The measured friction at DFT_{60} speed best matched SN64R data (*5*). The DFT tests ranked the laboratory slabs (Figure 3) the same as the skid trailer ranked the Test Track pavement sections (Figure 4). The ranking is shown in red next to the mix designation at the top of the graphs.

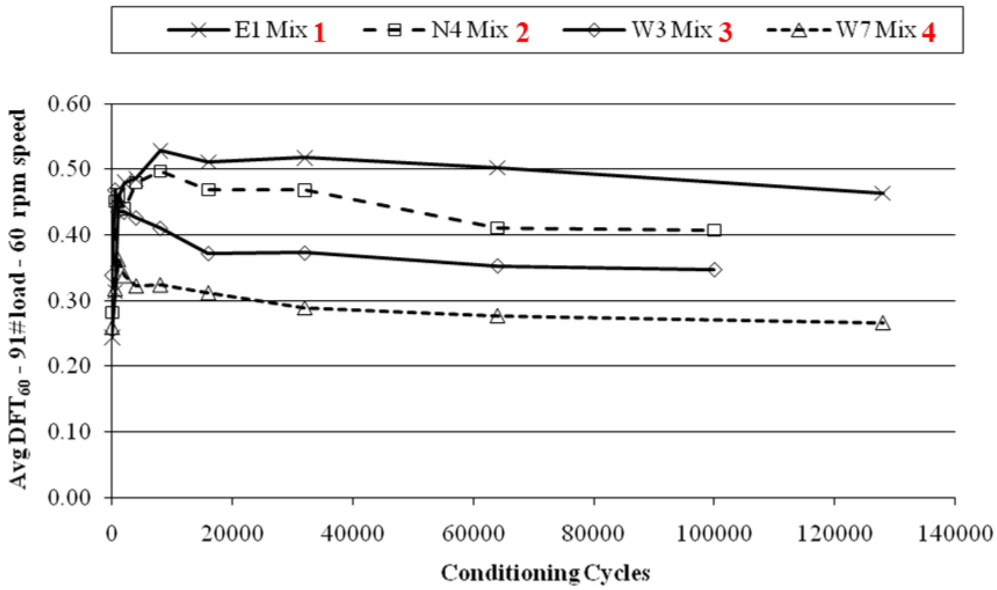

Figure 3 Laboratory DFT_{60} Values versus TWPD Conditioning Cycles for Four Slabs (*5*)

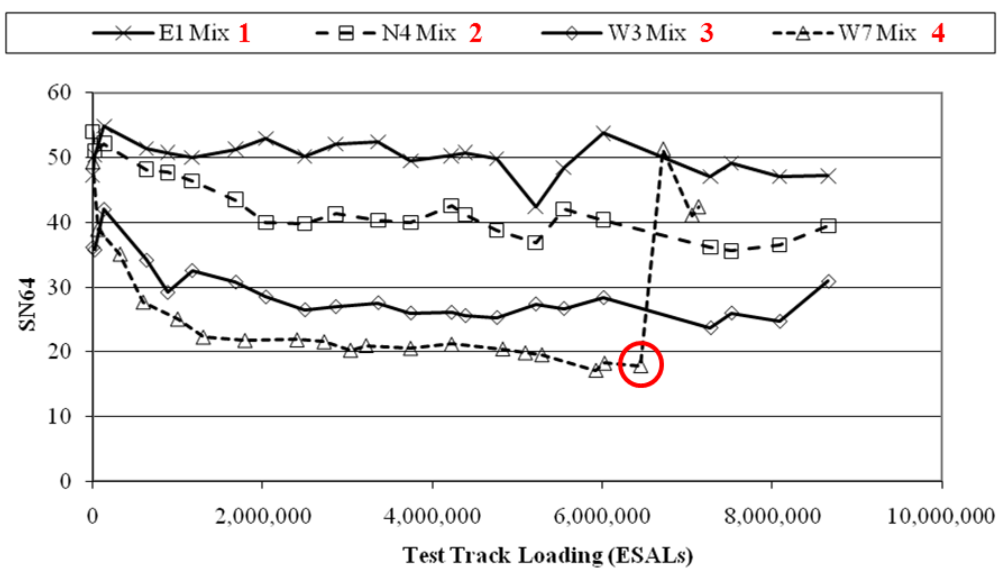

Figure 4 Field SN64R versus ESALs for Four Test Sections (*5*)

Figure 4 also shows that the surface mixture used on Test Track section W7 was replaced with a different surface mixture after six million ESALs due to its poor friction performance. Therefore, the terminal SN64R that was used in the research analysis is circled in red in Figure 4. The higher SNs in the figure for that section portray the friction performance of the new mixture.

A positive correlation was developed between the skid trailer SN64R field results and laboratory DFT_{60} results as shown in Figure 5. Note that the x-axis DFT values were multipled by 100 to agree with the units of measure used for the y-axis skid trailer friction values.

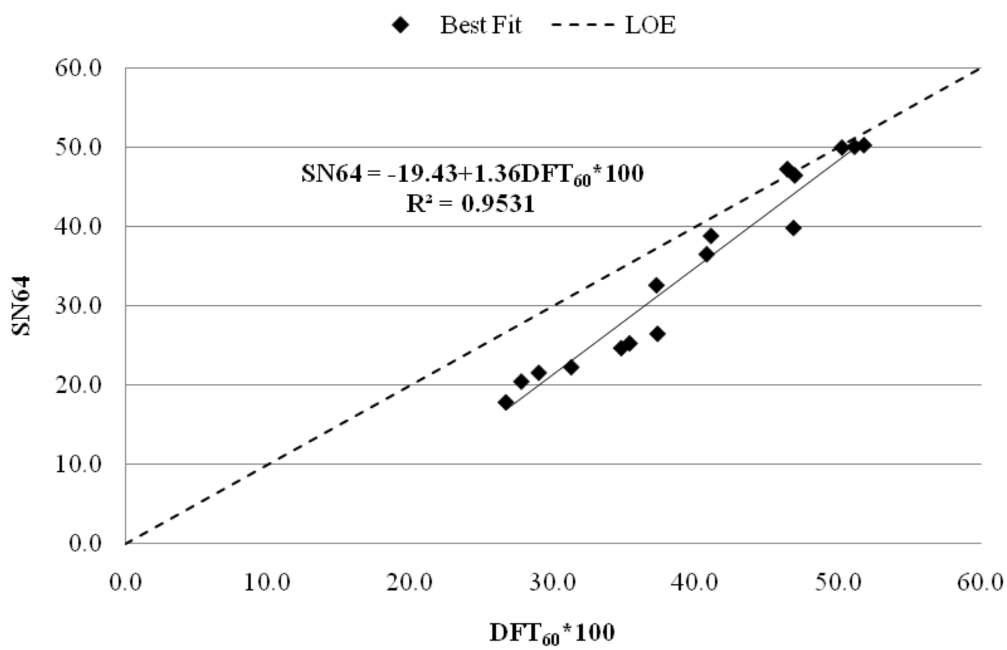

Figure 5 Laboratory (DFT_{60}*100) versus NCAT Test Track (SN64R) Correlation (*5*)

Correlating laboratory mixtures to field mixtures is important and useful, but there is an interest to improve the correlation between an aggregate source's ability to resist polishing with the overall mixture's ability to resist polishing under traffic. It is valuable for agencies and aggregate suppliers to identify aggregates that would be suitable for use in a surface mixture that are capable of maintaining good skid resistance during the life of the pavement.

2.2 Laboratory Conditioning Devices

Asphalt mixtures are composed primarily of aggregates and it is important to use aggregates that resist polishing to ensure that the mixtures maintain their friction properties. Although an aggregate might be initially characterized by a high level of angularity or texture and measure good friction values, it may not be suitable for a pavement surface layer if the aggregate cannot maintain a sufficient level of friction due to polishing under traffic. Laboratory equipment can assess the polishing resistance of aggregates and pavement surfaces. For the purpose of this research, the primary focus will be on the equipment used to polish aggregates.

Wu et al. tested 16 aggregate sources that varied in performance levels in asphalt concrete using a variety of impact tests, including the Los Angeles Abrasion Test, Micro-Deval, aggregate impact value, aggregate crushing value, and degradation in the gyratory compactor (*6*). Table 1 shows what the researchers characterized as a good, fair, and poor historical pavement performance rating, but does not focus on friction performance. For the purpose of this research and literature review, the focus will be on the Los Angeles Abrasion and Micro-Deval aggregate conditioning tests, as these are the tests commonly used in the United States.

Table 1 Pavement Performance Evaluation Criteria (*6*)

Pavement Performance Rating	Description
Good	Used for many years with no significant degradation problem during construction and no significant popouts, raveling, or potholes during service life.
Fair	Used at least once where some degradation occurred during construction and/or some popouts, raveling, and potholes developed, but pavement life extended for over 8 years.
Poor	Used at least once where raveling, popouts, or combinations developed during the first two years, severely restricting pavement service life.

2.2.1 Los Angeles Abrasion Test

The Los Angeles (L.A.) Abrasion (ASTM C535) device (Figure 6) has been used to assess coarse aggregate resistance to degradation. Previous research concluded that the L.A. Abrasion test does not correlate well with field pavement performance and acts more as an impact test rather than simulating the polishing action from heavy traffic in the field (*6*).

Figure 6 L.A. Abrasion Testing Equipment (*7*)

Figure 7 presents the L.A. Abrasion results of the sixteen aggregate sources compared with the historical pavement performance rating. These results demonstrate that the L.A. Abrasion test was not capable of delineating between aggregates as related to good, fair, and poor performance. In some cases, aggregate sources characterized as poor resulted in an L.A. Abrasion mass loss close to aggregate sources that were characterized as good.

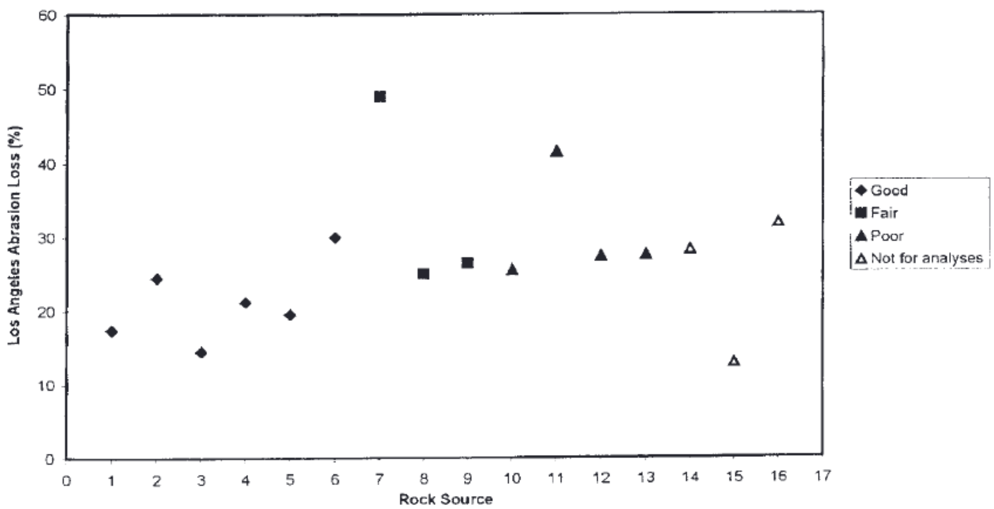

Figure 7 Pavement Performance Ratings with L.A. Abrasion Results (*6*)

2.2.2 Micro-Deval Aggregate Conditioning Test

The Micro-Deval device (Figure 8) is used to condition an aggregate sample to measure the aggregate's resistance to polishing, abrasion, and breakage. Previous research has shown the Micro-Deval test to be a good tool in evaluating coarse aggregate quality in the presence of water. An aggregate's quality and abrasion resistance may be categorized into three different performance levels as good, fair, or poor depending on the percent loss measured after Micro-Deval conditioning.

Figure 8 Micro-Deval Device

As mentioned previously, Wu et al. tested sixteen aggregate sources from asphalt concrete pavements with varying field performance. The study compared Micro-Deval performance ratings (good, fair, or poor) with the subjective Table 1 ratings of the asphalt concrete mixtures made by various state transportation agencies. They found that the Micro-Deval ratings were comparable to the agency ratings for most of the aggregate sources. As shown in Figure 9, the solid horizontal lines display the average of the Micro-Deval mass loss for each of the different groups rated by the state agencies. Wu et al. determined that 18% mass loss delineated aggregates of poor quality from the fair and good quality aggregates, which is depicted by the dashed line in the figure. It should be noted that the Micro-Deval test was the only impact test that showed clear delineations among the aggregate groups (*6*).

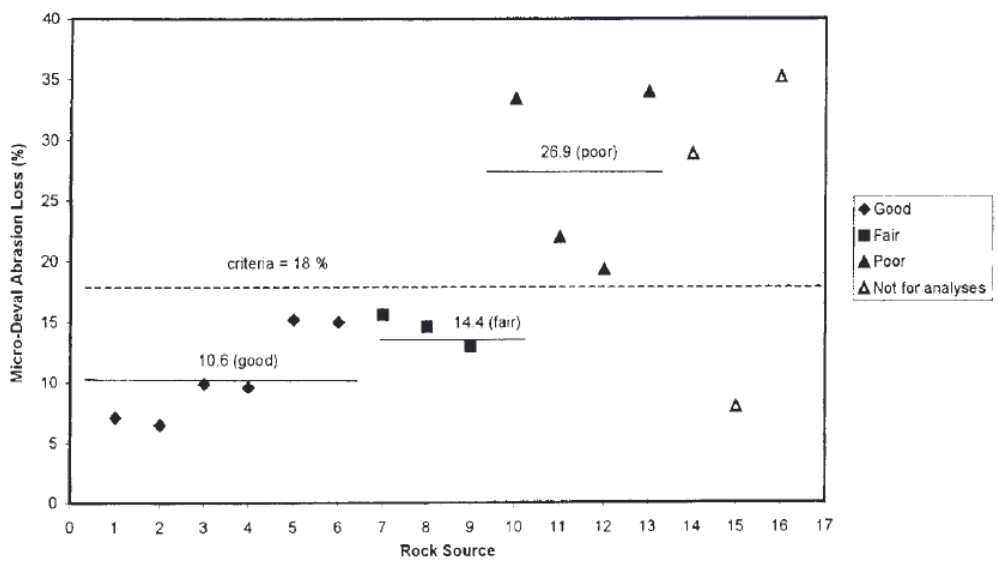

Figure 9 Pavement Performance Ratings with Micro-Deval Abrasion (*6*)

Similarly, Cooley et al. selected 72 different aggregate sources from eight different states (Alabama, Georgia, Florida, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee) and evaluated their quality using L.A. Abrasion and Micro-Deval tests (*8*). The study noted mixed results in the Micro-Deval; for example, only Micro-Deval results for Alabama and Georgia distinguish between the three categories of aggregates (good, fair, and poor) of historical performance. The researchers suggested that specifications for the Micro-Deval test method be dependent on parent aggregate mineralogy. Despite the mixed results, the Micro-Deval is still considered to be a useful tool in evaluating aggregate quality.

2.2.3 L.A. Abrasion and Micro-Deval Test Differences

As the Micro-Deval test procedure developed, it was compared to the widely accepted L.A. Abrasion. Research showed that the two tests resulted in significantly different results. The impact from the L.A. Abrasion test simulates the impact that aggregates experience during handling and construction, whereas the Micro-Deval test relates closer to what aggregates would experience in the field when subjected to traffic.

Cooley et al. studied 72 aggregate sources using the L.A. Abrasion and Micro-Deval found that the L.A. Abrasion resulted in a higher percent loss than that of the Micro-Deval (*8*). This can be attributed to the fact that the L.A. Abrasion test uses fewer, significantly larger 46.8 mm steel charges compared to the high number of smaller, 9.5 mm charges used in the Micro-Deval test. The baffles inside the L.A. Abrasion drum pick up the aggregate and steel charges and carry them around until they drop on the opposite side of the drum. This harsh impact tends to yield higher mass loss values for some high quality aggregates that have otherwise performed well in the field (*9*).

The L.A. Abrasion test is performed on oven-dried aggregates and the Micro-Deval tests aggregates in water. Aggregates are rarely dry in the field and they experience more polishing and abrasion than the type of impact simulated by the L.A. Abrasion test (*9*). Therefore, the Micro-Deval appears to be more appropriate in evaluating an aggregate's resistance to traffic wear while the L.A. Abrasion test is more appropriate in assessing aggregate breakdown during handling, mixing, and placement.

2.3 Aggregate Imaging Systems

Aggregate imaging analysis is an automated process of quantifying aggregate shape properties to provide a more objective measure of Superpave consensus property tests, such as American Association of State Highway Transportation Officials (*AASHTO) T304: Uncompacted Void Content of Fine Aggregates, ASTM D4271: Flat and Elongated Particles in Coarse Aggregates, and ASTM D5821: Percent of Fractured Particles in Coarse Aggregates.* Several different imaging systems have been developed and evaluated within the last decade to assess the ability to appropriately characterize aggregate shape properties. The focus of this work is on the recently developed AIMS2. A recent National Cooperative Highway Research Program study recommended the AIMS2 device to quantify aggregate shape characteristics (*10*).

2.3.1 The Second Generation Aggregate Imaging Measurement System

The Pine Instruments' AIMS2, as shown in Figure 10, is a computer automated system that captures aggregate images. The device analyzes these images to quantify both coarse and fine aggregate shape characteristics through a series of algorithms. The AIMS2 is equipped with two lighting configurations (back lighting and top lighting) and a microscope-camera system enclosed in a case to protect it from outside light sources (*11*).

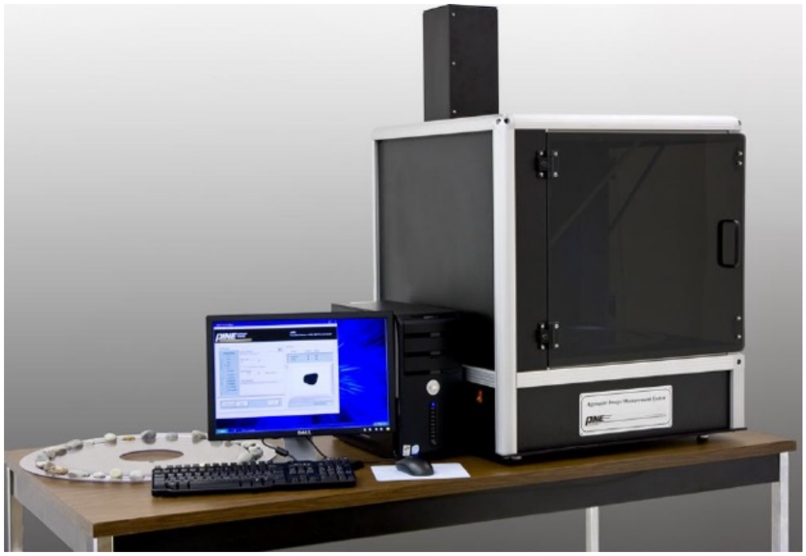

Figure 10 Second Generation Aggregate Imaging Measurement System (*12*)

Aggregate particles placed on a rotating tray are individually scanned such that the camera captures images of each particle. Coarse aggregates require three separate scans, while fine aggregates only use a single scan for analysis. For coarse aggregates, the first scan uses the back lighting to capture a black and white silhouette of each aggregate. This scan is used to quantify the aggregate's angularity using the gradient method, as discussed in the next chapter. Additionally, the first scan is used to record the centroid of the particle so the system may recognize the particle location for additional scans. Top lighting is used during the second scan to determine particle height measurements. The third scan captures greyscale images to analyze each particle's surface texture from wavelet analysis. These three scans are critical in quantifying coarse aggregate angularity (CAA), particle surface texture, sphericity, and flat and elongated (F&E) ratios. For fine aggregate, a single scan is used to quantify fine aggregate angularity (FAA) and two-dimensional form (Form2D). The AIMS2 software program exports the data into a spreadsheet containing the relevant shape characteristics for each particle and corresponding statistics for the sample group.

2.4 Relevant Research on AIMS

Researchers are working to replace the manual Superpave tests with an automated aggregate imaging system. Superpave consensus property tests are commonly used as part of material acceptance for several state agencies, but they are laborious, time consuming, and subjective.

Gudimettla et al. compared results obtained from Superpave consensus property tests with the first generation AIMS test results for a variety of aggregates (*12*). The first generation AIMS FAA and Form2D results ranked the aggregates the same when compared with AASHTO T304 results. One set of results is shown in Table 2 with the numerical ranking represented as a letter in parenthesis.

Table 2 Example of Results Obtained from AASHTO T304, AIMS FAA, and AIMS Form2D (*12*)

	AASHTO T304 FAA (Method A)	AIMS FAA			AIMS Form2D		
		2.36 mm	1.18 mm	0.600 mm	2.36 mm	1.18 mm	0.600 mm
1/4" Washed	44 (A)	4,081 (A)	4,729 (A)	4,422 (A)	8.5 (A)	9.0 (A)	8.8 (A)
2A Gravel	42 (C)	3,271 (C)	3,205 (C)	3,381 (C)	6.8 (C)	6.5 (C)	7.3 (C)
C Gravel	42.8 (B)	3,342 (B)	3,677 (B)	3,902 (B)	6.9 (B)	7.4 (B)	8.3 (B)

A comparison of the results from ASTM D5821 and AIMS CAA appeared to be inconclusive because they do not measure similar properties. A majority of the aggregates were reported to have 100 percent fractured faces when following ASTM D5821 procedure, while the AIMS provided different angularity values for those aggregates. The ASTM procedure does not measure angularity and the AIMS does not detect fractured faces (*12*). This introduces a potential limitation with the ASTM procedure, in that an aggregate source may be characterized by higher angularity when compared to another aggregate source as defined by AIMS, but the two could have the same percentage of fractured faces. The ASTM procedure would show no indication of any differences between the two aggregate sources when considering angularity. There is a need to be able to sufficiently quantify this parameter. Table 3 shows a few examples of the project's results obtained from ASTM D5821 and AIMS CAA.

Table 3 Example of CAA Results Obtained from ASTM D5821 and AIMS (*12*)

Project ID	Coarse Aggregates	ASTM D5821 CAA 1 Fractured Face (%)	ASTM D5821 CAA 2 Fractured Faces (%)	AIMS CAA
NJ 0671	8's	100	100	2,748
	57's	100	100	2,995
	RAP	99	1	2,714
ME 0570	1/2's	99	98	3,509
NE 0569	1/4 Washed	100	100	2,585
	2A Gravel	32	21	2,248
	C Gravel	60	43	2,314

Gudimettla et al. provided useful insight towards the advancement of using an automated aggregate imaging system as an alternative to Superpave consensus property tests, but Superpave consensus property tests are not intended to evaluate an aggregate's capability of providing adequate friction to a surface mixture (*12*). Superpave consensus property tests do not adequately provide coarse aggregate surface micro-texture measurements, but the AIMS is capable of measuring micro-texture, an important aggregate property that influences pavement friction (*1*).

Although the first generation AIMS device was used in the Superpave and AIMS comparison study, it can be assumed that with the advancements in the AIMS2 device, the results would yield similar rankings to that of the first generation. As part of the AIMS2 implementation study, results generated by the first generation AIMS device were compared with those of the second generation for a variety of aggregate sources, including 32 coarse aggregate samples and 21 fine aggregate samples. Both systems ranked the aggregate sources the same among each of the shape parameters and provided comparable results (*13*).

The University of Illinois at Urbana-Champaign conducted a series of research tasks for an ongoing project in cooperation with the Illinois Department of Transportation, which focused on evaluating the feasibility of using two aggregate imaging devices, AIMS2 and the Enhanced University of Illinois Aggregate Image Analyzer, in conjunction with the Micro-Deval (*14*). One research task determined that 210 minutes was sufficient polishing time in the Micro-Deval for the aggregates to reach terminal texture and angularity. However, for both image devices, the rate of texture loss reduced significantly after 105 minutes of conditioning in the Micro-Deval, indicating the initial point at which the aggregates began approaching terminal values.

Another University of Illinois research task tracked an aggregate's resistance to polishing, abrasion, and breakage (*16*). Researchers retained the material captured on the 9.5 mm sieve for 11 aggregate sources before subjecting them to conditioning in the Micro-Deval for 15, 30, 45, 60, 75, 90, 105, 180, and 210 minutes. The aggregate samples were analyzed using the AIMS2 and Illinois device prior to conditioning and after each conditioning cycle. Researchers found that both imaging devices were capable of detecting aggregate degradation in the Micro-Deval.

The researchers developed regression equations using statistical analysis to predict angularity and surface texture as a function of Micro-Deval conditioning time for each aggregate type and device in the form of Equation 1, Surface Texture Index (*16*). Each aggregate source was characterized by a unique equation with different fitting parameters to show the rate of texture or angularity loss. Table 4 shows an example of the fitting parameters used to model the AIMS2 angularity results, and Table 5 shows an example of the fitting parameters used to model the AIMS2 texture results.

$$Shape\ Property\ (t) = a + b * exp^{-ct} \tag{1}$$

where

a, b, c = Fitting parameters based on statistical analysis relating to initial, final, and rate of change in texture

t = Micro-Deval conditioning time (minutes)

Table 4 Example of AIMS2 Fitting Parameters for Predicting Angularity Loss from Micro-Deval Conditioning (*16*)

Aggregate	Fitting parameters			Goodness of fit		
	a	b	c	SSE	R^2	RMSE
FP1	1492	1185	0.0174	42313.4	0.968	77.7
FP2	1433	1232	0.014	59492.5	0.957	92.2
FP3	1384	1189	0.0155	62591.8	0.953	94.6
FP4	1877	1053	0.0185	41115.8	0.962	76.6
FP5	1443	1331	0.0186	71236.7	0.958	100.9
FP6	1924	560.6	0.0529	48740.8	0.856	83.4
FP7	2618	274.4	0.0239	9983.13	0.878	37.8
FP8	2112	1144	0.0114	84878.4	0.924	110.1
FP9	1590	1635	0.0248	30378.7	0.985	100.6
FP10	2098	730	0.019	22076.9	0.957	56.2
FP11	1130	1323	0.0209	105951	0.94	123

Table 5 Example of AIMS2 Fitting Parameters for Predicting Surface Texture Loss from Micro-Deval Conditioning (*16*)

Aggregate	Fitting parameters			Goodness of fit		
	a	b	c	SSE	R^2	RMSE
FP1	120.8	137.6	0.0266	547.7	0.97	8.8
FP2	151.1	162.1	0.0256	500.5	0.98	8.5
FP3	93.27	92.7	0.0304	190.5	0.98	5.2
FP4	97.16	65.95	0.0095	102.4	0.97	3.8
FP5	53.34	14.83	0.0341	43.2	0.83	2.5
FP6	164.7	64.5	0.0256	531.2	0.88	8.7
FP7	204.1	-49.39	0.0866	366.8	0.86	7.2
FP8	437.7	-16.49	-0.003	3287.2	0.06	21.7
FP9	659.1	29.18	0.9935	6603.2	0.1	46.9
FP10	436.8	161.8	0.0176	1489.8	0.94	14.6
FP11	353.8	-16.31	2.413	1805.8	0.12	16.1

While both measurements were successful in detecting aggregate degradation from Micro-Deval conditioning, there were some significant differences in the texture and angularity results for the particles analyzed. The AIMS2 had higher repeatability and was considered a more desired test. Moaveni et al. also specified that the AIMS2 results showed a better correlation with historical friction data obtained from Illinois Department of Transportation (*16*).

Mahmoud et al. and Moaveni et al. concluded that the use of the Micro-Deval for aggregate polishing in conjunction with the AIMS2 for aggregate shape analysis proved to be feasible for coarse aggregates (*14, 15*). With the success of this study, research should be taken a step further to show correlations of the polishing curves with field friction data. Additionally, the feasibility of using Micro-Deval with AIMS2 to detect changes in fine aggregate shape properties should be explored, as they are an important part of the mix design. Correlating these texture and angularity indexes obtained from the imaging devices with field friction data should be further studied, as these aggregate properties influence pavement performance, especially friction, and could be used as part of material acceptance tests and contribute to enhancing roadway safety.

CHAPTER 3 AIMS2 TEST DESCRIPTION

3.1 AIMS2 Aggregate Testing

The AIMS2 automatically quantifies aggregate shape characteristics. As a tray of aggregates rotates, a microscope-camera system captures images of the aggregates using top lighting or back lighting. A photo of this camera system is shown in Figure 11.

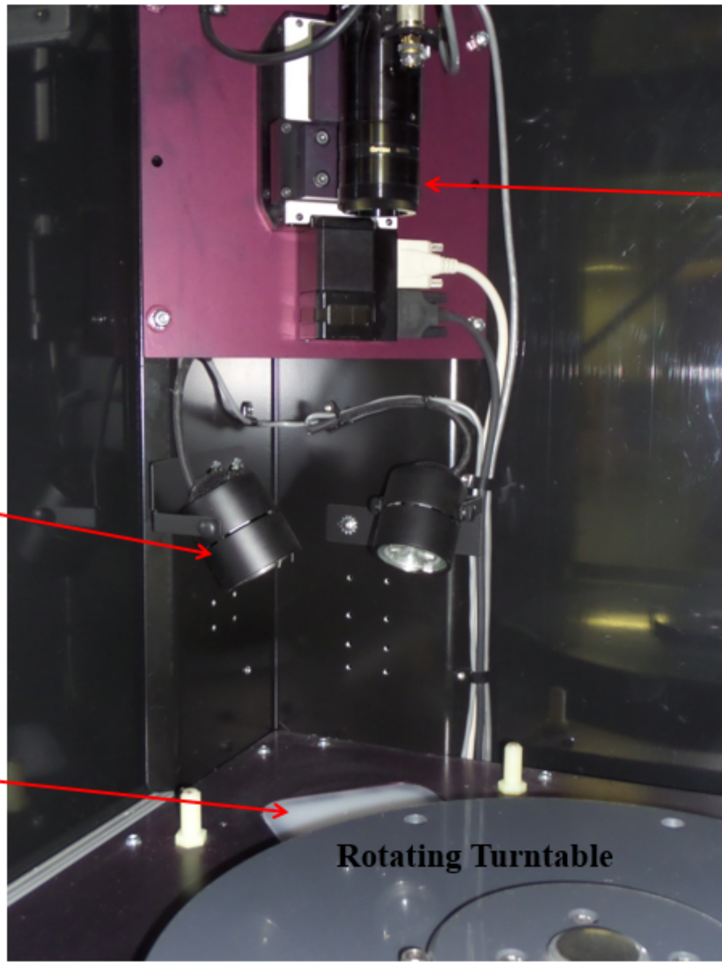

Figure 11 AIMS2 Microscope-Camera System

The AIMS2 software program uses the images of each coarse aggregate particle (retained on the No. 4 sieve) to calculate CAA, surface texture, sphericity (three-dimensional form), and F&E ratios. For fine aggregates (passing the No. 4 and retained on the No. 200 sieve), the image calculates FAA and Form2D but does not measure the surface texture. The software allows the operator to select the aggregate size that is being analyzed and the particle count they wish to achieve. For the purpose of this research, the AIMS2 scanned all particles placed on the tray, resulting in a range of approximately 60-90 scanned particles for coarse aggregates and 160-300 scanned particles for fine aggregates.

3.1.1 AIMS2 Coarse Aggregate Testing

Each coarse aggregate particle was placed in the trough, and particle orientation depended on how the aggregate randomly came to rest (Figure 12). The design of the tray and trough allows the system to align each aggregate directly under the camera to ensure that each aggregate is in full view for image acquisition.

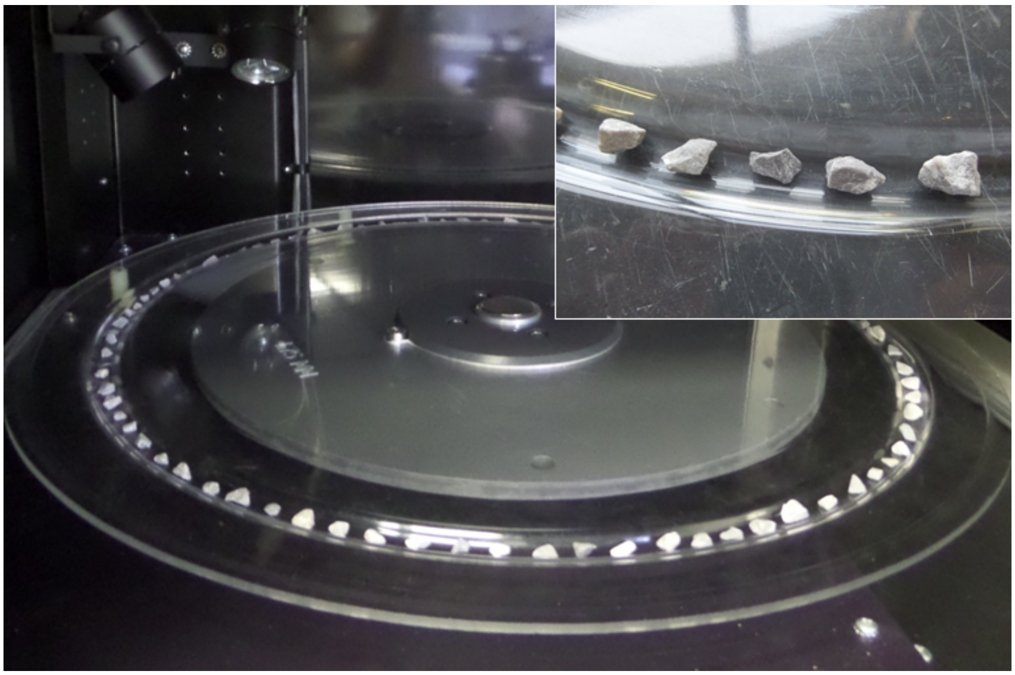

Figure 12 Coarse Aggregates Spread on Tray Trough

The first pass of image acquisition scanned each aggregate under the camera unit using back lighting. This created a black and white silhouette of each particle to determine the centroid and quantify angularity. If the entire particle was not in camera view, the particle was rejected from the analysis, and the tray rotated to the next particle. The second scan used top lighting to measure the particle height at the previously determined centroid. On the third scan, the camera unit magnified the particle to generate grayscale images to capture aggregate surface texture, as shown in Figure 13. The software program applied measurements from the three scans in a series of algorithms to calculate AIMS2 CAA, texture, sphericity, and F&E ratios.

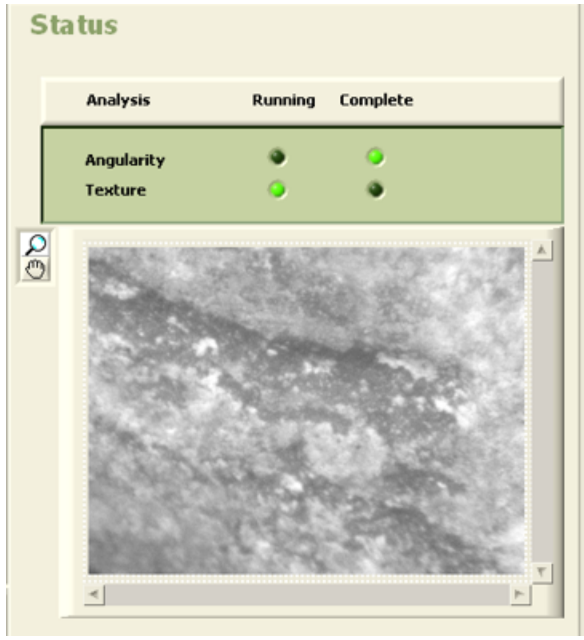

Figure 13 Grayscale Image Used to Capture Coarse Aggregate Texture

3.1.2 AIMS2 Fine Aggregate Testing

Fine aggregate image acquisition only requires one scan to obtain the particle shape properties. A transparent tray similar to what is used for the coarse aggregates uses backlighting to capture aggregate images. An opaque tray, designed for smaller fine aggregates (retained on or passing the No. 50 sieve) and more translucent particles, uses top lighting for image scans. For this research, the transparent tray was used for No. 16 aggregates that were dark enough for imaging purposes.

Fine aggregate particles were sprinkled into the rotating tray's trough until the tray was full (Figure 14). Particle orientation was based on how the particle randomly came to rest in the trough. It was important to spread out the fine particles but it was difficult to control the placement. The camera system used back lighting to capture images as the tray rotated. These images were used to quantify AIMS2 FAA and Form2D.

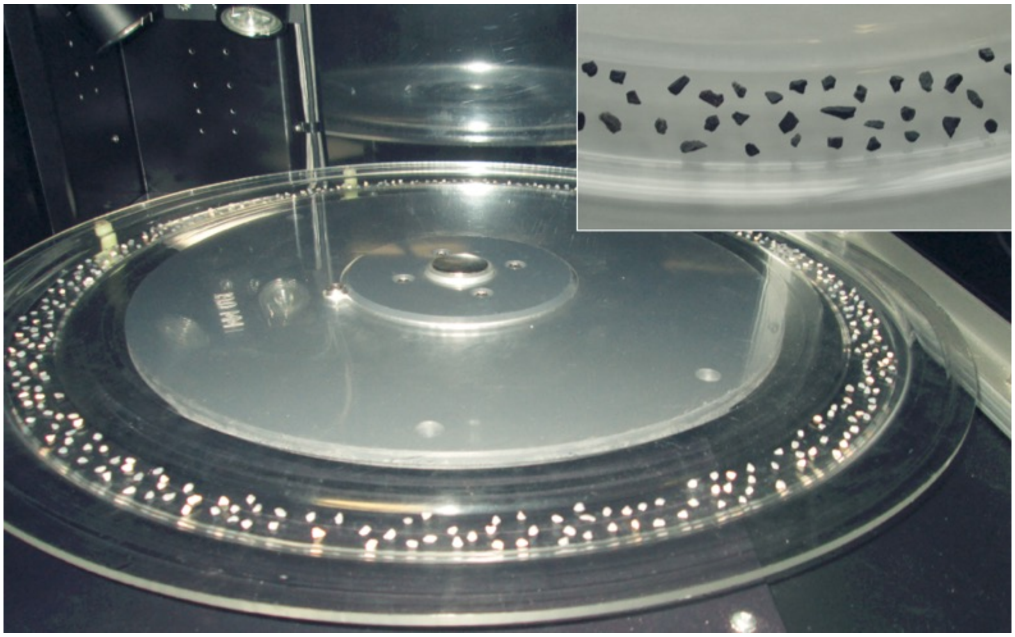

Figure 14 Fine Aggregates Spread on Tray Trough

3.2 AIMS2 Aggregate Shape Measurements

The AIMS2 software uses scanned images to calculate the necessary aggregate properties through a series of algorithms. The results are then exported into a Microsoft Excel file that may be used for further analysis. The Excel file is organized by shape parameter and includes all the raw data, corresponding basic statistics, and a graph that reflects the cumulative distribution of the particles for each parameter.

3.2.1 Aggregate Angularity

Coarse and fine aggregate angularity is captured from two-dimensional images of the first AIMS2 scan. A gradient method quantifies the variations at the particle boundary using a scale of 0 to 10,000. A particle characterized as a perfect circle would have an angularity index approaching a value of 0. The sharper the corners of the particle are, or the greater the change in inclination of the gradient vectors on the outer edge points, the higher the angularity index. AASHTO TP81 defines an angularity index of 3,300 or less as low angularity, 3,300 to 6,600 as medium angularity, and greater than 6,600 as high angularity. Figure 15 provides a representation of how gradient vectors appear for a smooth particle versus an angular particle.

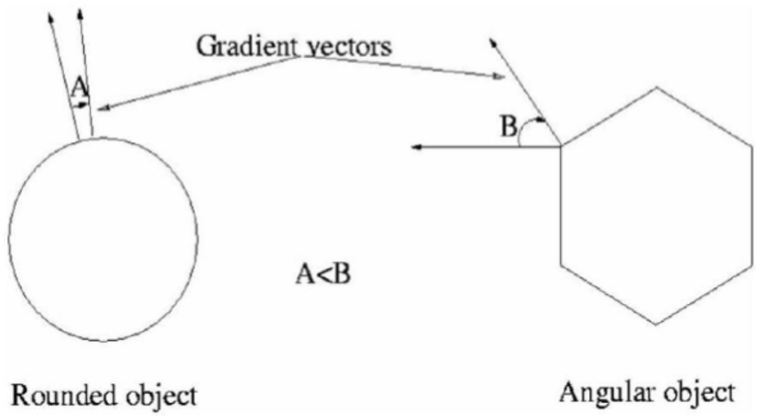

Figure 15 Gradient Vector for Smooth versus Angular Particle (*16*)

3.2.2 Surface Micro-texture

Surface micro-texture is a coarse aggregate property measured using wavelet analysis, which provides texture information in the horizontal, vertical, and diagonal directions. Particle micro-texture refers to the smoothness or roughness of a particle surface and is dependent on particle surface irregularities at a wavelength less than 0.5 mm. According to the AIMS2 method, the surface texture index ranges from 0 to 1,000 and is calculated "at a given decomposition level [as] the arithmetic mean of the squared values of the wavelet coefficients for all three directions" (*10*). A surface texture index approaching 0 indicates a smooth, polished aggregate surface. AIMS2 denotes a texture index of 260 or lower as low texture, 260 to 550 as medium texture, and above 550 as high texture.

3.2.3 Aggregate Form

Coarse and fine aggregate form is characterized by the AIMS2 using the images captured during the aggregate scans. Figure 16 shows a representation of what is referred to as form according to the AIMS2 device.

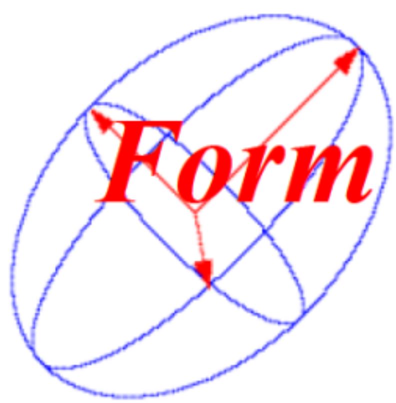

Figure 16 Representation of AIMS2 Aggregate Form (*11*)

Coarse aggregate form, referred to as sphericity in AASHTO TP81, is used to describe the overall three-dimensional shape of the particle. Sphericity ranges on a scale of 0 to 1, where a particle that is characterized by equal dimensions (cubical) has a sphericity value of 1. Therefore, a value that is characterized as a perfect circle would have a sphericity index approaching 0. According to the AIMS2 software, an index of 0.3 or less is considered low sphericity, 0.3 to 0.7 is considered medium sphericity, and an index greater than 0.7 is considered high sphericity.

Fine aggregate form (Form2D), referred to as two-dimensional form in AASHTO TP 81, is indicative of the changes in the particle radius in all directions of a two-dimensional image. The particle radius is defined as the distance between the particle center and the outer edge at a given point. Form2D is calculated using an equation with values ranging from 0 to 20, where a particle characterized as a perfect circle would have a value approaching 0. The AIMS2 software indicates that a Form2D value of 6 or less is considered low, 6 to 12 is considered medium, and a value greater than 12 is considered high.

3.2.4 Flat and Elongated Properties

The F&E properties for coarse aggregates are represented using four ratios based on the measured particle dimensions from the three scans: flatness ratio, elongation ratio, flat and elongated ratio, and flat value and elongated value per AASHTO TP 81. The variables used in the F&E ratios are defined the same as they were for calculating sphericity. For each of the above ratios, the AIMS2 software records the cumulative percentage of particles that were characterized by a ratio greater than 1:1, 2:1, 3:1, 4:1, or 5:1. Due to the large amount of data, only the F&E ratio was used for the coarse particles for this research.

The range of aggregate shape values AIMS2 considers to be low, medium, and high are summarized in Table 6.

Table 6 Summary of AIMS2 Index Ranges

AIMS2 Index	Aggregate Size	Low	Medium	High
Angularity	Coarse, Fine	0 -3,300	3,300-6,600	6,600-10,000
Texture	Coarse	0-260	260-550	550-1,000
Sphericity	Coarse	0-0.3	0.3-0.7	0.7-1.0
Form 2D	Fine	0-6	6-12	12-20

CHAPTER 4 EXPERIMENTAL PLAN

The purpose of this research was to analyze the laboratory polishing resistance of aggregates using of the Micro-Deval and AIMS2 compared to field friction performance data. This study applied portions of existing test standards, including: ASTM D7428, ASTM D6928, and AASHTO TP81. Micro-Deval and AIMS2 testing were conducted in the NCAT laboratory on coarse and fine particles of five aggregate sources. Particle shape properties were analyzed using the AIMS2 prior to any conditioning and after increments of Micro-Deval polishing.

4.1 Selection of NCAT Test Track Pavement Sections

Pavement sections from the 2000 and 2009 NCAT Test Track research cycles were selected based on their variation in mixture properties, field friction performance, and aggregate availability. Pavement surface mixtures that contained a high percentage of reclaimed asphalt pavment (RAP) material were avoided to ensure that the friction performance was dominated by the virgin aggregates in the mixture and not the reclaimed aggregate. Historical field friction data were obtained from NCAT's database for each selected pavement section to serve as ground truth field performance measures. Test Track friction measurements were collected to obtain skid numbers (SN40R) for each pavement section on a monthly basis following the testing protocol set forth in ASTM E501. The friction results for this study were obtained from NCAT's historic data records.

The first surface mix selected was a high friction surface treatment (HFST) composed of calcined bauxite ranging from No. 5 to No. 12 sized particles. The second mix type was an open graded friction course (OGFC) composed primarily of LaGrange granite. The third and fourth surface mixes, characterized as a stone matrix asphalt (SMA) mix and a fine-dense graded (FDG) mix, were composed primarily of Columbus granite. The fifth mix type was an SMA mix from the 2000 NCAT Test Track research cycle made primarily of Calera limestone. Table 7 provides a summary of the mixes selected and the mixture identifications used throughout the study. Some of the test sections characterized as an FDG Columbus granite surface mixture contained up to 25% RAP, but the RAP showed no effect on friction field performance. The FDG mix design without RAP was used in the control section, S9 (*17, 18, 19*).

Table 7 NCAT Test Track Section Mixture Identification

Mixture ID	Year Constructed	Sections	NMAS	Materials
HFST Bauxite	2006	E2, E3	N/A	Calcined Bauxite
OGFC LaGrange Granite	2009	N1, N2, S8	12.5 mm	78 LaGrange Granite
				Coarse Fraction RAP (15% by mix weight)
SMA Columbus Granite	2009	N12	12.5 mm	7 Columbus Granite
				89 Columbus Granite
				Other: Fly Ash, Hydrated Lime, Cellulose
FDG Columbus Granite	2009	N5, N6, N7, S9, S10, S11, S12	9.5 mm	89 Columbus Granite
				8910 Opelika Limestone Screenings
				M10 Columbus Granite
				Shorter Coarse Sand
SMA Calera Limestone	2000	W7	9.5 mm	7 Calera Limestone
				821 Calera Limestone
				Other: Fly Ash

4.2 Material Selection

Five aggregate sources were represented by the selected field friction performance sections: Columbus granite, LaGrange granite, calcined bauxite, Calera limestone, and Opelika limestone. Each source was screened into a coarse and fine sample, except for the calcined bauxite, which only provided a fine aggregate. A coarse aggregate sample was defined as material passing the 3/8 inch sieve and retained on the No. 4 sieve. A fine aggregate sample was defined as particles passing the No. 8 sieve and retained on the No. 16 sieve. Table 8 shows a summary of the aggregate properties.

Table 8 Summary of Laboratory Tested Aggregate Properties

Aggregate Type	Sieve Size	NCAT Stockpile	Gsa	Gsb	Absorption (%)
Opelika Limestone	No. 4	Opelika Limestone 78	2.863	2.769	1.2
	No. 16	Opelika Limestone 8910	2.812	2.784	0.4
Columbus Granite	No. 4	Columbus Granite 89	2.713	2.61	1.5
	No. 16	Columbus Granite M10	2.739	2.735	0.1
LaGrange Granite	No. 4	LaGrange 78	2.666	2.617	0.7
	No. 16	LaGrange M10	2.725	2.707	0.3
Calera Limestone	No. 4	Calera Limestone 78	2.871	2.836	0.4
	No. 16	Calera Limestone 820	2.779	2.645	1.8
Bauxite	No. 16	N/A	N/A	N/A	N/A

4.3 Test Procedure

The test procedures for the coarse and fine aggregates varied and are described separately. The Micro-Deval testing procedures for coarse and fine aggregates (ASTM D6928 and ASTM D7428) were used as the basis for conditioning the aggregates, but modifications were made for the purpose of this research study. Single-sized aggregate was tested, not the specified gradations. The total conditioning times were modified based on aggregate size and were divided into incremental conditioning times to track changes in aggregate shape parameters using the AIMS2.

4.3.1 Coarse Aggregate Micro-Deval and AIMS2 Testing Procedure

The testing procedure using the AIMS2 and Micro-Deval for all aggregate sources with #4 sieve size samples was as follows:

1. The aggregate sources were sampled from their corresponding stockpiles, washed, oven dried, and sieved to obtain particles passing the 3/8 inch sieve and retained on the No. 4 sieve.
2. Each processed sample was split per AASHTO T248 to obtain approximately 1,500 grams as required for Micro-Deval testing per ASTM D6928.
3. The Micro-Deval sample was split per AASHTO T248 to obtain 16 replicate AIMS2 samples of approximately 90 grams each. The AIMS2 procedure required a 50 coarse particle count minimum, which was approximately 90 grams. Using Excel's random number generator, three replicates of the 16 samples were selected for analysis in the AIMS2. Each of the three smaller random samples are referred to as replicates throughout this study.
4. The three replicates were measured in the AIMS2 device for angularity, texture, sphericity, and F&E ratios. The data were evaluated for outliers and repeatability using the Minitab statistical software as discussed later.
5. The selected replicates were recombined with the other sample replicates to make up the 1,500 gram Micro-Deval sample. The 1,500 gram sample was then conditioned in the Micro-Deval following ASTM 6928. The 1,500 gram sample was soaked in the Micro-Deval container for an hour in two liters of water, and 5,000 grams of steel charges were added to the container for conditioning.

   Based on the single No. 4 sieve size selected for coarse aggregate testing, a total conditioning time of 95 minutes was chosen from the standard Micro-Deval gradation that contained the greatest mass of the No. 4 material. Total conditioning time was rounded up to 100 minutes so the sample could be conditioned in 20-minute increments.

   Moaveni et al. found that 210 minutes was the necessary conditioning time for coarse aggregates to ensure that terminal angularity and texture indexes were reached. However, they noted that the rate of angularity and texture loss appeared to slow down significantly after 105 minutes of Micro-Deval conditioning, indicating 100 minutes of conditioning was approaching terminal conditioning (*15*).
6. After 20 minutes of Micro-Deval conditioning, the steel charges were removed using a magnet. The conditioned sample was washed over the No. 16 sieve, dried, and weighed. The material passing the No. 16 sieve was recorded as mass loss. In this study, a cycle

includes an increment of 20 minutes of polishing in the Micro-Deval followed by AIMS2 testing. The first cycle consists of AIMS2 testing prior to any conditioning.

7. Steps 3 through 6 were repeated until the sample completed five conditioning/testing cycles.
8. The Micro-Deval samples were not sieved to obtain particles only passing the 3/8 inch sieve and retained on the No. 4 sieve after conditioning. The AIMS2 rejects particles that are too small and do not fit entirely within camera view. Therefore, keeping the entire sample together was considered appropriate.

4.3.2 Fine Aggregate Micro-Deval and AIMS2 Testing Procedure

The testing procedure using the AIMS2 and Micro-Deval for all aggregate sources with No. 16 sieve samples was as follows:

1. The aggregate sources were sampled from their corresponding stockpiles, washed, oven dried, and sieved to obtain particles passing the No. 8 sieve and retained on the No. 16 sieve.
2. Each processed sample was split per AASHTO T248 to obtain approximately 500 grams required for Micro-Deval testing per ASTM D7428.
3. The Micro-Deval sample was split per AASHTO T248 to obtain 16 replicate AIMS2 samples of approximately 30 grams each. The AIMS2 procedure required a 150 fine particle count minimum, which was approximately 30 grams. Three replicates of the 16 AIMS2 samples were selected using Excel's random number generator. Each of the three smaller random samples are referred to as replicates in this study.
4. The AIMS2 measured FAA and Form2D of the three replicates for each of the fine aggregate sources. The AIMS2 data were evaluated for outliers and repeatability using Minitab statistical software as discussed later.
5. The selected replicates were recombined with the other sample replicates to make up the 500 gram Micro-Deval sample. The 500 gram sample was then conditioned in the Micro-Deval following ASTM D7428. The procedure was modified to condition the single-sized aggregate sample, not the gradation provided by the testing standard. The 500 gram sample was soaked in 0.75 liters of water in the Micro-Deval container for an hour. Approximately 1,250 grams of steel charges were added to the Micro-Deval container before conditioning.

   ASTM D7428 specifies a total conditioning time of 15 minutes for the prescribed gradation containing the greatest mass of the No. 16 sized particles. This study elected to have a minimum of three testing cycles with a minimum of 10 minutes of conditioning for each cycle. Based on these parameters, the total conditioning time was modified from 15 minutes to 30 minutes.
6. After 10 minutes of Micro-Deval conditioning, the steel charges were removed using a magnet. The conditioned sample was washed over the No. 50 sieve, dried, and weighed. The mass loss was recorded as the material passing the No. 50 sieve.

ASTM D7428 specifies that material passing the No. 200 sieve is considered lost material for the specified gradations. It was determined that the No. 200 sieve was too small of a sieve size when testing only No. 16 size aggregate particles. The Micro-Deval procedure for coarse aggregates (ASTM D7428) specified that particles passing the No. 16 sieve were considered lost material, which is two standard sieve sizes smaller than the No. 4 size particle tested. For consistency, lost material for the No. 16 fine particles tested was characterized as material passing the No. 50 sieve, two standard sieve sizes below the No. 16 sieve.

7. Steps 3 through 6 were repeated until the sample completed three conditioning/testing cycles for a total of 30 minutes of conditioning.
8. The Micro-Deval samples were not sieved to obtain particles only passing the No. 8 sieve and retained on the No. 16 sieve after conditioning. This was done to ensure the Micro-Deval sample remained together throughout the entire experiment.

4.4 Data Quality Control

Data quality control analysis was performed on AIMS2 test results to detect outliers among the data sets. The results were also checked with the AIMS2 precision statement to ensure that repeatable results were achieved. These activities are described in the following subsections.

Some of the replicates appeared to have significantly lower or higher data points for each shape property, which would misrepresent the true sample properties. Therefore, Minitab statistical software was used to analyze the data and identify any outliers within the sample.

After measurement in the AIMS2, the data from the three replicates for each aggregate source were combined into one data set for analysis. The combined three replicates for statistical analysis are referred to as a data set. Minitab provided a graphical summary using a boxplot to represent variability of the data. An example is shown in Figure 17. The rectangular box represents 50% of the data and the line in the middle of the rectangular box represents the median value of the data. The interquartile range is computed by subtracting the 25th percentile from the 75th percentile. The stems of the boxplot extend 1.5 times the interquartile range (*20*). Any data points outside these stems are represented by an asterisk (*) and were considered “first order outliers” and were removed from the data. These are circled in red in Figure 17.

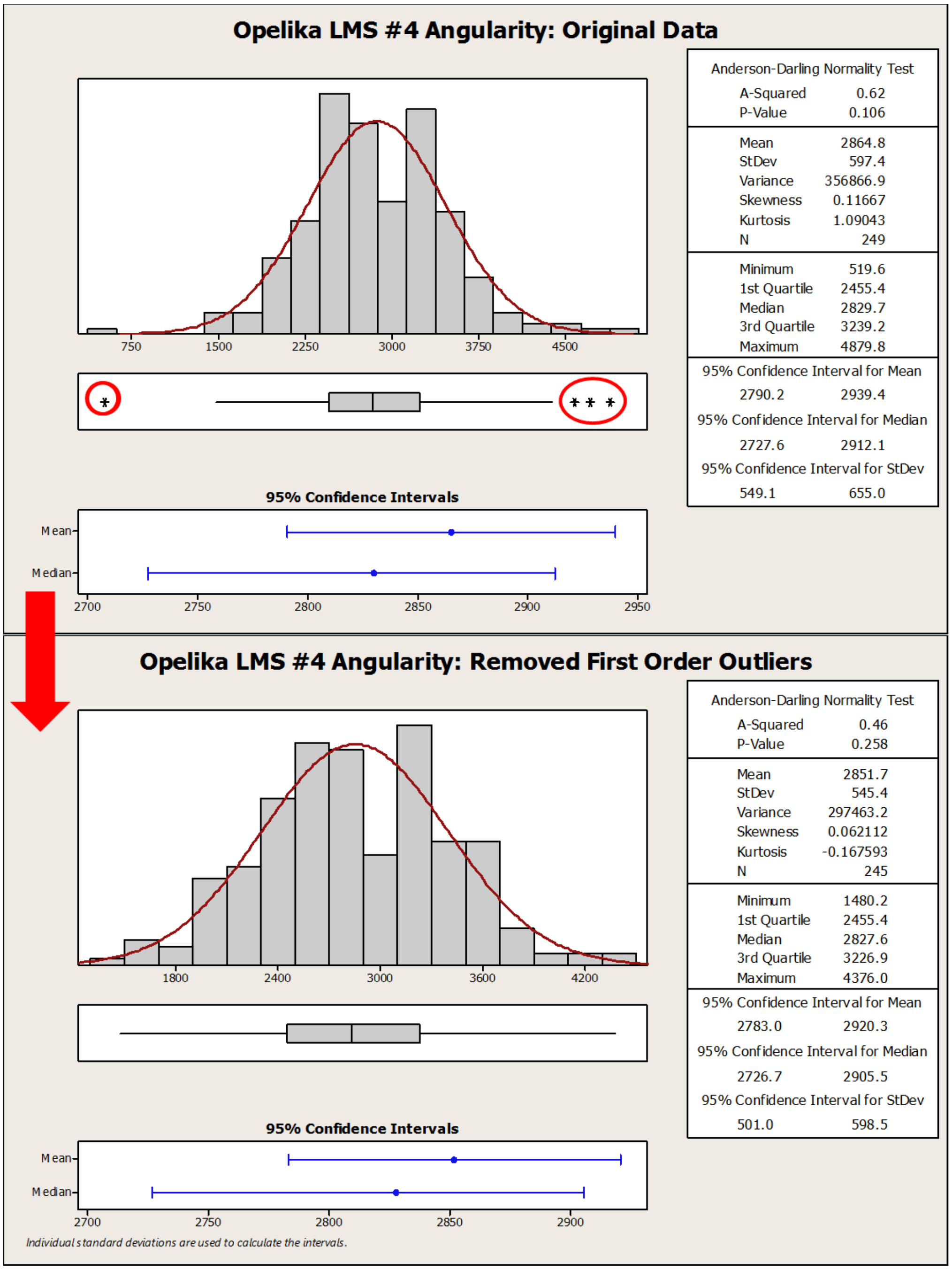

Figure 17 Example of Removing First Order Outliers from Data Set

A second level statistics was performed on the clean data set to determine if there were any second order outliers. This further analysis determined that all second order outliers would remain part of the analysis for all data sets. Minitab graphical summaries showing the distributions for AIMS2 CAA, FAA, and coarse aggregate texture can be found in the thesis (*21*).

The results for angularity and texture were only checked against the precision statement in AASHTO TP81. The precision statement specifies acceptable upper and lower limits with a coefficient of variation as a percent of the overall average. The coefficient of variation corresponding to AIMS2 angularity indexes is 2.9% and the coefficient of variation corresponding to AIMS2 texture indexes is 4.5%. Tables showing the overall mean, lower and upper limits, as well as the means of each replicate are provided in the thesis (*21*). Some of the replicates' means fell outside the precision statement but were reasonably close and were accepted for use in data analysis.

CHAPTER 5 LABORATORY RESULTS AND DISCUSSION

5.1 Micro-Deval Aggregate Mass Loss

The test protocol recorded Micro-Deval mass loss for both coarse and fine aggregates as previously described in Chapter 4. Material passing the No. 16 sieve was considered lost material for coarse aggregates, and material passing the No. 50 sieve was considered lost material for fine aggregates. The amount of mass loss due to conditioning in the Micro-Deval is an indication of aggregate durability. Figures 18 and 19 show the cumulative percent mass loss for coarse aggregates (CA) and fine aggregates (FA), respectively.

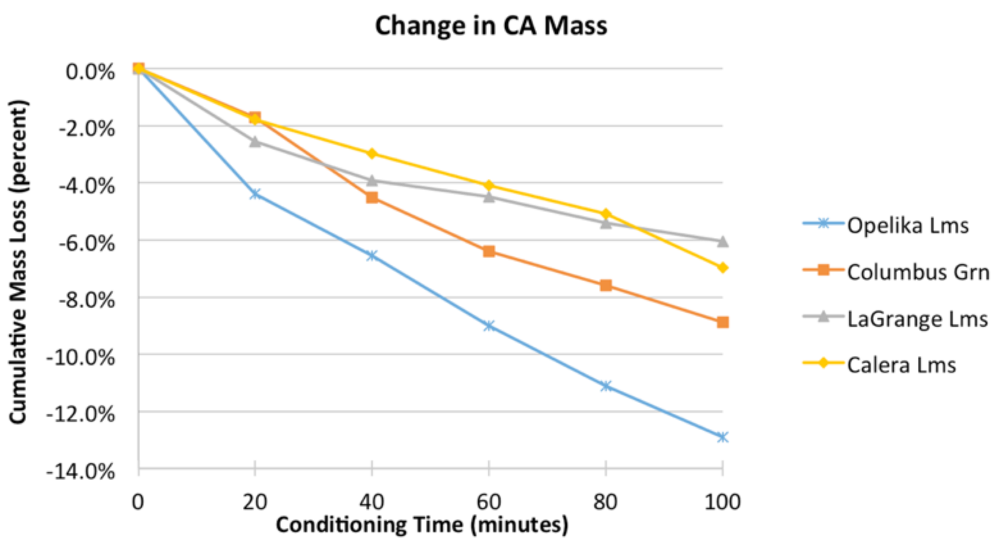

Figure 18 Change in Coarse Aggregate Mass Loss from Micro-Deval Conditioning

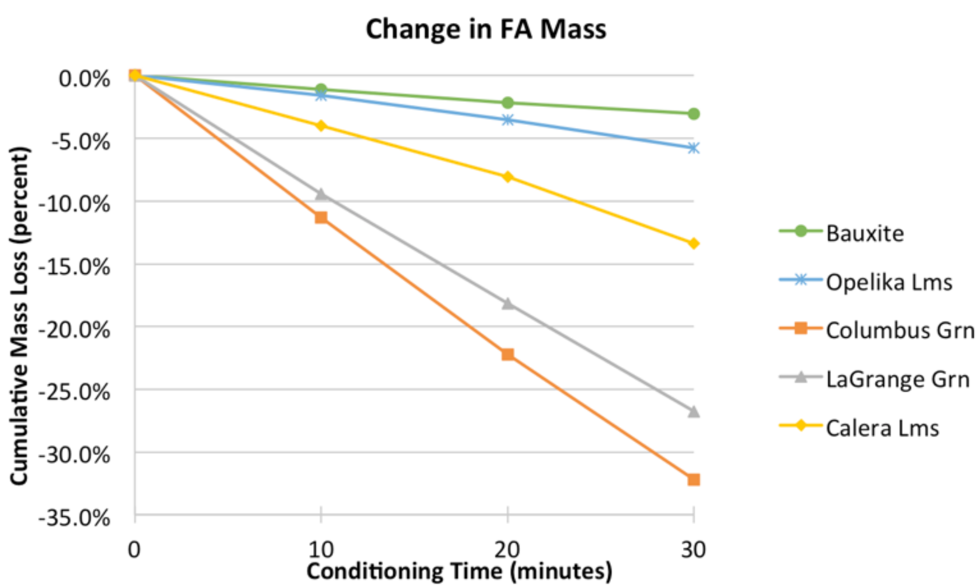

Figure 19 Change in Fine Aggregate Mass Loss from Micro-Deval Conditioning

As expected, all aggregate sources experienced some mass loss due to conditioning in the Micro-Deval. A steeper slope in the figure indicates a higher rate of mass loss for the aggregate. Fine aggregates experienced more percent mass loss after 30 minutes of conditioning than the coarse aggregates after 100 minutes of conditioning, with the exception of the Opelika limestone source. This may be attributed to the fine aggregate sample particles having a higher surface area exposed to abrasion than the coarse aggregate, resulting in more pieces broken off of multiple fine particles. The bauxite was characterized by the least percent mass loss among all fine aggregate samples tested, indicating that the bauxite was the most durable. This is consistent with field performance, as bauxite is the specified aggregate source for use in HFST.

Table 9 shows how the aggregate source rankings differ between coarse and fine aggregate tests. The ranking is based on the cumulative percent loss at the end of the total conditioning time (100 minutes for coarse aggregates and 30 minutes for fine aggragates). Bauxite was excluded from the table because only the fine aggregate was tested, and bauxite experienced the least amount of mass loss. The table shows that the ranking of aggregate durability based on Micro-Deval mass loss varied by the size of particle tested. Further development of friction tests may need to consider the particle size being tested. Chapter 6 compares the test results with field friction performance.

Table 9 Percent Mass Loss Ranking among Coarse and Fine Aggregates after Total Conditioning

Aggregate Source	Coarse Aggregate Ranking	Fine Aggregate Ranking
Opelika Limestone	4	1
Columbus Granite	3	4
LaGrange Granite	1	3
Calera Limestone	2	2

1 = lowest mass loss, 4 = highest mass loss

5.2 AIMS2 Aggregate Angularity

The AIMS2 device measured aggregate angularity for coarse and fine aggregates. Coarse aggregate angularity is associated with macro-texture and both CAA and FAA are associated with asphalt mixture aggregate structure. Figures 20 and 21 show the average AIMS2 CAA and FAA index after each conditioning interval.

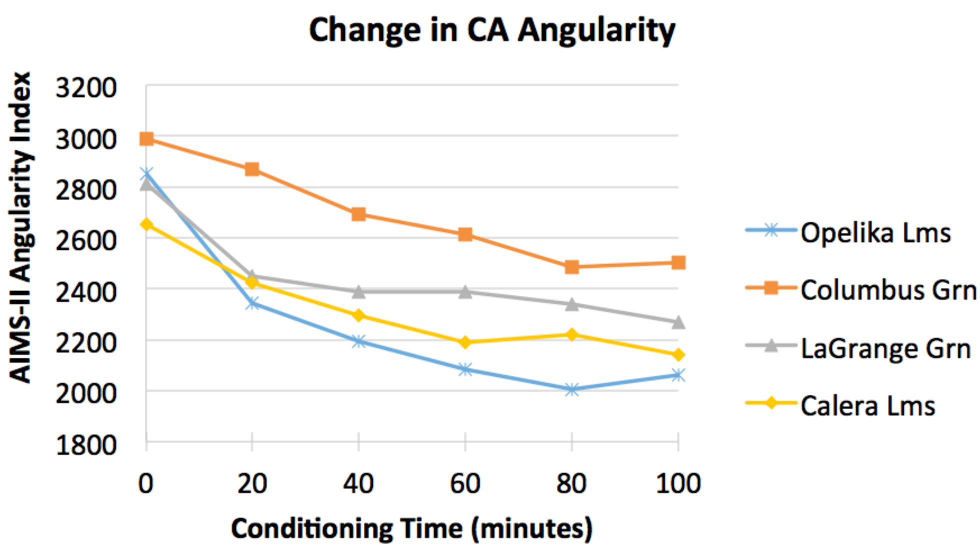

Figure 20 Change in AIMS2 Coarse Aggregate Angularity from Micro-Deval Conditioning

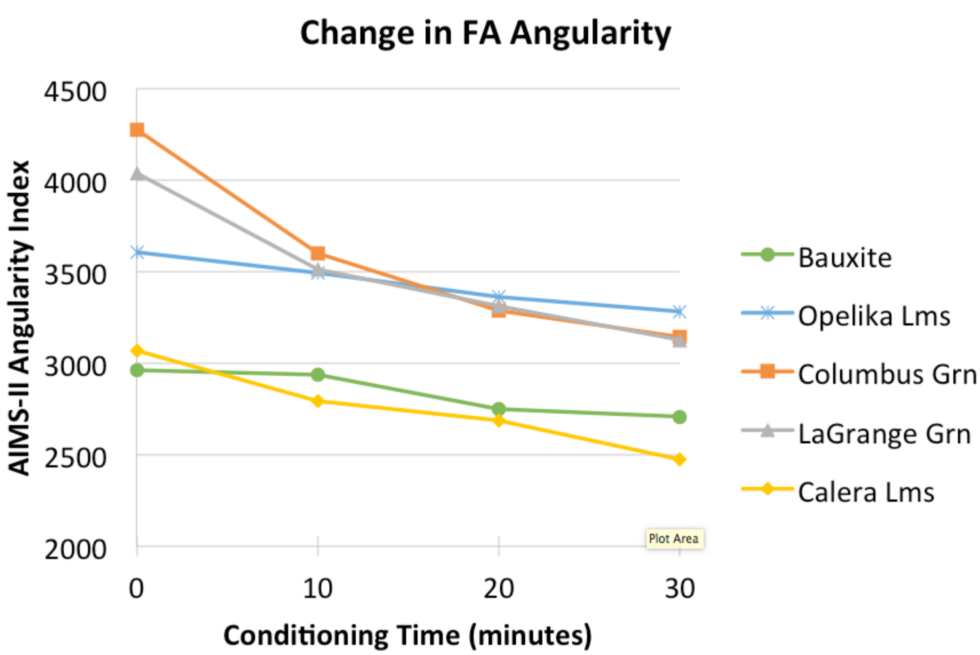

Figure 21 Change in AIMS2 Fine Aggregate Angularity from Micro-Deval Conditioning

The figures show that the aggregate angularity indexes decreased as conditioning (polishing) time increased in the Micro-Deval. Within the Micro-Deval container, the aggregate edges are abrading from the impact of the steel charges and surrounding aggregates. As the rate of angularity change decreases, the aggregate surfaces become more resistant to the abrasion. Moaveni et al. observed that for coarse aggregates, the rate of change in angularity significantly decreased at approximately 105 minutes of Micro-Deval conditioning time (*15*). The test results from this study showed that the rate of change decreased after 20 to 80 minutes of conditioning depending on the aggregate source tested. The fine aggregates did not have a clear point at which the rate of angularity loss reduced significantly. Future research studies should consider taking fine particles beyond 30 minutes of conditioning time if a terminal abrasion loss is of interest. The 30-minute conditioning time for this study was double the time specified in ASTM D7428.

There were differences between the angularity indexes of the coarse and fine aggregates from the same source. The fine aggregates were characterized by a higher initial angularity when compared to coarse aggregates. An aggregate may initially be characterized by a high angularity index, but it is important for the aggregate to be able to maintain an adequate level of angularity when subjected to polishing. Table 10 shows the percent reduction in angularity (angularity after 30 minutes conditioning divided by the initial angularity) to evaluate the aggregates' durability.

Table 10 Percent Loss in AIMS2 Angularity for Coarse and Fine Aggregates

Aggregate Source	Coarse Aggregate	Fine Aggregate
Opelika Limestone	27.7%	8.9%
Columbus Granite	16.7%	26.5%
LaGrange Granite	19.3%	22.6%
Calera Limestone	19.3%	19.5%
Bauxite	N/A	8.5%

The cumulative distribution of angularity indexes was tracked before Micro-Deval conditioning (BMD) and at each conditioning time (20, 40, 60, 80, and 100 minutes for coarse aggregates; 10, 20, and 30 minutes for fine aggregates). Figure 22 provides an example distribution for Opelika limestone coarse aggregate. The AIMS2 delineation between low, medium, and high angularity indexes are labeled and separated by vertical black lines within the graph. The cumulative distributions for all of the aggregate sources are found in the thesis (*21*).

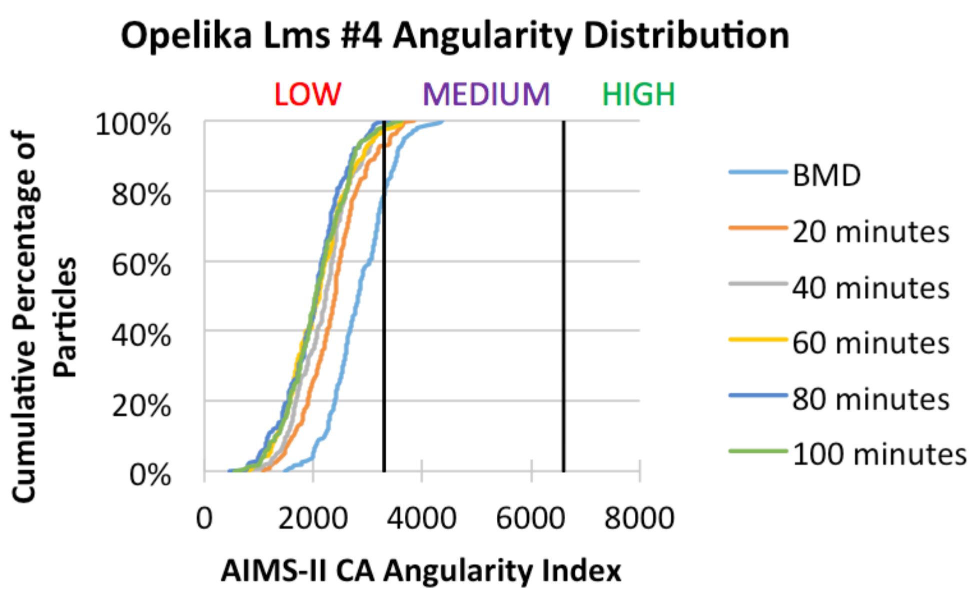

Figure 22 Example of AIMS2 Angularity Distribution Change for Opelika Limestone

A similar trend in the shift of the angularity distribution was observed for all aggregate sources. The distribution shifted to the left as the aggregates were conditioned in the Micro-Deval, indicating that a larger percentage of particles became more rounded when subjected to conditioning. The change in angularity distribution decreased with successive increments of polishing and was verified using the Kolmogorov-Smirnov test (K-S test) (*22*). Table 11 shows the K-S test results that correspond to Figure 22. The maximum difference between two successive distributions decreased as the cumulative amount of conditioning increased. The K-S test results for all aggregate distributions are found in the thesis (*21*).

Table 11 Example of K-S Test Results for Opelika Limestone No. 4 AIMS2 Angularity

Opelika Limestone No. 4 Angularity		
Comparisons	Max Difference	P-value
BMD vs 20	0.38	0.00
20 vs 40	0.16	0.01
40 vs 60	0.13	0.06
60 vs 80	0.09	0.34
80 vs 100	0.07	0.65
BMD vs 100	0.53	0.00

The K-S test results shown in Table 11 also present the corresponding p-value at a 95% confidence interval. A low p-value means the distributions are significantly different at a 5% level; these values are shown in red. The initial distribution, prior to any conditioning, and at the total conditioning time were compared to determine that the K-S test recognized a significant change in distribution caused by Micro-Deval conditioning. In Table 11, the Opelika limestone coarse aggregate begins to reach terminal polishing after 60 minutes. The K-S test results from the AIMS2 FAA showed several cases in which the distribution at 30 minutes of conditioning significantly differed from the distribution at 20 minutes. This validated the mass loss results that showed the tested fine aggregate sources needed more than 30 minutes conditioning time to reach terminal angularity values.

Figures 23 and 24 show the cumulative distribution of angularity for each of the coarse aggregate and fine aggregate sources after total conditioning time, respectively. The distribution curves had similar shape, so the location of the distribution curves ranks similarly to the mean value of each curve. Distribution curves further to the left had a lower mean value.

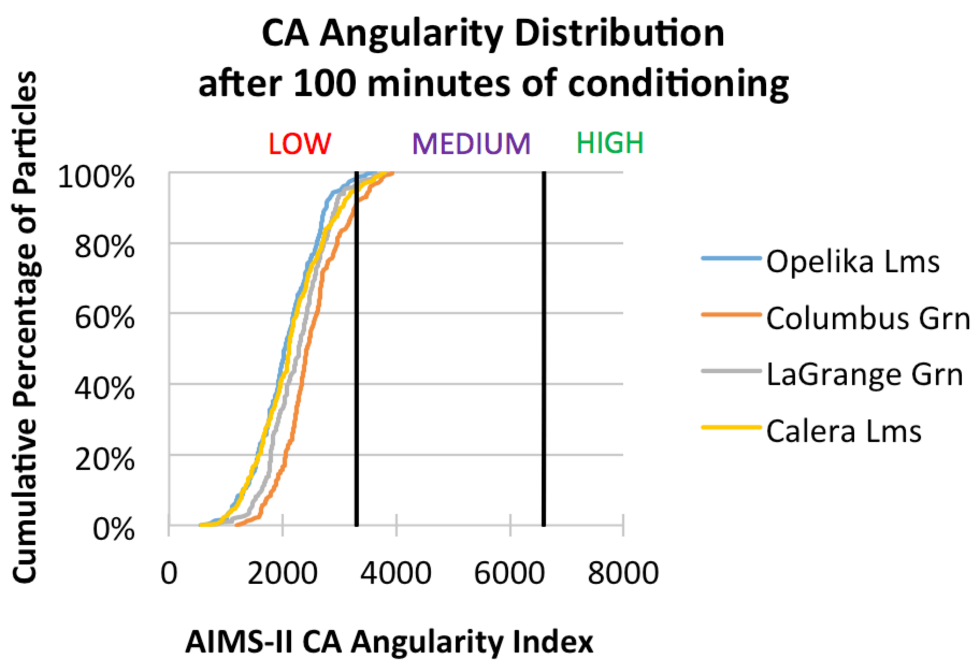

Figure 23 AIMS2 Coarse Aggregate Angularity Cumulative Distributions after 100 Minutes of Micro-Deval Conditioning

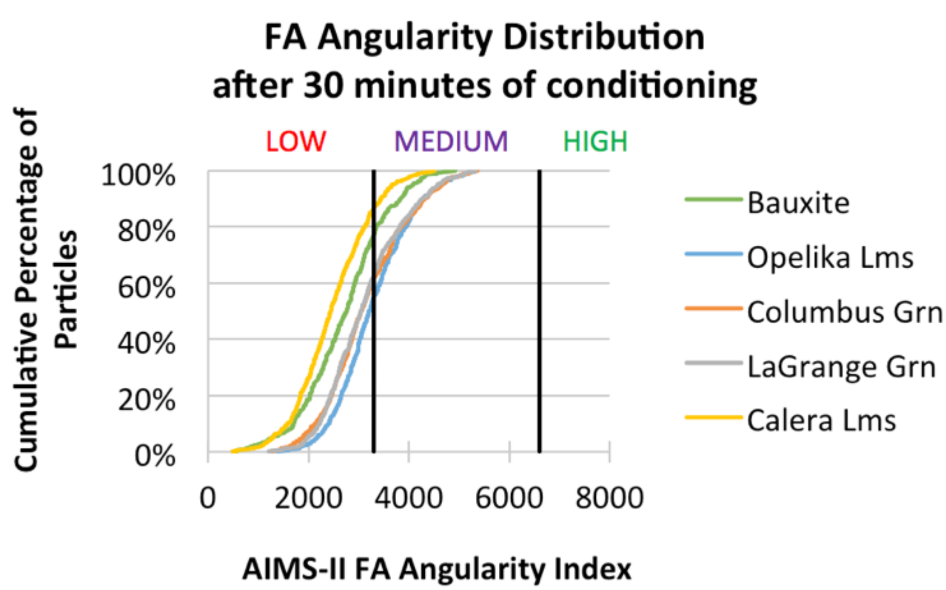

Figure 24 AIMS2 Fine Aggregate Angularity Cumulative Distributions after 30 Minutes of Micro-Deval Conditioning

5.3 AIMS2 Coarse Aggregate Texture

Figure 25 displays the AIMS2 texture index recorded after each Micro-Deval conditioning cycle for each coarse aggregate source. The texture index relates to the surface micro-texture of the individual particles, a parameter that influences the overall pavement friction. As expected, coarse aggregate surface texture decreased with increased Micro-Deval conditioning time. The figure shows distinctions among the different aggregate texture values. The Columbus granite was characterized by the roughest surface texture and the Opelika limestone was characterized by the smoothest surface texture. It is important for an aggregate to maintain adequate surface texture when subjected to polishing. Table 12 shows the loss of texture after 100 minutes of conditioning as a percent of initial surface texture.

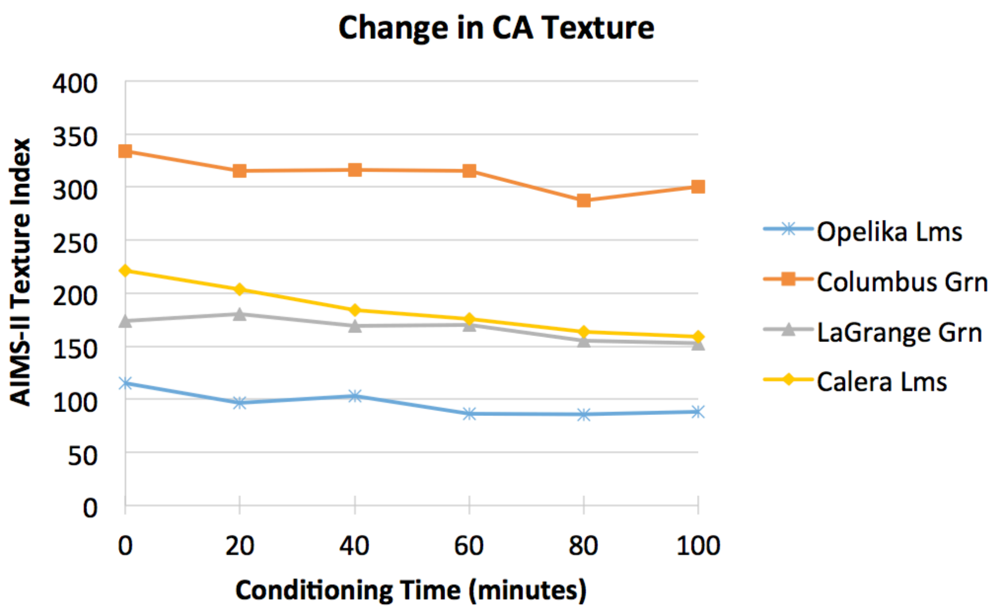

Figure 25 Change in AIMS2 Coarse Aggregate Texture from Micro-Deval Conditioning

Table 12 Percent Loss in AIMS2 Coarse Aggregate Texture after 100 Minutes of Conditioning

Aggregate Source	Percent Texture Loss
Opelika Limestone	23.8%
Columbus Granite	10.2%
LaGrange Granite	14.6%
Calera Limestone	28.2%

Figure 25 shows that the Calera limestone had a higher terminal texture index than both the LaGrange granite and Opelika limestone. However, Table 12 shows that the Calera limestone had the highest rate of texture loss after conditioning. If the Micro-Deval conditioning time was increased, it is possible that the Calera limestone could reach a terminal surface texture value less than that of the LaGrange granite. This is an important consideration, as an aggregate that might appear to have a higher initial surface texture may not retain its micro-texture under polishing conditions. This could result in a mixture's inability to maintain an adequate amount of pavement friction.

Similar to aggregate angularity, the cumulative distribution of coarse aggregate texture indexes were compared. Figure 26 shows an example of the No. 4 Opelika limestone with the corresponding K-S test results in Table 13. The cumulative distributions and corresponding K-S test results of all the aggregate sources are found in the thesis (*21*).

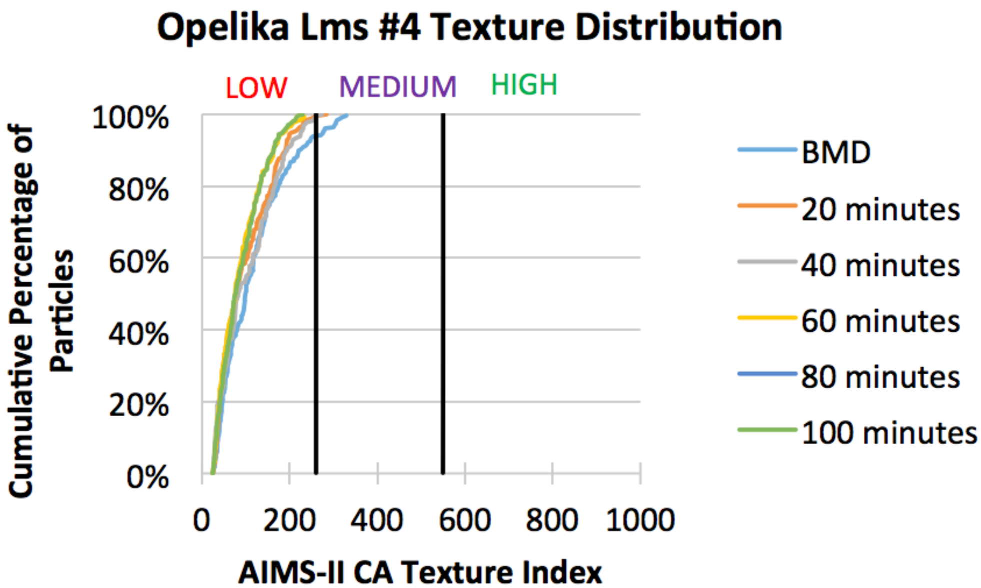

Figure 26 Example of AIMS2 Texture Distribution Change for Opelika Limestone

Table 13 Example of K-S Test Results for Opelika Limestone No. 4 AIMS2 Texture

Opelika Limestone No. 4 Texture		
Comparisons	Max Difference	P-value
BMD vs 20	0.14	0.03
20 vs 40	0.09	0.45
40 vs 60	0.17	0.01
60 vs 80	0.05	0.99
80 vs 100	0.06	0.92
BMD vs 100	0.16	0.01

Similar to the trends observed from the angularity results, the distribution of texture indexes shift toward lower texture with increased conditioning time. The differences between successive distributions decreases with increased polishing time and is quantified in Table 13. The maximum difference decreases by approximately half when comparing BMD conditioning versus 20 minute, and 80 minute versus 100 minute. There was no statistical difference between the samples after 60 minutes of conditioning. This statistical analysis agreed with Figure 25, which showed the Opelika limestone reached a terminal AIMS2 surface texture at 60 minutes of conditioning.

Figure 27 shows the cumulative distribution of surface texture for each aggregate source after 100 minutes of Micro-Deval conditioning. The Columbus granite consisted of the largest percentage of particles characterized by rougher texture compared to the other aggregate sources. Therefore, the Columbus granite would provide the most micro-texture on a pavement surface compared to other sources in this study and should provide high pavement surface friction.

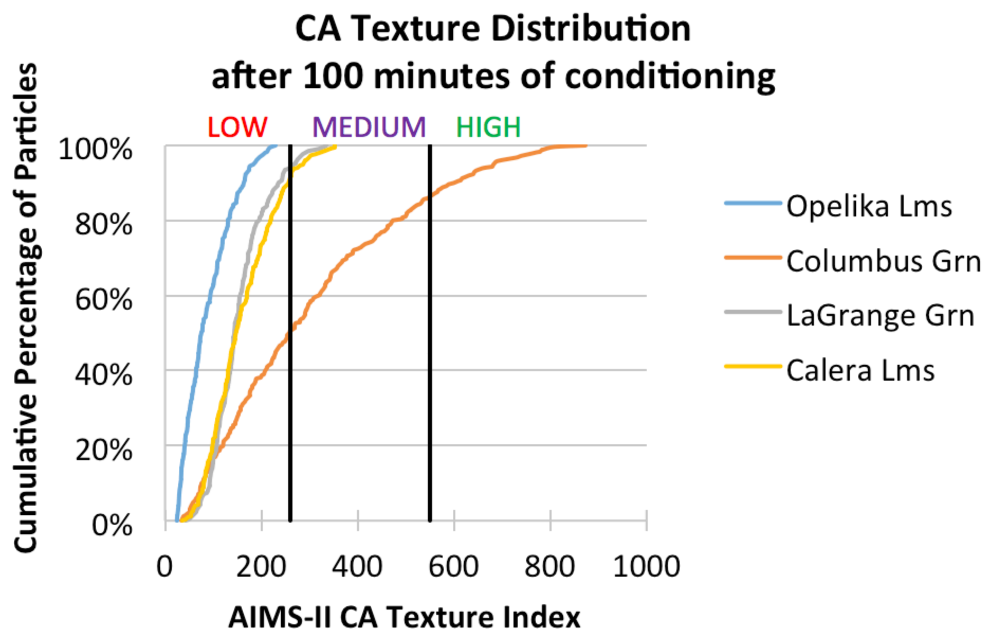

Figure 27 AIMS2 Coarse Aggregate Texture Cumulative Distribution Differences after 100 Minutes of Micro-Deval Conditioning

5.4 AIMS2 Coarse Aggregate Sphericity

Figure 28 shows the change in the average AIMS2 sphericity index for each coarse aggregate at each incremental polishing time. The figure reveals that there was no change in sphericity with increased Micro-Deval conditioning. Using AIMS2 criteria, all aggregate sources had a medium level of sphericity (values between 0.3 and 0.7). The Opelika limestone consistently had the lowest sphericity index, indicating that these particles tended to be slightly more spherical than the other aggregate sources. This was further demonstrated by the cumulative distribution of sphericity shown in Figure 29.

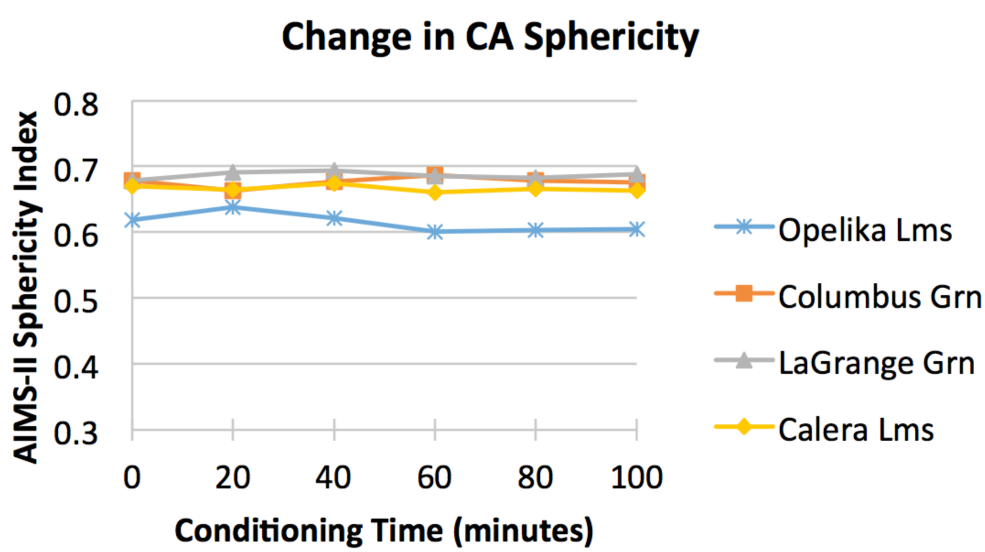

Figure 28 Change in AIMS2 Coarse Aggregate Sphericity from Micro-Deval Conditioning

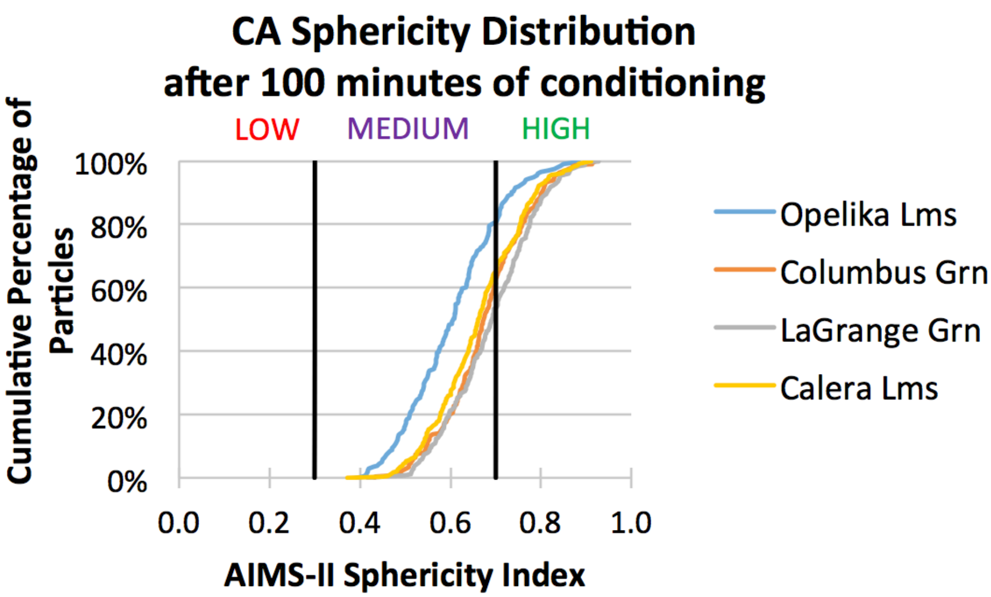

Figure 29 AIMS2 Coarse Aggregate Sphericity Cumulative Distribution Differences after 100 Minutes of Micro-Deval Conditioning

5.5 AIMS2 Coarse Aggregate Flat and Elongated (F&E) Ratio

Coarse aggregate F&E properties are associated with construction degregation and not tied to pavement friction. To complete the series of friction comparisons, the average AIMS2 F&E ratio for each coarse aggregate was monitored to determine any trends. Figure 30 reveals that there was no change in average F&E ratios with increased Micro-Deval conditioning time. These results agreed with the results for sphericity.

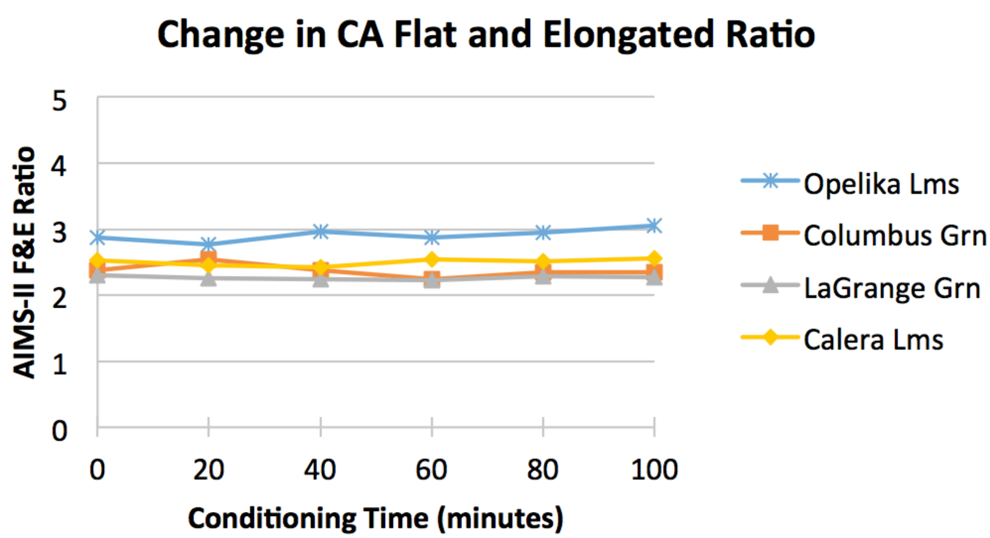

Figure 30 Change in AIMS2 Coarse Aggregate F&E Ratios from Micro-Deval Conditioning

5.6 AIMS2 Fine Aggregate Two-Dimensional Form (Form2D)

Fine aggregate Form2D was measured as Micro-Deval conditioning time increased. Figure 31 shows that AIMS2 Form2D values decreased with increased polishing time. This indicates that as the aggregates were polished, they became increasingly circular. Using AIMS2 criteria, all Form2D averages were characterized as medium values falling within the range of 6 to 12. The Opelika limestone measured the highest average value, which indicates that it portrayed a more elongated oval shape than the other aggregate sources. Bauxite measured a fairly consistent shape throughout conditioning, similar to its small change in angularity values shown in Figure 21 and Table 10.

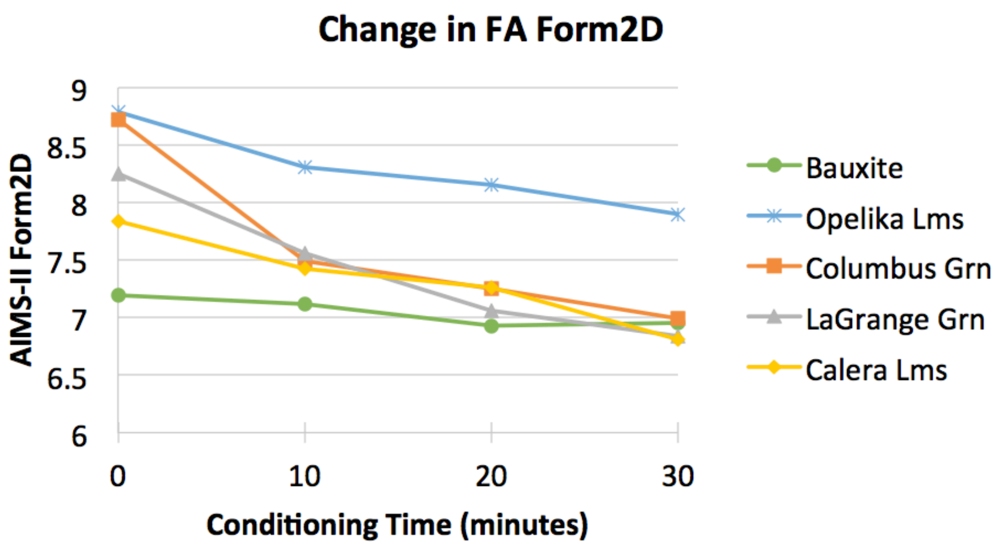

Figure 31 Change in AIMS2 Fine Aggregate Form2D from Micro-Deval Conditioning

The cumulative distribution was tracked at each conditioning time. The primary purpose of this was to show how bauxite compared to the other aggregate sources. Figure 32 shows the AIMS2 Form2D distribution of the bauxite before Micro-Deval conditioning and after each conditioning time interval. The bauxite reflected minimal changes in distribution after increased conditioning, demonstrating its durability and resistance to change in shape. For comparison, Figure 33 shows the Form2D cumulative distribution of the Columbus granite before and after incremental Micro-Deval conditioning. The corresponding K-S test results are shown in Table 14. The distributions of the Form2D value and the corresponding K-S test results for all aggregate sources are in the thesis (*21*). The Form2D distributions of the other aggregate sources were similar to what was observed with the No. 16 Columbus granite with a noticeable shift in distribution to the left after conditioning.

Figure 34 shows the distributions of Form2D values for each aggregate source after 30 minutes of conditioning. There are few differences among the aggregate sources except for the Opelika limestone. This indicates that there is little variation in the overall two-dimensional shape among the fine aggregates tested.

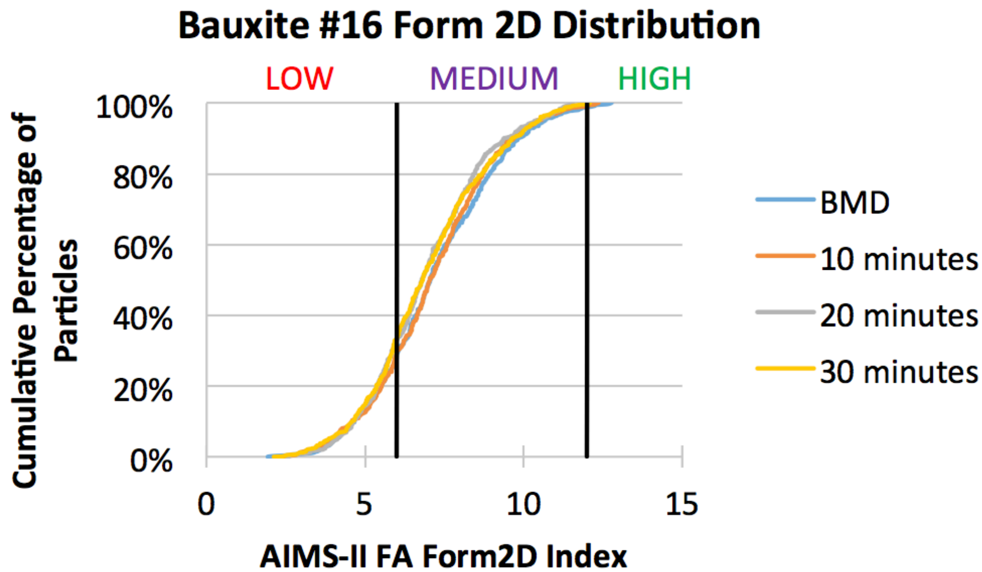

Figure 32 Change in AIMS2 Fine Aggregate Form2D Distribution for Bauxite

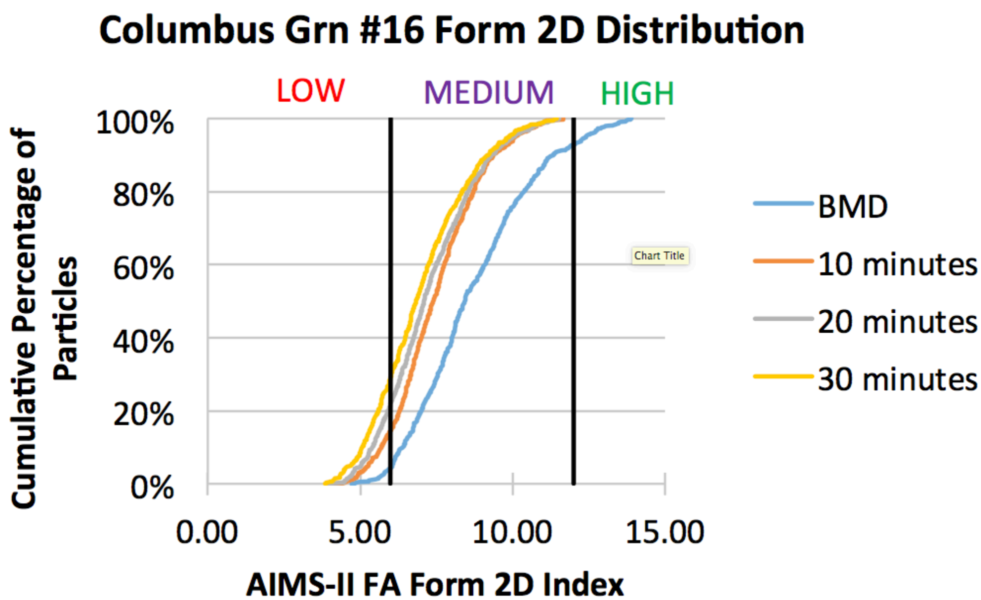

Figure 33 Change in AIMS2 Fine Aggregate Form2D distribution for Columbus Granite

Table 14 Example of K-S Test Results of AIMS2 Form2D Distributions for Bauxite and Columbus Granite

Comparisons	Bauxite		Columbus Granite	
	Max Difference	P-value	Max Difference	P-value
BMD vs 10	0.04	0.78	0.28	0.00
10 vs 20	0.08	0.12	0.10	0.00
20 vs 30	0.04	0.76	0.09	0.02
BMD vs 30	0.07	0.15	0.37	0.00

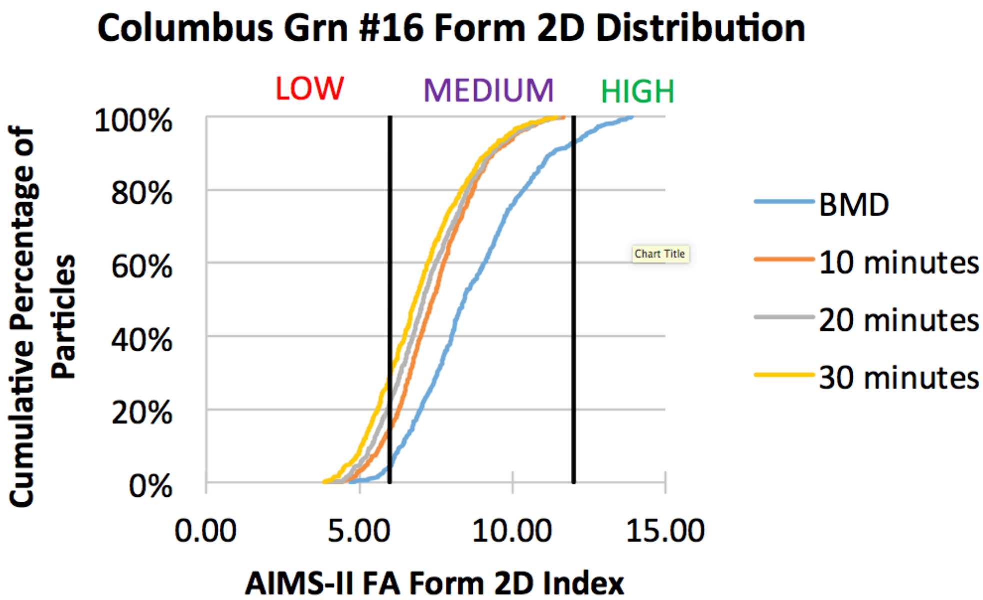

Figure 34 AIMS2 Fine Aggregate Form2D Distribution Differences after 30 Minutes of Micro-Deval Conditioning

5.7 Summary of Lab Results

All aggregate sources were measured for mass loss after conditioning in the Micro-Deval. The bauxite measured the least percentage of mass loss, indicating it was the most durable of the aggregate sources tested. The AIMS2 device detected changes in aggregate shape properties among both coarse and fine aggregates. Both AIMS2 CAA and FAA indexes decreased with increased Micro-Deval conditioning time, indicating that the aggregates became more rounded along the particle edges. The bauxite experienced the least amount of angularity loss. Coarse aggregate texture decreased with increased polishing.

Comparing the aggregate sources in this study, the Columbus granite measured a rougher surface texture before and after conditioning, indicating it would be a better aggregate source for a surface layer to provide surface friction. In comparison, the texture indexes of a limestone source may not provide suitable pavement friction.

Fine aggregate Form2D decreased with increased Micro-Deval conditioning, indicating the aggregates became more rounded. The bauxite showed minimal change in its particle shape after conditioning, validating its ability to resist the effects from polishing.

No trends were observed for coarse aggregate sphericity or F&E values with increased conditioning time. These two parameters do not play a role in pavement friction, so this did not introduce any hindrances when finding correlations between lab data and field friction data.

CHAPTER 6 COMPARISON OF AIMS2 LAB RESULTS AND FIELD FRICTION

This chapter compares the AIMS2 device results from the lab with the locked-wheel skid trailer results from the NCAT Test Track field test sections. The AIMS2 lab results for the Opelika limestone were omitted because none of the surface mixtures on the Test Track sections were composed of Opelika limestone as the dominant aggregate in the mix.

6.1 Field Friction Data

Locked-wheel skid trailer friction data (SN40R) were obtained from NCAT's 2009 Test Track research cycle. Field friction data, measured several months after completion of traffic loading, were omitted due to irregularities in the data.

Initially, the analysis ranked the field test sections on an individual basis but generated inconclusive results. Therefore, test sections were grouped according to the surface mix design, resulting in five separate groups of mixtures as summarized previously in Table 7. These groups included two sections of the HFST using bauxite, seven sections of FDG mix composed primarily of Columbus granite, one section of the SMA composed of Columbus granite, three sections of the OGFC composed of LaGrange granite, and one section characterized as an SMA composed primarily of Calera limestone. Figure 35 shows the design gradation of the four asphalt mix groups. Bauxite is not included because it is a HFST.

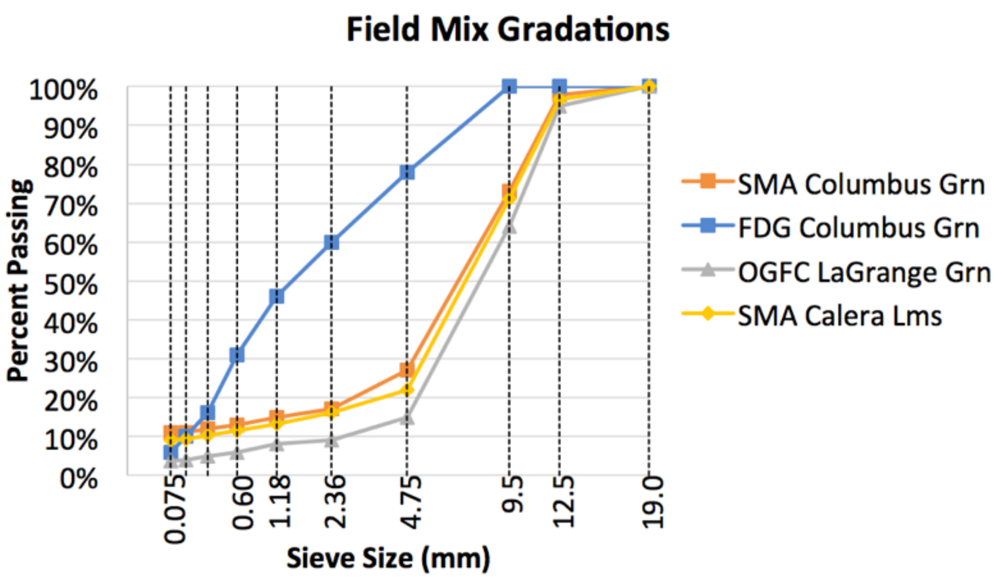

Figure 35 Mix Gradations for Test Track Section Groups

The field results were ranked based on average SN40R values for each group as shown in Figure 36. The friction value at 5.3 million ESALs for bauxite section E3 was very high (68.0) compared to section E2 (63.8). To justify removing this data point, the difference in SN40R values between section E3 and section E2 were examined and the difference at 5.3 million ESALs was more than two standard deviations away from the average difference between the two test sections, indicating there was some error resulting in the measurement. This was likely attributed to the skid trailer testing outside of the wheel path, which would result in a higher skid number than if the measurement were taken inside the wheel path. Therefore, bauxite section E2 SN40R value was used (circled in red in the figure) as opposed to taking an average of the two test sections.

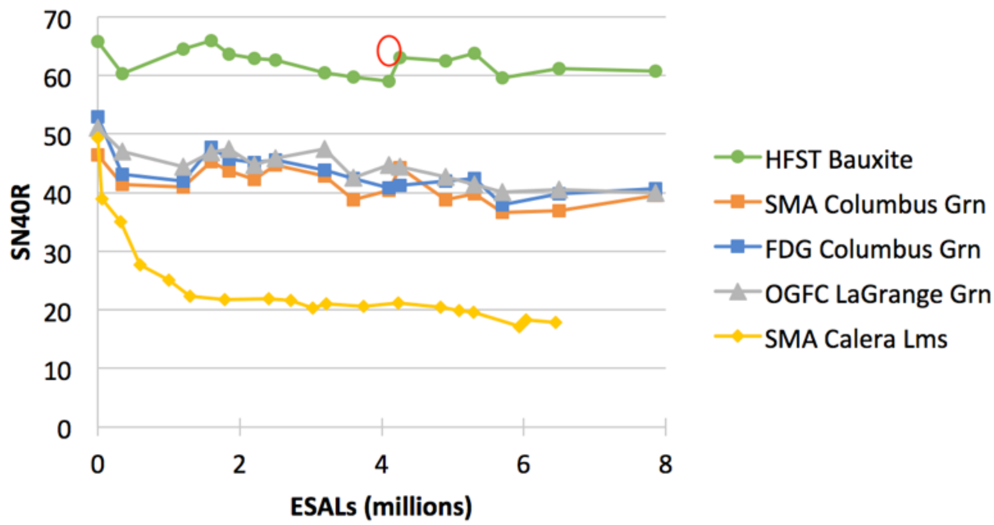

Figure 36 Average of Field SN40R Data Based on Mix Type

6.1.1 Defining Terminal Friction

Agencies generally focus on long-term friction properties, which are commonly called the terminal friction. Figure 36 shows an initial decline in field friction values, particularly shown with the Calera limestone surface mix. The field friction data showed the rate of friction loss for this mix reduced at around two million ESALs. At two million ESALs, all test sections approached a point at which the SN40R values were trending to a terminal friction condition. For this study, the SN40R at seven million ESALs was considered the end point of the terminal friction trend for all field test sections. A relatively flat linear trend is appropriate to portray terminal friction. A linear trend-line was applied to the friction data from two to seven million ESALs. The linear trend equations shown in Figure 37 were used to calculate average skid numbers from two to seven million ESALs for comparison with the AIMS2 angularity and AIMS2 texture indexes.

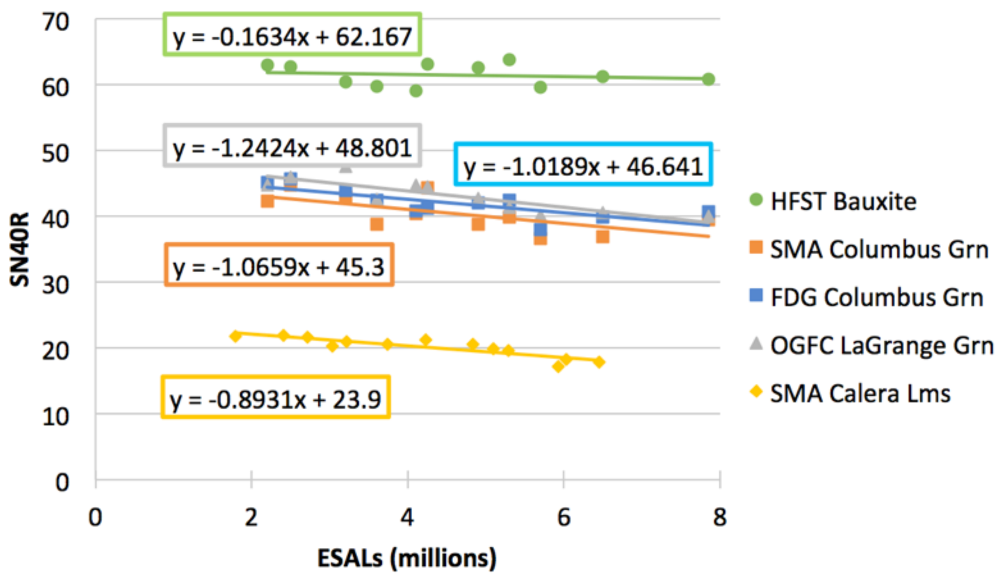

Figure 37 SN40R Terminal Friction for Each Test Track Group

6.2 Comparing AIMS2 Aggregate Angularity to Field Friction Performance

AIMS2 CAA and FAA were compared separately with the field friction performance. The skid number obtained from the field before the test sections were opened to traffic (0 ESALs) was compared with preconditioned AIMS2 indexes.

6.2.1 AIMS2 Coarse Aggregate Angularity and SN40R

During conditioning, four measurement intervals were selected at specific points in time to evaluate the correlation between the AIMS2 results and field friction. The first interval compared the field SN40R with the AIMS2 prior to conditioning from traffic in the field or the Micro-Deval in the lab. Lab results presented in Chapter 4 showed a linear decline from 20 to 100 minutes for AIMS2 CAA. The field friction performance data were based on the linear trend from 2 to 7 million ESALs. The end of the significant decline, AIMS2 CAA at 20 minutes and the field SN40R at 2 million ESALs were selected as the second interval of comparison. A third interval compared points in the middle of the linear decline, which included AIMS2 CAA at 60 minutes and SN40R at 4 million ESALs. AIMS2 CAA at 100 minutes was compared with the SN40R at 6 million ESALs as the fourth interval. Lab testing was carried out to 100 minutes of conditioning as a terminal value. It was anticipated that coarse aggregates would reach a terminal value based on a study by Moaveni et al., which found the AIMS2 indexes significantly reduced after 105 minutes of Micro-Deval conditioning (*15*). The results of the comparison are shown in Figure 38. Bauxite is not included in the figure because there were no coarse aggregate to test.

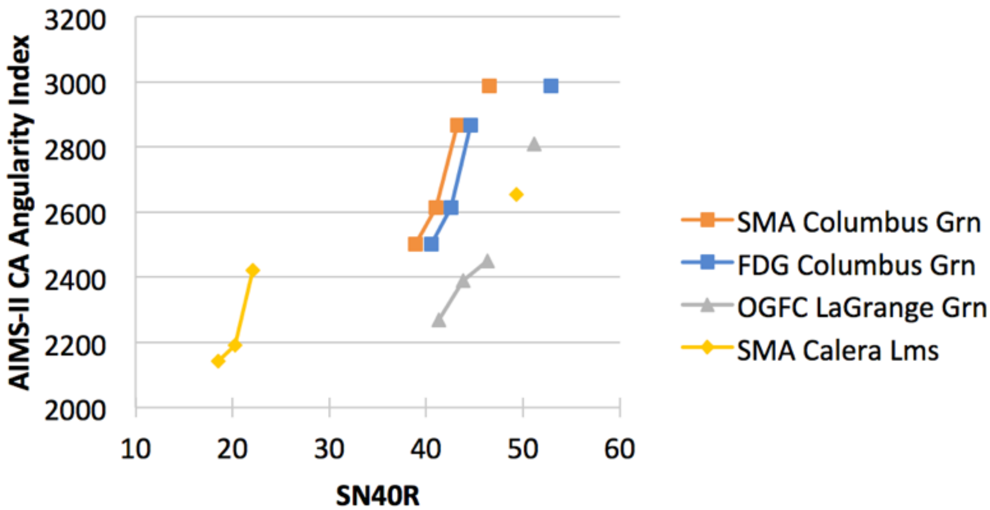

Figure 38 Comparison of AIMS2 Coarse Aggregate Angularity with Field Friction

The results showed inconsistencies among the data. In the field, the Calera limestone showed barely any reduction in the SN40R values after the initial two million ESALs of conditioning. However, in the laboratory, the AIMS2 angularity continued to decrease from approximately 2,400 to 2,200 after initial conditioning to 20 minutes. The steep slope of the Calera limestone reflects the change in laboratory properties while field friction remained reasonably constant. A similar trend was seen when comparing the Columbus granite AIMS2 angularity indexes with the field friction of the two mixes containing Columbus granite. Comparing the linear portion of the AIMS2 CAA data with the field friction linear trend provided more consistent results.

In Figure 39, trend-line equations were determined for the lab values from 20 to 100 minutes to calculate the average value to be used for comparison after conditioning at 20, 60, and 100 minutes. In Table 15, the AIMS2 CAA trend values and SN40R trend values were used to rank the aggregates and mixtures. The aggregates and mixtures were ranked from 1 to 3, where 1 denotes the aggregate or mixture having the highest AIMS2 index or SN40R. The AIMS2 lab values at 20, 60, and 100 minutes were plotted against the field SN40R friction values at 2, 4, and 6 million ESALs in Figure 40.

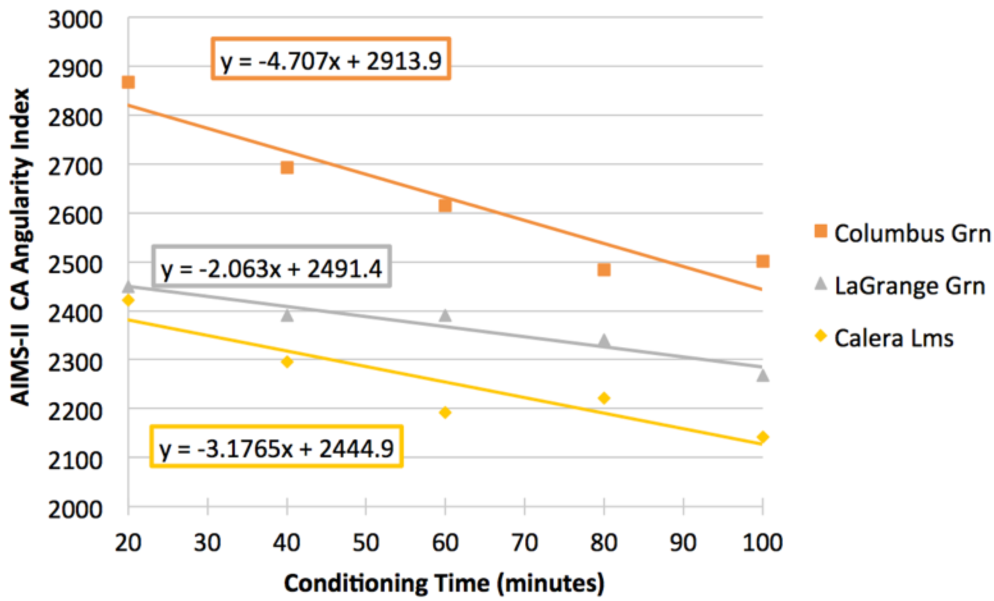

Figure 39 Linear Trend in AIMS2 Coarse Aggregate Angularity

Table 15 Ranking AIMS2 Coarse Aggregate Angularity and Field SN40R

Field Mix ID	Pre-conditioned	2M ESALs	4M ESALs	6M ESALs
OGFC LaGrange Granite	1	1	1	1
SMA/FDG Columbus Granite	3/1	2	2	2
SMA Calera Limestone	2	3	3	3
No. 4 Aggregate	**Pre-conditioned**	**20 minutes**	**60 minutes**	**100 minutes**
LaGrange Granite	2	2	2	2
Columbus Granite	1	1	1	1
Calera Limestone	3	3	3	3

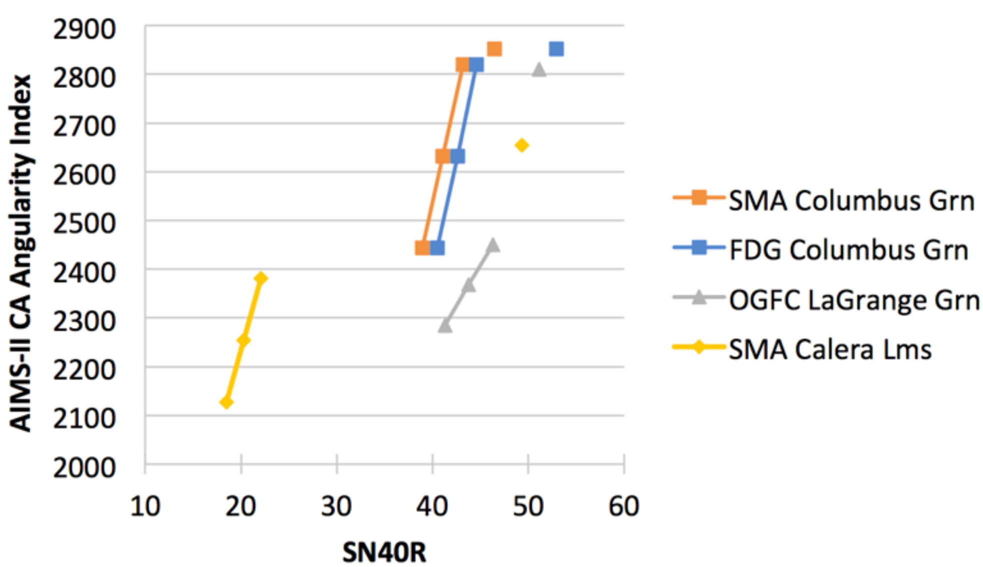

Figure 40 Comparing Trend-lines for Field Friction and AIMS2 Coarse Aggregate Angularity

The preconditioned ranking for field friction in Table 15 does not match the ranking based on the terminal trend-line. With the exception of the pre-conditioned rankings, the rankings of the mix types were identical regardless of which Columbus granite surface mix was used. This suggests the mix type had minimal impact on field friction performance. The No. 4 Calera limestone consistently ranked last after it was subjected to conditioning and the field mix composed primarily of Calera limestone consistently ranked last after being subjected to traffic polishing.

Figure 40 shows a positive relationship between the AIMS2 CAA and the field SN40R for each matched aggregate and mixture. A decrease in the CAA compared to a decrease in SN40R of the field surface mix. Unfortunately, a good correlation combining the AIMS2 CAA results and the field SN40R values could not be established. This poor correlation brings to question the capability of the AIMS2/Micro-Deval test protocol to relate to field friction performance. The AIMS2 lab results show the Columbus granite to be the aggregate characterized by the highest CAA, but the field results show the mix containing primarily LaGrange granite as exhibiting the best field friction performance. In the lab, the LaGrange granite exhibited AIMS2 CAA indexes that were closer to the Calera limestone, an aggregate known to yield poor friction performance in the field.

6.2.2 AIMS2 Fine Aggregate Angularity and SN40R

A similar process was carried out for evaluating the correlation between AIMS2 FAA of the No. 16 aggregate particles and the SN40R of the field surface mixtures. The AIMS2 FAA began to exhibit a linear trend at 10 minutes. A linear trend-line was applied to the data from 10 to 30 minutes as shown in Figure 41. The equations were used to compute average AIMS2 FAA values to rank the aggregates in Table 16 and to compare with the field SN40R friction values in Figure 42.

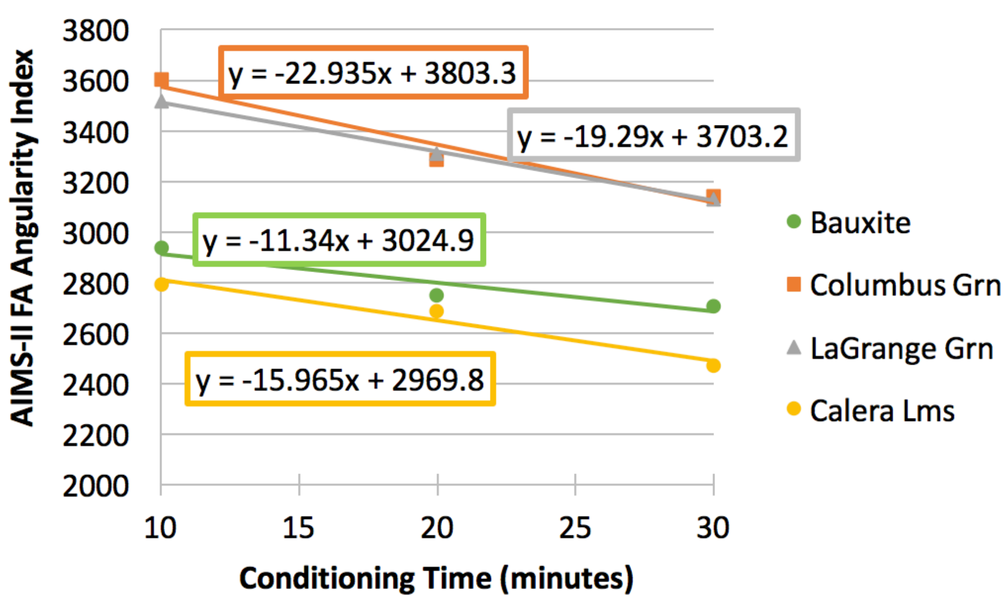

Figure 41 Linear Trend in AIMS2 Fine Aggregate Angularity

Table 16 Ranking AIMS2 Fine Aggregate Angularity and Field SN40R

Field Mix ID	Pre-conditioned	2M ESALs	4M ESALs	6M ESALs
HFST Bauxite	1	1	1	1
OGFC LaGrange Granite	2	2	2	2
SMA/FDG Columbus Granite	4/2	3	3	3
SMA Calera Limestone	3	4	4	4
No. 16 Aggregate	**Pre-conditioned**	**10 minutes**	**20 minutes**	**30 minutes**
Bauxite	4	3	3	3
LaGrange Granite	2	2	2	1
Columbus Granite	1	1	1	2
Calera Limestone	3	4	4	4

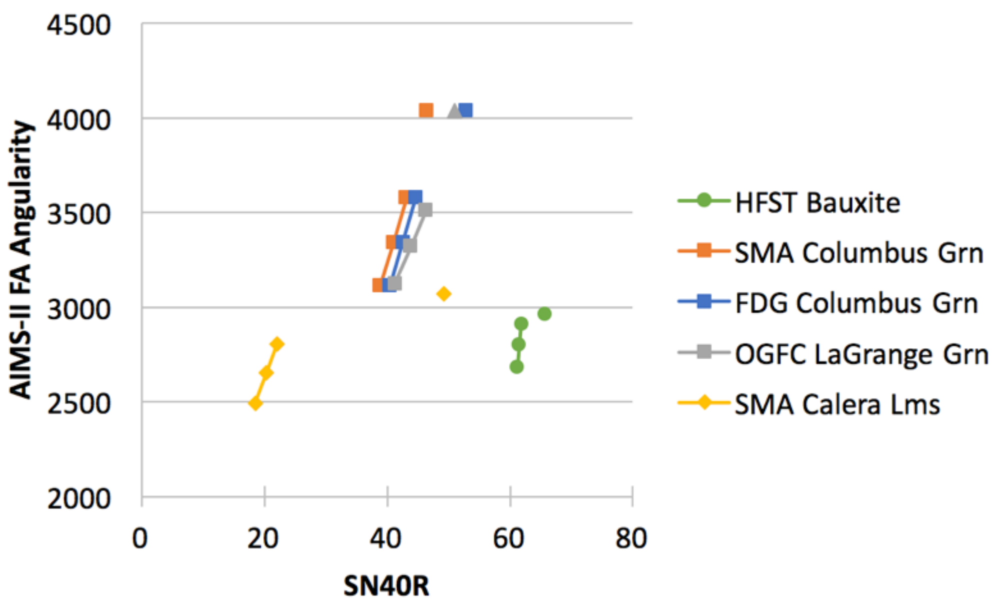

Figure 42 Comparing Trend-lines for Field Friction and AIMS2 Fine Aggregate Angularity

Figure 42 shows a positive relationship between the AIMS2 FAA and field SN40R friction for each matched aggregate and mixture. A decrease in the FAA compared to a decrease in SN40R of the field surface mix. The figure indicates no correlation between the AIMS2 FAA and the field SN40R values. The Calera limestone consistently exhibited the lowest FAA, which agrees with the SN40R results. However, the bauxite, which measured the highest field friction, measured the same FAA as the Calera limestone. If the bauxite results were removed, a possible correlation could be made between AIMS2 FAA and field friction among the granite sources and Calera limestone. The AIMS2 may not be suitable in evaluating aggregate sources with high polish resistance, such as the bauxite.

6.3 Comparing AIMS2 Texture to Field Friction Performance

The AIMS2 coarse aggregate texture results exhibited a linear trend from 20 to 100 minutes of conditioning time similar to the AIMS2 CAA. Linear trend-lines were applied, as shown in Figure 43, and the same four increments were selected for comparison. The AIMS2 lab results at 0, 20, 60, and 100 minutes were compared with the field's SN40R at 0, 2, 4, and 6 million ESALs. Figure 43 plots the values and Table 17 ranks the values.

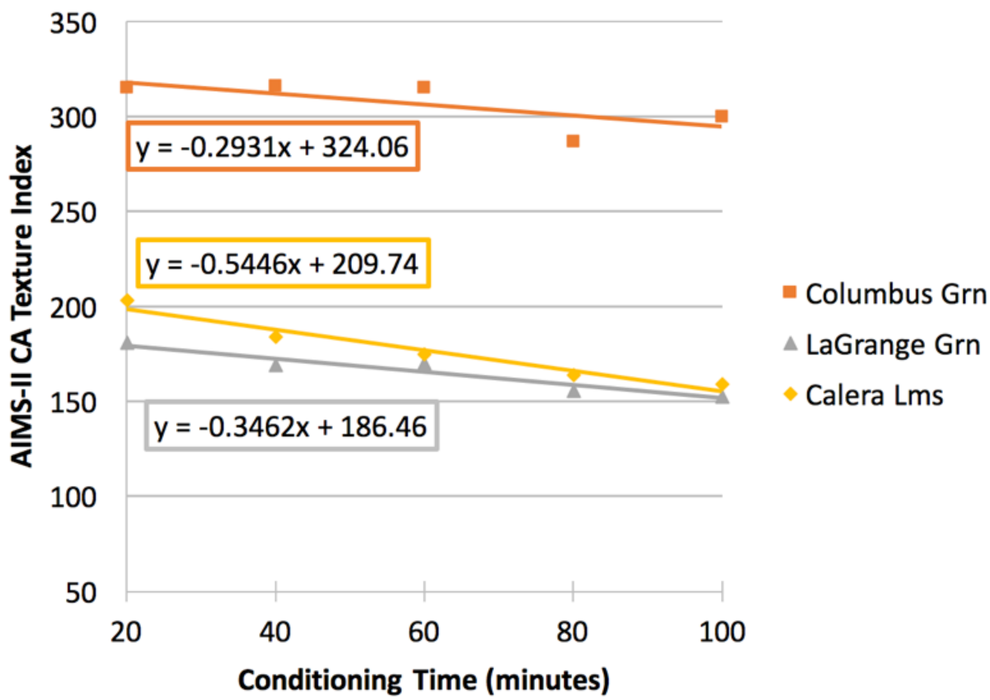

Figure 43 Linear Trend for AIMS2 Coarse Aggregate Texture

Table 17 Ranking AIMS2 Coarse Aggregate Texture and Field SN40R

Mix ID	Pre-conditioned	2M ESALs	4M ESALs	6M ESALs
OGFC LaGrange Granite	1	1	1	1
SMA/FDG Columbus Granite	3/1	2	2	2
SMA Calera Limestone	2	3	3	3
No. 4 Aggregate	**Pre-conditioned**	**20 minutes**	**60 minutes**	**100 minutes**
LaGrange Granite	3	3	3	3
Columbus Granite	1	1	1	1
Calera Limestone	2	2	2	2

Figure 44 shows that the AIMS2 coarse aggregate texture measurements did not correlate with the field SN40R friction measurements. The AIMS2 texture indexes for the LaGrange granite were consistently ranked the lowest, but the LaGrange granite surface mix exhibited the best field friction performance of the mixes studied. The LaGrange granite measured AIMS2 texture indexes that were similar to the Calera limestone texture indexes, which was not expected.

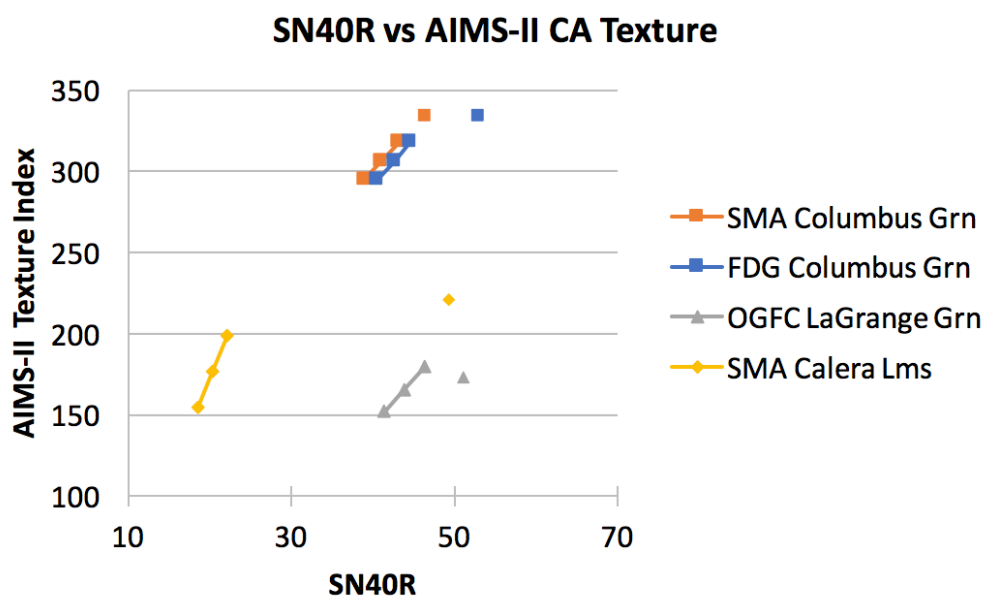

Figure 44 Comparing Trend-lines for AIMS2 Coarse Aggregate Texture and Field SN40R

6.4 Comparing Micro-Deval Mass Loss to Field Friction Performance

The cumulative percentage of the aggregate mass loss after Micro-Deval conditioning was compared to the field SN40R data. Table 18 shows the rankings of the field SN40R values, the mass loss for the coarse aggregates after 100 minutes of conditioning, and mass loss for the fine aggregates after 30 minutes of conditioning. An aggregate ranking of 1 indicates the aggregate yielded the least mass loss at the end of Micro-Deval conditioning. The ranking system for the coarse aggregate mass loss starts with 2 to be consistent with the ranking of the field and fine aggregate mass loss, as coarse aggregate bauxite was not tested in the lab. As noted earlier, the field mix types containing Columbus granite did not affect the SN40R ranking after conditioning and were combined in the table for simplicity.

Table 18 Ranking Field Friction, Coarse Aggregate Mass Loss, Fine Aggregate Mass Loss

Aggregate	Field SN40R	Coarse Aggregate Mass Loss	Fine Aggregate Mass Loss
Bauxite	1	N/A	1
Columbus Granite	3	4	4
LaGrange Granite	2	2	3
Calera Limestone	4	3	2

Table 18 shows that the good performance of the bauxite mass loss in the lab agreed with the bauxite friction performance in the field. However, the Columbus granite and LaGrange granite performed well in the field but exhibited a significantly higher cumulative mass loss compared to the Calera limestone, which exhibited very poor field performance. A correlation could not be made between laboratory cumulative mass loss and field friction. Figure 18 and Figure 19 show that cumulative mass loss for both the coarse and fine aggregates failed to reach a terminal value, which may have influenced this correlation.

6.5 Summary of Comparison Results

The results suggest a possible correlation could be established between AIMS2 FAA and the SN40R data when analyzing by aggregate type. However, a correlation could not be confirmed with the results obtained from this research study. The AIMS2 CAA and FAA measurements recognized the Calera limestone to be a poor aggregate for use in a surface mix. The field friction performance of the surface mixture composed primarily of Calera limestone ranked last and performed very poorly in the field. The correlation failed when comparing the AIMS2 FAA of the bauxite and the SN40R from the field. The lab results revealed bauxite to consistently have the lowest AIMS2 FAA, whereas the surface treatment in the field yielded the best friction performance.

The results failed to show correlation between AIMS2 coarse aggregate texture results with the SN40R measurements. The AIMS2 revealed that the Columbus granite measured a higher texture than the other aggregates. However, the field results showed that the LaGrange granite mix measured higher friction performance, but the LaGrange AIMS2 texture index was comparable to the Calera limestone. This was not expected because the Calera limestone was the dominant aggregate used in a poor performing mix from a friction standpoint.

The AIMS2 CAA, coarse aggregate texture, and FAA indexes could not be correlated with the field SN40R results. These results only reflect the findings of this research study. Additional research is needed to confirm these results and identify another method to establish a relationship between AIMS2 indexes and SN40R.

A correlation between the Micro-Deval mass loss and field SN40R values could not be identified. The ranking between the coarse aggregate mass loss, fine aggregate mass loss, and SN40R were not consistent between all aggregates tested with the exception of the bauxite. The lab results showed the cumulative mass loss for coarse and fine aggregates did not reach a terminal value and showed no indication of when that value could be reached.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

A testing protocol using the AIMS2 device to measure aggregate surface characteristics and the Micro-Deval aggregate conditioning device was evaluated to determine if a correlation could be established with the locked-wheel skid trailer SN40R measurements. Based on the results, the following conclusions and recommendations were made.

The AIMS2 CAA and FAA decreased with increased Micro-Deval conditioning. The AIMS2 device is capable of detecting changes in CAA and FAA when the aggregate is polished in the Micro-Deval. The conditioning time for evaluating the friction of coarse aggregates should be extended beyond 100 minutes to ensure that terminal values are reached. Similarly, the AIMS2 FAA failed to reach terminal values after 30 minutes of Micro-Deval conditioning, which is more than twice the amount of conditioning stated in ASTM D7428. Future friction research using the Micro-Deval should consider conditioning fine aggregate particles for more than 30 minutes.

The AIMS2 device delineated between aggregate types when analyzing the CAA indexes after conditioning. The two granite sources retained higher AIMS2 CAA than the two limestone sources. However, the AIMS2 FAA showed no clear delineation between aggregate types. The Opelika limestone exhibited the highest AIMS2 FAA, whereas the Calera limestone exhibited the lowest. The high field friction bauxite yielded the second lowest AIMS2 FAA indexes after conditioning.

The AIMS2 CAA showed similar decreasing trends with a decrease in the SN40R of the mixture in the field. However, a good correlation between the AIMS2 CAA and the field SN40R could not be established. The AIMS2 FAA decreased as the SN40R decreased, but a good correlation was not established between the two. The AIMS2 FAA for bauxite was low compared to its high field friction performance.

The AIMS2 device was capable of quantifying changes in aggregate texture when subjected to polishing in the Micro-Deval. The AIMS2 coarse aggregate texture decreased as Micro-Deval conditioning increased. Micro-Deval conditioning of 100 minutes appeared to be a sufficient amount of time for the aggregate texture to reach a terminal condition. The conditioning time could be extended beyond 100 minutes to confirm that terminal conditions are reached.

The AIMS2 coarse aggregate texture consistently ranked the aggregates throughout each conditioning cycle. The Columbus granite yielded the highest AIMS2 coarse aggregate texture index, whereas the Opelika limestone yielded the lowest. Limestone aggregates were expected to yield lower indexes because they tend to polish faster in pavement surface mixtures. However, the Calera limestone ranked the second highest in the lab but performed poorly in the field in regards to friction performance.

There was no correlation between AIMS2 coarse aggregate texture and field SN40R results. The LaGrange granite exhibited low AIMS2 coarse aggregate texture indexes, but the field friction results were good.

Micro-Deval mass loss did not reach a terminal condition during testing for either coarse or fine aggregates. Therefore, a correlation with the field SN40R could not be assessed. The bauxite yielded the least amount of mass loss compared to the other fine aggregates tested, which agreed with the SN40R ranking of the bauxite in the field. The Calera limestone exhibited less mass loss than other aggregates with better field friction performance.

The AIMS2 in conjunction with the Micro-Deval was unsuccessful in providing a good correlation of aggregate characteristics to field friction results. Only four aggregate sources were available for examining a correlation between AIMS2 lab results and field friction. Future friction research should consider testing more aggregate sources. Only two aggregate particle sizes were tested in the lab study, and field friction performance is dependent on more than just the contribution of a single-sized particle. The AIMS2 device is capable of measuring the surface of a pavement core less than 35 mm thick. It is recommended that a research study evaluate the capability of using the AIMS2 device to measure surface properties of a pavement core and determine if a correlation with the SN40R of the pavement mixture in the field can be established.

Using the AIMS2 device to analyze single-sized particles was a useful first step toward determining if the AIMS2 and Micro-Deval could be used as a laboratory test method for identifying friction aggregate. Additional research is needed to develop a stronger relationship between the lab aggregate properties and field friction performance.

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