APPLICATION OF IMAGING TECHNIQUES TO EVALUATE POLISHING CHARACTERISTICS OF AGGREGATES

FINAL REPORT

UF Project No.: 00115827

Agency No.: BDV31-977-28

Submitted to:

Florida Department of Transportation
605 Suwannee Street
Tallahassee, FL, 32399

UF | UNIVERSITY *of* FLORIDA

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December 2016

DISCLAIMER

UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Application of Imaging Techniques to Evaluate Polishing Characteristics of Aggregates		5. Report Date December 2016 6. Performing Organization Code 00115827
7. Author(s) Reynaldo Roque, Abolfazl Ravanshad, and Sanghyun Chun		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Florida Department of Civil and Coastal Engineering 365 Weil Hall P.O. Box 116580 Gainesville, FL 32611-6580		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDV31-977-28
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Management Center 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final 06/01/14-12/31/16 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Previous research conducted at the University of Florida (UF) to investigate the use of the Aggregate Image Measurement System (AIMS) and Micro-Deval (MD) to evaluate frictional performance of aggregates concluded that the current AIMS system cannot be reliably used because color variation in aggregate surfaces have an overwhelming effect on texture as measured by AIMS. In response, a new technique called Photometric Stereo-Independent Component Analysis (PS-ICA) was developed at UF that was able to effectively separate texture from color variation in images obtained by AIMS. The use of AIMS with the PS-ICA method and the MD polishing system was further evaluated in this study to determine its suitability for pre-evaluation purposes to reliably identify aggregates with acceptable frictional performance. Extensive evaluation of texture index (TI) values obtained using the PS-ICA method indicated that the system appeared to effectively mitigate the color variation effect. However, evaluation also revealed that specularity strongly influenced TI values for granite and siliceous wackestone aggregate. An approach developed using the PS-ICA method with modified light intensity was determined to result in the most consistent and reliable TI results for all aggregates evaluated, but the system could not completely mitigate effects of specularity, which causes erroneous results in texture analysis. The best approach to interpret TI values to neutralize effects other than reduction in surface roughness on TI (e.g., specularity) was identified for two types of aggregate: (1) those that exhibit specularity and (2) those that do not exhibit specularity. Thresholds were established for these two aggregate types based on the approaches identified. Independent analysis conducted to evaluate MD performance indicated that MD polishing resulted in polishing levels comparable to those observed in aggregates from in-service pavements. In conclusion, TI obtained from the PS-ICA method with modified light intensity developed for use with AIMS image processing system, along with MD-accelerated polishing technique, can be used for pre-evaluation purposes to effectively screen aggregates with acceptable frictional performance.

17. Key Word Aggregate, Image, Texture Index, Friction Performance, Accelerated Methods		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA, 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 106	22. Price

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ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the Florida Department of Transportation (FDOT) for providing technical and financial support. Special thanks go to project manager John Shoucair as well as Mark Gregory for their assistance in this project. Their efforts are sincerely appreciated.

EXECUTIVE SUMMARY

Pre-evaluation of aggregates using combined application of image processing and accelerated polishing technique has been of interest to many researchers. Previous research conducted at the University of Florida (UF) investigated the use of the Aggregate Image Measurement System (AIMS) and Micro-Deval (MD) to evaluate frictional performance of aggregates, and concluded that the current AIMS system cannot be reliably used since color variation in the aggregate surface has an overwhelming effect on texture measured by AIMS. In response, a new technique called Photometric Stereo-Independent Component Analysis (PS-ICA) was developed at UF that was able to effectively separate texture from color variation in images obtained by AIMS. The purpose of the study presented herein was to further evaluate the use of AIMS with the PS-ICA method and the MD polishing system and to identify an approach for microtexture analysis that can be used for pre-evaluation purposes to reliably determine aggregates with acceptable frictional performance.

Extensive evaluation performed of texture index (TI) values obtained using the PS-ICA method for a broad range of aggregates and polishing levels indicated the system appeared to effectively mitigate the color variation effect. However, the evaluation also revealed that for granite and siliceous wackestone aggregate, specularity strongly influenced TI values. An approach was developed to mitigate the effect of specularity by reducing light intensity in the AIMS device. It was determined that the PS-ICA TI method with modified light intensity effectively mitigated effects of color variation and specularity on TI and resulted in the most consistent and reliable TI results for all aggregates evaluated. However, the PS-ICA method along with modified light intensity was not able to completely mitigate effects of specularity, which cause erroneous results in texture analysis. TI values obtained using the PS-ICA method and modified light intensity were also determined to be most closely related to independent

texture measurement results obtained from scanning electron microscopy (SEM) analysis, which were not influenced by color variation or specularity.

Results of TI evaluation indicated that comparison of TI in absolute terms was not an appropriate way to interpret relative surface roughness among different aggregate types or even between polishing levels for some aggregates. Although color variation appeared to be effectively dealt with by the PS-ICA approach, the specularity effect was found to increase after polishing, a consequence that overwhelmed the effect of MD polishing. Also, comparison of TI in absolute terms may be problematic when aggregates have pores and other surface cavities that may register as deviations in surface profile, which cause surface roughness parameters to increase but do not affect friction. Therefore, it appears that comparison of TI in absolute terms may only be appropriate for aggregate with no specularity or pores. Aggregates used in Florida include both of these characteristics, so an alternative interpretation of was needed to effectively assess effects of polishing on TI.

Percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing was determined to best reflect surface roughness changes induced by polishing for aggregates not exhibiting specularity (limestones). For aggregates exhibiting specularity (granites or siliceous wackestone), percent reduction in PS-ICA TI between 50-minute and 180-minute MD polishing was determined to have the best potential for use in evaluating surface roughness changes induced by polishing.

The changes in PS-ICA TI mentioned above were used to establish thresholds for screening aggregates with acceptable frictional performance in the field. For aggregates not exhibiting specularity effect (limestones), a maximum allowable reduction of 50 percent in PS-ICA TI between unpolished and 50-minute MD polishing was determined based on aggregates known to exhibit acceptable frictional performance in the field. For aggregates exhibiting specularity effect (granite or siliceous wackestone), a maximum allowable reduction of 10 percent in PS-ICA TI between 50-minute and 180-minute MD polishing was determined based on aggregates known to exhibit acceptable frictional performance in the field.

Independent analysis was conducted to evaluate MD performance in terms of its ability to polish aggregates to levels similar to those observed in aggregates from in-service pavements. MD polishing was determined to result in polishing levels comparable to those observed in aggregates from in-service pavements, based on comparison of SEM-derived surface roughness parameters from MD-polished aggregates and field-polished aggregates.

In conclusion, TI obtained from the PS-ICA method with modified light intensity developed for use with AIMS image processing system, along with MD accelerated polishing technique, can be used for pre-evaluation purposes to effectively screen aggregates with acceptable frictional performance.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AFM	Atomic Force Microscope
AIMS	Aggregate Image Measurement System
BSS	Blind Source Separation
ESALs	Equivalent Single Axle Loads
FDOT	Florida Department of Transportation
FC	Friction Course
FN	Friction Number
ISO	International Organization for Standardization
MD	Micro-Deval
NCHRP	National Cooperative Highway Research Program
OGFC	Open-Graded Friction Course
PS-ICA	Photometric Stereo-Independent Component Analysis
RMS	Root-Mean-Square
SEM	Scanning Electron Microscopy
TI	Texture Index
UF	University of Florida
WLI	White Light Interferometry

CHAPTER 1
INTRODUCTION

1.1 Background

Friction resistance is one of the most critical performance characteristics of asphalt pavements since it has a great effect on the safety of the traveling public (Kokkalis, 1998 and Woodside and Woodward, 2002). Among numerous factors affecting friction resistance, pavement surface texture at the micro- and macro-scale has an important role in developing tire-pavement friction. In flexible pavements, surface characteristics highly depend on aggregate properties (Benson, 1970, Brown et al., 1989, and Kandhal and Parker, 1998). The role of aggregate in bituminous surfaces is to provide sufficient macrotexture to induce tire hysteresis (energy loss), facilitate water drainage in the tire contact area, and maintain friction by inducing tire-pavement grip (Dahir, 1979). Microtexture is highly related to the surface characteristics of aggregates, while macrotexture is primarily affected by aggregate shape, gradation, and mix design.

Finding a direct specification for the selection and use of aggregates to ensure satisfactory frictional performance has been a focus for many researchers and transportation agencies. This is especially imperative for acceptance of new aggregate sources; existing sources of high quality aggregates are being rapidly depleted, so there is a great need for new acceptable sources that can ensure suitable friction performance. Several researchers have attempted to develop laboratory test methods to evaluate aggregates and relate aggregate properties to skid resistance. The ability of aggregates to retain their microtexture under polishing has been used in the past as an index for selection and use of aggregates to ensure satisfactory frictional performance in the field (Diringer and Barros, 1990, and Masad et al., 2009). Polishing rate, which is a measure of the aggregate's ability to maintain microtexture when subjected to the polishing action of traffic, varies widely among different aggregate types (McDaniel and Coree, 2003, and Kowalski, 2007). Therefore, polishing techniques are part of any aggregate evaluation system.

In Florida, friction courses are required on the majority of state roadways to provide satisfactory skid resistance for asphalt pavements. Based on current specifications, coarse aggregates must meet chemical and physical requirements in laboratory tests to be accepted as an aggregate source for use in asphalt concrete. These approved aggregates can only be employed in friction courses if they exhibit satisfactory friction resistance in test sections, a process which involves several years and considerable expense. Therefore, there is a need to develop a more effective and expeditious evaluation system that is able to relate the measured properties of aggregates to their long-term frictional performance in the field.

In an effort to find an effective system to reliably pre-evaluate aggregates for use in friction courses, a research project was sponsored by Florida Department of Transportation (FDOT) to assess application of Aggregate Imaging Measurement System (AIMS) for this purpose (Roque et al., 2013). AIMS is a computer-controlled optical system which is able to capture aggregate shape characteristics including form, angularity and surface texture. An aggregate's relative resistance to polishing was determined using AIMS by measuring microtexture before and after accelerated polishing in Micro-Deval (MD). This was then compared to texture measurements of aggregate from pavements produced with the same aggregate type. AIMS uses gray scale images for texture analysis, but gray level variations can be attributed to color variation, roughness, or both. Fletcher et al. (2003) believed that by using multi-scale resolution wavelet transformation, AIMS could capture true texture and distinguish between variations in gray intensities due to variations in relief and other factors. The key conclusion based on findings of that study was AIMS in its current form cannot be reliably used to evaluate aggregate surface microtexture since color variation in the aggregate surface have an overwhelming effect on texture measured by AIMS (Ravanshad, 2014).

Recently, a new technique termed as Photometric Stereo-Independent Component Analysis (PS-ICA) was developed at University of Florida that is able to separate texture from the effects of color variation and specularity (glare) in images obtained from AIMS. This technique uses AIMS hardware only, and then applies a pre-processing algorithm to extract texture from aggregate image. A preliminary study exhibited excellent results in texture characterization of surfaces with known properties. This work presented herein was based on application of this novel technique along with an independent roughness measurement method to better understand quantitative aggregate image texture analysis and identify a method to assess long-term frictional performance of aggregate.

1.2 Objective and Scope

The primary objective of this research was to identify approaches for microtexture analysis of coarse aggregates that can be used for aggregate pre-evaluation in order to quickly and reliably distinguish aggregates with different frictional characteristics. This is important for acceptance purposes where it must be determined whether new aggregate sources can provide an acceptable level of surface friction resistance throughout the pavement service life. The overall approach was to characterize aggregate polishing resistance using combined application of the new PS-ICA imaging technique developed and accelerated polishing in laboratory using MD. The relationship between image texture parameters and actual aggregate surface roughness was evaluated. The most efficient interpretation method of image texture parameters for surface description of different aggregate types identified were then used to classify aggregates based on their frictional characteristics. Evaluation of MD performance in simulation of field polishing was another part of this study. Detailed objectives are summarized as follows:

- Evaluate the PS-ICA method for microtexture analysis of coarse aggregates to assess its potential for use in pre-evaluating frictional performance characteristics of aggregates.
    - Identify the best approach to interpret texture index (TI) obtained using PS-ICA method for use in characterizing different types of aggregate.
    - Identify PS-ICA TI thresholds for screening aggregates on the basis of their frictional performance in the field.
- Evaluate MD performance in terms of polishing aggregates to levels similar to those observed in aggregates from in-service pavements using Scanning Electron Microscopy (SEM) approach as an independent roughness measurements method.
- Identify whether any correlations exist between the indicators identified for use in PS-ICA TI threshold evaluation, SEM roughness parameter, and historical friction numbers (FNs) measured in the field.

Nine aggregate sources from different aggregate geologies were identified and collected for laboratory evaluation, including four aggregates exhibiting specularity (granite and siliceous wackestone) and five aggregates not exhibiting specularity (limestone). Also, ten roadway sections with the same aggregate sources as those used for laboratory evaluation were selected from different FDOT districts for coring and obtaining historical friction performance data (FN).

CHAPTER 2
EVALUATION OF THE PHOTOMETRIC STEREO-INDEPENDENT COMPONENT ANALYSIS (PS-ICA) METHOD

2.1 Background

Surface texture characterization of mineral aggregates has been a great challenge because it deals with determination of surface irregularities at very small scales (Ravanshad et al., 2015 and Masad et al., 2007). Digital image processing is a powerful tool that has been used by many researchers in the past decade to directly quantify surface microtexture of aggregates (Masad et al., 2001, Masad, 2001, Masad et al., 2007, Al-Rousan et al., 2007, Fletcher et al., 2003, Tutumluer et al., 2005, Sun et al., 2012). Multiple digital scanning systems have been developed using various image texture analysis algorithms to describe microtexture of individual particles (Masad et al., 2007). As a result of investigation performed in National Cooperative Highway Research Program (NCHRP) Project 555, Aggregate Image Measurement System (AIMS) was recommended for measuring aggregate shape characteristics (Masad et al., 2007). AIMS is a computer-controlled device capable of capturing aggregate shape characteristics including form, angularity, and surface texture. Figure 2-1 shows the AIMS device.

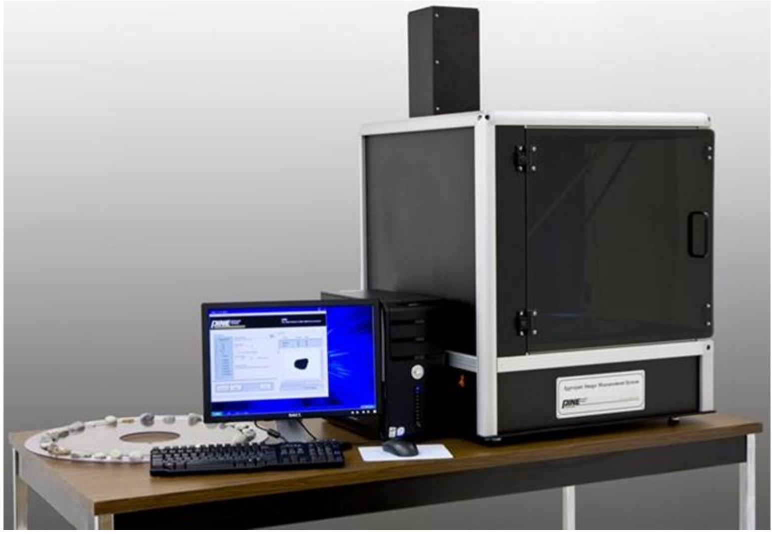


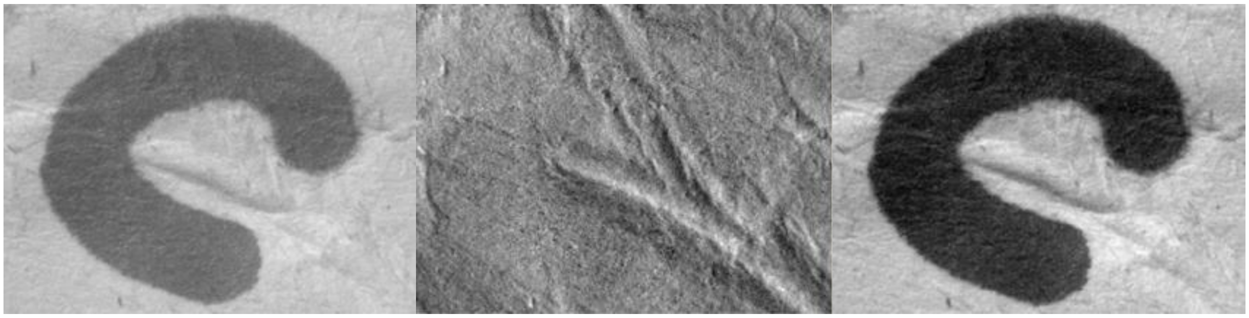
Figure 2-1 Aggregate Imaging Measurement System (AIMS2)

In 2011, a research project was initiated by FDOT and conducted by researchers at University of Florida (UF) to assess application of AIMS along with Micro-Deval (MD) polishing device for pre-evaluation of aggregates in friction courses. The key conclusion of the study was that AIMS in its current form could not be reliably used to evaluate aggregate surface microtexture, since color variation and specularity in the aggregate surface had an overwhelming effect on AIMS texture analysis.

Recently, a novel technique called Photometric Stereo-Independent Component Analysis (PS-ICA) was developed at UF with the motivation of finding a practical solution to the limitation of AIMS associated with the effects of color variation and specularity in texture analysis of aggregate image. A preliminary study showed excellent results in texture characterization of surfaces with known properties. The work presented herein involved the evaluation of the PS-ICA method to determine whether it results in the most consistent and reliable texture index (PS-ICA TI) to effectively characterize frictional performance of aggregates.

2.2 Overview of PS-ICA Method

It is well known that roughness or texture parameters can include effects from three-dimensional (3-D) surface height variations and/or two-dimensional (2-D) surface color variations (Ravanshad et al., 2015 and Wu, 2003). Obviously, 3-D texture is the variable of interest in aggregate image texture analysis. A single gray scale image is commonly employed by aggregate imaging systems to make the testing procedure faster, less costly, and more practical. However, previous studies have shown it is difficult to separate two mixed sources of texture (2-D and 3-D) using a single gray scale image (Ravanshad et al., 2015). Figure 2-2 illustrates how the PS-ICA method effectively separated a known color effect, which was introduced by drawing the letter C on a piece of paper, from the natural surface roughness of the paper. Figure 2-2 (a) shows the original single gray scale image, in which the surface roughness and the letter C are present and will both contribute to Texture Index (TI). Figures 2-2 (b) and 2-2 (c) show images after processing with the newly developed PS-ICA method, which effectively separated the surface roughness (Figure 2-2 (b)) from the color effect (Figure 2-2 (c): Ravanshad et al., 2015).



(a) (b) (c)

Figure 2-2 Illustration of PS-ICA to Separate 2-D and 3-D Texture: (a) Original Single Grayscale Image, (b) Image of 3-D Texture after PS-ICA, and (c) Image of 2-D Texture after PS-ICA (Ravanshad et al., 2015)

The PS-ICA method is based on using multiple stereo images. This technique uses AIMS hardware, but with different acquisition and analysis methods than the standard approach. The steps shown in Figure 2-3 summarize PS-ICA methodology in characterizing aggregate surface microtexture: image acquisition, pre-processing, texture analysis, and texture feature extraction.

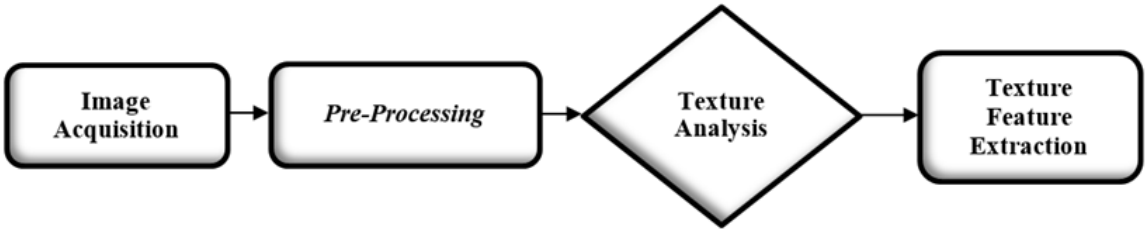


Figure 2-3 Elements of PS-ICA Method (Ravanshad et al., 2015)

The PS-ICA method uses photometric stereo method, for which images are taken from the same view under different lighting conditions. The suitability of using AIMS for taking stereo images was investigated in a previous study (Ravanshad et al., 2015), and it was determined that AIMS has nearly optimal illumination geometry for photometric stereo application. The hardware functions, including the light intensity of top-lighting units, can be manually controlled. The number of images required for photometric stereo depends on the algorithm and the number of unknown variables. For ICA, at least two images are required to separate two mixed independent texture sources (Ravanshad et al., 2015). Figures 2-4 (a) and (b) schematically depict two illumination conditions used to obtain photometric stereo images. A third image was also captured using same two light sources simultaneously (see Figure 2-4 (c).

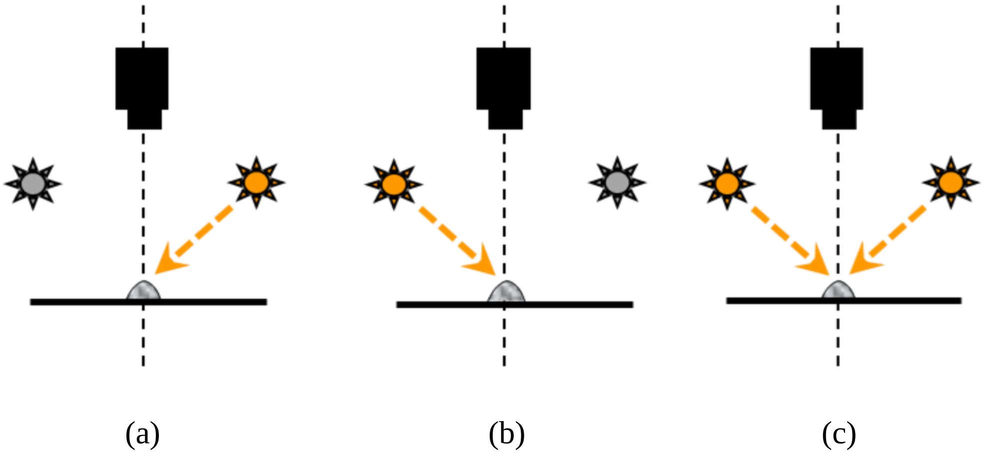


Figure 2-4 Illustration of the Three Illumination Conditions Used in This Study for Image Acquisition (Ravanshad et al., 2015)

ICA method was used as a pre-processing technique to retrieve 2-D and 3-D texture from aggregate stereo images. ICA is categorized under a vast group of algorithms called Blind Source Separation (BSS). A classic example for BSS is the cocktail party problem (see Figure 2-5), where samples are recorded from conversations among several groups using a given number of microphones (observations) with the goal of extracting the individual conversations (i.e., sources: Ravanshad, 2014). More details regarding how ICA works for this application can be found elsewhere (Ravanshad et al., 2015).

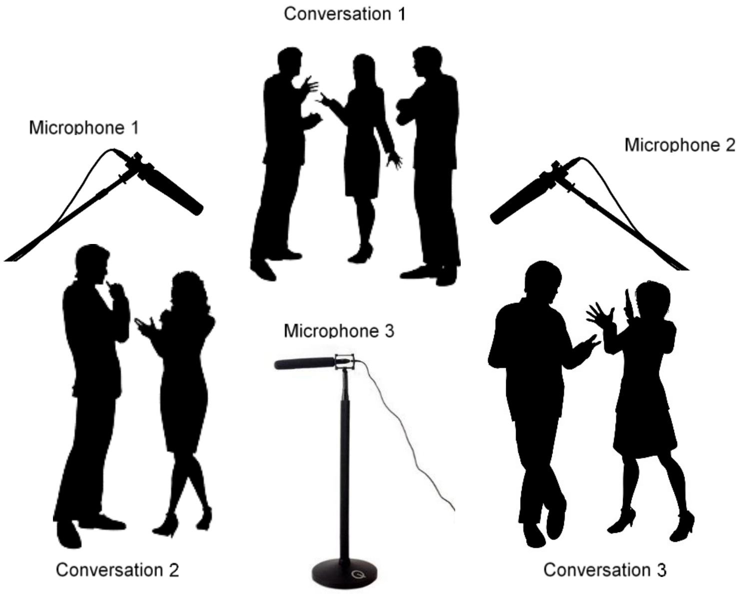


Figure 2-5 Visualization of Cocktail Party Problem (Ravanshad, 2014)

The next step was to select a texture analysis method to enable texture frequency extraction and the last step was texture feature extraction which is defined as the numerical description of a textured surface in terms of measurable parameters (Ravanshad, 2014). The extracted features to describe surface texture were determined based on the selected texture analysis method. In this study, the same algorithm for texture analysis used by AIMS was employed to extract texture feature. Texture index (TI), a transform-based parameter used by AIMS, is calculated based on wavelet transform, which provides a multi-scale framework for image texture analysis.

2.3 Materials

The materials and specimens obtained during a previous project (Roque et al., 2013) were used for this study. Thus, there was no need for collecting new materials. In the previous project, samples from different aggregate geologies and compositions were identified and collected for laboratory testing from sources which have been used in friction courses in Florida. Micro-Deval (MD) equipment was used for accelerated polishing of aggregates, and samples were subjected to polishing times of 50, 105 and 180 minutes. More details regarding sample preparation and procedure for MD polishing can be found in Roque et al., 2013.

In addition, several road sections constructed using same aggregate sources used for laboratory evaluation, were selected from different FDOT districts for evaluation and coring. All specimens, including virgin aggregates, laboratory-polished, and field-polished aggregates, were properly stored at UF for use in this study. It is noted that virgin and laboratory-polished aggregates were used. Also, only coarse aggregate specimens (9.5 mm to 12.5 mm size) were examined. Table 2-1 summarizes the nine aggregate types evaluated.

Table 2-1. Aggregate Information

Classification	Material Type	Material Source	Aggregate ID
Aggregates w/o specularity	Oolitic Limestone	Cemex	87090
	Oolitic Limestone	Titan America, LLC	87145
	Oolitic Limestone	White Rock Quarries	87339
	Oolitic Limestone	SDI Quarry	87648
	Limestone	Honduran Aggregate	HN717
Aggregates w/ specularity	Granite	Martin Marietta Materials	GA383
	Granite	Junction City Mining	GA553
	Granite	Martin Marietta Materials	NS315
	Siliceous Wackestone	Hubbard Materials Co.	70693

2.4 PS-ICA Approach

A set of experiments were designed to evaluate the performance of the PS-ICA technique. All nine aggregate types were scanned at different polishing and magnification levels. Fifty specimens of virgin and laboratory-polished samples from each aggregate type were selected for testing. Specimens were scanned individually using AIMS hardware at the three illumination conditions described to obtain multiple photometric stereo images from each specimen at four zoom levels (i.e., 6.27X, 9.4X, 12.6X, and 15.8X). This new procedure, which requires lighting and zoom level changes, was not automatic, and therefore required more time and effort to capture images from aggregate surfaces than the conventional approach. A system was developed to automatically change the light and magnification for taking pictures at different illumination conditions, which resulted in huge time saving and improvement on accuracy.

Obviously, the quality of the image has a great influence on texture analysis. Results of a previous research project (Roque et al., 2013) indicated that specularity, in addition to color variation, affects aggregate image texture analysis. Some aggregates consist of minerals such as silica that reflect light, resulting in specularity (glare) which causes erroneous results in texture analysis. A preliminary set of experiments were conducted to minimize specularity during the image acquisition process. A traditional technique, which is called polarizer-analyzer technique, was designed and installed on AIMS as shown in Figure 2-6. This technique uses a polarizer positioned in the light path somewhere before the specimen and an analyzer (i.e., a second polarizer) placed in between the specimen and camera. Even though this technique successfully reduced the specularity, the results were not satisfactory as filters changed the reflection mechanism.

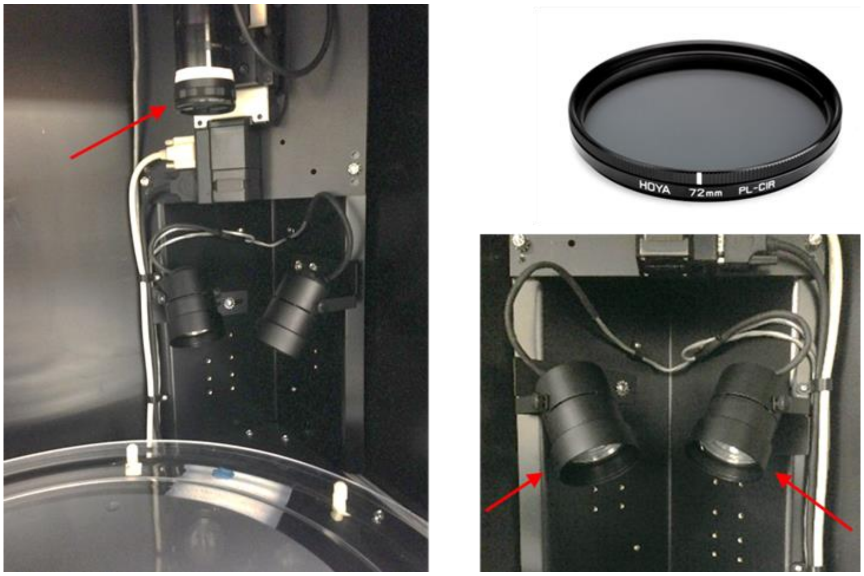


Figure 2-6 Design and Implementation of Polarizer-Analyzer Technique on AIMS-2

An alternative approach entailed the change of light intensity from the default value (i.e., level 9) to obtain the best exposure for the scene. Image histograms were used to seek the intensity level corresponding to the best exposure (see Figure 2-7). It should be noted that the effect of reduced light intensity was compromised as loss of contrast. For aggregates where glare was a big issue, testing was conducted at both default and reduced light intensities. In the case of Florida limestone where glare was not an issue, only default light intensity was used for imaging.

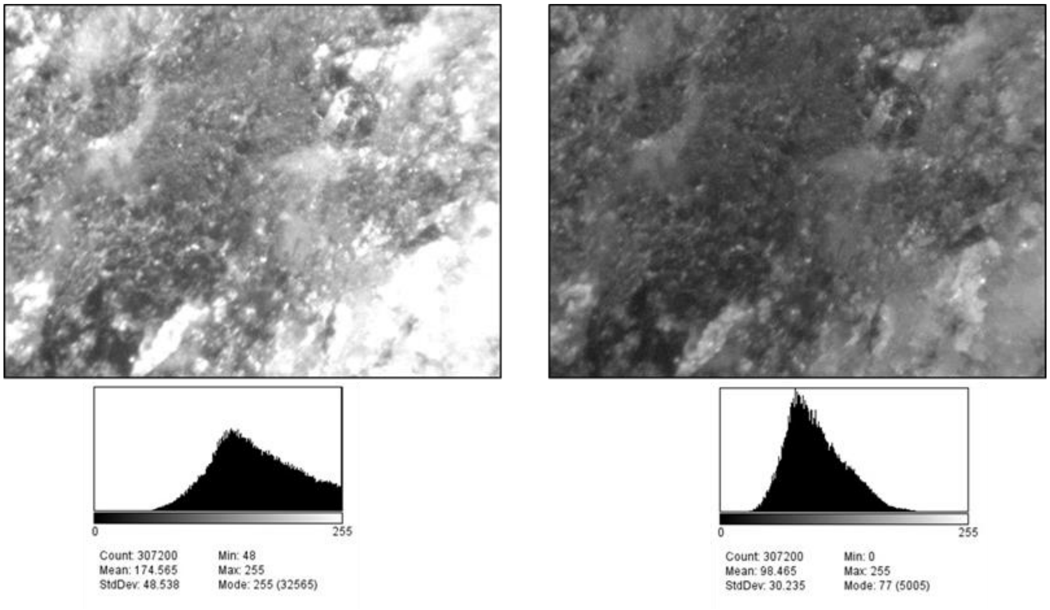
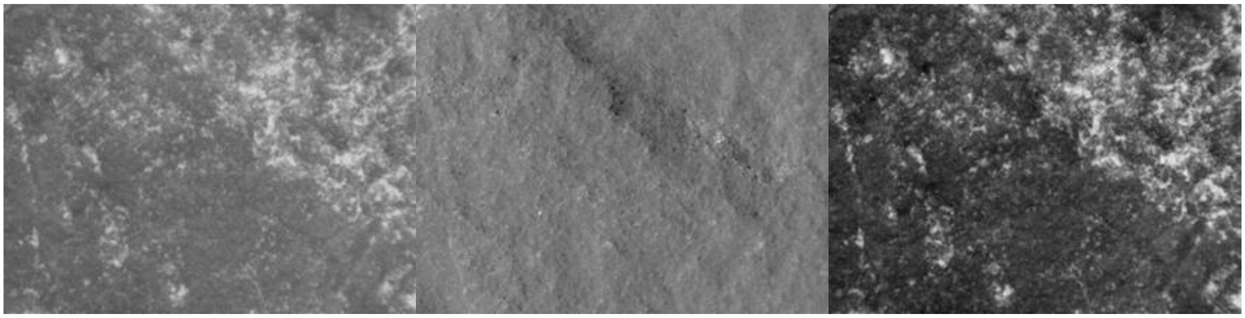


Figure 2-7 Use of Image Histogram to Identify the Light Intensity Corresponding to the Best Exposure

After acquiring images, pre-processing was conducted using the FastICA toolbox in MATLAB. Independent Components (IC) were then extracted and the component exhibiting color variation was rejected. Finally, a multi-resolution wavelet transform was applied to the processed images using MATLAB to calculate Texture Index (TI) as a measure of surface 3-D texture. Figure 2-8 shows an example output of the PS-ICA method, indicating how color effects were effectively separated. Figure 2-8 (a) shows the original single gray scale image, in which the surface roughness and the dust effect were present and contributed to TI. Figures 2-8 (b) and 2-8 (c) show images after processing with the newly developed PS-ICA method, which effectively separated the surface roughness (see Figure 2-8 (b)) from the color effect caused by the dust (see Figure 2-8 (c)).



(a) (b) (c)

Figure 2-8 Illustration of PS-ICA to Separate Effects of Color and Roughness: (a) Original Single Grayscale Image, (b) Image of Surface Roughness after PS-ICA, and (c) Image of Dust Effect after PS-ICA (Ravanshad et al., 2015)

2.5 Results

In this section, results of 33,600 images obtained by scanning 1,800 aggregate particles for virgin and laboratory MD-polished conditions with various illumination and zoom levels are presented. Figure 2-9 illustrates the results matrix, which was produced to take several factors into account.

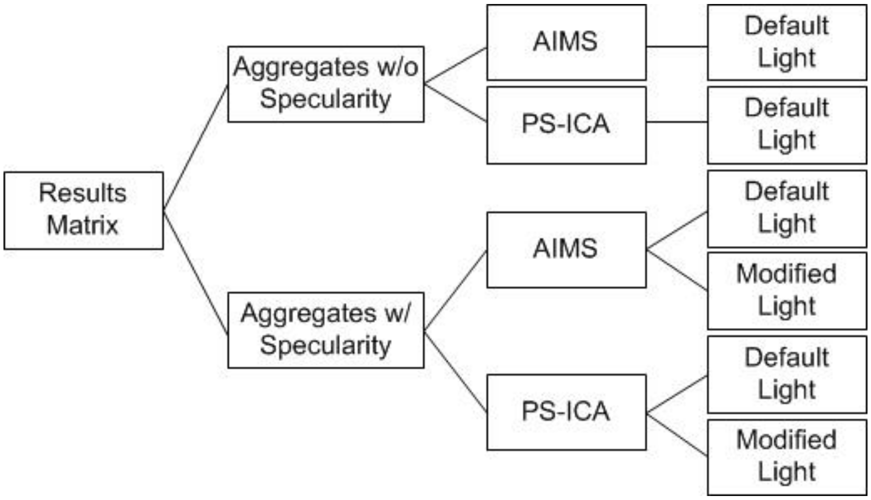
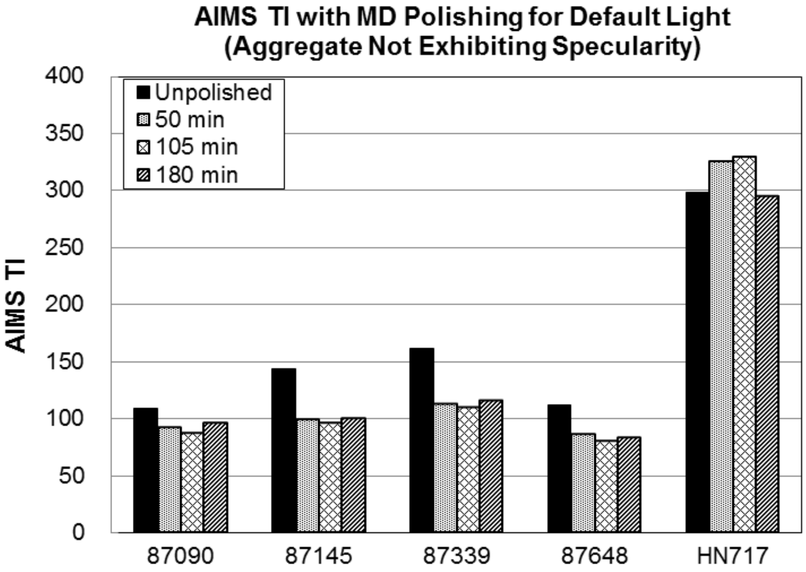


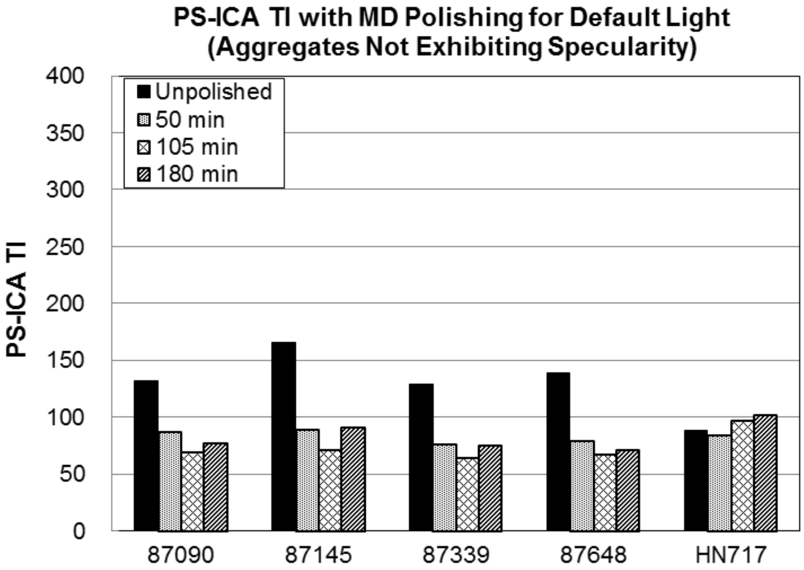
Figure 2-9 Results Matrix

The first factor considered was the effect of color variation on TI. All granites and siliceous wackestone aggregates, and one limestone aggregate (HN717), have highly non-uniform color pattern. However, all other limestones were uniform in color. The second factor was the type of analysis either the AIMS approach using a single image or the PS-ICA approach using multiple images. Lastly, the third factor was the light intensity to mitigate specularity effect on TI. Specularity, which may also be called glare, is intense reflected light that reduces visibility and results in artificially high TI. Excessive specularity can overwhelm the effects of reduced surface roughness on TI induced by polishing or wear for some aggregates. This phenomenon can be recognized when an increase in TI is observed with the progression of polishing. All limestones, which did not exhibit specularity effects, were scanned at default light intensity whereas granite and siliceous wackestone aggregates, which did exhibit specularity effects, were evaluated at both default and modified light intensities.

Figure 2-10 shows a summary of TI results obtained from AIMS method and PS-ICA method for limestone aggregates using default light intensity at 6.27X zoom level. The result for HN717 showed that the PS-ICA method was able to effectively mitigate the effect of color variation on TI. Since the other four limestones were uniform in color, the range of TI values was similar between results obtained from AIMS method and PS-ICA method. When the PS-ICA method was used, reductions in PS-ICA TI between unpolished and 50-minute MD polishing were positive for all limestone aggregates evaluated, indicating PS-ICA TI effectively captured reduction in surface roughness induced by MD polishing. However, MD polishing beyond 105-minute caused an increase in PS-ICA TI for these aggregates, indicating PS-ICA TI was being more strongly affected by factors other than reduction in surface roughness. Two possible factors that may explain this observation: (1) additional pores and cavities were exposed with increased MD polishing; and (2) the light-colored smoother surface resulted in excessive reflected light, which had an effect similar to specularity.



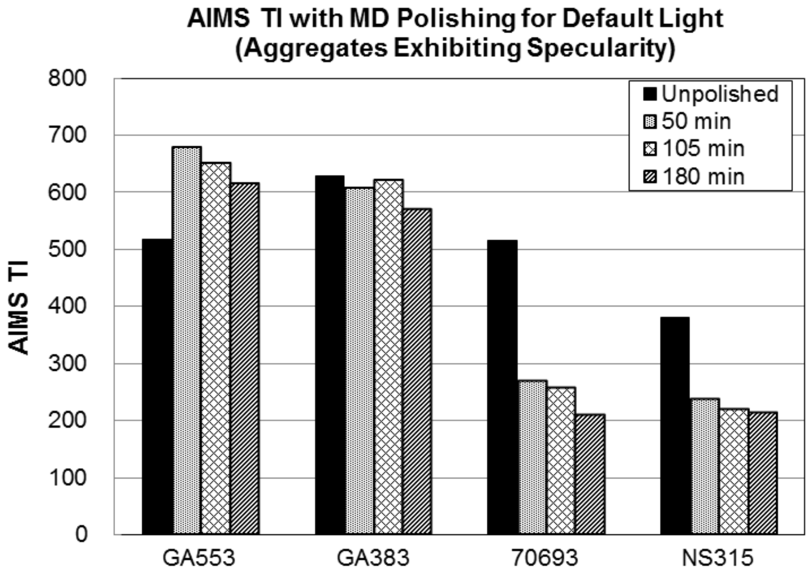
(a) AIMS TI



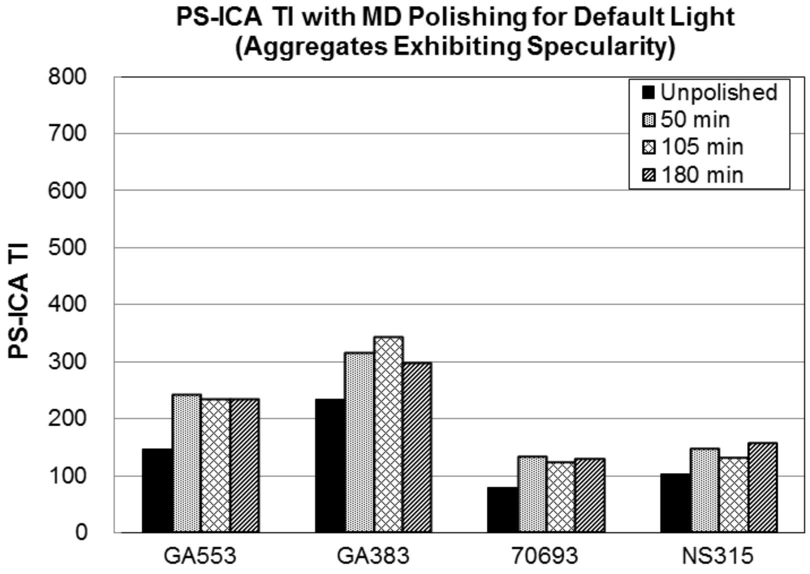
(b) PS-ICA TI

Figure 2-10 Change in TI with MD Polishing at Default Light Intensity for Aggregates Not Exhibiting Specularity (6.27X)

Figure 2-11 shows a change in TI with different levels of MD polishing obtained by AIMS and PS-ICA methods for aggregates exhibiting specularity with non-uniform color (granite or siliceous wackestone) at default light intensity. As expected, excessively high TI values were obtained from AIMS method at default light intensity for all aggregates, clearly indicating color variation and specularity significantly affected TI (see Figure 2-11 (a)).



(a) AIMS TI/Default Light



(b) PS-ICA TI/Default Light

Figure 2-11 Change in AIMS TI and PS-ICA TI with MD Polishing at Default Light Intensity for Aggregates Exhibiting Specularity (6.27X)

Figure 2-11 (b) indicated that the PS-ICA method was able to mitigate the effect of color variation on TI by reducing absolute TI values compared to those obtained from AIMS method. However, TI values were still significantly higher than limestones even when the PS-ICA method was applied. Also, an increase in TI was observed with the progression of polishing for all aggregates between unpolished and 50-minute MD polishing, indicating increased specularity overwhelmed effects of reduced surface roughness on TI. It appeared that the use of images at default light intensity with considerable number of saturated pixels resulted in misleading results for these aggregates.

Figure 2-12 shows change in TI with different levels of MD polishing obtained by PS-ICA method at modified light intensities for aggregates exhibiting specularity (granite and siliceous wackestone). Results indicate that modified light intensity was capable of further mitigating the specularity effect based on the consistent range of TI values relative to those obtained for limestone aggregates. However, the increased specularity effect was still present after 50-minute MD polishing and its effect overwhelmed the effect of MD polishing on TI.

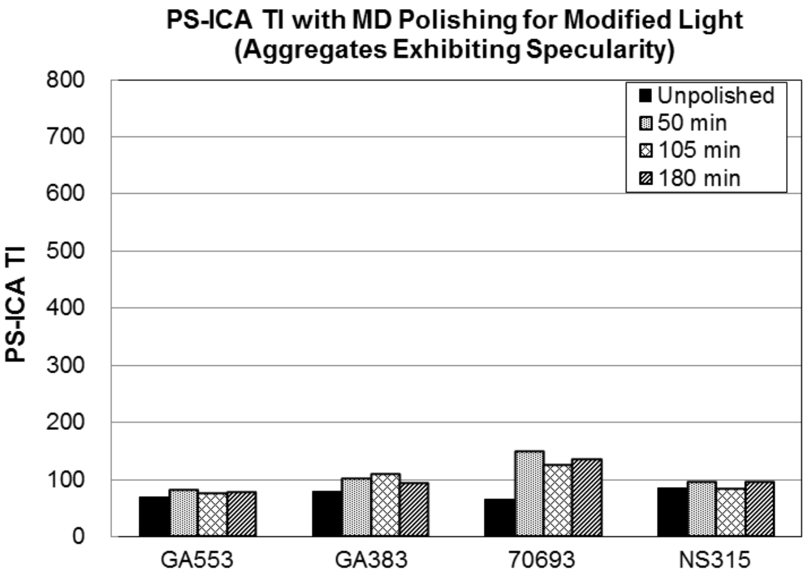


Figure 2-12 Change in PS-ICA TI with MD Polishing at Modified Light Intensity for Aggregates Exhibiting Specularity (6.27X)

2.6 Summary

The PS-ICA method in conjunction with modified light intensity effectively reduced effects of color variation and specularity on TI and resulted in the most consistent and reliable TI results for all aggregates evaluated. However, PS-ICA method with modified light intensity could not completely mitigate effects of specularity that overwhelmed effect of polishing on TI. Therefore, it appears that change in absolute values of TI may not provide enough information with respect to physical change in surface roughness with MD polishing due to the following factors: 1) specularity effect; 2) additional pores and cavities exposed; and 3) light-colored smoother surface resulted in excessive reflected light, which had an effect similar to specularity. These effects may overwhelm effects of reduced surface roughness induced by MD polishing on TI. Therefore, additional indexes may be required to better explain change in aggregate surface roughness/microtexture characteristics with MD polishing.

CHAPTER 3
EVALUATION OF THE SCANNING ELECTRON MICROSCOPY (SEM) TECHNIQUE AS AN INDEPENDENT TEXTURE MEASUREMENT

3.1 Background

In Chapter 2, the PS-ICA method was evaluated for use in determining surface texture of a wide range of aggregate sources at different polishing levels. The results were very promising, but effects of specularity (glare) and porosity were determined to affect texture index (TI) and could not be mitigated by the PS-ICA approach. Therefore, efforts presented in this chapter focused on identifying and using scanning electron microscopy (SEM) as an independent test method that is not susceptible to effects of specularity (glare) and/or color variation to visually and quantitatively evaluate the physical surface roughness of the aggregates. These results provided a connection to the physical interpretation of the TI values obtained from AIMS.

3.2 Selection of Right Profiler

The primary objective was to characterize micro-texture of coarse aggregates using an independent roughness measurement technique that was not susceptible to effects of specularity and color variation. One of the big challenges was to choose an appropriate profiler to measure aggregate micro-texture. The rapid advancement of optical technology over the last few decades has resulted in the development of a wide range of surface profiling instruments. Efforts were made to find the optimal instrument for our application. A brief review of surface roughness measurement techniques is presented herein. A discussion of requirements, restrictions, and limitations with respect to the material types, measurement needed, and availability of devices is then presented to justify the selected methodology, scanning electron microscopy (SEM) stereoscopy.

According to the International Organization for Standardization (ISO) 25178-6, surface texture measurement methods can be classified into three groups: (1) line profiling; (2) areal topography; and (3) area integrating (Figure 3-1) (Vorburger et al., 2007). A high resolution probe is used in line profiling methods to generate a quantitative profile Z(x) of surface texture. Areal topography creates three dimensional surface topography Z(x, y) by way of either rastering (a scan pattern: side to side, top to bottom) a series of parallel profiles or by application of some quantitative image processes. The last category involves area-integrating methods, where a surface is examined all at once and a statistical quantity representing the average surface peaks and valleys are produced (Vorburger et al., 2007). Figure 3-1 shows examples of these three types of methods.

Line profiling and areal topography are most suitable for evaluation of aggregate surfaces and for comparison to TI. These two types of methods are divided into two broad categories; contact and non-contact methods.

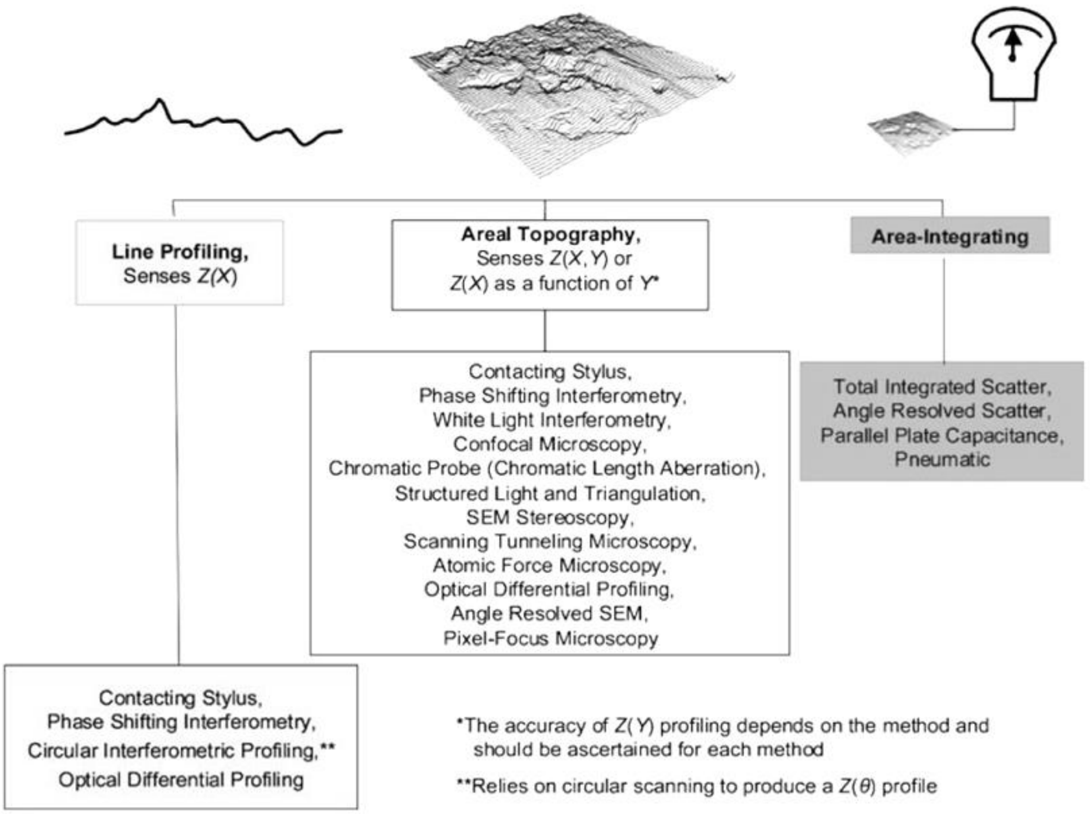


Figure 3-1 Surface Roughness Measurement Classification Methods with Examples (Vorburger et al., 2007)

3.2.1 Contact Methods

Profilers such as stylus profilometry or scanning probe microscopy employ a stylus type device to assess the surface of an object. A small contacting force is applied at the tip of the stylus (Vorburger et al., 2007, Schmit et al., 2007, and Camilo, 2015). Although these instruments have a good lateral resolution (e.g. 1-2 micrometer for mechanical stylus) in theory, the lateral resolution is limited by the interaction of the tip with surface asperities (Vorburger et al., 2007). Also, these instruments are very delicate and their measurement speed is relatively slow. Depending on the surface, the sharp stylus tip may introduce micro scratches and more importantly for application with Florida limestone, the stylus is susceptible to jamming or even breaking in aggregates with negative texture features (e.g. pores). In addition, the specimen surface must be cleaned prior to measurement, which is an issue of serious concern for limestone aggregates or aggregates recovered from the field with residual binder on the surface (Vorburger et al., 2007 and Camilo, 2015). Finally, aggregate shape (curvature) and height variation in surface roughness encountered with aggregates was yet another factor that made it clear that contact methods were not suitable for purposes of this research. Figure 3-2 shows a model for contact methods.

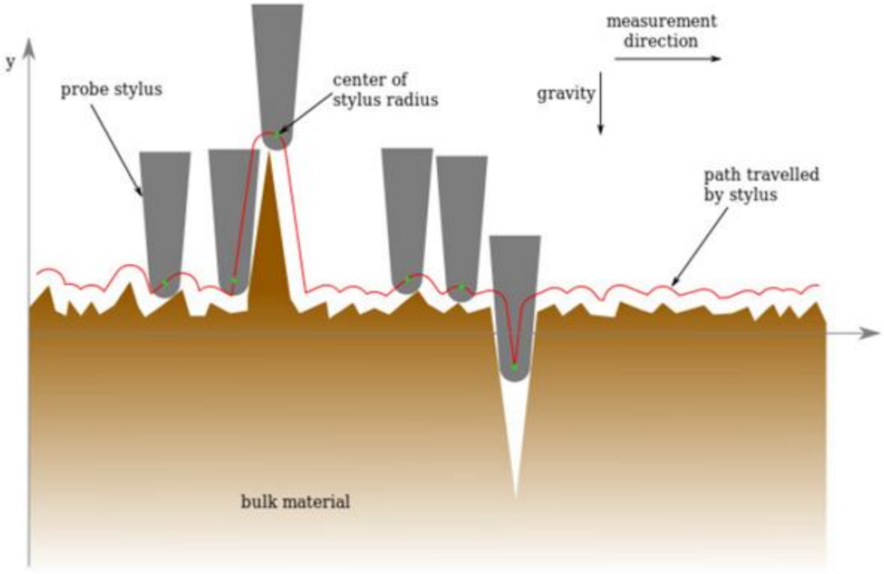


Figure 3-2 Model for Contact Methods (Camilo, 2015)

3.2.2 Non-Contact Methods

3.2.2.1 Optical Methods

Optical methods such as Interferometry and Confocal Microscopy use a beam of light to illuminate the surface under measurement (Camilo, 2015, and Hocken et al., 2005). Optical methods are non-destructive and are faster than contacting techniques. AIMS is considered an optical method. According to the literature, the main shortcomings of optical techniques are: (1)

limited resolution, either the horizontal resolution, which is dictated by wavelength of light used, or the vertical resolution; and (2) sensitivity to surface properties other than surface height such as optical constant, fine features on the surface that cause diffraction, and deep valleys (Vorburger et al., 2007, and Camilo, 2015).

All these effects have been observed in using AIMS for the application of texture measurement of aggregates used in Florida. Many aggregates are composed of various minerals, resulting in large variability in optical properties. Therefore, it was concluded that light-based roughness measurement method was unsuitable for providing an independent texture measurement for purposes of this research.

3.2.2.2 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is widely used in research and industry to characterize a variety of material properties including surface roughness. SEM uses an electron beam and a detector to collect signals produced from interaction of electrons with the irradiated specimen surface. These signals are then transformed to images (Goldstein et al., 2003, Reed, 2005, Ravanshad, 2014). Although some 3-D information is available in SEM images, stereo-vision techniques are required for 3-D reconstruction (Camilo, 2015, and Ravanshad, 2014). SEM has much better resolution than optical methods. The primary disadvantages of SEM include: its expensive process, which involves highly sophisticated equipment and specimen preparation methods (specimens must be coated to be conductive for testing: Goldstein et al., 2003, Reed, 2005, Ravanshad, 2014; as well as advanced 3-D reconstruction software; and the process is highly time-consuming. Table 1 shows the resolution of different surface roughness measurement methods discussed above. SEM clearly provides the resolution necessary to evaluate aggregate surface texture for comparison to AIMS measurements.

Table 3-1 Resolution of Different Surface Roughness Measurement Methods

Type	Contact or Noncontact	Resolution	
		Lateral	Vertical
Stylus	Contact	1-2 µm	5 nm
Optical	Non-contact	1 µm	0.5-1 nm
SEM Stereoscopy	**Non-contact**	**2-4 µm**	**10-20 nm**
Tunneling Microscopy	Non-contact	0.3 µm	0.02 nm

3.2.3 Other Factors on Selection of Measurement Method

There are various other factors that should be considered in selection of an instrument for surface roughness measurement. One of the most important factors is the measurement scale, which can be described by the measurement area and the resolution of interest. For example, an optical technique can be used to scan a relatively large specimen with area less than a few square millimeters, but a scanning probe such as Atomic Force Microscope (AFM) is only suitable for a specimen smaller than 100 micrometers (Camilo, 2015). Since AIMS measures aggregate specimens in the range of several millimeters, the instrument used for comparison should cover a similar size.

Another important factor is sample surface characteristics. Not all instruments can be used for soft and hard materials, shiny and opaque surfaces, clean and dusty materials, rough and smooth samples, or porous and non-porous surfaces. As discussed above, the reflectance properties of aggregates vary from spot to spot, surface of virgin aggregate is dusty, and surface of field polished aggregates has residual binder. The method selected should be relatively unaffected by these factors.

Another factor is availability of device. The University of Florida has a wide range of contact and non-contact devices including mechanical stylus, White Light Interferometry (WLI), AFM, and SEM. Therefore, availability was not a major issue. Speed of testing and sample preparation is also merit consideration, but for purposes of this project, which involved obtaining a limited number of reference measurements, this was not a major issue. However, this would clearly be an issue for selection of an appropriate production level device.

In the final analysis, SEM was determined to be the best candidate to provide the most reliable independent measurements needed for this study. SEM equipment and 3-D reconstruction software necessary to perform SEM stereomicroscopy technique was available. Additional details regarding the methodology used are provided in the following section.

3.3 SEM Test Method

SEM is a microscope used to visualize and characterize various types of materials at scales ranging from nanometer (nm) to millimeter (mm) (Goldstein et al., 2003, and Ravanshad et al., 2015). Specimen is bombarded with an electron beam and a detector is used to collect the signals produced from interaction of electrons with the irradiated specimen. These signals are then transformed to images. Depending on the mode of detection, examining an object with SEM can provide a variety of information, including surface topography, morphology, composition and crystallography (Goldstein et al., 2003, Reed, 2005, and Ravanshad et al., 2015).

Stereomicroscopy technique was employed to quantitatively characterize aggregate surface micro-texture. Tilting method (Figure 3-3), the most common technique in SEM stereomicroscopy, was used to obtain multiple images of the same area at various tilt angles (Reed, 2005, and Ravanshad et al., 2015). Reconstruction was conducted using advanced software called MeX 3-D. Three images were obtained from each sample, one without tilting and two with tilting angles (Ravanshad et al., 2015). As mentioned earlier, SEM presents some difficulties for specimen preparation. SEM specimens must be conductive for examination. However, since aggregate samples are typically not conductive, specimen coating was essential. Various techniques exist for specimen coating, including sputtering and evaporation methods.

For the purpose of this study, aggregates were coated using sputter method with gold/palladium (Au/Pd), which a thin layer of conductive material is placed on the specimen surface (Ravanshad et al., 2015).

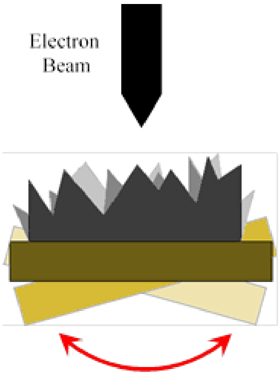


Figure 3-3 Illustration of SEM Tilting Method (Ravanshad et al., 2015)

3.4 SEM Results

Although single SEM images contain some 3-D information, more sophisticated techniques are required to recover accurate 3-D surface roughness from SEM. Once obtained, statistical parameters can be calculated to quantitatively describe surface roughness. SEM images obtained were reconstructed to 3-D surface using MeX 3D software, which is able to take account of relative height of surface asperities and surface curvature effects (Ravanshad et al., 2015). The capability of accounting for surface curvature was one of the reasons that SEM approach was considered the best for purposes of this study.

MeX 3D generates a variety of statistical parameters to evaluate surface roughness of aggregate specimens. Average roughness (height variation) of selected area (S_a) and root-mean-square (RMS) roughness of selected area (S_q) were used to quantitatively describe surface roughness of each specimen. S_a is the most commonly used statistical roughness parameter. It is the deviation of the profile from the mean absolute height of the surface as defined by the arithmetic average of the absolute values of the measured data points (Loberg et al. 2010). In mathematical form, S_a can be expressed as follows:

$$S_a = \frac{1}{l_x l_y}\int_0^{l_x}\int_0^{ly} |Z(x,y)|\, dxdy \qquad (3-1)$$

Where, l_x and l_y are the side lengths of the sampling area, and Z is the height distance from the reference plane. The second parameter used to characterize surface roughness, S_q, is the root-mean-square average of the surface roughness, which represents the dispersion of measured data points from a reference surface. Its mathematical form is as follows:

$$S_q = \sqrt{\frac{1}{l_x l_y}\int_0^{l_x}\int_0^{ly} |Z(x,y)|^2\, dxdy} \qquad (3-2)$$

These two SEM surface roughness parameters (S_a and S_q) were obtained using one SEM device on the nine aggregates presented in Table 2-1. Three different conditions for aggregate specimens were evaluated: unpolished, MD-polished, and field-polished conditions. SEM visual images were also obtained for each aggregate condition and Tables 3-2 and 3-3 summarize SEM S_a and S_q obtained from aggregate specimens for unpolished, 180 minute MD-polished and field-polished conditions.

Table 3-2 SEM Surface Roughness Parameter, S_a

Aggregate ID	S_a (μm)			% Reduction	
	Unpolished	MD-Polished	Field-Polished	Unpolished to MD-Polished	Unpolished to Field-Polished
87090	23.6	6.2	16.8(SA)/14.4(LA)	73.7	28.8(SA)/39.0(LA)
87145	15.6	6.2	8.8	60.3	43.6
87339	14.7	14.2	10.3(LT)/10.2(HT)	3.4	29.9(LT)/30.6(HT)
87648	14.2	14.1	N/A	0.7	N/A
HN717	12.2	8.7	N/A	28.7	N/A
GA553	12.0	10.7	12.8(LT)/13.9(HT)	10.8	-6.7(LT)/-15.8(HT)
GA383	18.3	11.6	9.2	36.6	49.7
70693	11.1	5.6	9.7	49.5	12.6
NS315	12.1	10.8	11.2	10.7	7.4

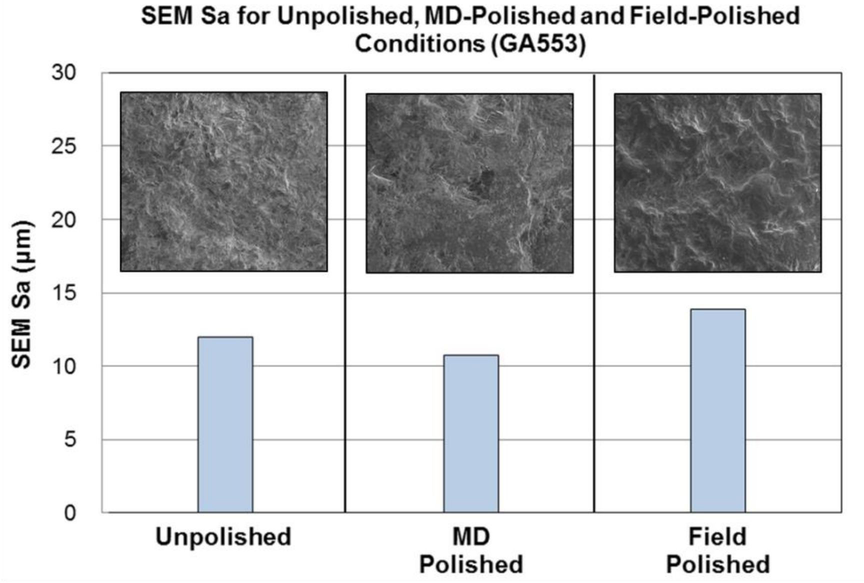
Note: SA = Shorter Aging, LA = Longer Aging, LT = Lower Traffic and HT = Higher Traffic

Table 3-3 SEM Surface Roughness Parameter, S_q

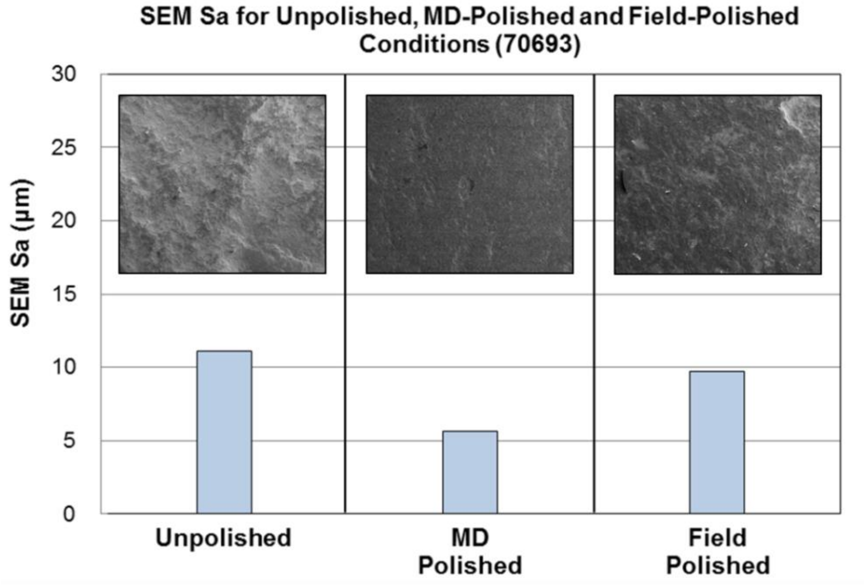
Aggregate ID	S_q (μm)			% Reduction	
	Unpolished	MD-Polished	Field-Polished	Unpolished to MD-Polished	Unpolished to Field-Polished
87090	32.1	9.0	23.7(SA)/19.4(LA)	72.0	26.2(SA)/39.6(LA)
87145	20.7	8.7	12.6	58.0	39.1
87339	19.9	19.5	15.7(LT)/13.9(HT)	2.0	21.1(LT)/30.2(HT)
87648	19.0	19.0	N/A	0	N/A
HN717	15.8	12.5	N/A	20.9	N/A
GA553	15.6	14.4	16.8(LT)/17.8(HT)	7.7	-7.7(LT)/-14.1(HT)
GA383	23.5	15.6	12.1	33.6	48.5
70693	15.5	7.8	13.5	49.7	12.9
NS315	15.8	14.5	14.8	8.2	6.3

Note: SA = Shorter Aging, LA = Longer Aging, LT = Lower Traffic and HT = Higher Traffic

Figures 3-4 and 3-5 show two representative SEM S_a results for both aggregates exhibiting specularity and aggregates not exhibiting specularity. All SEM images and surface roughness parameters obtained for all aggregates are included in Appendices A and B. In this Chapter, since similar trend was observed between S_a and S_q results in terms of percent reduction with MD polishing and field polishing, only S_a results are presented for simplicity and to avoid redundancy. It appears that results obtained from the SEM system were reasonable as independent roughness measurements, which is not susceptible to effect of specularity (glare) and color variation. However, there are potential variables other than reduction in surface roughness that affect S_a results of field-polished aggregates, including dust, breaks and absorbed asphalt on aggregate surface. Also, relatively higher SEM S_a values obtained from unpolished limestone aggregates may indicate potential effects of porosity-induced negative texture on SEM measurements.

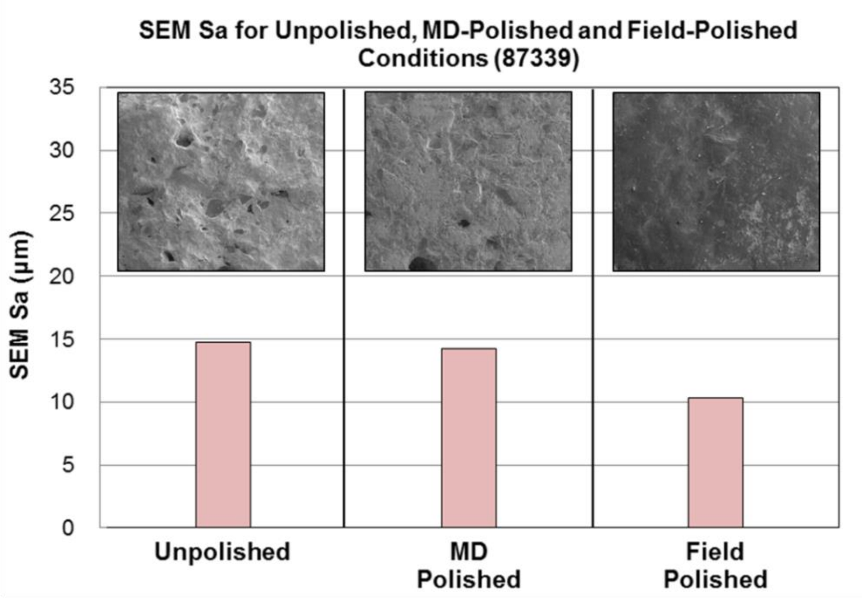


(a) GA553

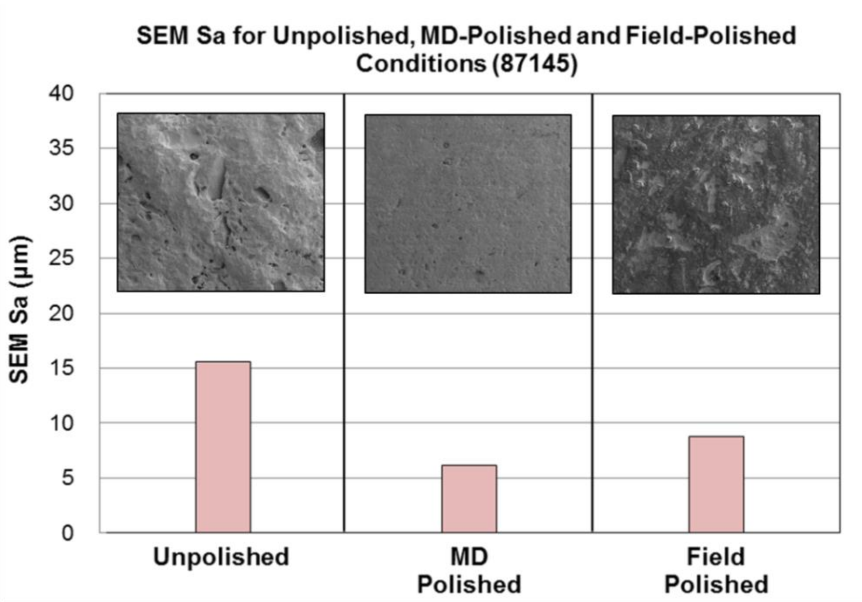


(b) 70693

Figure 3-4 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for Aggregates Exhibiting Specularity



(a) 87339



(b) 87145

Figure 3-5 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for Aggregates Not Exhibiting Specularity

3.5 Summary

The goal of this task was to obtain a set of independent surface roughness measurements for use as a reference for comparison and further evaluation of the AIMS system, including the PS-ICA method. A review was conducted on the potential surface roughness measurement methods to choose the most appropriate instrument for purpose of this study. SEM stereomicroscopy technique was chosen to measure surface roughness of virgin, laboratory MD-polished, and field-polished aggregates. Results obtained from the SEM system were reasonable as an independent surface roughness measurement, which is not susceptible to effects of specularity (glare) and/or color variation. It appears that the SEM results effectively capture and quantify reduction in surface roughness of aggregates induced by MD polishing.

CHAPTER 4

IDENTIFICATION OF THE BEST APPROACH TO INTERPRET PS-ICA TI FOR USE IN CHARACTERIZING DIFFERENT AGGREGATE TYPES

4.1 Background

Results of a prior research project and this research effort have revealed that the following three aggregate characteristics not associated with surface roughness affect the value of Texture Index (TI) as determined using standard procedures associated with the AIMS II device:

- Color variation;
- Porosity; and
- Specularity (glare)

All three characteristics result in higher TI values. A system to mitigate effects of color variation called PS-ICA was developed at UF. The system involved obtaining three images with three different light sources in the AIMS II device. Extensive evaluation of TI values obtained using the PS-ICA system for a broad range of aggregates and polishing levels indicated the system appeared to effectively mitigate color variation effect (see Chapter 2). However, the evaluation also revealed that for some aggregates, specularity strongly influenced TI values, an effect that was somewhat masked by the color variation effect. An approach was developed to mitigate effect of specularity by reducing light intensity used to obtain images in the AIMS II device. This modified lighting approach was used to obtain another set of TI values for aggregates exhibiting specularity. The approach was determined to partially mitigate the effects of specularity, but it was concluded that more complete mitigation of the effect would likely require changes in hardware in the AIMS II device. It was also determined that effects of pores, which are primarily associated with Florida limestone aggregates, could not be mitigated with measurements obtained from the existing AIMS II system.

The next important step in this research effort was to further evaluate the approaches developed to mitigate the effects of color variation and specularity on TI and to identify the best approach to interpret the TI values for characterizing surface roughness of different aggregate types. An independent reference measurement of surface roughness using a system unaffected by color variation and specularity was needed for this purpose. SEM stereomicroscopy was identified as the most suitable system to accomplish this. Reference measurements obtained from two representative aggregates using SEM stereomicroscopy were used: a granite (GA553) that exhibited high color variation and specularity; and an oolitic limestone (87339) that was uniform in color and did not exhibit specularity. Hence, these two aggregates encompassed the range of TI values (highest and lowest) of all nine aggregates included in this study. Surface roughness parameters from SEM stereomicroscopy for these two aggregates in unpolished and highly polished states were presented in Chapter 3.

These reference measurements were used in this task to further evaluate the approaches developed to mitigate the effects of color variation and specularity on TI and to identify the best approach to interpret the TI values for characterizing surface roughness of different aggregate types. Results of evaluations and further analyses performed are presented in this chapter. The primary objective was to identify the best approach to interpret texture index (TI) for use in characterizing different aggregate types. The following tasks were involved in accomplishing this objective:

- Compare TI values obtained using different testing and data interpretation procedures and light intensities to reference surface roughness parameter obtained using SEM stereomicroscopy to identify the interpretation procedure that results in TI values most consistent with the reference measurements.

- Identify sources of inconsistencies between the two measurements and determine whether further interpretation can lead to TI values more consistent with reference measurements.
- Identify alternate interpretation of TI values that can mitigate known issues and allow for consistent assessment of aggregate surface roughness for different aggregate types.

4.2 Evaluation of Texture Index

Texture Index (TI) values obtained using different testing and data interpretation procedures and light intensities were evaluated by comparing to surface roughness parameter from SEM stereomicroscopy. The following is a definition of parameters evaluated:

- SEM Sa (micro-meter): the deviation of the profile from the mean absolute height over the surface as defined by the arithmetic average of the absolute values of the measured data points.
- AIMS TI: TI obtained using the standard imaging and interpretation procedures currently recommended for use with the AIMS II device.
- PS-ICA TI: TI obtained using the Photometric Stereo-Independent Component Analysis (PS-ICA) interpretation method developed in a prior research project, which involved obtaining three images with three different light sources in the AIMS II device.
- Default Light: TI was obtained using default light intensity currently recommended for use with the AIMS II device. Default lighting was used for all aggregates in this study and for both AIMS TI and PS-ICA TI.
- Modified Light: TI was obtained using modified light intensity according to the procedure developed in this study. Modified light was used to mitigate effect of specularity, so it was

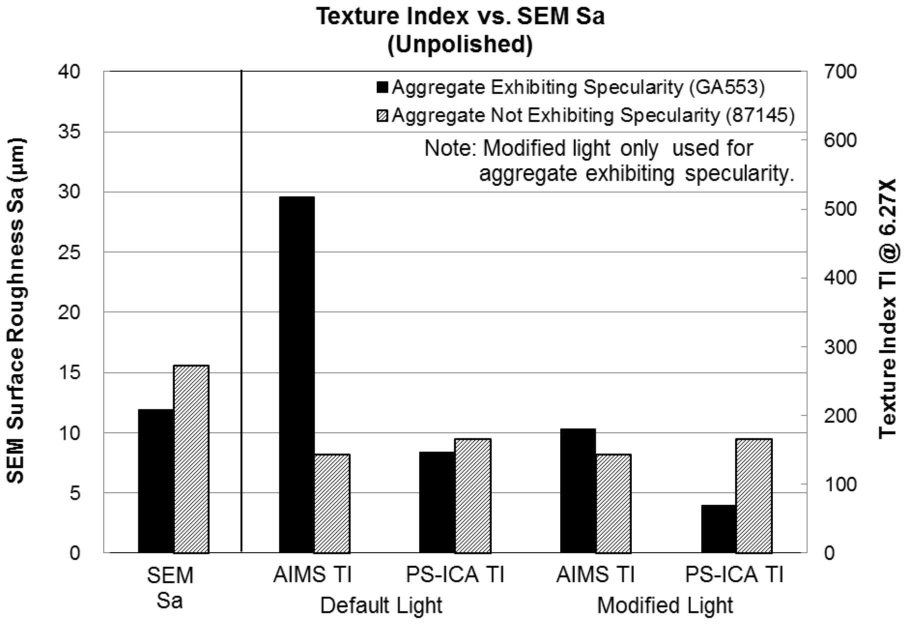
used only for aggregates for which specularity was a potential issue (granites and siliceous wackestone). Modified lighting was used for both AIMS TI and PS-ICA TI.

All TI values are dimensionless, while SEM Sa is in micrometers, so the two can only be compared in relative terms.

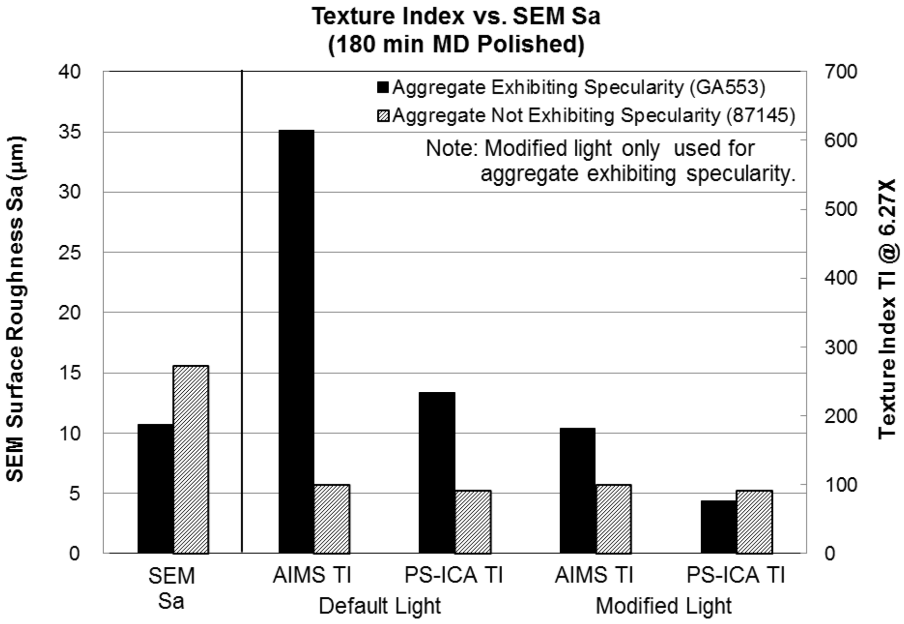
4.2.1 Comparing Aggregates Exhibiting Specularity to Aggregates Not Exhibiting Specularity

Figure 4-1 shows that only the TI values obtained using PS-ICA TI and modified light intensity resulted in TI values consistent with SEM surface roughness parameter Sa. Whereas the SEM Sa for both unpolished (Figure 4-1(a)) and polished (Figure 4-1(b); 180 minute in Micro-Deval (MD)) oolitic limestone aggregate (87145) was greater than for the granite aggregate (GA553), all other TI values obtained without PS-ICA and/or modified light intensity exhibited the reverse trend. These results clearly indicate the effectiveness of the PS-ICA method in mitigating color variation effect and of the modified light intensity approach in mitigating specularity effect.

It is noted that higher surface roughness of the oolitic limestone is consistent with visual observation of the SEM images and images from the AIMS II device. Also, although granites as a whole are generally thought to have better frictional characteristics than limestones, both of the aggregates tested are known to exhibit good friction performance in the field. In addition, the Florida oolitic limestone is known to have pores that are interpreted as deviations in surface profile. Pores result in higher surface roughness parameter and TI but do not enhance surface friction.



(a) unpolished



(b) 180 minute MD-polished

Figure 4-1 Texture Index (AIMS and PS-ICA) and SEM Surface Roughness Parameter S_a for Aggregate Exhibiting Specularity and Aggregate Not Exhibiting Specularity

Since TI values from standard imaging and interpretation procedures currently recommended for use with the AIMS II device (i.e., AIMS TI) have clearly been determined to not accurately reflect aggregate surface roughness for aggregates with color variation and specularity effect, only PS-ICA TI values with modified light intensity were used in comparisons presented from this point forward. It is noted that modified light intensity was used only with aggregates with potential for specularity effect (i.e., not with oolitic Florida limestone aggregates).

4.2.2 Comparing Unpolished to Polished

Figures 4-2 and 4-3 show that PS-ICA TI accurately captured the effect of polishing for aggregate not exhibiting specularity, but did not for aggregate exhibiting specularity, even when modified light intensity was used. Micro-Deval (MD) polishing should cause surface roughness parameters to decrease, an effect that was captured by SEM roughness parameter Sa for both aggregate types. The effect was captured for aggregate not exhibiting specularity by PS-ICA TI, but not for aggregate exhibiting specularity, for which an increase in PS-ICA TI was observed after polishing. This result indicates that effect of specularity increased after polishing, thereby resulting in a relative increase in TI. In other words, increased specularity appeared to overwhelm the reduction in surface roughness induced by polishing. SEM surface roughness parameter shows the correct trend because the method is not affected by specularity.

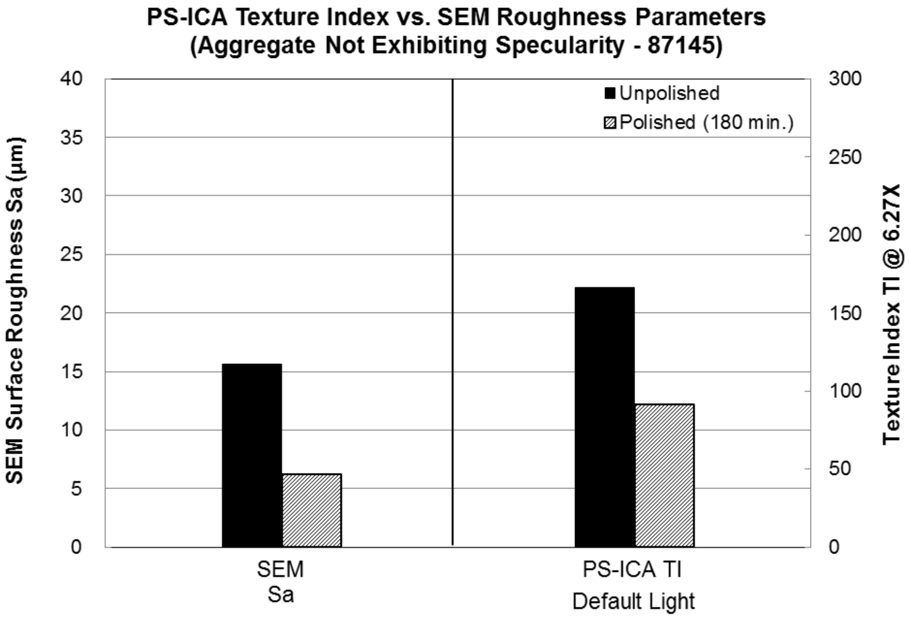


Figure 4-2 Unpolished and Polished PS-ICA Texture Index and SEM Surface Roughness Parameter for Aggregate Not Exhibiting Specularity

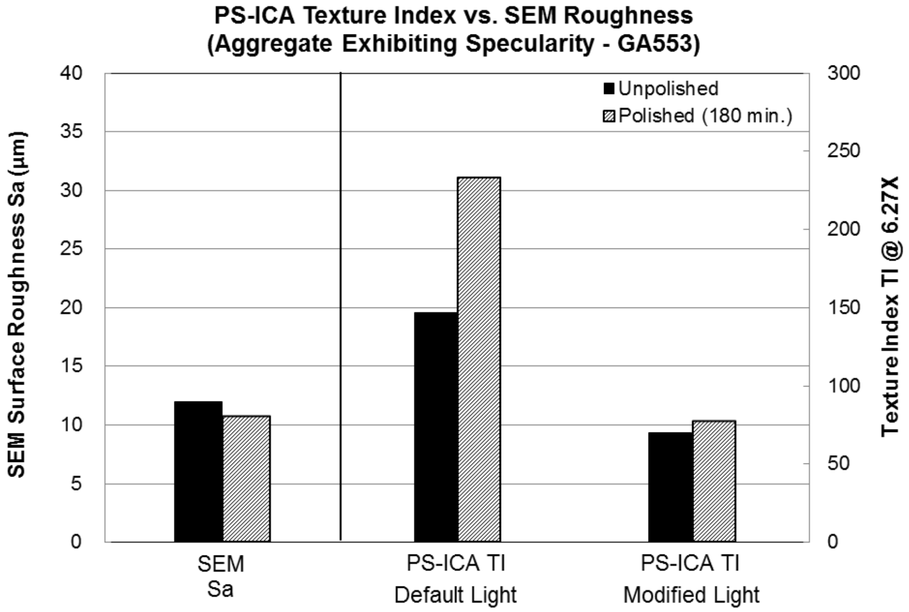


Figure 4-3 Unpolished and Polished PS-ICA Texture Index and SEM Surface Roughness Parameter for Aggregate Exhibiting Specularity

4.2.3 Attempts to Further Mitigate Specularity

The research team attempted to further mitigate effects of specularity by analyzing the variance of TI values. The idea was to identify and eliminate outliers that caused excessively high TI values from the data used to obtain average TI. Unfortunately, this analysis did not result in any substantive change in relative TI values between unpolished and polished aggregate. It appears specularity effect is well distributed among the aggregates, so its effect cannot be isolated by analysis of variance.

4.3 Alternative Interpretation of TI

Results of TI evaluation have clearly indicated that comparison of TI in absolute terms may not be an appropriate way to interpret relative surface roughness among different aggregates types or even between polishing levels for some aggregates. Although color variation appeared to be effectively dealt with by the PS-ICA approach, the specularity effect was found to increase after polishing, a consequence that increased TI in a manner that overwhelmed the reduction in TI caused by Micro-Deval (MD) polishing. Also, comparison of TI in absolute terms may be problematic when aggregates have pores and other surface cavities that may register as deviations in surface profile, which cause surface roughness parameters to increase but do not affect friction. Therefore, it appears that comparison of TI in absolute terms may only be appropriate for aggregates with no specularity or pores. Aggregates used in Florida include both of these characteristics, so either an alternative interpretation of TI needs to be identified or improvements to the system hardware need to be made to further mitigate effects of specularity and pores.

4.3.1 Relative Change in TI

Use of relative change in TI between different polishing levels can potentially neutralize effects of specularity and pores on TI. However, the effect of specularity and pores must be similar for the conditions being compared in order for this approach to work. Unfortunately, results presented in Chapter 2 of this report clearly indicated that the specularity effect is not the same (it increases) for unpolished aggregates exhibiting specularity than for those polished in Micro-Deval (MD). In other words, MD polishing reduced PS-ICA TI by reducing surface roughness, but also increased PS-ICA TI because specularity effect was greater. The net increase in PS-ICA TI indicated that the increase in specularity effect overwhelmed the effect of reduced surface roughness. Therefore, an analysis was conducted of the relative change in TI between different levels of MD polishing to further evaluate the relative effect of specularity on PS-ICA TI using the nine aggregates included in this study.

Figures 4-4 and 4-5 show percent reduction in PS-ICA TI between different levels of MD polishing for the five aggregates not exhibiting specularity and for the four aggregates exhibiting specularity, respectively. Percent reduction was determined for the following conditions:

- 0/50: between unpolished (0 minute in MD) and after 50 minute in MD
- 50/105: between 50 minute and 105 minute in MD
- 105/180: between 100 minute and 180 minute in MD
- 50/180: between 50 minute and 180 minute in MD

The following equation was used:

$$\%\,Reduction = 100 \times \frac{PS\text{-}ICA\,TI(lp) - PS\text{-}ICA\,TI(gp)}{PS\text{-}ICA\,TI(lp)} \qquad (4-1)$$

Where, PS-ICA TI (gp) = PS-ICA TI value for greater MD polishing, and PS-ICA (lp) = PS-ICA value for less MD polishing.

Therefore, positive values indicate a reduction in PS-ICA TI, which implies that the reduction in surface roughness induced by MD polishing had a greater effect on PS-ICA TI than did the increase in specularity effect. Conversely, negative values indicate that the increased specularity had a greater effect than the reduction in surface roughness.

Figure 4-4 indicates that the best interpretation of PS-ICA TI for limestone aggregates not exhibiting specularity is by way of the reduction in PS-ICA TI between unpolished and 50 min. MD polishing and between 50 minute and 105 minute MD polishing. Reduction for these two polishing levels is strongly positive for all four aggregates, indicating that PS-ICA TI effectively captured reduction in surface roughness induced by MD polishing. However, MD polishing greater than 105 minute (105/180) caused an increase in PS-ICA TI, indicating PS-ICA TI was being more strongly affected by factors other than reduction in surface roughness. Two possible factors that may explain this observation are: (1) additional pores and cavities were exposed with increased MD polishing; and (2) the light-colored smoother surface resulted in excessive reflected light which had an effect similar to specularity. The overall effect between 50 minute and 180 minute of MD polishing was a combination of the reduction in PS-ICA TI observed between 50 minute and 105 minute and the increase observed between 105 minute and 180 minute.

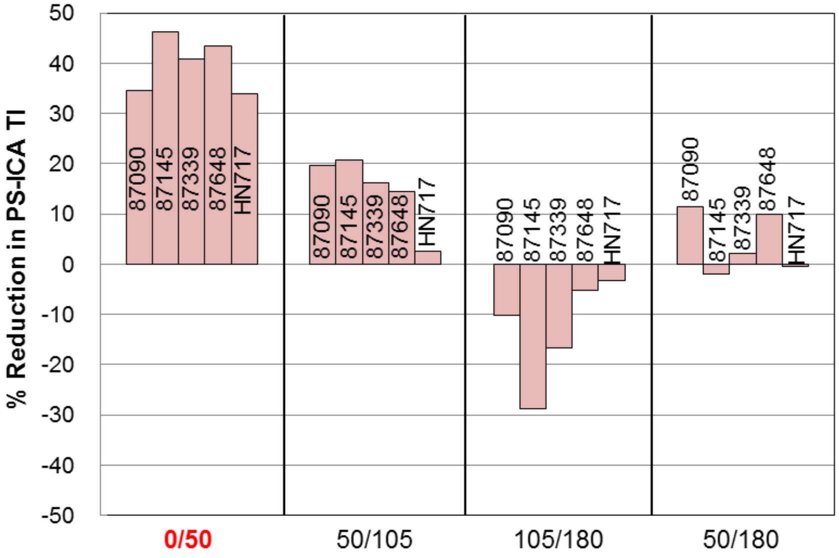


Figure 4-4 Percent Reduction in PS-ICA TI between Different MD Polishing Levels for Aggregates Not Exhibiting Specularity

Figure 4-5 indicates that the decision of which PS-ICA TI interpretation is the best for aggregates exhibiting specularity is much less clear. The percent reduction for all four granites was negative between unpolished and 50 minute MD polishing, indicating increased specularity overwhelmed effects of reduced surface roughness. Figure 4-2 also shows the effects of MD polishing greater than 50 minute were mixed for these aggregates. From 50 minute to 105 minute of MD polishing, there was a reduction in PS-ICA TI for three of the aggregates, whereas an increase in PS-ICA TI (negative percent reduction) was observed between 105 minute and 180 minute MD polishing for the same three aggregates. So, for these three aggregates, it appears that reduced surface roughness more strongly influenced PS-ICA TI than did increased specularity between 50 minute and 105 minute MD polishing, while the reverse was true between 105 minute and 180 minute. One of the granites (GA383) exhibited a trend opposite to the other three aggregates: i.e., an increase in PS-ICA TI (negative percent reduction) between 50 minute and

105 minute and a decrease between 105 minute and 180 minute. For all four aggregates, the overall effect between 50 minute and 180 minute of MD polishing was a combination of the change in PS-ICA TI observed between 50 minute and 105 minute and the change observed between 105 minute and 180 minute.

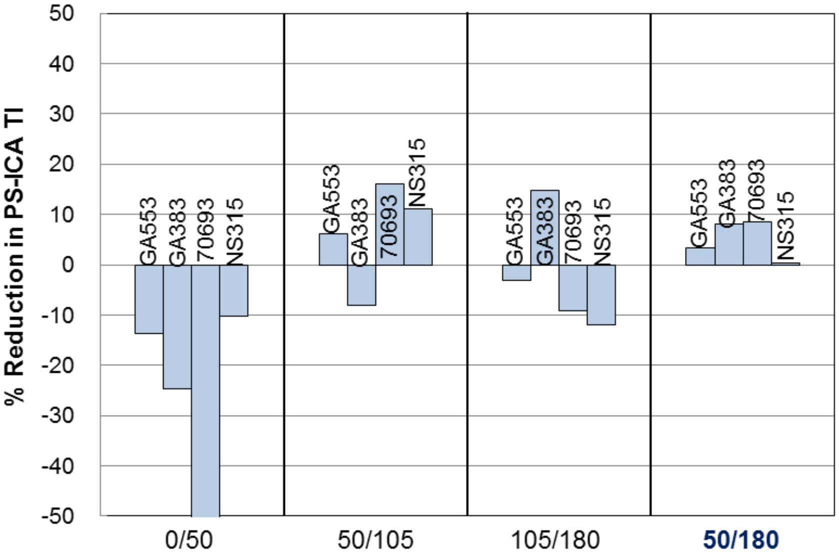


Figure 4-5 Percent Reduction in PS-ICA TI between Different MD Polishing Levels for Aggregates Exhibiting Specularity

At this point, it is hard to say to what extent the relative change in PS-ICA TI for aggregates exhibiting specularity are meaningful in terms of evaluating surface roughness or resistance to polishing. The change in PS-ICA TI between 50 minute and 180 minute MD polishing resulted in the most consistent effect for all four aggregates exhibiting specularity. Percent reduction in PS-ICA TI was positive for all four aggregates (though nearly zero for NS315 granite), indicating that the effect of MD polishing on reducing surface roughness was coming through more strongly than the effect of specularity. Further evaluation of the effectiveness of this interpretation will be discussed later in this report.

4.4 Summary

The purpose of this task was to identify the best approach to interpret texture index (TI) for use in characterizing different aggregate types. TI results obtained using different testing and data interpretation procedures and light intensities indicated that only the modified testing and data interpretation procedure known as PS-ICA along with modified light intensity is able to mitigate known issues and allow for consistent assessment of aggregate surface roughness for different aggregate types. However, even when this approach was used, TI values for aggregates exhibiting specularity was greater after polishing than before, indicating that specularity effects were dependent on degree of polishing. Attempts to further mitigate specularity effects from TI data were unsuccessful.

The use of relative change in TI between different MD polishing levels was explored as a potential way to interpret TI values that may neutralize effects of specularity and pores on TI. Potential effectiveness of relative change in TI, which was defined as percent reduction of PS-ICA TI, was evaluated by exploring the patterns of relative changes in TI for the nine aggregates included in this study. The evaluation led to several findings:

- For aggregates not exhibiting specularity effect, change in PS-ICA TI between unpolished and 50 minute MD polishing strongly reflected the reduction in surface roughness induced by MD polishing. The change in PS-ICA TI between 50 minute and 105 minute MD polishing continued to reflect the reduction in surface roughness induced by MD polishing, but not as strongly as between unpolished and 50 minute MD polishing.
- MD polishing greater than 105 minute to 180 minute for these five limestone aggregates increased PS-ICA TI, which appeared to have been caused by additional pores and cavities being exposed with increased MD polishing or because the smoother surface of these

light-colored aggregates resulted in excessive reflected light that had an effect similar to specularity.

- For aggregates exhibiting specularity effect, change in PS-ICA TI between unpolished and 50 minute MD polishing strongly reflected the increase in specularity effect induced by MD polishing, which overwhelmed the effect of reduction in surface roughness.
- MD polishing greater than 50 minute (50 minute to 105 minute and 105 minute to 180 minute) for granite aggregates resulted in a combination of increasing PS-ICA TI caused by increased specularity effect and reduction in PS-ICA TI induced by MD polishing.
- The change in PS-ICA TI between 50 minute and 180 minute MD polishing resulted in the most consistent effect for granite aggregates exhibiting specularity. Percent reduction in PS-ICA TI was positive for all four aggregates (though nearly zero for NS315 granite), indicating that the effect of MD polishing on reducing surface roughness was coming through more strongly than the effect of specularity.

These findings led to the following conclusions regarding the most promising interpretation of TI to evaluate surface roughness of different aggregate types:

- Percent reduction in PS-ICA TI between unpolished and 50 minute MD polishing appears to best reflect surface roughness changes for aggregates not exhibiting specularity.
- Percent reduction in PS-ICA TI between 50 minute and 180 minute MD polishing appears to have the best potential for use in evaluating surface roughness changes in aggregates exhibiting strong specularity.

Further evaluation of the effectiveness of this interpretation and its usefulness to establish criteria for aggregate polishing resistance will be discussed in following chapters.

CHAPTER 5
IDENTIFICATION OF THE THRESHOLDS FOR SCREENING THE AGGREGATES ON SUITABILITY FOR FRICTION PERFORMANCE

5.1 Background

Results of previous research project and of this research effort have indicated that only the modified testing and data interpretation procedures known as Photometric Stereo-Independent Component Analysis (PS-ICA) along with modified light intensity resulted in Texture Index (TI) values consistent with Scanning Electron Microscopy (SEM) roughness parameters. However, even when this modified approach was used, TI values of aggregates exhibiting specularity (e.g., granite and siliceous wackestone) was greater after polishing than before, indicating that specularity effects overwhelmed effects of polishing. Also, TI values of aggregates not showing specularity (e.g., limestone) was being more strongly affected by other factors than reduction in surface roughness for polishing levels greater than 50-minute in Micro-Deval (MD). Specularity, which may also be called glare, is intense reflected light that reduces visibility and results in artificially high TI. Excessive specularity can overwhelm effects of reduced surface roughness on TI induced by polishing or wear for some aggregates. This phenomenon can be recognized when an increase in PS-ICA TI is observed between unpolished and 50-minute of MD polishing.

Based on the results analyzed in Chapter 4, it was determined that the use of relative change in TI between different MD polishing levels would provide a potential way to appropriately interpret TI values that may neutralize effects other than reduction in surface roughness on TI. Potential effectiveness of relative change in TI, which was defined as percent reduction of PS-ICA TI, was evaluated by investigating the patterns of relative changes in TI for the nine aggregates included in this study. As a result, the percent reduction of PS-ICA TI, which was proposed to further mitigate specularity and pore effects on TI, between unpolished and 50-minute MD polishing was determined to be the best for aggregates without specularity (e.g. limestone). For aggregates exhibiting specularity effect (e.g., granite and siliceous wackestone), percent reduction between 50-minute and 180-minute MD polishing appeared to have the best potential for use in evaluating surface roughness changes.

All the results presented in previous chapters, as well as historical friction performance data (i.e. friction number) for field sections constructed using studied aggregates, were analyzed to identify potential to establish thresholds that can screen the aggregates in terms of suitability for friction performance in the field. The following tasks were involved in accomplishing this objective:

- Evaluate TI values measured at different levels of MD polishing to identify indicators that provide the best potential for use in pre-evaluating the surface roughness changes in aggregates.
- Identify potential PS-ICA TI thresholds for screening the aggregates with respect to suitability for friction performance.
- Analyze historical friction performance of studied aggregates in the field using friction number (FN).

5.2 Evaluation of Texture Index (TI)

Results of TI evaluation in Chapter 4 indicated that the use of relative change in TI between different polishing levels may be used to potentially neutralize effects of specularity and pores on TI. A comprehensive analysis was conducted for the relative change in PS-ICA TI between different MD polishing levels to determine the most promising approach to interpret TI values for use in pre-evaluating characteristics of change in surface roughness for different aggregate types. A summary of aggregates used in this task are shown in Table 2-1.

As previously shown in Figure 4-4, for aggregates not exhibiting specularity effect, change in PS-ICA TI between unpolished and 50-minute MD polishing strongly reflected the reduction in surface roughness induced by MD polishing. The change in PS-ICA TI between 50-minute and 105-minute MD polishing continued to reflect the reduction in surface roughness induced by MD polishing, but not as strongly as between unpolished and 50-minute MD polishing. However, MD polishing greater than 105-minute (105/180) started causing an increase in TI. This indicates that PS-ICA TI was being more strongly influenced by factors other than reduction in surface roughness by MD polishing. Possible factors that may explain this observation include (1) additional pores and cavities were exposed with increased MD polishing and (2) the light-colored smoother surface resulted in excessive reflected light which had an effect similar to specularity. So, it appears the overall effect between 50-minute and 180-minute of MD polishing on TI consists of a combination of the reduction in PS-ICA TI between 50-minute and 105-minute and the increase in PS-ICA TI between 105-minute and 180-minute. Therefore, it was determined that the best interpretation of PS-ICA TI would be accomplished by using percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing.

As also discussed in Chapter 4, for aggregates exhibiting specularity effect, the decision for the best PS-ICA TI interpretation was much less clear. Increase in PS-ICA TI between unpolished and 50-minute MD polishing strongly reflected the specularity effect, which overwhelmed effects of reduced surface roughness induced by MD polishing on TI. The overall effect between 50-minute and 180-minute of MD polishing on TI was composed of a combination of increase in PS-ICA TI caused by increased specularity effect and reduction in

PS-ICA TI induced by MD polishing. For MD polishing levels greater than 50-minute, it appeared that reduced surface roughness more strongly affected PS-ICA TI than the effect of increased specularity. In particular, the change in PS-ICA TI between 50-minute and 180-minute MD polishing resulted in the most consistent effect for all four aggregates exhibiting specularity with positive percent reductions in TI, indicating that the effect of MD polishing on reducing surface roughness is more strongly involved than the effect of specularity on TI. Therefore, the most appropriate interpretation of PS-ICA TI was determined as percent reduction in PS-ICA TI between 50-minute and 180-minute of MD polishing.

These findings led to the following conclusions regarding the most promising approach to interpret TI values for use in pre-evaluating surface roughness changes of different aggregate types.

- For aggregates not exhibiting specularity effect (e.g., limestone including Honduran limestone), percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing seems to best reflect the changes in surface roughness characteristics.
- For aggregates exhibiting specularity effect (e.g., granite and siliceous wackestone), percent reduction in PS-ICA TI between 50-minute and 180-minute MD polishing appears to provide the best potential for use in evaluating surface roughness changes in aggregates.

Therefore, these two parameters were employed for use in threshold assessment. Also, it was noted that PS-ICA TI values obtained at the magnification level of 6.27X, which was determined to be the best or most appropriate in this study, were used for evaluation.

5.3 Identification of TI Thresholds for Pre-Evaluation of Aggregates

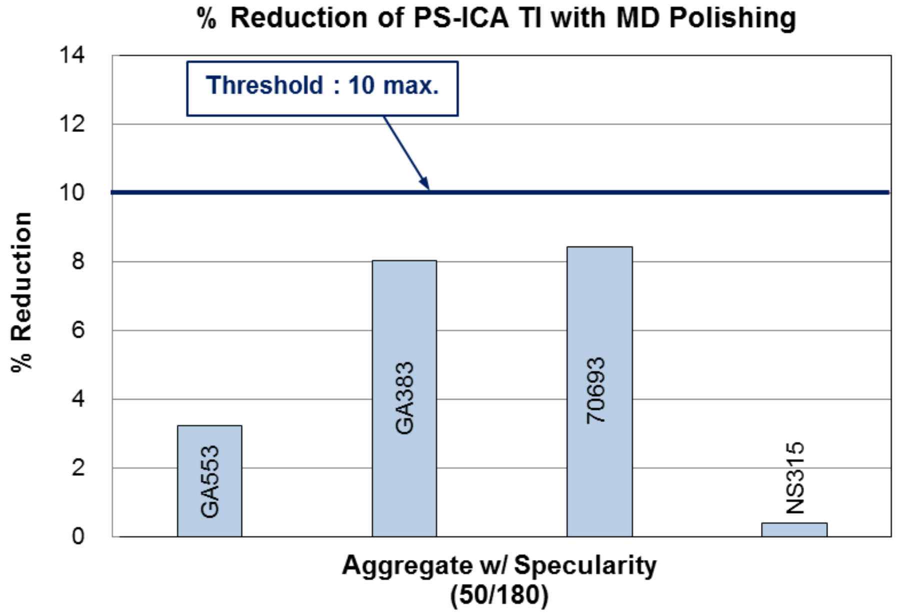
The primary objective was to identify thresholds that can be used for pre-evaluation of aggregates in order to reliably screen aggregates currently being accepted by Florida Department of Transportation (FDOT) for use in friction courses of flexible pavements. This is important for acceptance purposes where it must be determined whether new aggregate sources can provide an acceptable level of surface friction resistance throughout the pavement service life. Therefore, there is a need to establish an effective and expeditious evaluation system that is capable of relating the measured properties of aggregates to their long-term frictional performance in the field. All aggregate sources used in this research are currently accepted by FDOT for friction course application and are well-known to exhibit acceptable frictional performance in the field. Therefore, values obtained for these aggregates can serve as a reference to establish thresholds for acceptable performance.

Figure 5-1 and 5-2 show percent reduction of PS-ICA TI with polishing for different types of aggregates evaluated. As previously explained, the percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing was used for aggregates without specularity effect, and the percent reduction in PS-ICA TI between 50-minute and 180-minute polishing was used for aggregates with specularity effect. All aggregates evaluated were divided into two groups, aggregates with specularity effect and aggregates without specularity effect. For aggregates with specularity effect, percent reductions in PS-ICA TI between 50-minute and 180-minute MD polishing varied between 0.4 and 8.4. For aggregates with no specularity effect, percent reductions in PS-ICA TI between 0 and 50-minute MD polishing ranged between 33.9 and 46.3. Therefore, thresholds for use as pre-evaluation criteria of aggregates that exhibit suitable performance were recommended as follows:

- For aggregates exhibiting specularity effect, a maximum allowable reduction in PS-ICA TI of 10 percent between 50-minute and 180-minute (50/180) MD polishing was recommended.

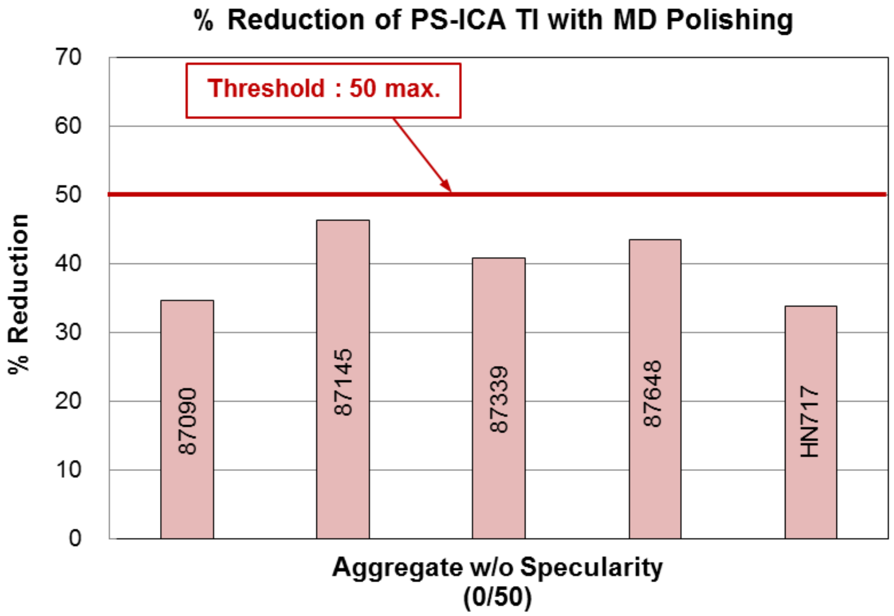
- For aggregates not exhibiting specularity effect, the maximum allowable reduction in PS-ICA TI of 50 percent between unpolished and 50-minute (0/50) MD polishing was recommended.

However, due to the exceptionally high unpolished surface roughness for all limestone aggregates evaluated in this study (i.e., Florida limestone and Honduran limestone), further evaluation of thresholds may be needed for more common limestones.



Note: 1. 50/180 = 50- to 180-minute MD polishing

Figure 5-1 Percent Reduction in PS-ICA TI with MD Polishing for Aggregates Exhibiting Specularity



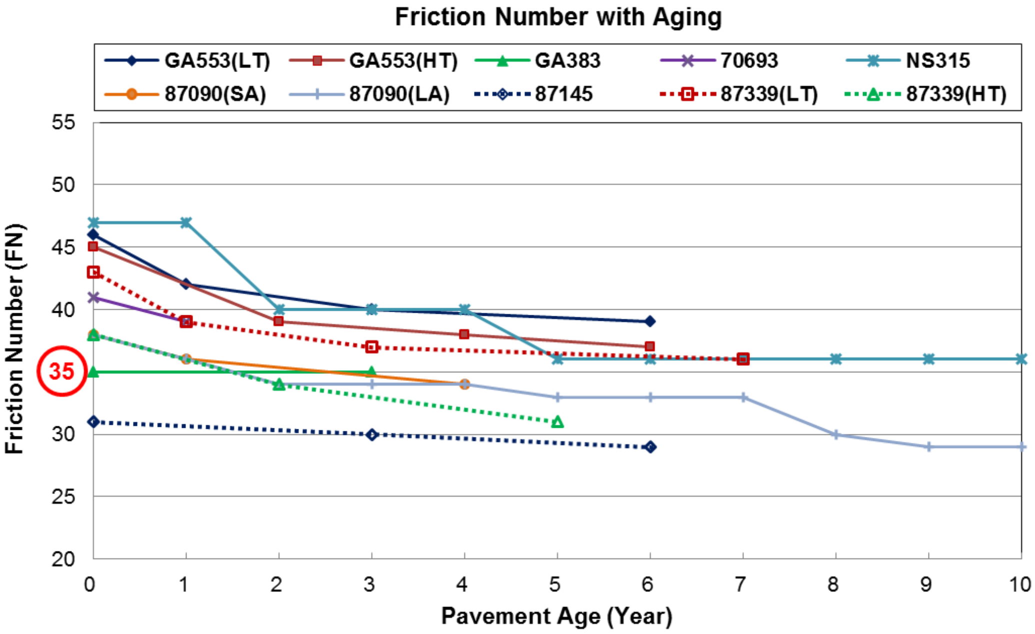
Note: 1. 0/50 = unpolished to 50-minute MD polishing

Figure 5-2 Percent Reduction in PS-ICA TI with MD Polishing for Aggregates Not Exhibiting Specularity

5.4 Field Friction Performance

FDOT specifies a minimum FN requirement of 35 for newly constructed pavement surface. Historical friction performance data and traffic information was obtained for roadway sections constructed using same aggregate sources used in the laboratory evaluation of this study. Asphalt mixture type used for these sections was limited to open-graded friction courses (OGFC) including FC-5 or FC-5M in order to minimize the effects of different mixture variables (i.e., mix design or gradation variables) on friction performance by maintaining similar macro-texture between test sections. It is noted that all OGFC was constructed using 100 percent approved aggregates (i.e., no blended aggregates) and roadways with high design speed and multi-lane facilities were selected for evaluation.

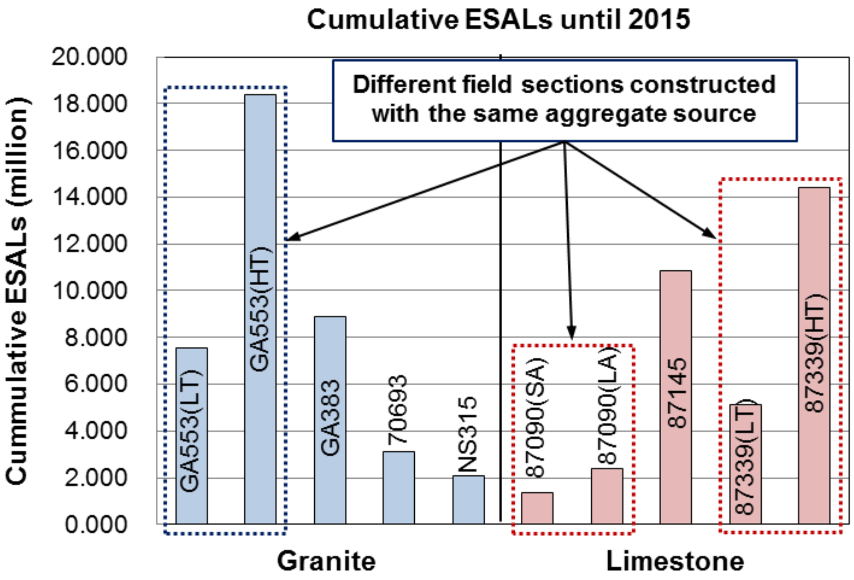
Figure 5-3 presents historical FN data for all project sections. In general, FN decreased with pavement aging, and the rate of reduction in FN decreased over time. Granite aggregates generally exhibited higher FN than limestone aggregates. All field sections met FDOT's initial minimum FN requirements except for one section constructed with limestone aggregate (87145). However, no significant reduction in FN over time was identified for this section (87145) during six years of service period, which indicate relatively good field friction performance. This may indicate a potential error associated with the initial FN measurement for this section. It is interesting to note that this section (87145) exhibited the highest percent reduction in PS-ICA TI value between unpolished and 50-minute (0/50) MD polishing among all limestone aggregates evaluated (see Figure 5-2), which supports the validity of the PS-ICA TI indicators identified for use as thresholds in this study.



Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging
2. FN 35 = Minimum initial FN required by FDOT for new construction

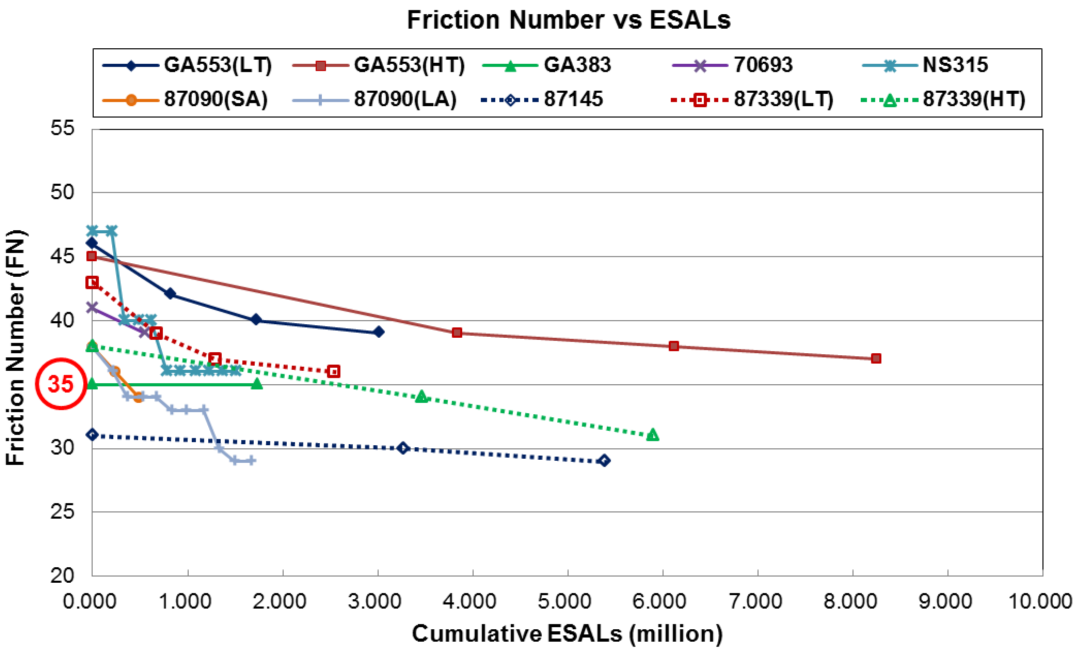
Figure 5-3 Friction Number with Aging

Since surface mixture type was restricted to OGFC, efforts were made to evaluate the effects of traffic and aggregate type on frictional performance characteristics in the field. The trend of reduction in FN with respect to the increase in Equivalent Single Axle Loads (ESALs) was evaluated between test sections with different aggregate types. Figure 5-4 represents cumulative ESALs in millions through 2015 and Figure 5-5 shows FN as a function of ESALs for all test sections. Figure 5-6 shows results grouped as either granite or limestone. FN generally decreased as traffic application increased and the rate of reduction in FN decreased with the increase in ESALs. Overall, granite aggregates exhibited higher FN than limestone aggregates.



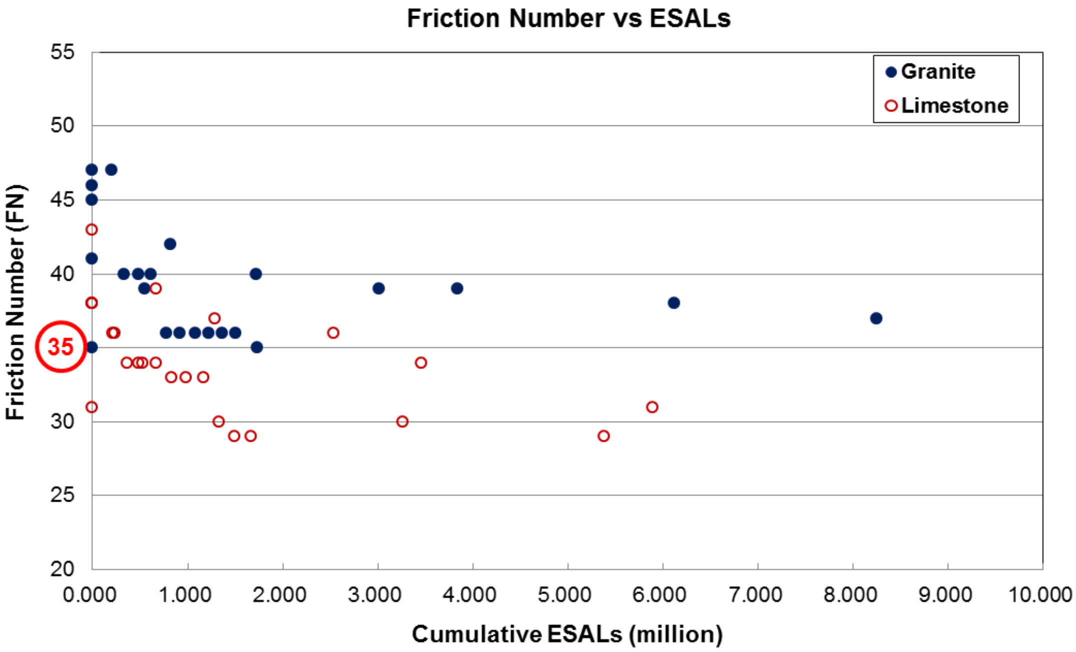
Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging
2. 70693 = Siliceous Wackestone

Figure 5-4 Cumulative ESALs for Field Test Sections until 2015



Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging
2. FN 35 = Minimum initial FN required by FDOT for new construction

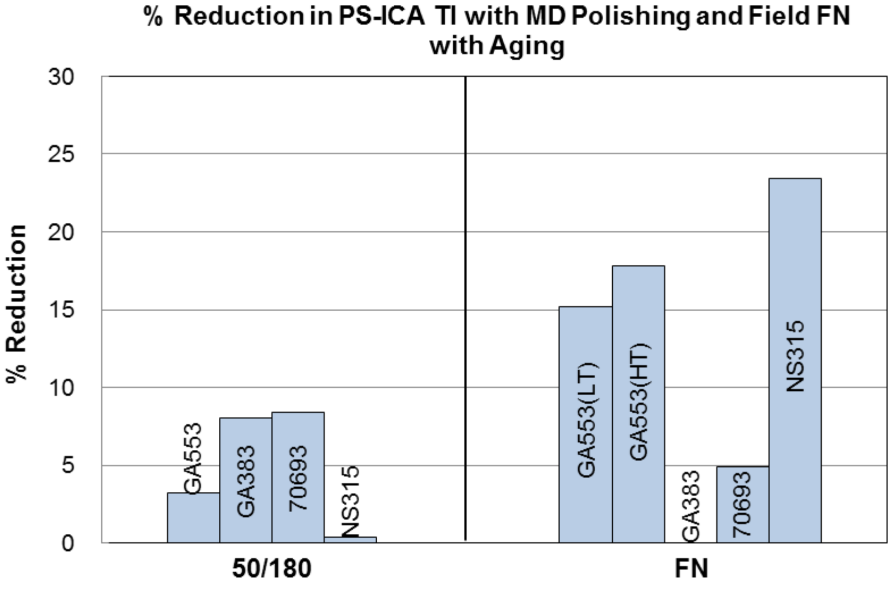
Figure 5-5 Friction Number vs. ESALs for All Field Test Sections



Note: 1. FN 35 = Minimum initial FN required by FDOT for new construction

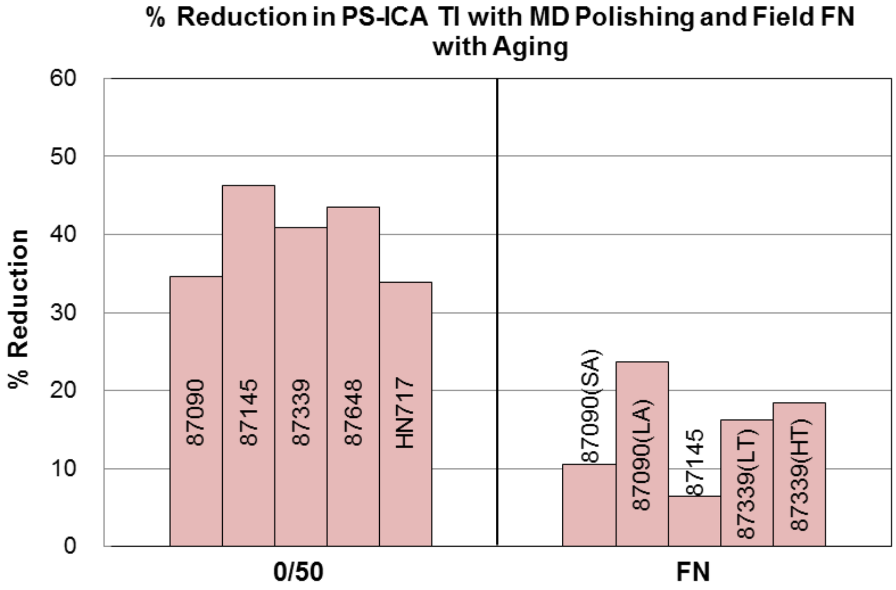
Figure 5-6 Friction Number vs. ESALs Grouped by Two Aggregate Types

In addition, efforts were made to identify whether any trends exist between the indicators used in threshold assessment and measured FNs in the field. Results presented in Figure 5-7 indicate that for granite aggregates, an average reduction in PS-ICA TI of 5 percent between 50-minute and 180-minute MD polishing resulted in an average reduction in FN of 12 percent in the field. For limestone aggregates, Figure 5-8 shows an average reduction in PS-ICA TI of 40 percent between unpolished and 50-minute MD polishing resulted in an average reduction in FN of 15 percent in the field. At this point, it is hard to reach any conclusive explanations regarding the correlations between PS-ICA TI threshold indicators and characteristics of decrease in FNs for individual aggregates since there are too many potential variables that affect FNs measured in the field.



Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging
2. 50/180 = 50- to 180-minute MD polishing
3. 70693 = Siliceous Wackestone

Figure 5-7 Relative Percent Reduction in PS-ICA TI Thresholds and Field FNs with Aging for Aggregates Exhibiting Specularity



Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging
2. 0/50 = unpolished to 50-minute MD polishing

Figure 5-8 Relative Percent Reduction in PS-ICA TI Thresholds and Field FNs with Aging for Aggregates Not Exhibiting Specularity

5.5 Summary

The purpose of work presented in this chapter was to identify PS-ICA TI thresholds for use in screening aggregates in terms of their suitability for friction performance in the field. PS-ICA TI values obtained at different MD polishing levels were analyzed. Two indicators, percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing for limestone aggregate without specularity effect and percent reduction in PS-ICA TI between 50-minute and 180-minute MD polishing for granite or siliceous wackestone with specularity effect, were determined to provide the most promising approach to interpret TI values for use in pre-evaluating change in surface roughness characteristics. Efforts resulted in establishment of thresholds of these two parameters for use in pre-evaluation of aggregates. Findings associated with the objective are summarized as follows:

- For aggregates not exhibiting specularity effect (i.e., limestone), a maximum allowable reduction of 50 percent in PS-ICA TI between unpolished and 50-minute MD polishing was recommended to provide suitable friction performance.
    - Due to the specific nature of exceptionally high original surface roughness for all limestone aggregates evaluated in this study, further evaluation of this threshold may be required for more common types of limestone.
- For aggregates exhibiting specularity effect (i.e., granite or siliceous wackestone), a maximum allowable reduction of 10 percent in PS-ICA TI between 50-minute and 180-minute MD polishing was recommended for suitable friction performance.
- Results of historical field friction performance analysis for studied aggregates using FN support the validity of the PS-ICA TI indicators identified for use as thresholds in this study.

CHAPTER 6

EVALUATION OF MICRO-DEVAL (MD) PERFORMANCE IN POLISHING AGGREGATES

6.1 Background

Previous research has indicated that Micro-Deval (MD) is a quick and reliable test that provides good correlation to field performance that can be used to evaluate aggregate abrasion resistance and durability for pavement applications (Lang et al., 2007 and Rogers, 2003). The MD apparatus consists of aggregates interacting with steel balls and water in a rotating steel container. MD test results, in conjunction with reliable aggregate surface roughness measurement methods, provide excellent potential to evaluate polishing resistance of aggregates from different sources for quality control or quality assurance purposes. Figure 6-1 shows MD apparatus and Figure 6-2 illustrates aggregate and steel balls interaction mechanism in MD apparatus.

Figure 6-1 MD Apparatus

Figure 6-2 Aggregate and Steel Balls Interaction Mechanism in MD Apparatus (Masad et al., 2009)

The American Association of State Highway and Transportation Officials (AASHTO) adopted MD as a standard test method (AASHTO T327) in 2005 entitled “Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus.” According to the AASHTO T327 testing procedure, 1,500 grams of aggregate samples are washed and soaked in water for at least 1 hour prior to test. The prepared samples are then placed in a steel container and loaded with 5,000 grams of steel balls and 2000 ml of tap water. The sample is subjected to approximately 9,600 to 12,000 revolutions, and the weight loss of samples (i.e. weight of aggregate that passed a #16 sieve size) is calculated and reported.

The purpose of the work presented herein was to evaluate MD performance in terms of its ability to polish aggregates to levels similar to those observed in aggregates from in-service pavements. This was accomplished by evaluating MD-polished and field-polished aggregates using scanning electron microscopy (SEM). SEM visual images and surface roughness parameters obtained from the unpolished and polished aggregate samples were evaluated for this purpose. Efforts were also made to compare results of SEM roughness parameters before and after MD polishing with historical field friction performance data to identify any correlations between the results. The following tasks were involved in accomplishing this objective:

- Assess validity of SEM results to determine whether changes in SEM surface roughness parameters consistently reflect changes in surface roughness observed in SEM visual images.
- Once confidence in SEM results is established, then evaluate MD performance by comparing SEM-derived surface roughness parameters obtained from MD-polished aggregates to those obtained from field-polished aggregates.
- Determine whether any correlations exist between changes in SEM surface roughness parameters before and after MD polishing and changes in historical friction numbers (FNs) measured in the field.

6.2 Confidence in SEM Results

Two surface roughness parameters (S_a and S_q) were measured using one SEM device on all nine aggregates shown in Table 2-1. Since similar trend was observed between S_a and S_q results in terms of percent reduction with MD polishing and field polishing, only S_a result was used to simplify and to avoid redundancy. Figure 6-3 shows percent reduction in SEM S_a between unpolished and 180 minute MD-polished specimens were positive for all nine aggregates. This indicates reduction in surface roughness of aggregates induced by MD polishing was captured by reduction in SEM S_a. Figures 6-4 through 6-7 show SEM images obtained from unpolished and 180 minute MD polished samples for two representative aggregates exhibiting specularity and aggregates not exhibiting specularity, respectively. For each aggregate type, two sets of images were selected: one exhibiting lower percent reductions in S_a (GA553 and 87339) and the other exhibiting higher percent reduction in Sa (70693 and 87145). Comparison of SEM visual images obtained before and after MD polishing and percent reduction in surface roughness parameters indicated that aggregates with smoother surface after MD polishing resulted in higher percent reductions in SEM S_a. Also, rougher surfaces were observed in visual images after MD polishing for aggregates with lower percent reductions in SEM S_a. This physical change visually confirmed by SEM images verified that the SEM results effectively capture and quantify reduction in surface roughness of aggregates induced by MD polishing. SEM images and surface roughness parameters obtained before and after MD polishing for all aggregates are included in Appendices A and B.

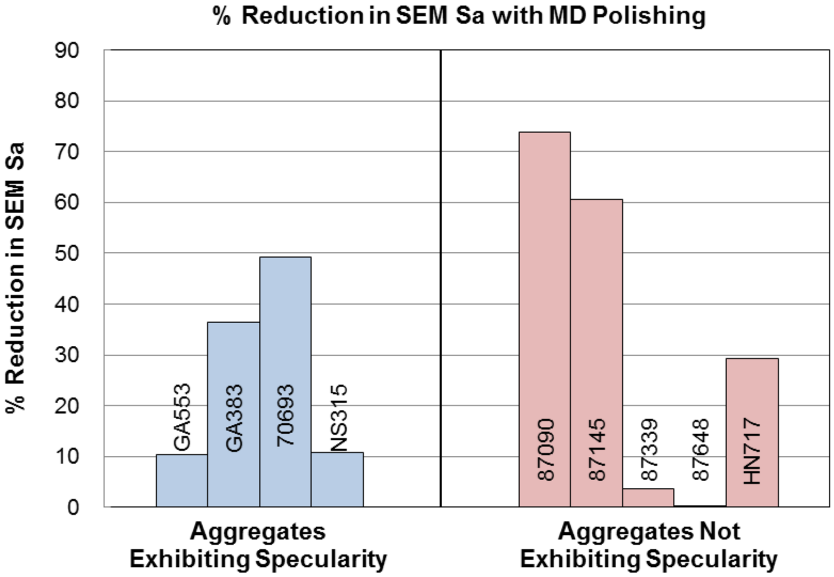
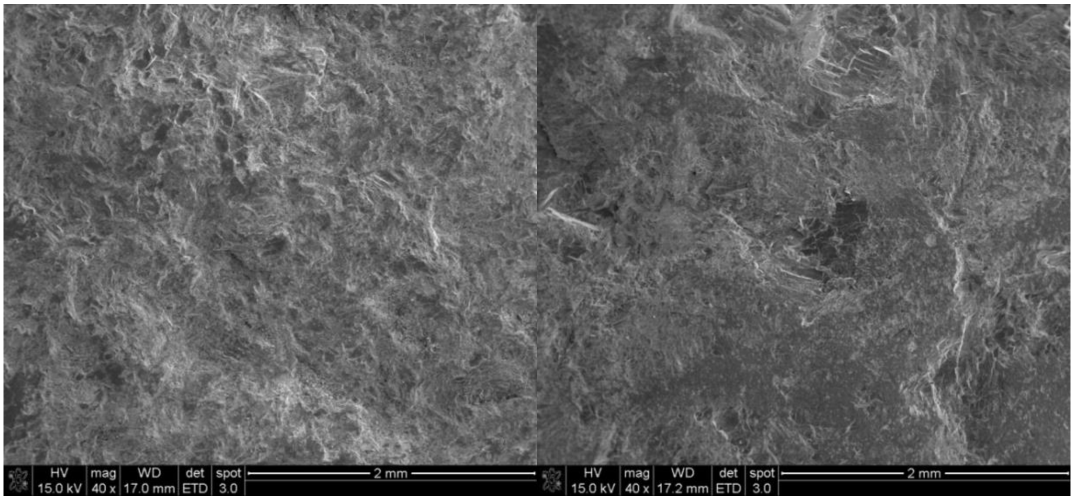
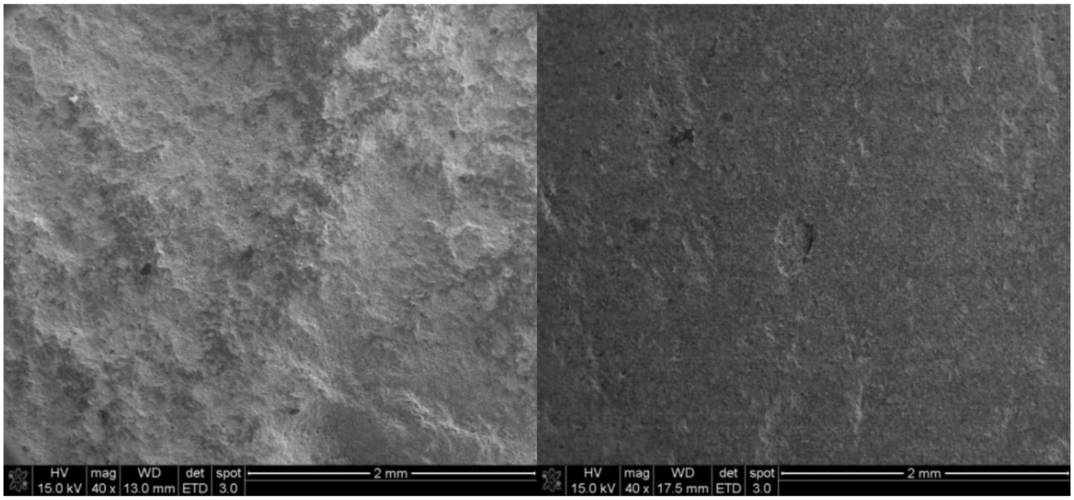


Figure 6-3 Percent Reductions in SEM S_a with MD Polishing



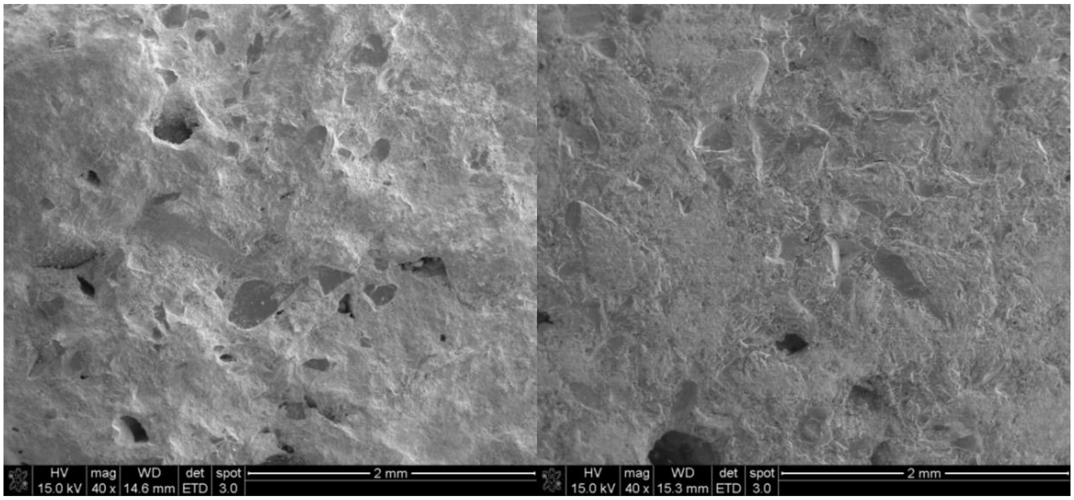
(a) unpolished (b) 180 minute MD polished

Figure 6-4 SEM Images Obtained from Unpolished and Polished Aggregate Samples for GA553 (Lower Percent Reduction in S_a with MD Polishing)



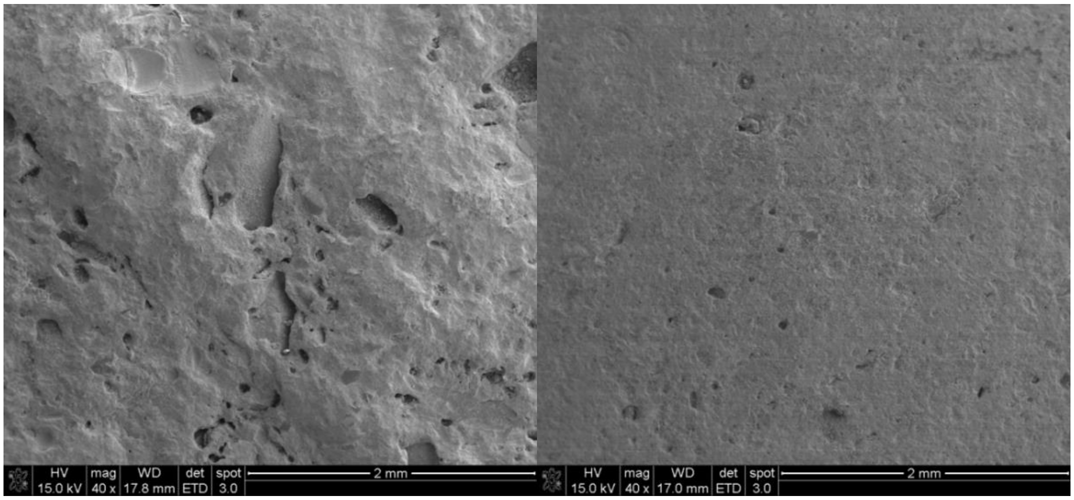
(a) unpolished (b) 180 minute MD polished

Figure 6-5 SEM Images Obtained from Unpolished and Polished Aggregate Samples for 70693 (Higher Percent Reduction in S_a with MD Polishing)



(a) unpolished (b) 180 minute MD polished

Figure 6-6 SEM Images Obtained from Unpolished and Polished Aggregate Samples for 87339 (Lower Percent Reduction in S_a with MD Polishing)

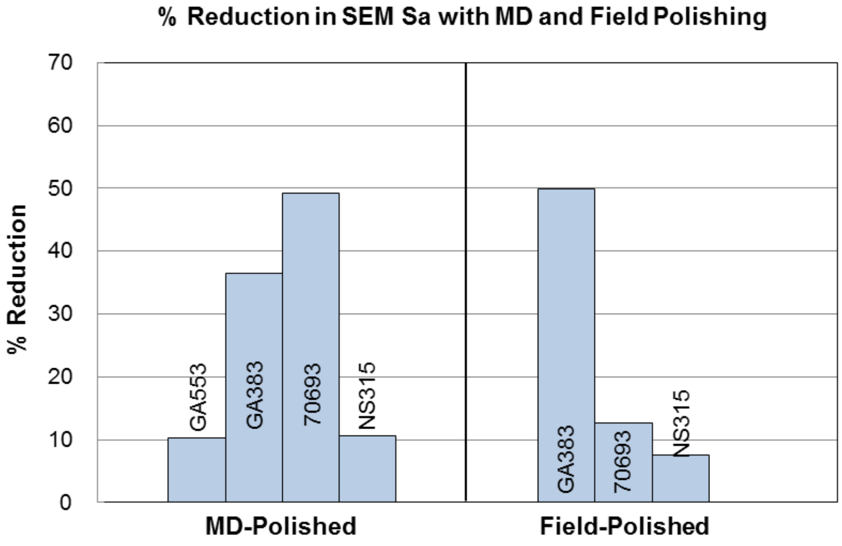


(a) unpolished (b) 180 minute MD polished

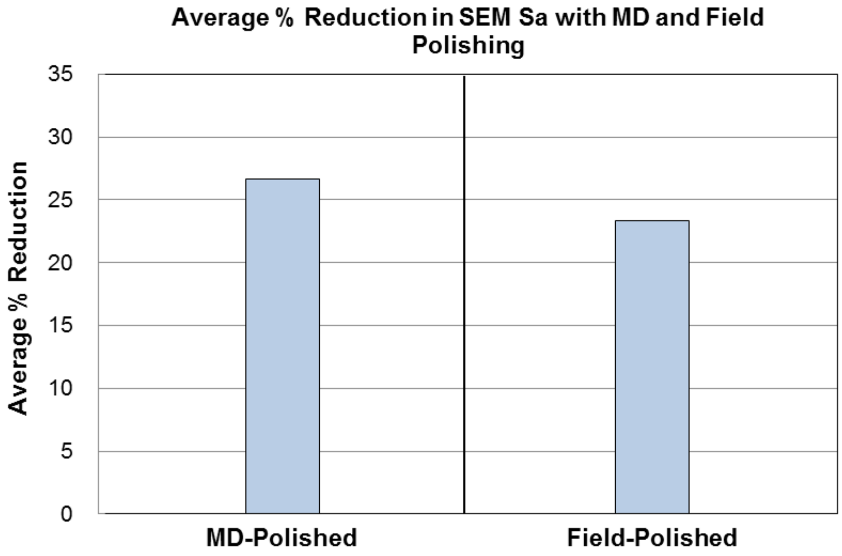
Figure 6-7 SEM Images Obtained from Unpolished and Polished Aggregate Samples for 87145 (Higher Percent Reduction in S_a with MD Polishing)

6.3 Evaluation of MD Performance

Figures 6-8 and 6-9 show percent reduction in SEM S_a measured using MD-polished and field-polished samples for aggregates exhibiting specularity and aggregates not exhibiting specularity. It is noted that results obtained from field-polished GA553 samples, which exhibited an increase in percent reduction of S_a between unpolished and field-polished condition, were not included. For both aggregate types, the range of percent reduction in SEM S_a measured from MD-polished samples was comparable to that obtained from field-polished samples. This indicates that MD resulted in polishing levels similar to those observed in aggregates from in-service pavements. Overall, aggregates not exhibiting specularity indicated about five to ten percent higher average reduction in SEM Sa than aggregates exhibiting specularity for both MD-polished and field-polished conditions. However, no clear correlations were observed for results of individual aggregates between MD-polished and field-polished conditions. This is probably due to potential factors other than reduction in surface roughness that affect Sa results of field-polished aggregates, including dust, breaks, and absorbed asphalt on aggregate surface. Also, there are too many uncontrolled variables between field-polished aggregate samples obtained from different sections (e.g., aging time, traffic, etc.) to reach more definitive explanations.

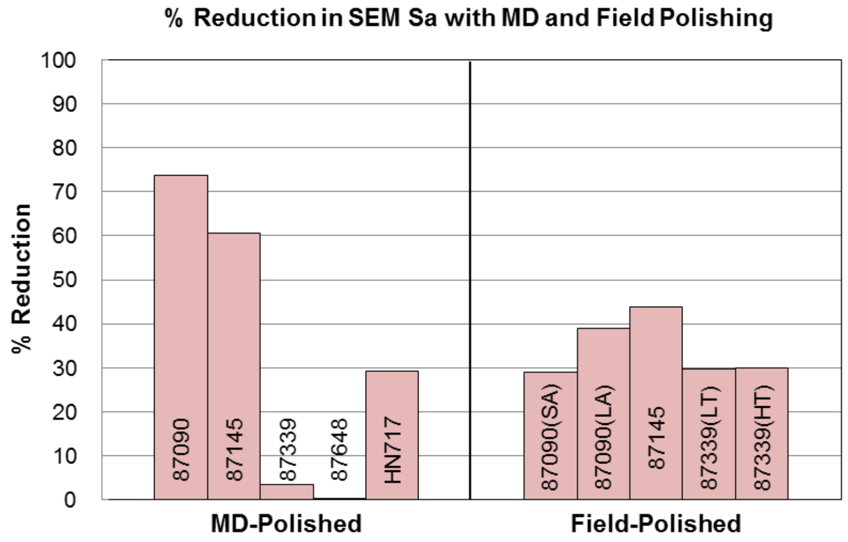


(a) individual aggregates

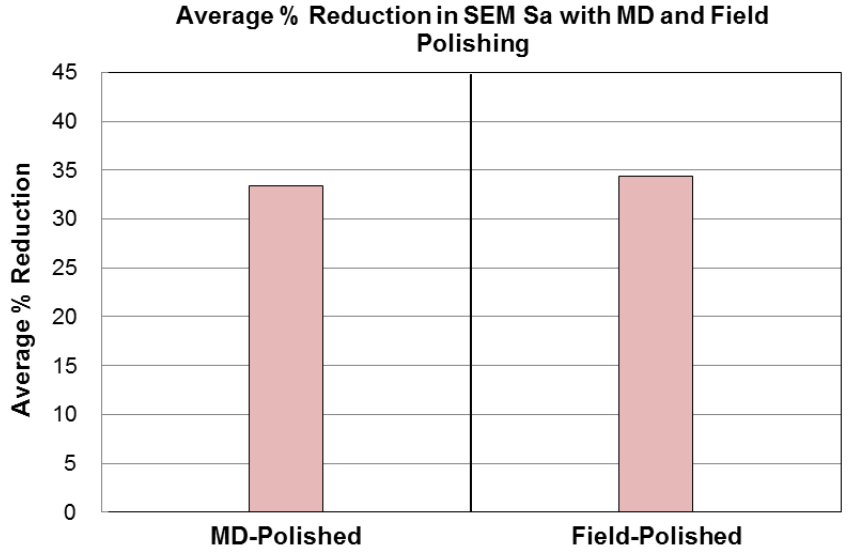


(b) average

Figure 6-8 Percent Reductions in SEM S_a with MD and Field Polishing for Aggregates Exhibiting Specularity



(a) individual aggregates

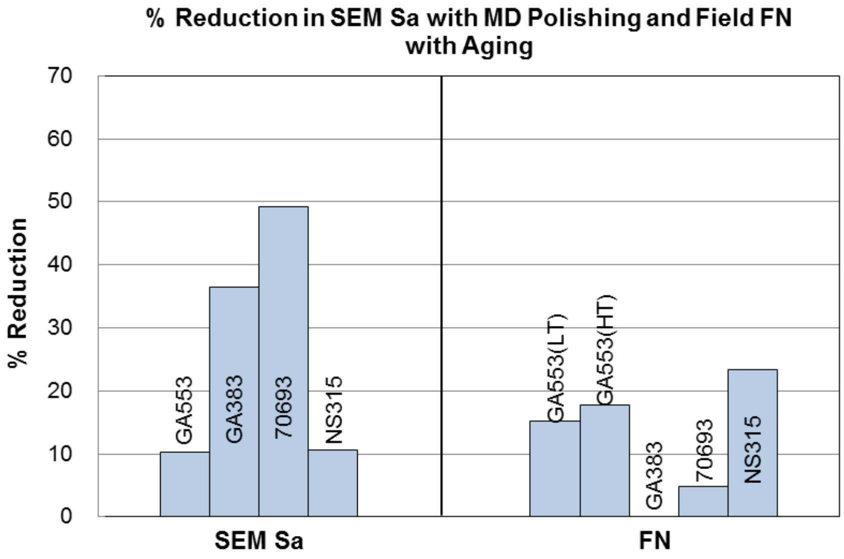


(b) average

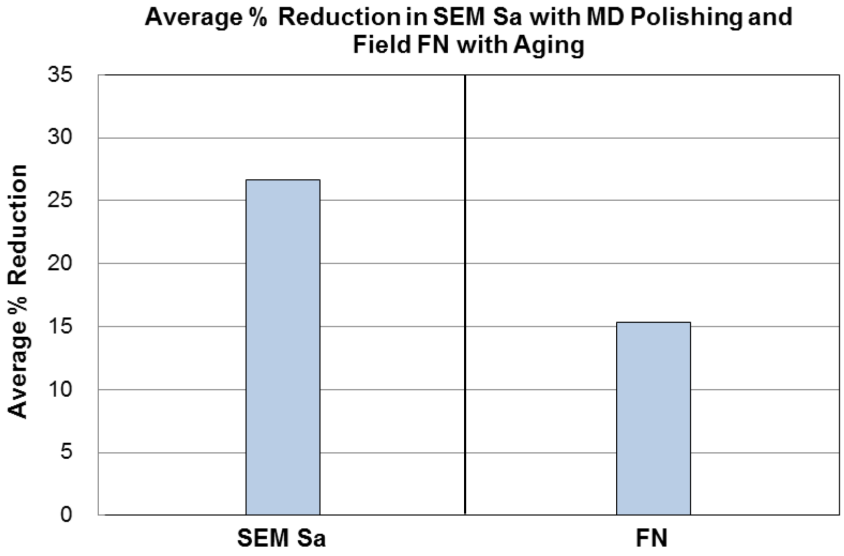
Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging

Figure 6-9 Percent Reductions in SEM S_a with MD and Field Polishing for Aggregates Not Exhibiting Specularity

Figures 6-10 and 6-11 show percent reduction in SEM S_a for MD-polished samples and percent reduction in field FN for aggregates exhibiting specularity and aggregates not exhibiting specularity. Percent reduction in FN for field project sections was determined using historical FN data shown in Figure 5-3 (Roque et al. 2016). Results indicate that average reduction in SEM S_a of 25 percent (aggregates exhibiting specularity) and 35 percent (aggregates not exhibiting specularity) with MD polishing corresponded to about 15 percent average reduction in FN in the field for both aggregate types. It is interesting to note that both SEM roughness parameters with MD polishing and historical FN in the field exhibited a range of positive percent reduction. This may further support the validity of MD performance in terms of its ability to simulate relevant changes in surface roughness induced by field aggregate polishing. However, there are too many potential variables that affect historical FN measurements between different field sections (e.g., traffic, design speed, climate, layer material properties, drainage condition, surface contamination) to expect correlations between MD polishing and field FN for individual aggregates.



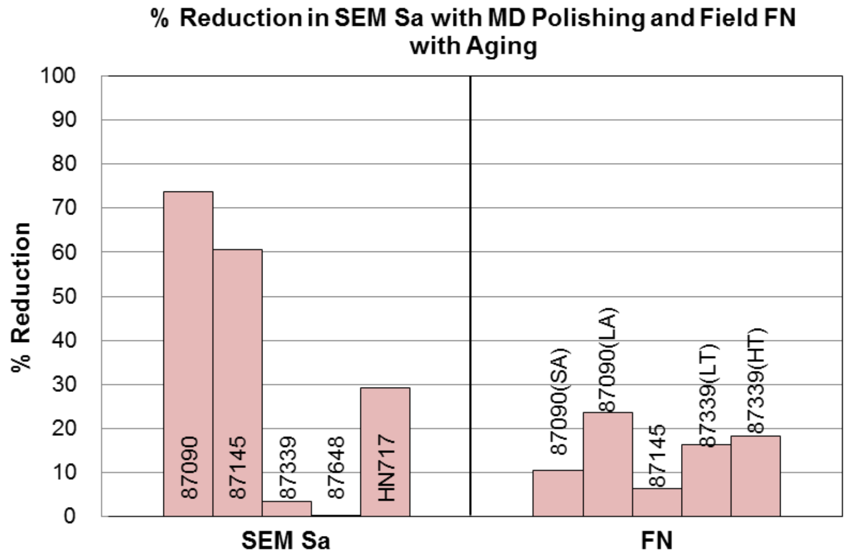
(a) individual aggregates



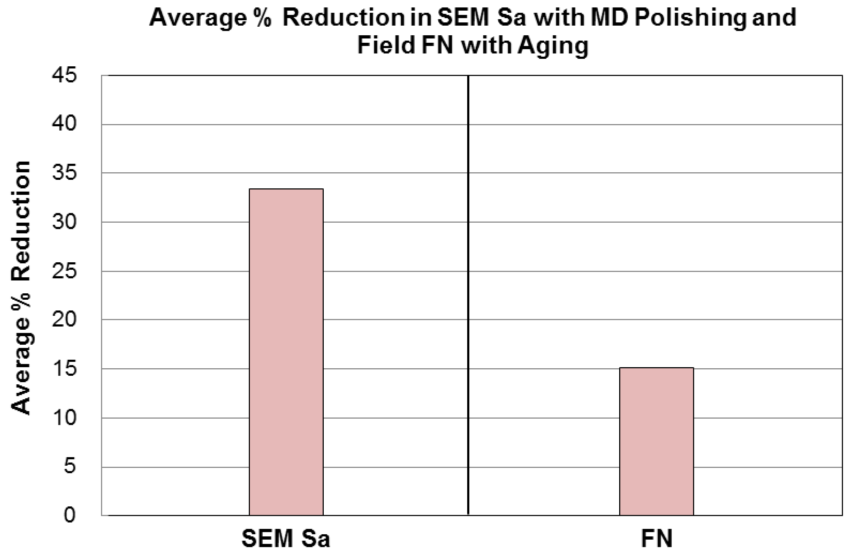
(b) average

Note: 1. LT = Lower Traffic, HT = Higher Traffic

Figure 6-10 Percent Reduction in SEM S_a with Field FN with Aging for Aggregates Exhibiting Specularity



(a) individual aggregates



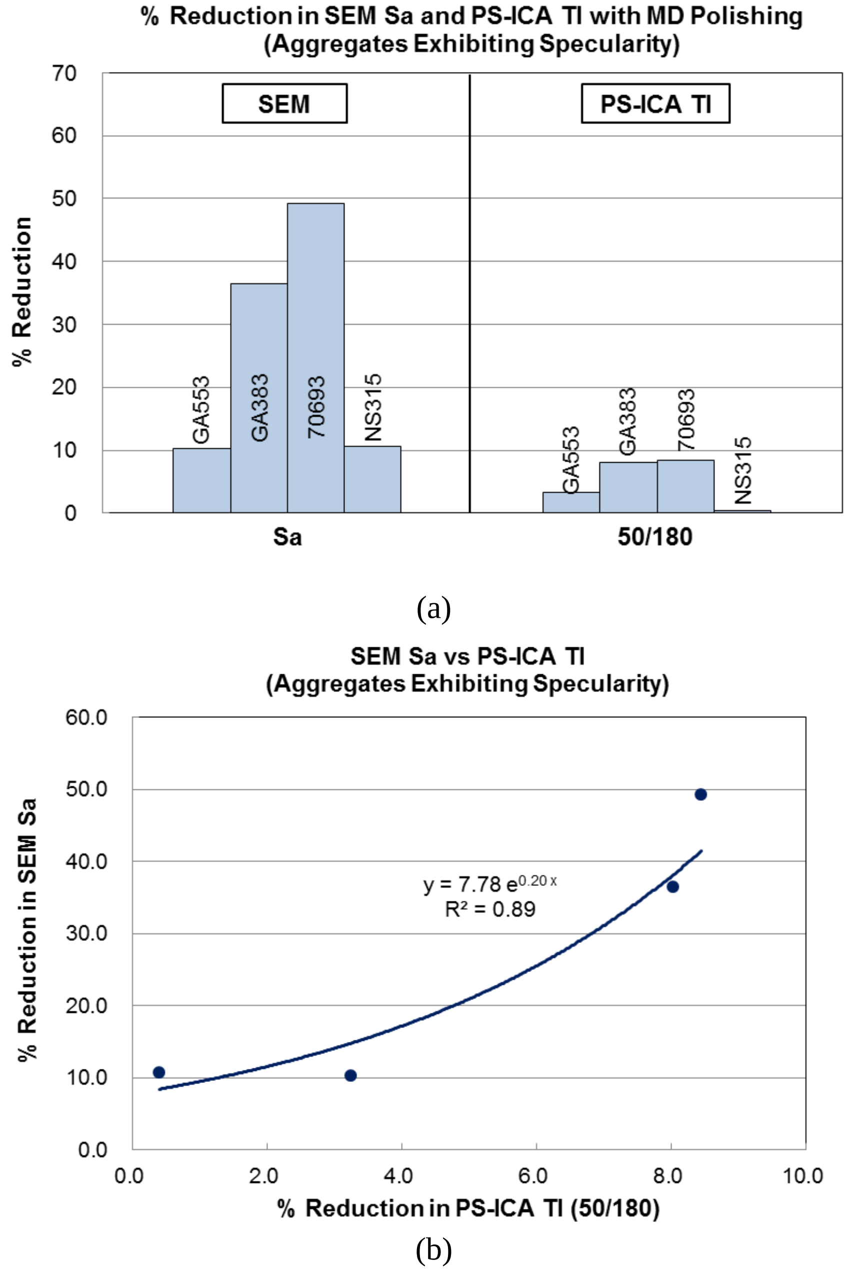
(b) average

Note: 1. LT = Lower Traffic, HT = Higher Traffic, SA = Shorter Aging, and LA = Longer Aging

Figure 6-11 Percent Reduction in SEM S_a with Field FN with Aging for Aggregates Not Exhibiting Specularity

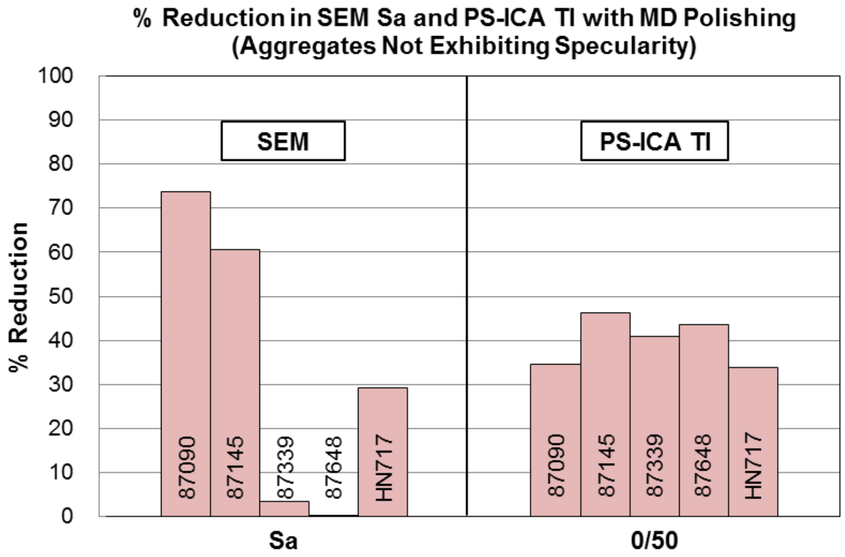
6.4 Correlations between SEM Roughness Parameters and PS-ICA TI Thresholds

Efforts were made to identify whether any trends exist between the indicators used in PS-ICA TI threshold assessment and SEM roughness parameter S_a. Figure 6-12 indicates around 25 percent average reduction in SEM S_a between unpolished and 180-minute MD polishing resulted in about five percent average reduction in PS-ICA TI between 50-minute and 180-minute MD polishing. For aggregates exhibiting specularity, Figure 6-12 shows a potential correlation between SEM roughness parameter S_a and PS-ICA TI thresholds, which further supports the validity of the PS-ICA TI indicators identified for use as thresholds in this study. As shown in Figure 6-13, for aggregates not exhibiting specularity, an average reduction in SEM S_a of 35 percent between unpolished and 180-minute MD polishing resulted in around 40 percent average reduction in PS-ICA TI between unpolished and 50-minute MD polishing, which indicates comparable results in terms of average percent reductions between the two parameters evaluated. However, no apparent correlations were identified between SEM roughness parameters and PS-ICA TI thresholds for individual aggregates.



Note: 1. 50/180 = 50- to 180-minute MD polishing

Figure 6-12 Percent Reduction in SEM S_a and PS-ICA TI with MD Polishing



Note: 1. 0/50 = unpolished to 50-minute MD polishing

Figure 6-13 Percent Reduction in SEM S_a and PS-ICA TI with MD Polishing

6.5 Summary

MD performance was evaluated in terms of its ability to polish aggregates to levels similar to those observed in aggregates from in-service pavements. Findings and remarks associated with the objective are summarized as follows:

- Comparison of SEM visual images obtained before and after MD polishing and percent reductions in surface roughness parameters indicated that aggregates with rougher surface after MD polishing resulted in lower percent reductions in SEM Sa. The fact that physical changes visually observed by SEM images were captured by reduction in SEM Sa indicated the SEM results effectively quantified reduction in surface roughness of aggregates induced by MD polishing.
- Both for aggregates exhibiting specularity and aggregates not exhibiting specularity, average percent reduction in SEM Sa measured from MD-polished samples was similar to that

obtained from field-polished samples. This indicates that MD resulted in polishing levels comparable to those observed in aggregates from in-service pavements.

  - In general, limestone aggregates exhibited about five to ten percent higher average reduction in SEM Sa than granite aggregates for both MD-polished and field-polished conditions.
  - However, there are too many uncontrolled variables between field-polished aggregate samples obtained from different sections to reach more definitive explanations in terms of correlations between MD-polished and field-polished conditions.

- Results of SEM roughness parameters before and after MD polishing and historical FN support the validity of MD performance in terms of its ability to simulate relevant changes in surface roughness induced by field aggregate polishing.
  - However, there are too many potential variables that affect historical FN measurements between different field sections to expect correlations between MD polishing and field FN for individual aggregates.

CHAPTER 7
CLOSURE

7.1 Summary and Findings

Evaluation of the Aggregate Imaging Measurement System (AIMS) image processing system and the Micro-Deval (MD) accelerated polishing technique was conducted to develop procedures for pre-evaluation of aggregates to quickly and reliably screen aggregates with different frictional performance. Thresholds were established for use in screening aggregates in terms of their suitability for frictional performance in the field based on texture index (TI) parameters determined using an approach called Photometric Stereo-Independent Component Analysis (PS-ICA) method with modified light intensity. The PS-ICA method and modified light intensity were developed to mitigate effects of color variation and specularity, which had been found to artificially increase and sometimes overwhelm the effect of surface roughness on TI. The main findings of this study are summarized below:

<u>Evaluation of PS-ICA Methods</u>

- It was determined that the PS-ICA method in conjunction with modified light intensity resulted in the most consistent and reliable values of texture index (PS-ICA TI) to effectively characterize frictional performance for all aggregates evaluated.
- However, PS-ICA method with modified light intensity could not completely mitigate effects of specularity that causes erroneous results in texture analysis.
- PS-ICA TI values were determined to be most closely related to independent texture measurements obtained from scanning electron microscopy (SEM) analysis, which were not influenced by color variation or specularity.

Identification of the Best Approach to Interpret PS-ICA TI

- Percent reduction in PS-ICA TI between unpolished and 50-minute MD polishing appears to best reflect surface roughness changes caused by polishing for aggregates not exhibiting specularity (limestones).
  - Higher PS-ICA TI after continued polishing beyond 105-minutes appears to have been caused by exposure of additional pores, cavities, and increased specularity resulting from very smooth surface of these light-colored aggregates.
- Percent reduction in PS-ICA TI between 50-minute and 180-minute MD polishing appears to have the best potential for use in evaluating surface roughness changes in aggregates exhibiting strong specularity (granites or siliceous wackestone).
  - Change in PS-ICA TI between unpolished and 50-minute MD polishing for these aggregates strongly reflected the increase in specularity, which overwhelmed the effect of reduction in surface roughness on TI.
  - MD polishing greater than 50-minute (50-minute to 105-minute and 105-minute to 180- minute) for granite aggregates resulted in a combination of increasing PS-ICA TI caused by increased specularity effect and reduction in PS-ICA TI induced by MD polishing.
  - The change in PS-ICA TI between 50-minute and 180-minute MD polishing consistently resulted in reduction of PS-ICA TI for all aggregates evaluated, indicating that the effect of MD polishing on reducing surface roughness was coming through more strongly than the effect of specularity.

Identification of PS-ICA TI Threshold for Pre-Evaluation of Aggregates

- For aggregates not exhibiting specularity effect (limestone), a maximum allowable reduction of 50 percent in PS-ICA TI between unpolished and 50-minute MD polishing was determined based on aggregates well-known to exhibit acceptable frictional performance in the field.
  - Due to the specific nature of exceptionally high original surface roughness for all limestone aggregates evaluated in this study, further evaluation of this threshold may be required for more common types of limestone.
- For aggregates exhibiting specularity effect (granite or siliceous wackestone), a maximum allowable reduction of 10 percent in PS-ICA TI between 50-minute and 180-minute MD polishing was determined based on aggregates well-known to exhibit acceptable frictional performance in the field.

Evaluation of MD Performance in Polishing Aggregates

- MD polishing was determined to result in polishing levels comparable to those observed in aggregates from in-service pavements.
  - The range of percent reductions in SEM roughness parameters measured from MD-polished samples were similar to those obtained from field-polished samples for all aggregates evaluated.

7.2 Conclusions

Texture index (TI) obtained from the PS-ICA system with modified light intensity developed for use with the AIMS image processing method, along with MD accelerated polishing technique, can be used for pre-evaluation purpose to effectively screen aggregates with different frictional performance. The two PS-ICA TI thresholds, depending on whether aggregates exhibiting specularity or not, are recommended for screening.

LIST OF REFERENCES

Al-Rousan, T., Masad, E., Tutumluer, E., and Pan, T., "Evaluation of Image Analysis Techniques for Quantifying Aggregate Shape Characteristics," *Journal of Construction and Building Materials*, Vol. 21, No. 5, 2007.

Benson, F. J., "Effects of Aggregate Size, Shape, and Surface Texture on Properties of Bituminous Mixtures – A Literature Survey," in *Highway Research Board Special Report,* Issue 109, Transportation Research Board, National Research Council, Washington, D. C., pp. 12-22, 1970.

Brown, E. R., McRea, J. L., and Crawley A. B., "Effect of Aggregates on Performance of Bituminous Concrete," in *Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements* (STP24555S), H. Schreuders and C. Marek, Eds., ASTM International, West Conshohocken, PA, pp. 34-63, 1989.

Camilo, H. L. J., *Surface Roughness Estimation by 3-D Stereo SEM Reconstruction*, Master Thesis, Universidad Nacional de Colombia, Colombia, 2015.

Dahir S., "A Review of Aggregate Selection Criteria for Improved Wear Resistance and Skid Resistance of Bituminous Surfaces," *Journal of Testing and Evaluation*, Vol. 7, 1979.

Diringer, K. T., and Barros, R. T., "Predicting the Skid Resistance of Bituminous Pavements through Accelerated Laboratory Testing of Aggregates," *Surface Characterization of Roadways, International Research and Technologies*, ASTM International, West Conshohocken, PA, Vol. 1301, pp. 61-76, 1990.

Florida Department of Transportation (FDOT), *Florida Test Method for Friction Measuring Protocol for Patterned Pavements,* (FM 5-592), FDOT, Tallahassee, FL, September 2014.

Fletcher, T., Chandan, C., Masad, E., and Sivakumar, K., "Aggregate Imaging System for Characterizing the Shape of Fine and Coarse Aggregates," *Transportation Research Record, Journal of Transportation Research Board*, Vol. 1832, pp. 67-77, 2003.

Goldstein, J., Newbury, D. E., Joy, D. C., Lyman, C. E., Echlin, P., Lifshin, E., Sawyer, L., Michael, J. R., *Scanning Electron Microscopy and X-Ray Microanalysis,* 3rd Edition, Springer, New York, 2003.

Hocken, R. J., Chakraborty, N., and Brown, C., Optical Metrology of Surfaces. *CIRP Annals-Manufacturing Technology*, Volume 54, Issue 2, pp. 169-183, 2005.

Kandhal, P. S., and Parker Jr, F., *Aggregate Tests Related to Asphalt Concrete Performance in Pavements,* National Cooperative Highway Research Program Report 405, Transportation Research Board, Washington, D. C., 1998.

Kowalski, K. J., *Influence of Mixture Composition on the Noise and Frictional Characteristics of Flexible Pavements*, Ph.D. Dissertation, Purdue University, West Lafayette, IN, 2007.

Kokkalis A. G., "Prediction of Skid Resistance from Texture Measurements," *Proceedings of the Institution of Civil Engineers: Transportation*, Vol. 129, No. 2, pp. 85-93, 1998.

Lang, A. P., Range, P. H., Fowler, D. W., and Allen, J. J., "Prediction of Coarse Aggregate Performance by Micro-Deval and Other Soundness, Strength, and Intrinsic Particle Property Tests," *Transportation Research Record, Journal of Transportation Research Board*, No. 2026, National Research Council, Washington D. C., 2007.

Loberg, J., Mattisson, I., Hansson, S., and Ahlberg, E., "Characterization of Titanium Dental Implants I: Critical Assessment of Surface Roughness Parameters," *The Open Biomaterials Journal*, Vol. 2, pp. 18-35, 2010.

Masad, E., "Review of Imaging Techniques for Characterizing the Shape of Aggregates Used in Asphalt Mixes," *ICAR 9th Annual Symposium*, 2001.

Masad, E., Al-Rousan, T., Button, J., Little, D., and Tutumluer, E., *Test Methods for Characterizing Aggregate Shape, Texture, and Angularity,* Final Report of NCHRP Project 555, National Cooperative Highway Research Program, Washington, D. C., 2007.

Masad, E., Rezaei, A., Chowdhury, A., and Harris, P., *Predicting Asphalt Mixture Skid Resistance based on Aggregate Characteristics*, Texas Transportation Institute, Research Report 09/0-5627-1, Texas A&M University, College Station, TX, 2009.

McDaniel, R. S., and Coree, B. J., *Identification of Laboratory Techniques to Optimize Superpave HMA Surface Friction Characterization*, Phase I Final Report SQDH 2003-6, North Central Superpave Center, Purdue University, West Lafayette, IN, 2003.

Ravanshad, A. *Image Texture Analysis to Evaluate Frictional Characteristics of Aggregates*, Ph.D. Dissertation, University of Florida, Gainesville, FL, 2014.

Ravanshad, A., Roque, R., Khodam, H. M., and Tebaldi, G., "Extracting Aggregate Surface Microtexture from Stereo Image Using a Blind Source Separation Algorithm," *Journal of Computing in Civil Engineering*, 2015.

Reed, S. J. B., *Electron Microprobe Analysis and Scanning Electron Microscopy in Geology*, 2nd Edition, Cambridge, New York, 2005.

Rogers, C. A., "Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario," *Advances in Aggregate and Armourstone Evaluation 13,* 2003.

Roque, R., Ravanshad, A., and Lopp, G., *Use of Aggregate Image Measurement System (AIMS) to Evaluate Aggregate Polishing in Friction Surfaces*, Final Report of Florida Department of Transportation, University of Florida, Gainesville, FL, August 2013.

Roque, R., and Ravanshad, A., "Application of Imaging Techniques to Evaluate Polishing Characteristics of Aggregates, Task 1: Evaluation of the PS-ICA Method," *Task Report of Florida Department of Transportation*, University of Florida, Gainesville, FL, July 2015.

Roque, R., and Ravanshad, A., "Application of Imaging Techniques to Evaluate Polishing Characteristics of Aggregates, Task 2: Evaluation using Profiler," *Task Report of Florida Department of Transportation*, University of Florida, Gainesville, FL, November 2015.

Roque, R., Ravanshad, A., and Chun, S., "Application of Imaging Techniques to Evaluate Polishing Characteristics of Aggregates, Task 3: Evaluate Physical Interpretation of Image," *Task Report of Florida Department of Transportation*, University of Florida, Gainesville, FL, December 2015.

Roque, R., Ravanshad, A., and Chun, S., "Application of Imaging Techniques to Evaluate Polishing Characteristics of Aggregates, Task 4: Evaluate Thresholds for Screening the Aggregates," *Task Report of Florida Department of Transportation*, University of Florida, Gainesville, FL, December 2016.

Schmit J., Creath K., and Wyant J. C., *Surface Profilers, Multiple Wavelength, and White Light Intereferometry, Optical Shop Testing*, John Wiley & Sons, Inc., 3rd Edition, 2007.

Sun, W., Wang, L., and Tutumluer, E., "Image Analysis Technique for Aggregate Morphology Analysis with Two-Dimensional Fourier Transform Method," *Transportation Research Record, Journal of Transportation Research Board*, Vol. 2267, pp. 3-13, 2012.

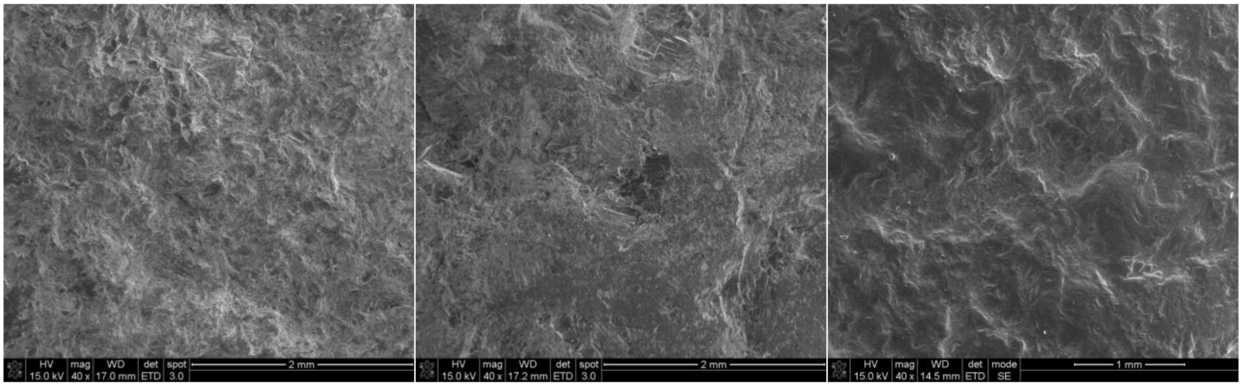
Tutumluer, E., Pan, T., and Carpenter, S. H., *Investigation of Aggregate Shape Effects on Hot-Mix Asphalt Performance Using an Image Analysis Approach*, Transportation Pooled Fund Study TPF-5 (023), FHWA, U.S. Department of Transportation and University of Illinois at Urbana-Champaign, 2005.

Woodside, A. R., and Woodward, W. D. H., *Wet Skid Resistance*, Inc. O'Flaherty, Highways, The Location, Design, Construction and Maintenance of Road Pavements, Elsevier Ltd, 2002.

Wu, J., *Rotation Invariant Classification of 3D Surface Texture Using Photometric Stereo*, Ph.D. Dissertation, Heriot-Watt University, Edinburgh, 2003.

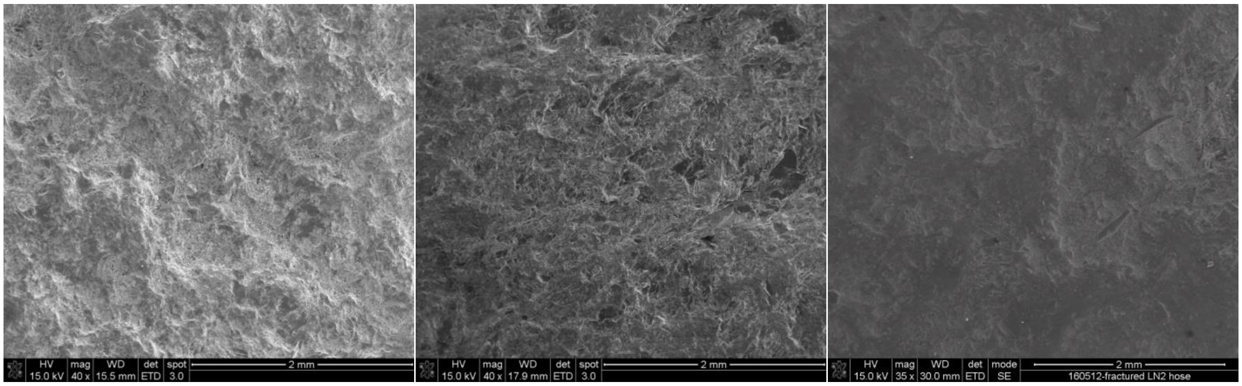
Vorburger, T. V, Rhee, H. G., Renegar, T. B., Song, J. F., and Zheng, A., "Comparison of Optical and Stylus Methods for Measurement of Surface Texture," *International Journal of Advanced Manufacturing Technology*, Vol. 33, pp. 110-118, 2007.

APPENDIX A: SEM IMAGES OBTAINED FROM UNPOLISHED, MD-POLISHED AND FIELD-POLISHED AGGREGATE SAMPLES



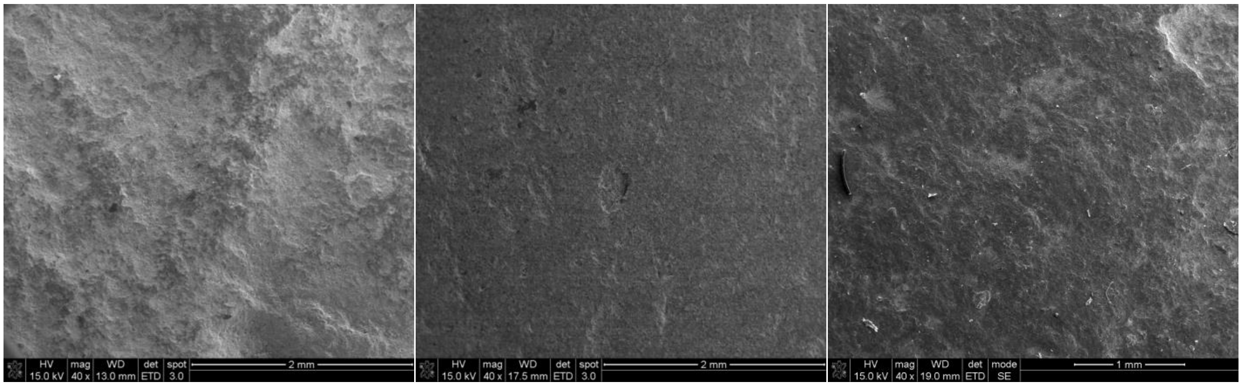
(a) unpolished (b) MD-polished (c) field-polished

Figure A-1 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for GA553



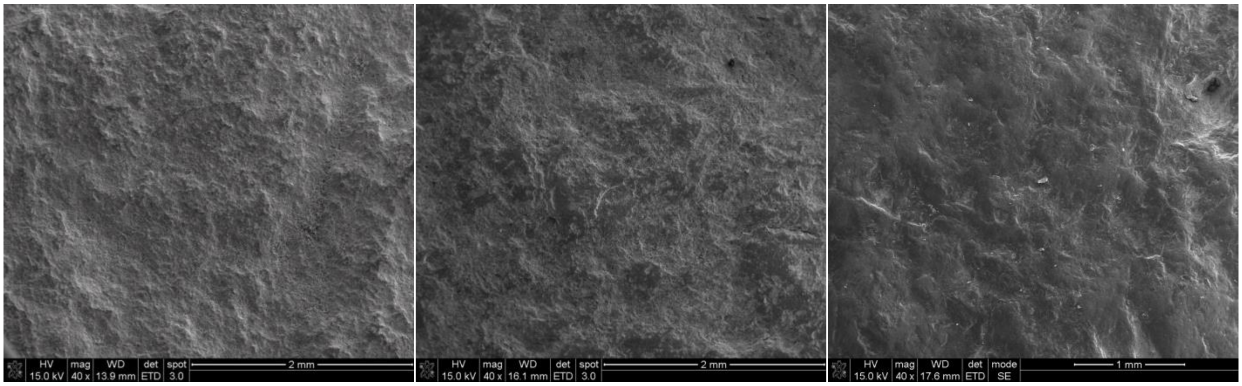
(a) unpolished (b) MD-polished (c) field-polished

Figure A-2 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for GA383



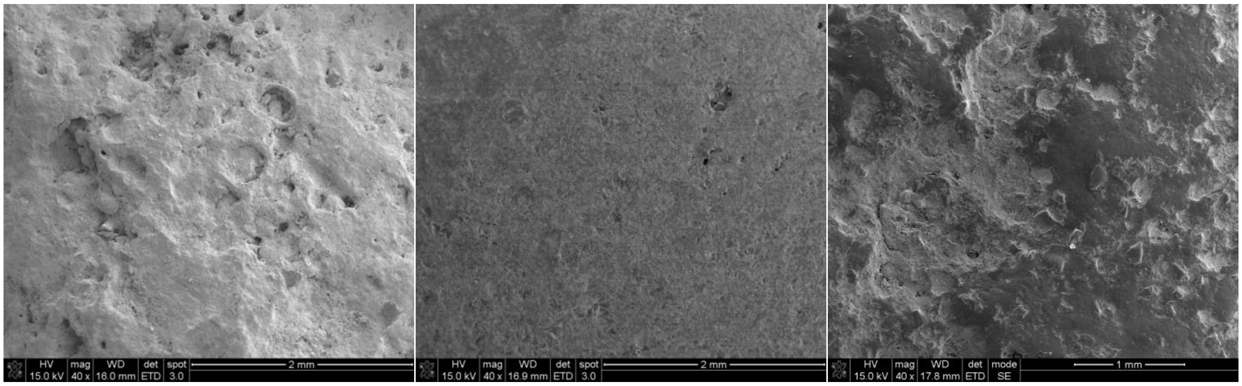
(a) unpolished (b) MD-polished (c) field-polished

Figure A-3 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 70693



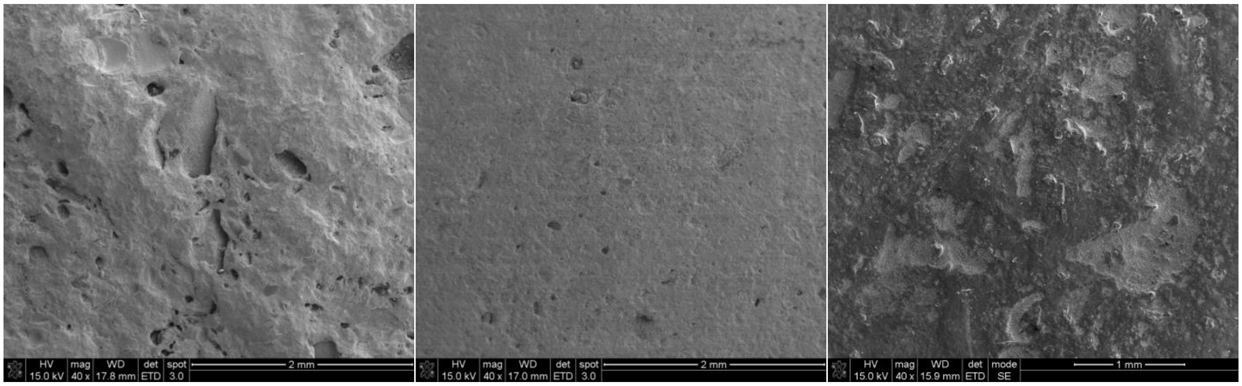
(a) unpolished (b) MD-polished (c) field-polished

Figure A-4 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for NS315



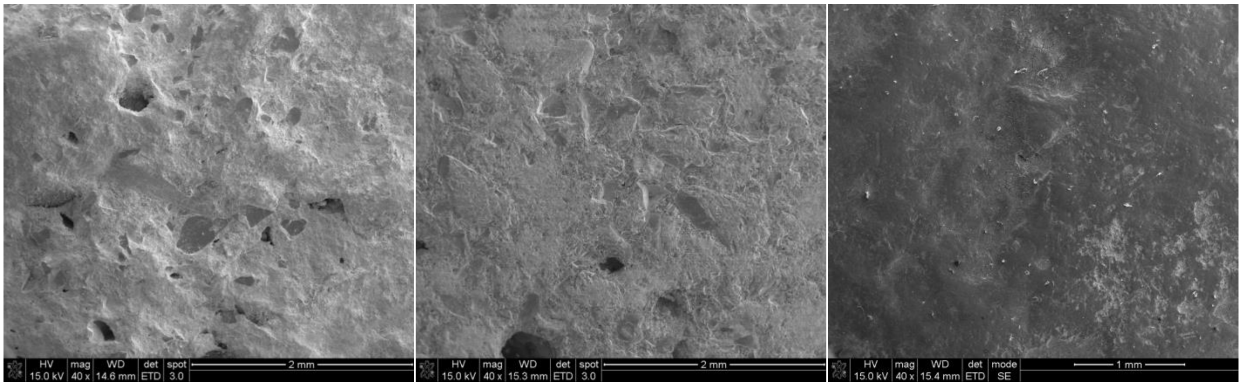
(a) unpolished (b) MD-polished (c) field-polished

Figure A-5 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87090



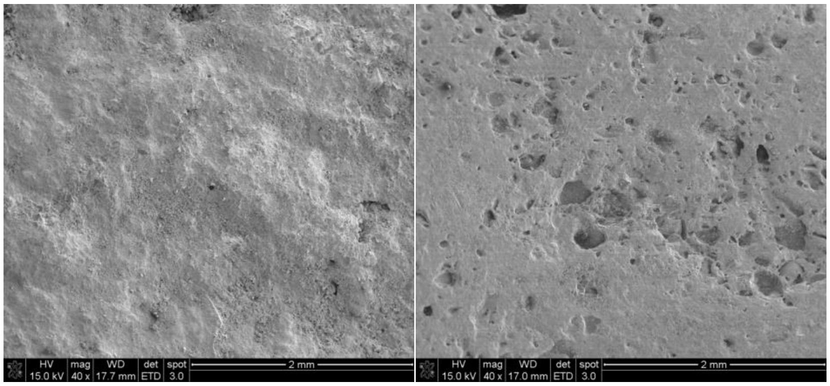
(a) unpolished (b) MD-polished (c) field-polished

Figure A-6 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87145



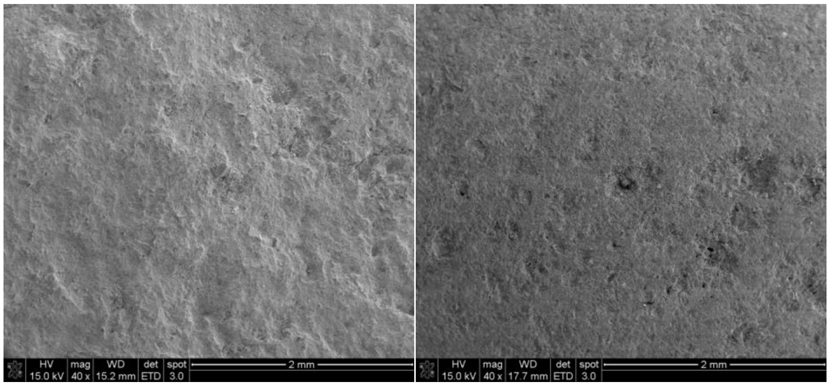
(a) unpolished (b) MD-polished (c) field-polished

Figure A-7 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87339



(a) unpolished (b) MD-polished

Figure A-8 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87648 (Image for field-polished sample is not applicable.)



(a) unpolished (b) MD-polished

Figure A-9 SEM Images Obtained from Unpolished, MD-Polished, and Field-Polished Aggregate Samples for HN717 (Image for field-polished sample is not applicable.)

APPENDIX B: SEM SURFACE ROUGHNESS PARAMETER FOR UNPOLISHED, MD-POLISHED, AND FIELD-POLISHED AGGREGATE SAMPLES

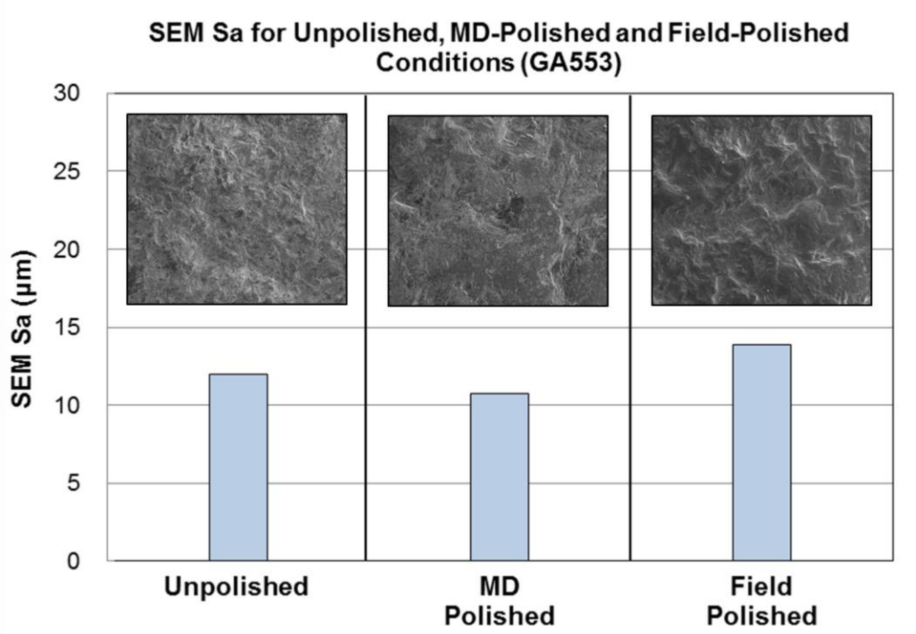


Figure B-1 SEM Surface Roughness Parameter for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for GA553

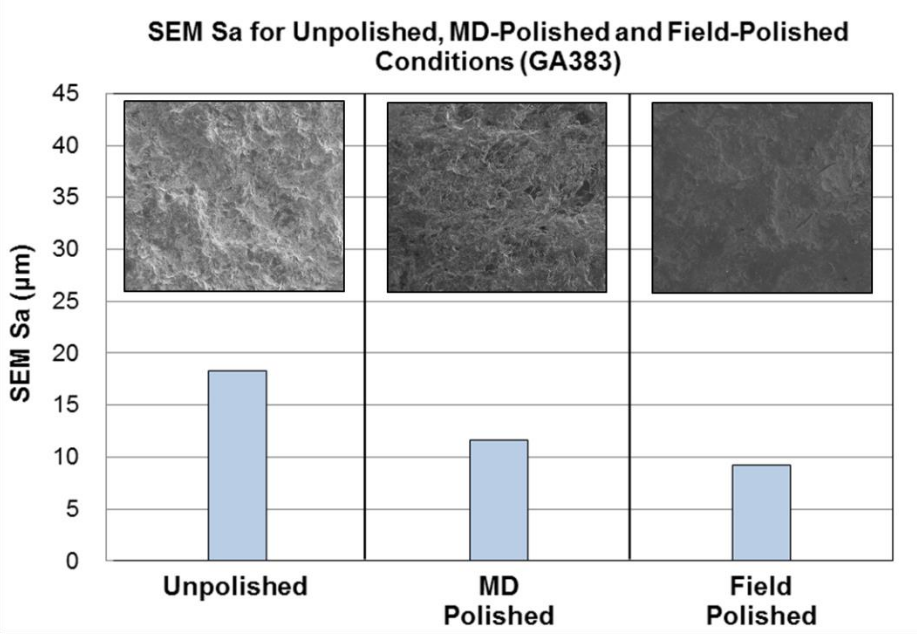


Figure B-2 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for GA383

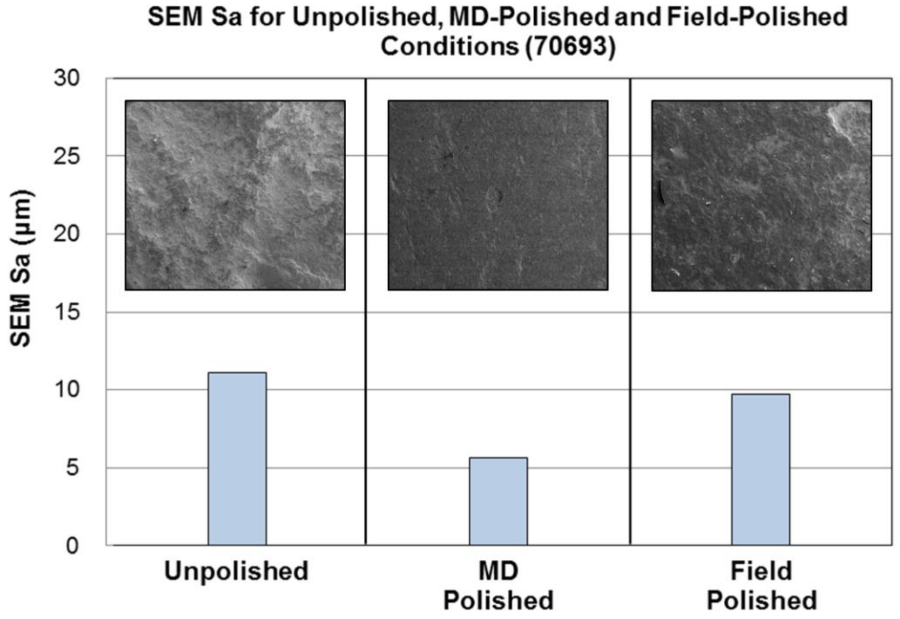


Figure B-3 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 70693

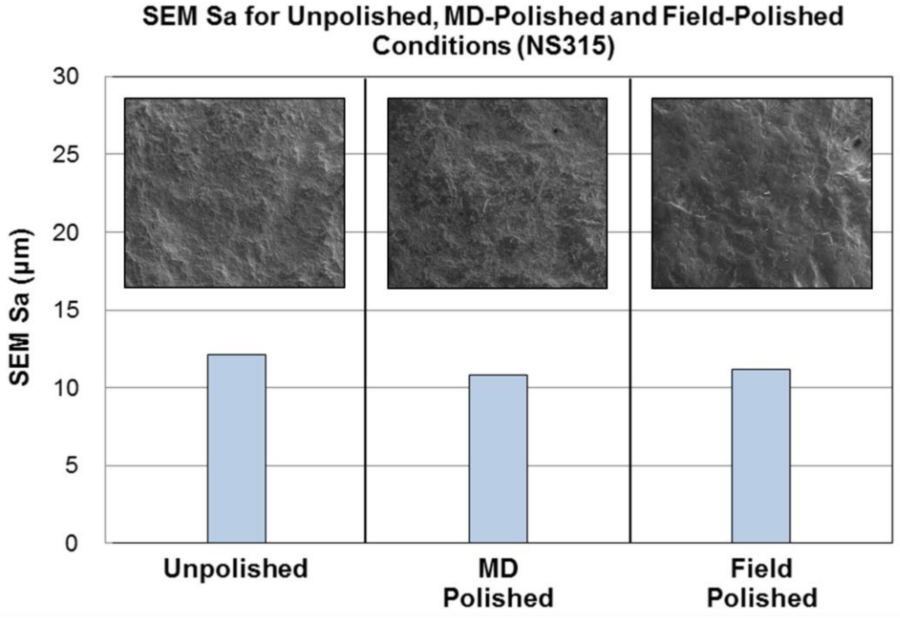


Figure B-4 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for NS315

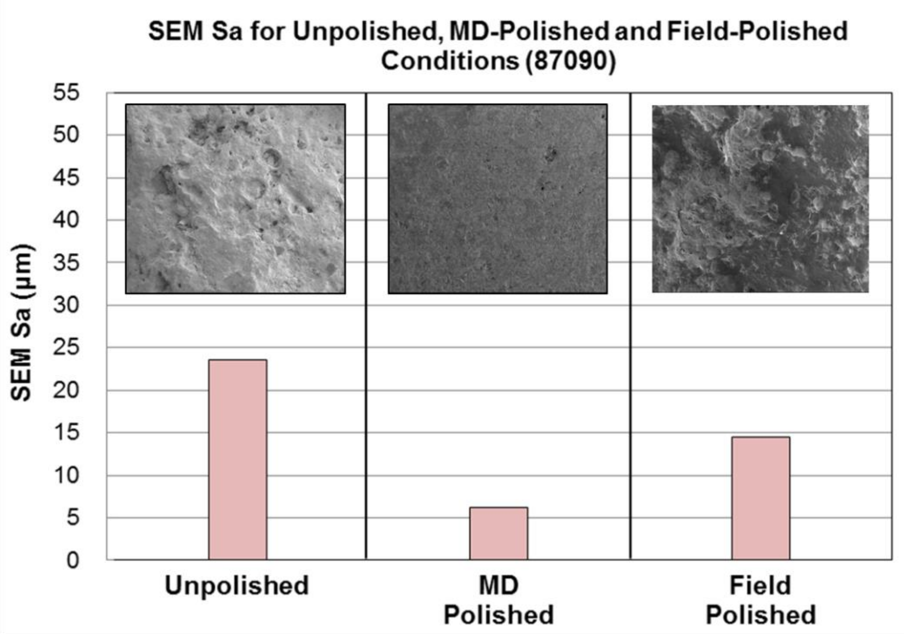


Figure B-5 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87090

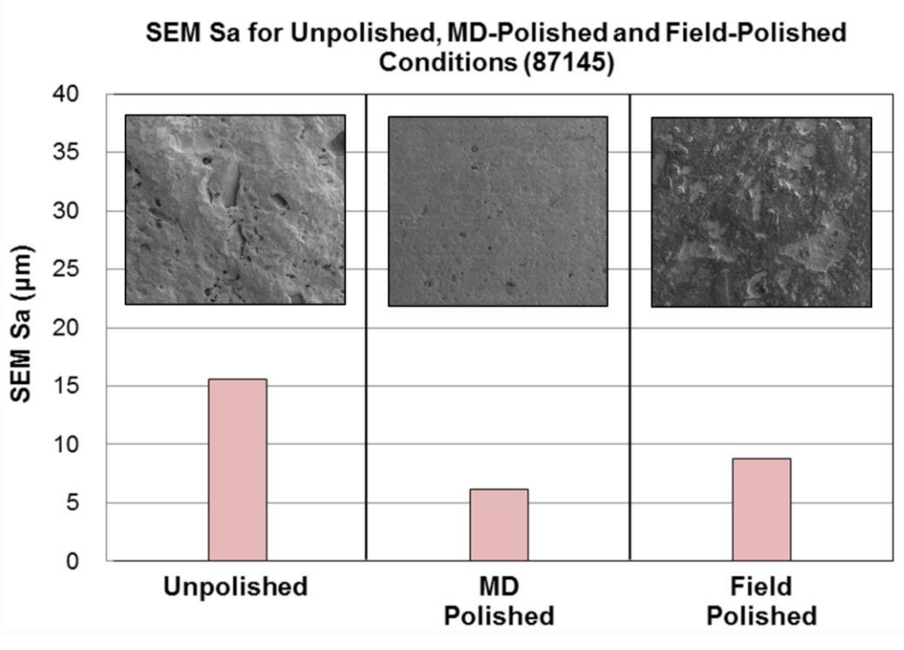


Figure B-6 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87145

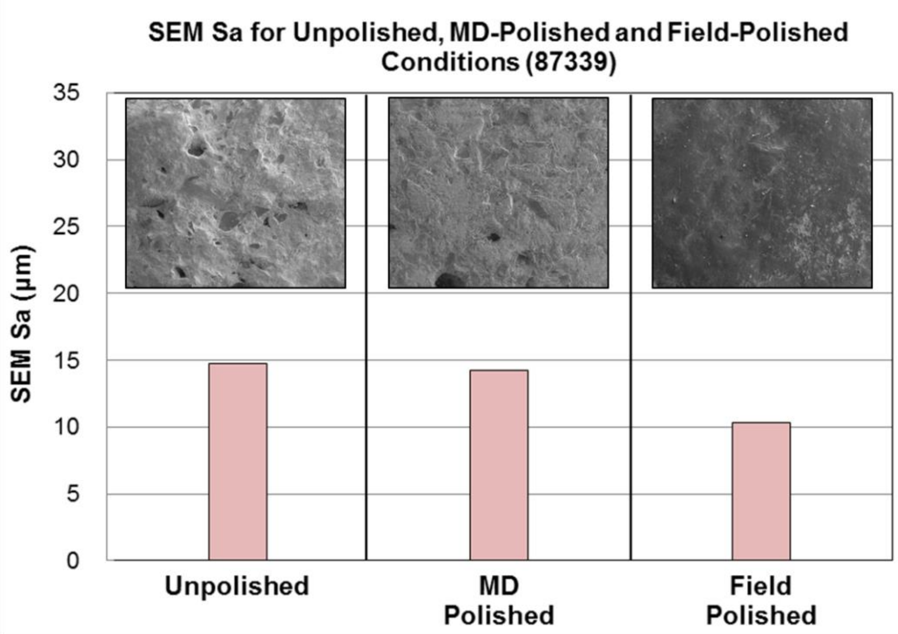


Figure B-7 SEM Surface Roughness Parameters for Unpolished, MD-Polished, and Field-Polished Aggregate Samples for 87339