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Aggregate Image Measurement System 2 (AIMS2): Final Report

Highways for LIFE Technology Partnership Program
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FOREWORD

Aggregate shape characteristics influence the structural performance of hot-mix asphalt, hydraulic cement concrete, and unbound aggregate pavement layers, as well as the skid resistance of pavement. Their accurate classification is essential to stone-matrix and warm-mix asphalt technologies. This report documents the development and testing of an industry-ready tool—the Aggregate Image Measurement System 2 or AIMS2—to evaluate aggregate shape properties using digital imaging. Testing procedures using the AIMS2 have been adopted as Provisional Standards by the American Association of State Highway and Transportation Officials. The technology has the potential to improve the quality, durability, and safety of pavements.

The refinement of the late-stage prototype and interlaboratory study of the AIMS2 was supported by a grant from the Highways for Life Technology Partnerships Program. The Technology Partnerships Program provided grants to assist general industry make the leap from promising late-stage prototypes to market-ready products and promoted partnerships with State and local highway agencies to demonstrate the technologies under real-world conditions.

This report will be of interest to State and local departments of transportation, Federal Highway Administration division offices, highway research institutions, aggregate producers, and highway construction contractors.

Cover photo courtesy of Pine Instrument.

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16. Abstract:

As part of a national initiative sponsored by the Federal Highway Administration under the Highways for LIFE program, Pine Instrument Company was awarded a grant to improve the design of the research instrument to analyze aggregate properties using digital imaging technology, conduct a ruggedness study on the new design, perform an interlaboratory study, and evaluate the potential commercial viability of the new instrument. This final report outlines the work and conclusions of this project.

Current methods for determining the characteristics of aggregate shapes, which influence the structural performance of asphalt design, hydraulic cement concrete, and unbound aggregate pavement layers, are difficult, time-consuming, and subjective. This report describes a project to improve the design of the Aggregate Image Measurement System 2 (AIMS2), which uses a variable magnification microscope-camera system and two different lighting configurations to capture aggregate images for analysis and software with the ability to objectively quantify aggregate shapes on the macro and micro scales. Also reported are the results of a ruggedness study on the improved design, an interlaboratory study, and an evaluation of the commercial viability of the new instrument.

Comparison testing showed that the AIMS1, the research prototype, and the AIMS2 provided similar ranking of aggregates and comparable results. Ruggedness testing validated that operating parameters were appropriately controlled and provided reproducible results. The interlaboratory study, which involved 32 laboratories, found that AIMS2 outputs have reasonable coefficients of variation for all sizes of aggregate excepting the 0.075-mm size. The project demonstrated that AIMS2 can provide objective and reproducible shape characterization of aggregates.

Considerable interest in the AIMS2 has been demonstrated in the United States and other countries, and marketing is being pursued by the manufacturer.

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SI* (MODERN METRIC) CONVERSION FACTORS

Symbol	When You Know	Multiply By	To Find	Symbol
		APPROXIMATE CONVERSIONS TO SI UNITS		
		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 yard	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 (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	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	35.314	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 (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
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	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

EXECUTIVE SUMMARY

The overall project scope of Highways for LIFE grant to Pine Instrument Company was to improve the design of the research instrument to analyze aggregate properties using digital imaging technology, conduct a ruggedness study on the new design, perform an interlaboratory study, and evaluate the potential commercial viability of the new instrument. This final report outlines the work and conclusions of this project.

Aggregate shape characteristics are well known to be important in influencing the structural performance of asphalt design, hydraulic cement concrete, and unbound aggregate pavement layers. The current methods for determining these characteristics have proven to be difficult, time-consuming, and subjective. An industry need has been identified to develop a technology platform to measure these material characteristics utilizing consistent, repeatable, and objective means for both within-laboratory and between-laboratory situations. Such a technology platform must withstand the marketability thresholds and commercial viability expectations of the industry.

The equipment developed and used in the initial research was intended for investigating the possibility of using digital image analysis to characterize aggregate shape properties and to investigate the relationship of those characterizations to pavement and aggregate performance. It was not selected with manufacturability or laboratory usability as primary objectives. This initial technology platform proved the applied concepts feasible, but the technology also proved to be expensive and cumbersome to operate. Therefore, a new system was needed that met both the cost and functionality needs of the industry. This grant project developed a product that melded marketability and applicability into an industry tool.

The Aggregate Image Measurement System 2 (AIMS2) technology uses a variable magnification microscope-camera system and two different lighting configurations to capture aggregate images for analysis. The first lighting scheme creates a backlit image, which provides a particle silhouette. This image is converted to a binary tiff file analyzed for the shape characteristics of angularity and cross-sectional form. The second lighting scheme utilizes oblique top lighting, which illuminates the surface of each particle. A gray-scale image of the particle surface is captured and analyzed providing a surface texture characterization. The three-dimensional form of each particle is also extracted from the focal plane position, at the particle surface, while the texture image is captured.

While the system in its entirety is commonly referred to as the AIMS2, the heart of the technology is the AIMS SOFTWARE©. This software consists of a series of algorithms that objectively quantify aggregate shape properties on the macro scale, which are features greater than 0.5 mm such as angularity, form, and flat and elongated ratios, as well as features on the micro scale, which are typically less than 0.5 mm in size, such as surface texture. Both coarse and fine aggregates are characterized with the AIMS Software© algorithms. For simplicity, the entire system, including both hardware and software, is simply referred to here as the AIMS2.

During this project, a migration from the original research prototype platform, designated AIMS1, to a newly designed product platform, designated AIMS2, was accomplished. Upon

completion of the new design, independent laboratory testing was conducted on the AIMS2 hardware platform. This testing included the calibration of the AIMS2 to the AIMS1 as well as experiments to confirm that the testing methodology was sound. Texas A&M University was selected to perform the tests on the new equipment under the direction of Dr. Eyad Masad. The facility was selected because of its staff's extensive expertise in materials research and experience with the AIMS1 research system, as well as its extensive database containing a variety of well-characterized materials.

The results of the comparison testing between AIMS1 (the research system) and AIMS2 (the system developed within this project) proved that the two systems provide the same ranking of aggregates and provide comparable results. Additionally, the ruggedness testing validated that operating parameters were appropriately controlled and provided reproducible results. Specific parameters and control limits are recommended to ensure reproducible AIMS2 characterization.

Phase II of this project conducted an interlaboratory study (ILS) utilizing eight AIMS2 systems in more than 32 laboratories. The statistical analysis of the ILS data shows that the system outputs have reasonable coefficients of variation for all sizes of aggregate except the 0.075 mm. Additional work is necessary to address the 0.075-mm (ASTM #200) sieve size variability.

The ILS also provided a foundation for the precision statements of the proposed test methods for testing aggregate materials with digital imagery. The procedures that were developed address the need for conformity in the testing methodology that is required to take this technology to a level of acceptance. Research shows clear links of aggregate shape to pavement performance. This project demonstrated the ability of AIMS2 to provide an objective and reproducible shape characterization of aggregates. As the technology is applied on a wider scale, establishing clear relationships between the AIMS2 characterizations values and in-place pavement performance will be a goal.

Because there is a need for objective and accurate aggregate shape characterization and the ILS experiment demonstrated the AIMS2 as a robust tool for characterizing aggregate materials, there is a great deal of interest in the AIMS2 technology from many U.S. State transportation departments as well as from various entities in Canada, Brazil, China, and Italy. Domestic aggregate producers have also expressed interest as this technology provides a means for quantifying the consistency and quality of aggregate products.

Pine Instrument Company is pursuing the traditional facets of marketing—pricing, placement, packaging, and promotion—in addition to other aspects of the commercial viability of AIMS2. The details are provided within this report.

The material testing procedures for aggregate material shape characterization using the AIMS2, which were developed and refined as part of this project, have been published as Provisional Standards by the American Association of State Highway and Transportation Officials.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

The Federal Highway Administration partially funded this project through the Highways for LIFE Technology Partnerships Program Grant DTFH61-08-G-00003. The purpose of the Technology Partnerships Program is to work with the highway construction industry to accelerate the adoption of promising innovations. The overall scope of this project, undertaken by Pine Instrument Company, was to take a system developed for research applications investigating aggregate shape characteristics and reconfigure it into an industry-viable tool. This technology utilizes digital imaging technology to capture and analyze images of aggregate particles to provide particle shape information. The goals of this grant were to improve the design, simplify the operation, establish the system and methodology as sound, perform an interlaboratory study to evaluate the precision of the results, and evaluate the commercial viability of the technology.

This Introduction provides a brief background into the importance of aggregate shape properties and how that importance led to this work and covers the scope and goals of the project. The Equipment section provides an overview of the technology concept and the initial research equipment in which the technology had been established. This section also discusses the new technology platform. The Experimental Plan section discusses the calibration of the new system to the original, the ruggedness testing, and the interlaboratory study (ILS) that was completed within this project. The Material Testing Procedures section discusses the test and practice procedures that have been developed as part of this effort, which have been adopted as Provisional Standards by the American Association of State Highway and Transportation Officials (AASHTO). The Commercialization section outlines Pine Instrument Company's plans and project observations regarding the viability of this technology platform. The Conclusion provides a concise summary of this project grant and the targeted path forward.

BACKGROUND

Aggregate shape characteristics are well known to be important in influencing the structural performance of hot-mix asphalt (HMA), hydraulic cement concrete, and unbound aggregate pavement layers. Aggregate shape characteristics also influence the skid resistance of pavement surfaces. As such, accurate and consistent characterization of these properties will contribute to the enhancement of pavement performance and public road safety.

Current methods utilized for evaluating aggregate shape characteristics have proven to be time-consuming and subjective. There has been an identified industry need for a system to evaluate these properties utilizing a consistent, repeatable, and objective methodology. Measuring the shape properties of aggregates with an objective system will yield significant and immediate benefits to the transportation industry that can be realized by incorporating the improved aggregate shape characterizations into the design of pavement structures. A technology platform that can offer an objective means of qualifying aggregate shape properties to meet specifications will help ensure consistent pavement performance.

In addition to improving pavement structural performance, a technology platform that provides automated, consistent, repeatable, and objective outcomes has the potential for increasing public safety by providing a means for qualifying aggregate shape and surface texture, which are related to pavement friction properties, sometimes referred to as skid resistance. Furthermore, as the development of warm-mix technology continues in pavement applications due to its reduced energy footprint, aggregate properties will continue to be a critical parameter in pavement design. Consequently, a system of this sort has the potential to contribute significantly to the design of safe, high-quality, and long-lasting pavements. Large savings due to reduced requirements for maintenance and rehabilitation can also be realized.

It is also believed that the lack of accurate characterization of aggregates can lead to specifications that either overemphasize the need for superior aggregate characteristics or, in contrast, allow for the use of marginal aggregates. The delivery of a technology platform as an industry tool that provides accurate and objective aggregate characterization will contribute to the improvement of pavement material specifications. This improvement in material characterization will allow highway engineers to accurately select locally available materials that can be used in pavement construction while maintaining, and potentially improving, pavement performance. The use of local materials is highly favorable given the cost and logistical issues associated with transporting aggregates long distances.

OBJECTIVE

The objective of this project undertaken by Pine Instrument Company in conjunction with the Federal Highway Administration was to design, develop, and fabricate a viable industry instrument to characterize aggregate shape properties utilizing digital imaging technology. This system would include hardware to capture the images and software capable of analyzing those images and to provide useful and meaningful data. As part of achieving this overall objective, a technology platform needed to be developed that would also withstand the tests of repeatability, reproducibility, objectivity, and ruggedness for both within-laboratory and between-laboratory situations. Finally, this technology platform needed to be evaluated against standard marketability thresholds and commercial viability expectations. The remainder of this report covers these areas in full detail.

CHAPTER 2. EQUIPMENT

TECHNOLOGY

This project was launched on the basis of a prototype research system that was designed for investigating the possibility of using digital image analysis to characterize aggregate shape properties and to investigate the relationship of those characterizations to pavement and aggregate performance. This research system was called the Aggregate Image Measurement System (AIMS1). The system was not designed with manufacturability or convenience of use as primary objectives, and the initial platform proved to be costly to manufacture and cumbersome to operate. Therefore, a new system design was selected that met both the objectives of the project and melded industry requirements and expectations into the system. This system is referred to as AIMS2.

To best understand this project, a brief understanding of the technology is needed. The original research prototype platform, AIMS1, used a variable magnification microscope-camera system and two different lighting modes to capture aggregate images for analysis. The first lighting scheme creates a backlit image, which provides a particle silhouette. This image is converted to a binary tiff file analyzed for the shape characteristics of angularity and cross-sectional form. The second lighting scheme utilizes top lighting, which illuminates the top of each particle. A high-magnification, gray-scale image of the particle surface is captured and analyzed for a micro-texture characterization. The height of each particle is also captured from the position of the focal plane in this texture image, providing a three-dimensional form of each particle.

ORIGINAL SYSTEM

The research system utilized a large panel backlight and a microscope ring light for these different illuminations. The illumination hardware on the research system was costly, and uniform illumination was difficult to achieve . The multiple interconnections between system components made setup and troubleshooting of the equipment difficult. The AIMS1 system also had no provision to eliminate ambient laboratory lighting from influencing the results. The AIMS1 system is shown in figure 1.

The heart of the systems is the AIMS Software©. Both coarse and fine aggregates are now characterized with the AIMS Software© algorithms. This software consists of a series of analysis algorithms that objectively quantify aggregate shape properties on both the macro scale (coarse and fine aggregate angularity, form, and flat and elongated ratio) as well as properties on a micro scale such as surface texture. For simplicity, the entire system will simply be referred to as the AIMS2.

Migration from the original AIMS1 research prototype platform to the newly designed AIMS2 production platform called retained the basic operating premise of variable magnification imaging combined with multiple illumination scenarios. However, it was desired to update the system components to less expensive and more robust hardware, to provide an enclosure to eliminate the ambient light concerns, and to simplify the overall equipment operation.

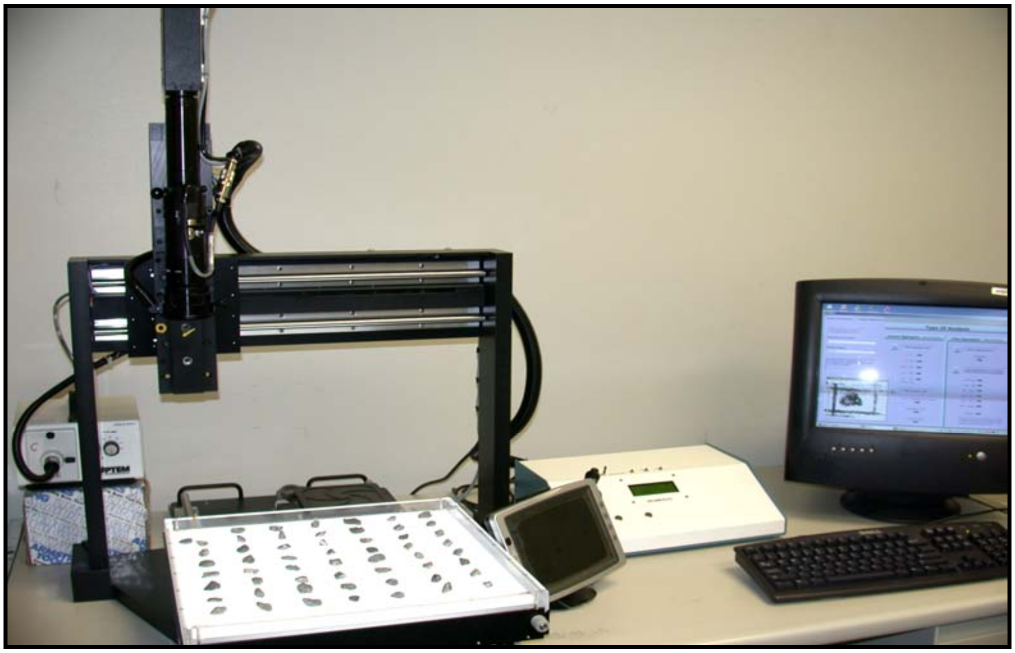

Figure 1. Photo. Original research Aggregate Imaging Measurement System equipment (AIMS1) (photo courtesy of Pine Instrument).

The new system hardware represents an improvement over the research equipment. The redesign addressed the issues with ambient lighting effects, improved both the backlighting and the top lighting performance, tackled manufacturability issues, and streamlined the operator interface. The new system represents an improvement in overall performance in an integrated system.

Camera technology had progressed significantly after the AIMS1 system was developed. Camera image sensor technology had increased available resolutions while decreasing costs. An updated camera was selected to take advantage of these technology improvements. The higher resolution camera also provided an opportunity to eliminate one of two objective lenses used on the research unit while maintaining the image resolution required for the analysis. The second objective lens had a different focal length, which required a second physical microscope position. The camera-microscope unit was repositioned manually; therefore, eliminating this second objective lens simplified the design and operation of the equipment.

The AIMS1 unit used a microscope ring light in conjunction with external spot lights to achieve the desired top lighting. This configuration was difficult to precisely control. The large backlight panel also proved to be difficult to control for uniform lighting over the entire scan area. Efficient, precise, long-lasting LED technology was selected for both the top-lighting and backlighting requirements to address these shortcomings.

NEW SYSTEM

The AIMS1 used an x-y-z gantry system to index the particles for imaging. This setup was expensive and difficult to align. A turntable configuration was selected for the AIMS2, powered by a stepper-motor gear-head combination to provide the sturdy platform needed for presenting the material to the imaging area. This configuration provides an added advantage by helping to reduce the size requirements of the backlight.

The AIMS2 turntable configuration utilizes a removable tray specific for each aggregate size to position the particles properly for imaging. The research system required the operator to place each coarse particle onto the table position accurately at specific grid points. The AIMS2 turntable trays simplify the material loading by requiring the operator to place the particles in a groove in the tray. Separation between particles is required, but the system also has routines to identify touching particles so that they are not included in the results. Fine particles are simply dispersed thinly over the tray groove in a manner similar to that used in the AIMS1 system.

Figure 2. Photo. New Aggregate Imaging Measurement System equipment (AIMS2) (photo courtesy of Pine Instrument).

In addition to making for easy cleanup, the removable tray design helps address another issue with the research equipment, associated with fine materials. The AIMS1 system was unable to capture images of translucent fine materials. Fine particles of light-colored materials often proved to be too translucent to provide adequate contrast and often were not captured with the original system’s backlighting. The new system allows for trays of different colors to help provide contrast between the material particles and the background. The new system is supplied with a black opaque tray and a selectable feature that permits the material sample to be top-lighted for contrast in lieu of backlighting.

The dispersal of the fine material samples over the image field of view in a manner that produces no touching particles is impractical. Analyzing multiple particles as though they were one incorrectly influences the output values generating erroneous data. The research AIMS1 system utilized a Touching Particle Factor (TPF) algorithm to detect multiple fine particles that touched, appearing as one mass. This TPF algorithm worked reasonably well but was based on particle area and was thus sensitive to actual particle size, even within a single Superpave sieve size.

A new algorithm was devised for the AIMS2 system that reduced the sensitivity to particle size. This new method of detecting and removing touching particles from the analysis uses a geometric evaluation based on shape, called the convex hull perimeter. The convex hull perimeter is a track circumscribing the perimeter of the particle outline without any concave features. Areas around the perimeter that have a concave shape, like the valleys typically created when particles touch, are bridged. This convex hull perimeter is compared to the length of the actual silhouette perimeter including the concave valleys as a ratio called the convex hull perimeter ratio (CHPR). The CHPR value of 1.07 was determined to be effective at removing touching particles while still including angular particles in the data. This method is independent of actual particle size.

Details of the AIMS2 equipment and software are available online in the AIMS2 Operation Manual at http://www.pineinst.com/test/pdf/LMAFA2.pdf. The manual presents instructions for operation and maintenance and discusses the analyses and reports that the system generates.

CHAPTER 3. EXPERIMENTAL PLAN

Upon completion of the new design, AIMS2, the project moved into two stages of independent testing. This testing compared the AIMS2 results against the AIMS1 results and confirmed that the testing methodology was rugged.

Texas A&M University (TAMU) was selected to perform the tests on the new equipment under the direction of Eyad Masad, Ph.D., P.E. The TAMU facility was selected because of the staff's extensive expertise in construction materials and materials research and familiarity with the AIMS1 system, as well as the facility's extensive database containing a variety of well-characterized materials. Samples of these well-characterized materials were scanned with the AIMS2 to compare the results. The complete report of the TAMU study is provided in appendix A. This report contains three sections: Chapter 1—Improvements of the AIMS, Chapter 2—Ruggedness Evaluation of AIMS2, and Chapter 3—Interlaboratory Study.

CALIBRATION

Chapter 1 of the TAMU Report (appendix A) discusses the calibration of the AIMS2 results to the AIMS1 results. Materials were scanned with the new hardware, and the results were compared to the research system results. The data demonstrated that the AIMS2 system provides material characterization similar to that of the AIMS1 research equipment. With this confirmation that the characterizations are comparable, the research relating material shape characterizations to performance that was completed with the AIMS1 equipment can be considered applicable to the shape characterizations provided by the AIMS2 system. (See references 1, 2, 3, and 4.)

The calibration tests comparing the research AIMS1 to the new AIMS2 demonstrated that most of the outputs of the new system match the research edition quite well. Angularity and form data output from the new system aligned very closely with the old system's output. This was expected, as the image analysis algorithms had not been changed; only the image acquisition hardware had been updated. However, the texture output was found to be of a different magnitude on the new system when compared to the AIMS1. This difference in texture was not unexpected, as the updated equipment provided increased capabilities in both lighting and camera performance. The new system continued to rank the various materials in a similar manner as the old with respect to each other. The output was simply of a different scale. Because of research completed with the original equipment in studying texture and its relationship to in-place performance, it was desirable to maintain the texture scale of the research system. It was decided that the best solution to address this shift in scale was to apply a shift factor to the new system's data.

This shift of texture in the AIMS2 system with respect to the AIMS1 system is the result of three converging design changes: enhanced illumination, improved camera performance, and the enclosed chamber for image acquisition. The new top-light design provides oblique-angle spot lighting, which provides excellent contrast to the particle surface compared to the ring lighting of the AIMS1 system. The new camera provides improved gray-scale texture images by providing a more precise control of the image intensity. Finally, the enclosure eliminates ambient lighting to provide a controlled lighting environment for image acquisition. It is believed that the new system represents an improvement in performance, while maintaining excellent correlation to previous results that have been linked to pavement materials performance.

RUGGEDNESS TESTING

The second stage of the testing was designed to confirm that the testing methodology was rugged. Ruggedness, in this meaning, is not the ability of the equipment to stand up to abuse, but the ability of the testing methodology to handle small, anticipated, variations in the parameters used for capturing the data. It confirms that the operational parameters that occur within the equipment, laboratory environment, and system operation do not significantly impact the results. This testing followed the guidelines of ASTM C1067, "Standard Practice for Conducting a Ruggedness or Screening Program for Test Methods for Construction Materials."

Material sampling and preparation procedures are well established in the aggregate industry, and these guidelines had been applied for sample preparation with the AIMS1 research. There was no need to reevaluate these material sampling procedures, and the appropriate existing procedures were followed for the ruggedness testing.

The AIMS2 system is computer-controlled with little operator input required to characterize material samples. As such, the ruggedness factors that were selected focused on gaining an understanding of the level of control required during system operation as well as during system calibration to provide a rugged testing process. Special accommodation was made in the test software to permit imputing variability into the system to simulate the acquisition parameter variation. These controls variations are not available during normal operation of the AIMS2.

Fine-aggregate characterization requires slightly different operating parameters than coarse-aggregate characterization requires. Separate tests and factors were selected for coarse and fine characterizations, although some factors were common to both (see table 1).

Table 1. Factors Selected for Coarse and Fine Characterizations

Fine Aggregate Factors	Coarse Aggregate Factors
A: Tray Color	A: Tray Size
B: Illumination Intensity	B: Illumination Intensity
C: Doors (open vs. closed)	C: Door (open vs. closed)
D: Touching Particle Filter	D: Focus Limit
E: Magnification	E: Magnification
F: Number of Particles	F: Tray Height
G: Ambient Light	G: Ambient Light

The ruggedness testing included several different materials. Separate analyses were run using dark-colored coarse aggregates, light-colored coarse aggregates, dark-colored fine aggregates, and light-colored fine aggregates. Two sizes of fine samples were selected (#30 and #16). Each of the characterizations specified within the ASTM C1067 procedure (two replicates of eight unique configurations) was statistically analyzed. Fine aggregate output includes angularity and form 2D. Coarse aggregate characterizations of angularity, texture, sphericity, and flat and elongated ratio were analyzed for factor significance. During the ruggedness testing, 10 experiments were conducted, which are detailed in appendix A, chapter 2.

CONCLUSIONS OF CALIBRATION AND RUGGEDNESS TESTING

The results of the comparison between AIMS1 (the research system) and AIMS2 (the system developed within this project) proved that the two systems provide the same ranking of aggregates and give comparable results. Consequently, the numerous research studies utilizing the AIMS1 system are applicable to the AIMS2 characterizations.

The ruggedness study following ASTM C1067-00 identified several factors that were found to be statistically significant in affecting the AIMS2 results. The semitransparent doors originally selected were not able to minimize the impact of ambient light; therefore, nontransparent doors were installed to provide the required isolation.

An additional ruggedness study following ASTM E1169 identified several system control parameters that could affect the AIMS2 shape characterizations. Consequently, limits were established for these parameters to minimize their influence on the results. These parameter limits were set as system defaults where appropriate. The parameters and limits listed in table 2 are recommended as settings for the parameters to ensure rugged AIMS2 results.

Table 2. Recommendations for AIMS2 To Be Rugged

Aggregate Factors	Recommended Limits
Light Illumination	-1 and 0.
Tray Size	Use tray size specified for each aggregate size.
Tray Color	Use opaque tray for #50, #100 and #200 aggregates.
Door Position	Door must be closed.
Ambient Light	Not significant with doors closed.
Focus (depth of field)	A maximum variation of 1% from the settings.
CHPR	Nonchangeable parameter (1.07).
Zoom Level	Within ±0.5% of nominal setting.
Tray Height	Height calibration must follow the Operation Manual procedure.

CHRP = convex hull perimeter ratio

INTERLABORATORY STUDY

The final phase of this project was to conduct the ILS to evaluate the repeatability and reproducibility of the system. This experiment followed ASTM C802, "Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials." Three different material sources with varying mineralogy were selected, each type containing material sizes #200 (0.075 mm) to 25 mm retained.

The original plan for the ILS outlined and budgeted in the project proposal was for five AIMS2 systems to be used in the ILS, with one additional control unit at the TAMU laboratory. Due to the high level of interest in the AIMS2 technology, three additional systems were manufactured to accommodate all of the interested laboratories and still meet the project schedule. These eight systems were sent to the 32 laboratories that participated in the ILS.

This ILS provides two different precision estimates for the test method: a single-operator precision (within-laboratory precision) and multilaboratory precision (between-laboratory precision). The details of the study are presented in appendix A, chapter 3.

To ensure that the ILS materials were of uniform characteristics, the TAMU laboratory sampled and fractionated each material according to established procedures, separating each material into eight samples, one for each ILS system. Each of these eight samples (all sizes) was then scanned through a single AIMS2 system at TAMU. This system was not used to generate any of the ILS data set, but was used as a control. This procedure ensured uniform material samples and provided a baseline for the material characterizations, set by an experienced lab.

The labs participating in the ILS did not have experience with the AIMS2, nor did they initially have the necessary equipment. Each lab was provided instructions and a complete AIMS2 unit including the enclosure, microscope, computer, and sample trays. Also provided with each system were the three material samples of Superpave sieve sizes (#200 to 25 mm). These materials—a granite, a gravel, and a limestone mineralogy—were selected to provide a range of material characteristics.

Each system was shipped to and set up at multiple laboratories. Each lab, after setting up the system, checked system calibration to ensure proper operation. Each of the three material samples, which contained multiple aggregate sizes, was scanned twice by the same operator, with the second, replicate scan performed on a different day to provide within-lab system repeatability. Once the scans were completed (two scans of three material samples), the system was repacked and shipped to the next participating lab, where the process was repeated.

The results of the ILS provided repeatability and reproducibility information for different shape indices and parameters provided by the AIMS2. The data also suggested that the #200 (0.075 mm) retained analysis was more variable than the other sizes. This variability is attributed to touching particles influencing this size.

Additional work is necessary to improve the performance of the system for the 0.075-mm (ASTM #200 sieve) retained material due to multiple particles (touching) being analyzed as a single particle. The determination of an improved touching particle filter value (CHPR) for this size (0.075 mm) is expected to reduce the variations in the measurements and reduce the variation reported for this size. Because of this additional work, the 0.075-mm data are not included in the precision table recommendations.

The coefficient of variation should be used to describe the precision of the results to avoid bias against materials with low AIMS2 characterization values. Each AIMS2 shape parameter requires a separate precision value. Table 3 presents the recommended values for the precision table to be included within the analysis specification for the AIMS2 characterizations. (Additional detail on the study's precision results is available in appendix A, chapter 3.) Overall, the single-operator and multilaboratory precision results are considered acceptable coefficient of variation values given the natural variation in aggregate materials.

Table 3. Precision for Sizes 25 mm, 19 mm, 12.5 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.60 mm, 0.30 mm, and 0.15 mm

	Within Laboratory		Between Laboratory	
Aggregate Shape Characteristic	**Coefficient of Variation**	**Acceptable Range of Two Test Results**	**Coefficient of Variation**	**Acceptable Range of Two Test Results**
Angularity	2.9%	8.3%	4.3%	12.2%
Texture	4.5%	12.7%	7.1%	20.0%
Sphericity	1.2%	3.4%	2.6%	7.4%
Flat or Elongated	2.1%	5.9%	3.4%	9.7%
2D Form	2.7%	7.7%	3.5%	10.0%

CHAPTER 4. MATERIAL TESTING PROCEDURES

Detailed material testing procedures were developed as a part of this project. These procedures were followed by the ILS participants. Although the participating laboratories did not sample or prepare the materials used in the study, TAMU followed the sample preparation procedures for the ILS materials used in this study. The procedures developed outline the required steps for aggregate material shape characterization and are written in a standards format appropriate for AASHTO. As such, two proposed test method procedures were drafted and submitted to AASHTO for consideration. The preliminary AASHTO Technical Group review produced several suggestions for improving and clarifying the procedure documents. The draft procedures were modified per those recommendations and resubmitted for further consideration. AASHTO subsequently approved these procedures with minor changes as provisional standards, and they were published in *AASHTO Provisional Standards,* 2010 edition.(5)

- AASHTO TP81-10, "Standard Method of Test for Determining Aggregate Shape Properties by Means of Digital Image Analysis."
- AASHTO PP64-10, "Standard Method for Determining Aggregate Source Shape Values from Digital Image Analysis Shape Properties."

Precision and bias information (table 3) has been added through the AASHTO Subcommittee on Materials 2010 ballot and will be published in the 2011 edition of the Standards. A detailed discussion of the analyses undertaken are included in appendix A, chapter 3.

CHAPTER 5. COMMERCIALIZATION

The construction industry has undergone a dramatic shift over the past decade and is no longer viewed as reluctant to adopt changes. The success of technology-oriented programs like Superpave has influenced the industry to be more receptive to advances in technology. The industry has also demonstrated that it is willing to move into newer technologies, such as stone-matrix asphalt (SMA) and warm-mix asphalt (WMA), when the technology is shown to be beneficial.

SMA and WMA are technologies that were originally applied in Europe. SMA is a stable, rut-resistant mixture that relies on stone-to-stone contact to provide skeletal strength and durability. SMA performance is directly attributed to aggregate shape properties, so accurate aggregate characterization and selection is necessary to produce a successful SMA mixture.

WMA technologies permit asphalt pavement producers to lower the material compaction temperatures by 50 °F to 100 °F (28 °C to 55 °C). A significant decrease in energy consumption as well as a reduction in the release of volatile gases can be attributed to the lower temperature. These factors will help metropolitan areas meet air quality standards. The lower temperature and reduced hazardous fumes also create a safer working environment for construction workers. Proper aggregate classification is essential when using WMA.

As higher demands are placed on the industry as a whole, the contractor will seek technology for a competitive advantage. The advances in applied technology will allow objective science to replace subjective opinions. To succeed in the new world of construction, contractors need to apply new technology, and technicians must be trained to use it.

As a result of these industry trends, there is strong interest in the AIMS2 concept. There is interest in the system from many U.S. State departments of transportation. There is also interest in the AIMS2 in Canada, Brazil, China, and Italy. Domestic aggregate producers have also expressed interest, as this technology provides a means for quantifying the consistency and quality of aggregate products.

MARKETING

Pine Instrument Company has identified several target markets for this new and innovative technology. In the earliest phase of the product life cycle, the target markets will be government agencies and academic institutions. As the product moves up the life-cycle curve, early adopters from the aggregate and construction industries will be the next target market. As the product becomes more accepted, aggregate suppliers will look to acquire the device for their quarries. In addition, contractors will purchase the instrument to verify the properties of the aggregates they are using and also to compare their aggregates to each other to hone their competitive edge and price points with each other.

Pine Instrument's marketing strategy for this technology includes positioning the product on the premise that the device provides objectivity in the characterization of aggregate materials. The simple operation of the equipment, repeatability, and ruggedness in both within-laboratory and between-laboratory applications and the objectivity achieved as compared to existing methods are the main selling points.

In addition to the material characterization advantages demonstrated within this project, new and continuing research is suggesting that there are other applications of aggregate shape characterization that will benefit from the AIMS2 technology. As these new concepts are demonstrated, they will provide additional reasons for the industry to apply AIMS2 technology.

To implement this strategy successfully, the traditional facets of marketing—price, placement, packaging, and promotion—will be used to achieve marketing goals.

Pricing

Based on market feedback and customer responses, the AIMS1 unit was priced too high to compete with other existing tools and methodologies. During Phase I of this project, it was determined that the AIMS2 could be offered at a level that the market would find acceptable while also developing a product that melded marketability and applicability into an industry tool able to withstand the tests of repeatability, reproducibility, objectivity, and ruggedness for both within-laboratory and between-laboratory situations.

Placement

The ILS study garnered wide exposure and placement opportunities for the AIMS2 unit during that phase of the project. The product will now be placed into the market by selling directly to the consumer.

Packaging

The AIMS2 is an enclosed device; the image acquisition chamber is approximately 30 in. by 30 in. and 45 in. high (0.7 m by 0.7 m by 1.1 m). The imaging chamber, along with the computer interface system, typically occupies a laboratory bench that is 30 in. by 72 in. (0.7m by 1.8 m). Operation of the equipment is simple and straightforward. The project objectives were met, so that the AIMS2 has a relatively small footprint and is unaffected by the environment of the typical testing laboratory. With proper care and packaging of the camera and microscope unit, the AIMS2 device can be moved within a lab or to other locations without much difficulty.

Promotion

Several techniques will be used to promote the AIMS2, including direct sales, trade shows, journal and Internet advertising, and public relations efforts, and additional research into frictional properties. Direct sales efforts will be conducted by the manufacturer's personnel. Promotion efforts will also include attending national industry trade shows such as World of Asphalt/World of Aggregates as well as regional trade and association conferences. The AIMS2 will also be promoted to target markets by advertising in trade publications such as *Aggregates*

Manager, Asphalt Contractor, Asphalt Pro, and others. Technical journals will be leveraged with articles, and technical presentations will be made describing the instrument's flexibility, objectivity, and overall benefits.

The relationship of aggregate texture to pavement skid resistance is well known, and although not part of the original grant program; the AIMS2 can be used to characterize the rate of change of aggregate texture in degradation tests, such as the Micro-Deval. These results can then be used during the pavement design process to model frictional characteristics of pavements. The AIMS2 system has also been used to characterize pavement core sample surface macrotexture features. Macrotexture has been shown to be an important feature for obtaining adequate pavement friction. These characterizations extend the capabilities of the AIMS2 system beyond aggregate shape analysis into pavement friction applications.

The current interest levels in the AIMS2 device, coupled with the ongoing research in aggregate laboratory analysis relating to pavement performance and skid resistance, bodes well for the future sales and acceptance of the AIMS2 device in the construction industry.

CHAPTER 6. CONCLUSION

During Phase I of this grant, it was determined that a newer, more robust version of the AIMS1 that would meet the project goals could be developed. Furthermore, this new system, designated as the AIMS2, could be manufactured at a cost that would meet the price expectations of the target markets.

There were known shortcomings within the AIMS1 system. The new system implemented features to address those shortcomings, such as ambient light effects, translucent materials, and simplifying the operation. The result was improved performance in the new system while retaining the link to the research completed on the original system.

There is a great deal of interest in the device. Discussions with potential customers of the AIMS2 have indicated that the target markets are ready to move forward with the new and improved AIMS2.

The completed ILS provided the repeatability and reproducibility information required for applying the AIMS2 technology for material characterizations. This information will permit governing agencies to utilize standards, such as AASHTO material standards for material classifications. With this standardization in mind, two test methods were developed and submitted to AASHTO for consideration. These draft standards were published in *AASHTO Provisional Standards*, 2010 edition. A provisional standard is expected to be implemented within the AASHTO standards, which may be used up to 8 years prior to becoming what is known as a full standard. This provisional specification period permits users to apply a standardized procedure and yet allow adjustments and improvements within the protocol to be implemented with relative ease.

Research shows clear links between aggregate shape to pavement performance. This project has demonstrated that the AIMS2 technology provides an objective and reproducible shape characterization of aggregates. As the technology is applied on a wider scale, establishing clear relationships for the AIMS2 characterizations values to in-place pavement performance will be a research goal.

APPENDIX A

TEXAS A&M UNIVERSITY REPORT

A Report Submitted to Pine Instruments as Part of FHWA Grant Number DTFH61-08-G-00003

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CHAPTER 1

IMPROVEMENTS OF THE AGGREGATE IMAGE MEASUREMENT SYSTEM (AIMS)

INTRODUCTION

The Aggregate Image Measurement System (AIMS) was developed to measure aggregate shape characteristics using a computer controlled motion; and image processing and analysis techniques.[1] AIMS is capable of capturing the aggregate characteristics over a range of aggregates sizes from 37.5 mm (1.5 in) to 0.075 mm (ASTM #200 sieve). The direct measurements of the aggregates are characterized in terms of shape, angularity, and surface texture. Figure 1.1 shows an illustration of the AIMS system.

This study introduces a new prototype of AIMS (see Figure 1.2)—which will be, in this report, referred to as AIMS2, while AIMS1 (see Figure 1.1) will refer to the old system that was available before the initiation of this study. Although the physical design and process of capturing images were changed between AIMS1 and AIMS2, the algorithms used for the images analysis are the same. This report includes the results of calibrating the new system to confirm that the two systems are producing similar results for the same set of aggregates. The results from the ruggedness study to assess system operational performance, identify significant inputs,

[1] E. Masad, T. Al-Rousan, M. Bathina, J. McGahan, and C. Spiegelman, "Analysis of Aggregate Shape Characteristics and its Relationship to Hot Mix Asphalt Performance," *International Journal of Road Materials and Pavement Design,* vol. 8, no. 2, pp. 317–50, 2007.

and determine appropriate limits for those inputs, are presented herein as well. The repeatability and reproducibility of AIMS from an Interlaboratory Study (ILS) is discussed for multiple users and laboratories.

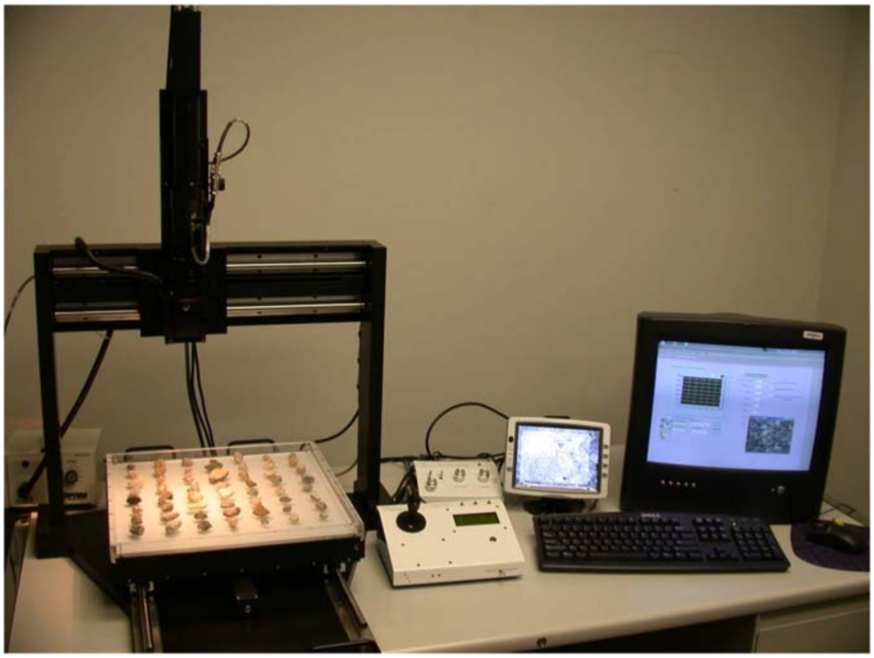

Figure 1.1. A picture of AIMS1.

Aggregates are arranged on a lit tray and a digital camera captures images which are analyzed using AIMS SOFTWARE©. The aggregate angularity is depicted by measuring the irregularity of a particle surface from a black and white image using a bottom lit tray. The texture index is obtained from gray-scale images that are analyzed using the wavelet analysis method.[2]

Figure 1.2. A picture of AIMS2.

AIMS2 CALIBRATION

The calibration was done in order to insure the two systems, AIMS1 and AIMS2, were producing similar results for the same set of aggregates. In the development of the new prototype of AIMS2, all of the resulting parameters from the two systems were compared to each other for a set of 32 coarse aggregate samples and 21 fine aggregate samples. Fifty-six particles were scanned from each aggregate source. The comparison of the angularity of the fine and coarse aggregates are shown in Figure 1.3. The angularity values of the two AIMS systems are comparable.

[2] E. Masad, T. Al-Rousan, M. Bathina, J. McGahan, and C. Spiegelman, "Analysis of Aggregate Shape Characteristics and its Relationship to Hot Mix Asphalt Performance," *International Journal of Road Materials and Pavement Design,* vol. 8, no. 2, pp. 317–50, 2007.

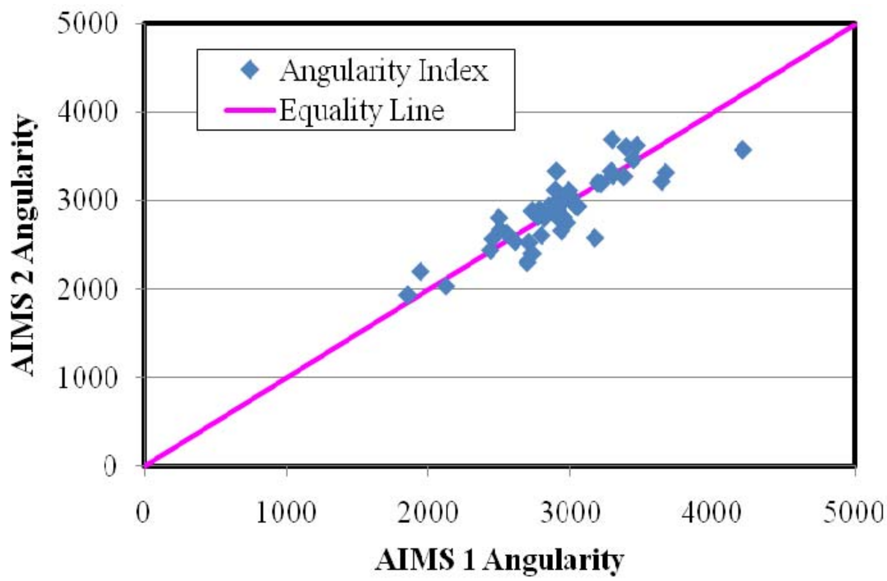

Figure 1.3. Angularity of AIMS1 and AIMS2.

AIMS1 and AIMS 2 texture results, shown in Figure 1.4, rank the aggregates in the same order. However, due to the difference in the cameras and lighting used in AIMS2 and AIMS1, the range of the scale of the texture results of the two systems were different. The scale range for the studied aggregates for AIMS1 was 0 – 600 while the scale for AIMS2 was 0 – 200. It was found that a multiplication shift factor of 2.4563 for the AIMS2 data would provide results comparable to those of AIMS1. The texture values of AIMS1 and AIMS2 after applying the shift factor are shown in Figure 1.5.

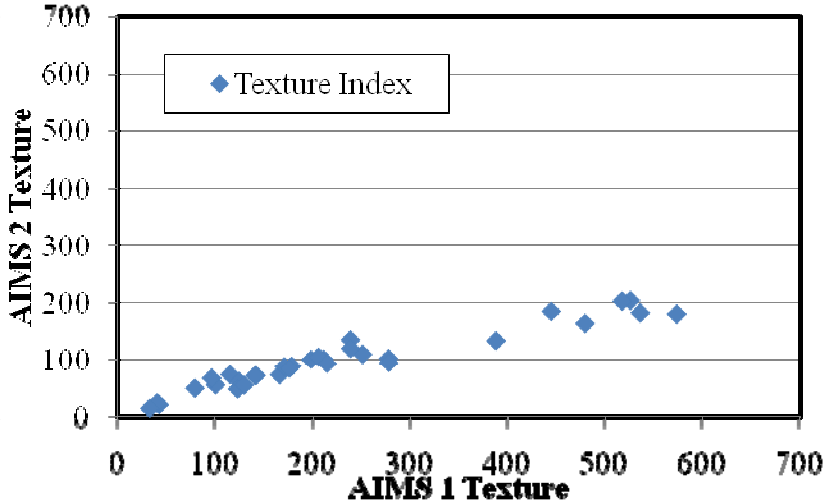

Figure 1.4. Texture of AIMS1 and AIMS2.

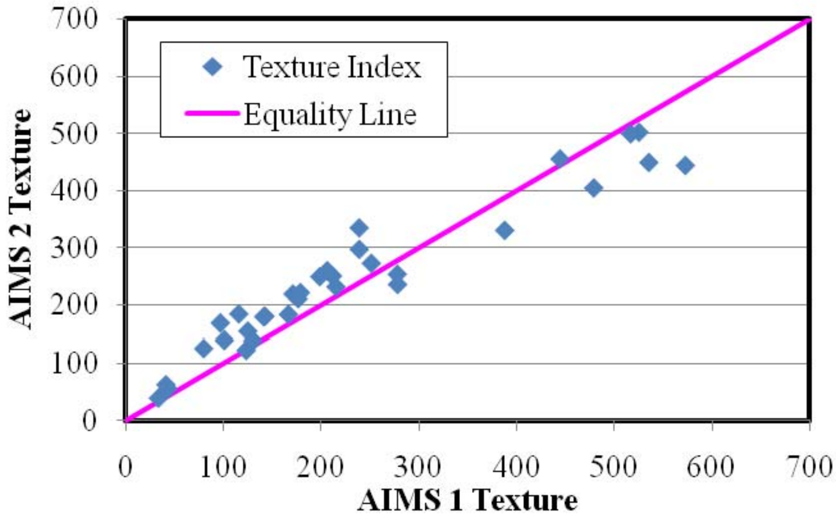

Figure 1.5. Texture of AIMS1 and AIMS2 shifted.

The comparison between AIMS1 and AIMS2 results proved that the two systems provide the same ranking of aggregates and give comparable results. Consequently, the classification system developed previously by the TAMU research team for AIMS1[3] can be used to classify aggregates based on AIMS2 results.

[3] E. Mahmoud, L. Gates, E. Masad, S. Erdogafan, and E. Garboczi, "Comprehensive Evaluation of AIMS Texture, Angularity, and Dimension Measurements," *Journal of Materials in Civil Engineering,* vol. 22, no. 4, pp. 369–79, 2010.

CHAPTER 2

RUGGEDNESS EVALUATION OF AIMS2

INTRODUCTION

Different operational and environmental factors can cause significant variability in the resulting measurements if they are not identified and controlled. A ruggedness study was conducted to determine the sensitivity of the test method due to changes in levels of these important factors. The results of the ruggedness study can be used to establish appropriate ranges for the parameters in questions by determining the effect of worst-case variation in operating conditions within the tested tolerance range. Two different ASTM standards were used to conduct the ruggedness analysis and predict the effect of the factors tested.

Several factors were selected for evaluating the ruggedness of measuring the characteristics of fine and coarse aggregates based on previous experience of the experimental variations that can affect the test results. The high and low limits for each factor were selected based on limits that would reasonably occur in the test if no particular measures were taken to control them. The factors selected were light illumination, tray size or color, door position, ambient light, zoom level, focus, tray height, number of fine aggregates, and CHPR value.

The light illumination, used for both coarse and fine aggregates, is the top and bottom lighting required to capture aggregate images. The top light is required to capture aggregate texture images and the bottom lighting is required to capture the aggregate angularity images. The light intensity limits were selected to be above and below the operational settings.

Each sieve range has a corresponding tray size for the coarse aggregates. The different trays have a specific trough size to align the aggregates under the camera unit. The fine aggregates only use one tray size, but there are two different tray colors. Light-colored fine aggregate which may be transparent using the typical bottom light with a clear tray, should use a darker opaque colored tray with the top light to capture the angularity images. The limits chosen for the ruggedness evaluation were the different tray sizes or color.

AIMS2 system has transparent doors, which are thought to be adequate to block the effects of ambient light while allowing the operator to view the systems progress. Two door positions, completely open or closed, were tested to determine the significance of the door position.

The ambient light was tested to determine the effect of exterior light surrounding the system (i.e., facility lighting system). This is important since the system is supposed to be used in different laboratories, which can have different lighting. The limits, either on or off, were tested for the ambient light.

The zoom level, tray height, and focus are all system parameters which need to be controlled such that these factors do not introduce variability in the results. The zoom level of the camera is used to determine the area captured by the angularity and texture images. The camera unit focuses on the aggregate surface of the coarse aggregate texture image. The tray height is measured from the top of the inside surface of the AIMS2 base. A particle thickness is measured as the difference between the height of a particle surface and the height of the inside surface of the AIMS2 base. The number of fine aggregates was used as a factor to determine if the results are affected be slight changes in the number of aggregates analyzed.

Due to the manual spreading of the fine aggregates onto the tray, some fine aggregates are touching; touching aggregates are analyzed by AIMS2 as a single particle. The Convex Hull Perimeter Ratio (CHPR), described in Chapter 2, is used to eliminate touching particles that could be analyzed as a single particle.

AIMS2 RUGGEDNESS ANALYSIS USING ASTM C 1067-00

The first ruggedness analysis was carried out according to ASTM C 1067-00 "Conducting a Ruggedness or Screening Program for Test Methods for Construction Materials." This test method was used to detect sources of variation in the test method due to the factors tested.

Seven factors were selected for the fine and coarse aggregates based on previous experience with the experimental factors that could cause significant variation in the test results. The high and low limits for each factor were selected based on limits that could reasonably occur in the test if no particular measures were taken to control them.

Experimental Procedures

Following the ASTM C 1067-00 procedure, 16 scans were performed: two replicate sets of eight determinations each. A determination refers to a certain combination of the values for the factors included in the analysis. Scans 1 through 8 are duplicated for the study to obtain scans 9 through 16 in the analysis. Table 2.1 shows a template of the factors and limits for the scans preformed.

From these scans, an effect factor can be calculated to determine the statistical significance of the limits for each factor. ASTM C1067 contains details about calculations necessary for determining the effect factor. An effect factor $\geq$ 5.59 represents a significant effect with a 5% probability for drawing an erroneous conclusion (ASTM C1067, Section 7.6). If the effect factor is $\leq$5.59 then the factor is considered not significant (NS) with a 95% level of confidence.

Table 2.1. Template of Ruggedness Scans for ASTM C 1067-00

Replicate Scans Number 1

			Scan Number							
Factor	Low Limit	High Limit	1	2	3	4	5	6	7	8
A	a	A	a	a	a	a	A	A	A	A
B	b	B	b	b	B	B	b	b	B	B
C	c	C	C	c	C	c	C	c	C	c
D	d	D	D	D	d	d	d	d	D	D
E	e	E	e	E	e	E	E	e	E	e
F	f	F	F	f	f	F	F	f	f	F
G	g	G	G	g	g	G	g	G	G	g

Replicate Scans Number 2

			Scan Number							
Factor	Low Limit	High Limit	9	10	11	12	13	14	15	16
A	a	A	a	a	a	a	A	A	A	A
B	b	B	b	b	B	B	b	b	B	B
C	c	C	C	c	C	c	C	c	C	c
D	d	D	D	D	d	d	d	d	D	D
E	e	E	e	E	e	E	E	e	E	e
F	f	F	F	f	f	F	F	f	f	F
G	g	G	G	g	g	G	g	G	G	g

Experiment 1 dealt with coarse aggregate, and Experiment 2 was conducted for the analysis of the fine aggregates. The results from Experiment 1 were used as a guidance to change the limits of the factors for the coarse aggregates and examine ruggedness under these new limits as part of Experiment 3. Experiment 4 investigated the normal variations within the AIMS2 system for both the coarse and fine aggregates. A summary of these experiment are shown in Table 2.2.

Table 2.2. Summary of Ruggedness Experiments Using ASTM C 1067-00

Experiment	Purpose of the Experiment	Aggregate Sizes
1	Preliminary Study to Determine the Appropriate Limits for a Rugged System	9.5 mm (0.375 in)
2	Preliminary Study to Determine the Appropriate Limits for a Rugged System	1.18 mm (ASTM #16 sieve) and 0.60 mm (ASTM #30 sieve)
3	Based on Experiment 1, a Further Investigation of the Limits	9.5 mm (0.375 in)
4	Investigation of the Normal Variations Within the System	9.5 mm (0.375 in) and 0.60 mm (ASTM #30)

Experiment 1

Experiment 1 was conducted for the evaluation of the coarse aggregates using the procedure in ASTM C 1067. The analysis was done for two coarse dark and light aggregates of the same size, 9.5 mm (0.375 in). Images of particles from the dark-colored and light-colored aggregate are shown in Figure 2.1.

Figure 2.1. Dark and light 9.5 mm (0.375 in) aggregates used in Experiment 1.

The high and low limits for each factor were selected based on limits that would reasonably occur in the test if no particular measures were taken to control them. The factors and limits chosen for the coarse aggregates are shown in Table 2.3.

Table 2.3. Coarse Aggregate Factors and Limits Used in Experiment 1

Factor	Coarse Aggregate Study Factors:	Low Limit	High Limit
A	Tray size	12.5 mm	4.75 mm
B	Light illumination (Top and Bottom Light)	-4	+4
C	Door Position	Close	Open
D	Focus	0	+1
E	Zoom level	-5%	+5%
F	Tray Height	-1 mm	+1 mm
G	Ambient light (On, Off)	On	Off

The limits for the tray size were selected as one tray size above and one tray size below the correct tray size. The light illumination is the top and bottom lighting required to capture the images. The light illumination limits were selected as +4 and -4 from the operational setting to decrease and increase the system lighting. The AIMS2 doors limits were chosen as completely open or completely closed to predict the significance of the door position, which could let some additional ambient light inside the compartment where particles are images. The focus, zoom level, and tray height were used to evaluate the acceptable variability for each factor. The focus was used to find the depth of the aggregate particle when the camera focuses on the particle surface for the texture image. The tray height was the distance from the camera to the tray. The ambient light was used to account for the performance of the doors in eliminating the effect of different intensities of exterior lighting.

It was found that the bottom light during the angularity scans was producing dark shadowed lines around the trough. These dark shadows introduced an additional, uncontrollable error in the test results by reducing the total number of particles scanned especially with the lower light intensities. The coarse aggregates ruggedness study was therefore preformed a second time with different trays. Experiment 1a results discussed hereafter were those that were obtained with the use of trays that produced dark shadowed lines, while Experiment 1b refers to the results from using trays that did not have dark shadowed lines.

Table 2.4 and Table 2.5 list the results from AIMS2 for the dark and light coarse aggregates for Experiment 1a. Table 2.6 and Table 2.7 list the results for Experiment 1b.

Table 2.4. Results of Dark 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 1a

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2826.68	265.71	0.65	2.92
Scan 2	2767.43	280.40	0.70	2.33
Scan 3	2756.97	264.41	0.73	2.03
Scan 4	2747.62	270.23	0.64	3.11
Scan 5	2658.89	250.85	0.67	2.79
Scan 6	3135.49	272.17	0.75	1.84
Scan 7	2846.78	272.74	0.73	2.04
Scan 8	2774.34	271.54	0.68	2.56
Scan 9	2763.31	272.66	0.63	3.12
Scan 10	2781.10	272.47	0.71	2.18
Scan 11	2759.57	264.60	0.74	2.00
Scan 12	2762.95	270.94	0.64	3.16
Scan 13	3030.97	282.86	0.65	2.82
Scan 14	2848.53	255.47	0.77	1.76
Scan 15	2756.67	272.36	0.74	2.00
Scan 16	2825.92	269.46	0.68	2.56

Table 2.5. Results of Light 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 1a

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2434.41	43.74	0.65	2.71
Scan 2	2407.84	42.89	0.69	2.20
Scan 3	2462.07	44.79	0.73	1.98
Scan 4	2507.19	41.70	0.64	3.02
Scan 5	2336.08	37.78	0.64	2.75
Scan 6	2476.93	35.40	0.75	1.78
Scan 7	2448.42	41.28	0.71	2.06
Scan 8	2435.48	43.97	0.67	2.43
Scan 9	2422.70	40.76	0.66	2.68
Scan 10	2453.50	42.10	0.69	2.21
Scan 11	2484.49	44.04	0.73	1.98
Scan 12	2435.96	41.92	0.64	3.01
Scan 13	2807.60	40.11	0.64	2.59
Scan 14	2691.57	40.69	0.69	1.98
Scan 15	2401.64	40.84	0.71	2.05
Scan 16	2407.32	44.07	0.67	2.43

Table 2.6. Results of Dark 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 1b

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2648.27	263.47	0.65	2.95
Scan 2	2682.28	264.23	0.70	2.35
Scan 3	2722.65	264.35	0.74	2.02
Scan 4	2784.45	260.64	0.63	3.31
Scan 5	2828.15	257.26	0.65	3.07
Scan 6	2850.43	257.84	0.75	1.91
Scan 7	2703.87	258.45	0.72	2.17
Scan 8	2753.98	260.55	0.69	2.56
Scan 9	2628.28	265.41	0.65	2.95
Scan 10	2731.97	265.11	0.70	2.35
Scan 11	2781.50	264.90	0.74	2.02
Scan 12	2732.04	263.02	0.63	3.28
Scan 13	2788.81	256.58	0.65	3.05
Scan 14	2892.87	259.52	0.75	1.95
Scan 15	2719.25	258.93	0.72	2.15
Scan 16	2765.43	261.26	0.68	2.65

Table 2.7. Results of Light 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 1b

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2429.46	46.98	0.65	2.79
Scan 2	2322.89	45.19	0.68	2.38
Scan 3	2477.50	46.51	0.72	1.99
Scan 4	2481.87	45.55	0.62	3.17
Scan 5	2352.98	42.99	0.63	3.04
Scan 6	2422.59	44.76	0.72	1.95
Scan 7	2459.10	44.29	0.70	2.13
Scan 8	2417.34	44.88	0.67	2.54
Scan 9	2351.49	46.68	0.65	2.79
Scan 10	2421.08	46.39	0.68	2.30
Scan 11	2532.09	46.54	0.73	1.99
Scan 12	2466.29	46.04	0.62	3.16
Scan 13	2376.74	43.32	0.63	2.94
Scan 14	2396.31	44.61	0.72	1.94
Scan 15	2444.22	43.99	0.70	2.14
Scan 16	2414.69	44.06	0.67	2.53

The statistical analysis identified the statistical significant factors for Experiments 1a and 1b. The results of the factors were found to be significant or not significant (NS). The summary of the analysis for the coarse aggregates is shown in Table 2.8.

Table 2.8. Coarse Aggregates Summary of Results Used in Experiment 1

	Experiment 1a		Experiment 1b		
	Light	Dark	Light	Dark	Factors
Angularity	NS	NS	NS	160.03	Tray size
	NS	NS	96.34	NS	Light illumination
	NS	NS	NS	25.24	Door Position
	NS	NS	NS	408.77	Focus
	NS	NS	NS	NS	Zoom level
	NS	NS	NS	NS	Tray Height
	NS	NS	NS	NS	Ambient light
Texture	19.39	NS	4933.41	20737.60	Tray size
	25.86	NS	NS	NS	Light illumination
	NS	NS	NS	NS	Door Position
	5.89	NS	NS	235.86	Focus
	NS	NS	164.87	220.20	Zoom level
	NS	NS	NS	NS	Tray Height
	6.25	NS	NS	17.65	Ambient light
Sphericity	NS	255.69	8431.15	27870.38	Tray size
	NS	NS	2696.45	606.57	Light illumination
	NS	NS	32.90	NS	Door Position
	NS	NS	NS	NS	Focus
	121.02	56.09	567676.59	210883.99	Zoom level
	4305.08	13049.38	9961142.09	5330850.92	Tray Height
	NS	NS	NS	NS	Ambient light
Flat or Elongated 3:1	876.31	2119.02	8095.51	27942.97	Tray size
	NS	NS	121.76	118.08	Light illumination
	NS	NS	NS	NS	Door Position
	NS	NS	241.74	162.87	Focus
	1375.34	400.86	137713.27	169145.47	Zoom level
	84311.45	122749.74	3483469.88	7088424.96	Tray Height
	25.61	12.01	49.65	424.29	Ambient light

Overall, the angularity and texture variations were significant due to the tray size, light illumination, ambient light, door position, focus, and zoom level. The sphericity and flat or elongated 3:1 results had more significant factors than the angularity and texture results. The tray size, light illumination, door position, focus, zoom level, and tray height affected both the sphericity and flat or elongated results. The ambient light affected only the flat or elongated results. Since the ambient light had a statistical significance on the results, but the AIMS2 door position did not, it was concluded the AIMS2 doors were not shedding the exterior light as designed. As will be discussed later, this lead to changing the doors to be non-transparent that did not allow ambient light into the system.

Experiment 2

Four fine aggregates were used in the analysis of Experiment 2. The four aggregates consisted of both a dark- and light-colored aggregates in two sieve ranges, 1.18 mm (ASTM #16 sieve) and 0.60 mm (ASTM #30 sieve). These aggregates are shown in Figure 2.2 and Figure 2.3. The fine aggregate factors and limits are listed in Table 2.9.

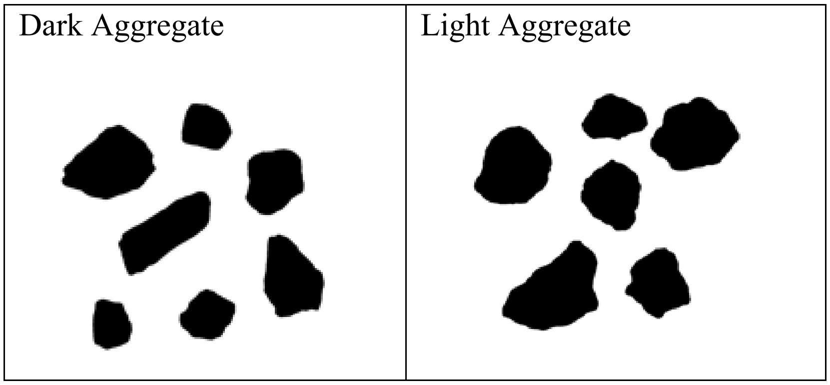

Figure 2.2. Dark and light 1.18 mm (ASTM #16 sieve) aggregates used in Experiment 2.

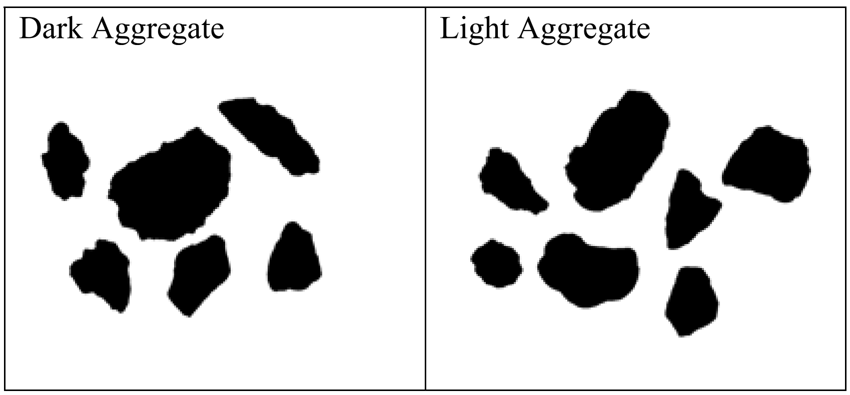

Figure 2.3. Dark and light 0.60 mm (ASTM #30 sieve) aggregates used in Experiment 2.

Table 2.9. Fine Aggregate Factors and Limits Used in Experiment 2

Factor	Fine Aggregate Study Factors:	Low Limit	High Limit
A	Tray color	Clear Tray	Opaque Tray
B	Light illumination (Top and Bottom Light)	Top -4 Bottom 0	Top +4 Bottom +4
C	Door Position	Closed	Open
D	CHPR	0	0.02
E	Zoom level	-5%	+5%
F	Particle Count	-25	+25
G	Ambient light	On	Off

One tray size is used for all the fine aggregates, but the user must select the tray color, either clear or opaque, depending on the aggregate size and color. The top or bottom lighting for the fine aggregates is directly related to the tray color; the bottom is used if the tray color is clear and the top light is used if the tray color is opaque. For the clear tray, the bottom light was not able to analyze the images at -4 as was used for the coarse aggregates, therefore the limits were changed to 0 and +4 as shown in Table 2.9. The top lighting was kept at the same limits of +4 and -4. The particle count was added to determine the effect of analyzing more or less than the operational number of particles. The CHPR value was used to eliminate touching particles that could be captured and analyzed as a single particle. The results for the dark and light fine aggregates are shown in Table 2.10 to Table 2.13.

Table 2.10. Results of Dark 1.18 mm (ASTM #16) Fine Aggregates Used in Experiment 2

	Angularity	2D Form
Scan 1	2733.38	7.01
Scan 2	2773.50	6.90
Scan 3	2749.41	7.06
Scan 4	2728.83	7.15
Scan 5	4232.48	8.84
Scan 6	4130.45	8.77
Scan 7	3974.41	8.53
Scan 8	3886.20	8.54
Scan 9	2760.43	7.00
Scan 10	2750.34	6.90
Scan 11	2741.02	7.04
Scan 12	2730.96	7.18
Scan 13	3933.64	8.46
Scan 14	4095.74	8.76
Scan 15	4038.62	8.74
Scan 16	3984.80	8.70

Table 2.11. Results of Light 1.18 mm (ASTM #16) Fine Aggregates Used in Experiment 2

	Angularity	2D Form
Scan 1	3361.02	7.62
Scan 2	3395.39	7.56
Scan 3	3450.58	7.77
Scan 4	3364.33	7.69
Scan 5	3518.22	7.75
Scan 6	3502.52	7.84
Scan 7	3418.22	7.63
Scan 8	3493.94	7.65
Scan 9	3336.29	7.57
Scan 10	3326.40	7.57
Scan 11	3392.10	7.84
Scan 12	3367.07	7.66
Scan 13	3505.06	7.72
Scan 14	3520.79	7.84
Scan 15	3464.49	7.62
Scan 16	3498.74	7.63

Table 2.12. Results of Dark 0.60 mm (ASTM #30) Fine Aggregates Used in Experiment 2

	Angularity	2D Form
Scan 1	3865.54	8.07
Scan 2	4035.04	8.34
Scan 3	3888.82	7.94
Scan 4	3940.66	8.19
Scan 5	4257.11	8.72
Scan 6	4524.45	9.00
Scan 7	4448.05	8.69
Scan 8	4488.10	8.74
Scan 9	3932.82	8.13
Scan 10	4021.97	8.23
Scan 11	3816.84	7.91
Scan 12	3923.79	8.03
Scan 13	4267.24	8.74
Scan 14	4566.33	8.95
Scan 15	4444.20	8.95
Scan 16	4506.22	8.76

Table 2.13. Results of Light 0.60 mm (ASTM #30) Fine Aggregates Used in Experiment 2

	Angularity	2D Form
Scan 1	3476.30	7.29
Scan 2	3529.06	7.23
Scan 3	3512.45	7.27
Scan 4	3490.71	7.26
Scan 5	3251.36	7.38
Scan 6	3361.33	7.49
Scan 7	3215.62	7.44
Scan 8	3144.88	7.42
Scan 9	3518.83	7.26
Scan 10	3518.01	7.31
Scan 11	3503.70	7.27
Scan 12	3518.25	7.23
Scan 13	3230.41	7.36
Scan 14	3351.78	7.57
Scan 15	3159.08	7.47
Scan 16	3180.98	7.48

The factors, which could cause significant variation based on the limits tested, were identified for the fine aggregates. The summary of the analysis is shown in Table 2.14. The tray color was significant in affecting angularity and 2D form results for both aggregate colors and all sizes. All of the seven factors were significant for either the angularity or the 2D form for one or more of the four fine aggregate samples tested. Since both the AIMS2 door and the ambient light were significant, the AIMS2 doors seem to be assisting to some extent in shedding exterior light. However, replacing the doors to non-transparent should decrease or eliminate the influence of ambient light.

Table 2.14. Fine Aggregates Summary of Results Used in Experiment 2

	1.18 mm (ASTM #16)		0.60 mm (ASTM #30)		
	Dark	Light	Dark	Light	Factors
Angularity	533994.64	1826.07	952321.83	125990.04	Tray color
	NS	NS	NS	387.33	Light illumination
	NS	NS	4796.95	15.10	Door Position
	NS	27.78	331.31	293.74	CHPR
	NS	NS	13.70	NS	Zoom level
	NS	NS	349.59	75.06	Particle Count
	NS	8.94	60.90	13.52	Ambient light
2D Form	241891.77	103.93	32755.39	7789.89	Tray color
	NS	NS	28.00	NS	Light illumination
	NS	NS	45.84	5.76	Door Position
	6.44	9028.55	NS	NS	CHPR
	NS	384.09	NS	34.92	Zoom level
	NS	77.40	NS	32.19	Particle Count
	NS	NS	NS	9.89	Ambient light

Experiment 3

Additional analyses were performed on the coarse aggregates from Experiment 1 (Figure 2.1) to determine the appropriate limits that would not affect the AIMS2 results. In Experiment 3, some of the previous factors from Experiment 1 were removed and the limits of the remaining factors were tightened. A "dummy factor" was introduced to put in place of the removed factors. These "dummy factors" did not change any of the settings. AIMS2 doors factors were not included in Experiment 3 since it was important to focus on the remaining factors. Table 2.15 lists the Experiment 3 coarse aggregate factors and limits. The results of the 9.5 mm (0.375 in) coarse aggregates are shown in Table 2.16 and Table 2.17 for the dark and light aggregates. The effect factors were found to determine the significance of the factors tested. The summary of the effect factors are shown in Table 2.18.

Table 2.15. Coarse Aggregate Factors and Limits Used in Experiment 3

Factor	Coarse Aggregate Adjusted Study Factors:	Low Limit	High Limit
A	Tray size	9.5 mm	4.75 mm
B	Light illumination (Top light and Bottom light)	-4	+4
C	"Dummy Factor"	0	0
D	"Dummy Factor"	0	0
E	"Dummy Factor"	0	0
F	Tray Height	-0.5 mm	+0.5 mm
G	Ambient light	On	Off

Table 2.16. Results of Dark 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 3

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2703.54	261.97	0.65	2.97
Scan 2	2570.88	261.76	0.69	2.43
Scan 3	2741.46	261.72	0.70	2.41
Scan 4	2732.39	262.35	0.66	2.88
Scan 5	2630.47	270.62	0.66	2.85
Scan 6	2539.57	268.44	0.69	2.41
Scan 7	2714.99	270.44	0.70	2.36
Scan 8	2688.32	268.80	0.67	2.79
Scan 9	2642.89	260.08	0.65	2.93
Scan 10	2656.08	262.86	0.69	2.44
Scan 11	2689.69	261.48	0.70	2.40
Scan 12	2733.28	263.37	0.66	2.89
Scan 13	2625.65	268.98	0.66	2.81
Scan 14	2608.40	269.83	0.69	2.43
Scan 15	2737.52	268.91	0.70	2.35
Scan 16	2722.96	268.96	0.66	2.81

Table 2.17. Results of Light 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 3

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2329.30	41.40	0.64	2.94
Scan 2	2374.09	41.29	0.68	2.42
Scan 3	2434.67	41.28	0.68	2.38
Scan 4	2443.27	42.03	0.65	2.86
Scan 5	2349.79	40.99	0.65	2.82
Scan 6	2328.91	42.29	0.68	2.40
Scan 7	2408.62	40.77	0.68	2.36
Scan 8	2371.11	40.71	0.65	2.76
Scan 9	2303.40	41.79	0.64	2.96
Scan 10	2373.15	41.59	0.68	2.44
Scan 11	2406.42	40.98	0.68	2.40
Scan 12	2403.76	41.64	0.65	2.88
Scan 13	2345.61	41.50	0.64	2.88
Scan 14	2325.77	41.20	0.67	2.43
Scan 15	2406.41	40.74	0.69	2.34
Scan 16	2373.41	42.02	0.65	2.78

Table 2.18. Coarse Aggregates Summary of Results Used in Experiment 3

	Experiment 3		
	Light	Dark	Factors
	64.12	NS	Tray size
	7308.12	337.25	Light illumination
	NS	NS	"Dummy Factor"
Angularity	9.66	NS	"Dummy Factor"
	293.44	NS	"Dummy Factor"
	37.33	NS	Tray Height
	NS	NS	Ambient light
	NS	13151.15	Tray size
	NS	NS	Light illumination
	NS	NS	"Dummy Factor"
Texture	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	Tray Height
	NS	NS	Ambient light
	27.87	5344.64	Tray size
	1602.37	3849.15	Light illumination
	NS	NS	"Dummy Factor"
Sphericity	7.79	NS	"Dummy Factor"
	NS	11.26	"Dummy Factor"
	847660.40	7085309.92	Tray Height
	NS	21.33	Ambient light
	3753.97	746.50	Tray size
	5271.79	207.21	Light illumination
	7.01	NS	"Dummy Factor"
Flat or Elongated 3:1	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	11256827.41	2005250.58	Tray Height
	480.54	42.50	Ambient light

The angularity results of both aggregates (light and dark) showed significant variation to only the light illumination. Several factors for the light aggregate angularity were significant including tray size, tray height and two "dummy factors". The texture results have significant variations due to changes in the tray size only. The sphericity and flat or elongated 3:1 results were affected by changes in the tray size, light illumination, tray height, ambient light, and two "dummy factors".

Experiment 4

Since there were some "dummy factors" shown to be significant in Experiment 3, Experiment 4 was conducted using all factors as "dummy factors." This was done to determine if the normal variations within the AIMS2 system were rugged. The dark, 9.5 mm (0.375 in) (Figure 2.1) and light and dark, 0.60 mm (ASTM #30) (Figure 2.3) fine aggregates were used in Experiment 4. In addition, the doors were changed to non-transparent which no longer allowed ambient light into the system. Table 2.19 lists the factors and the limits for Experiment 4. These were the same for the coarse and fine aggregates. The results from Experiment 4 for the coarse and fine aggregates are shown in Table 2.20, Table 2.21, and Table 2.22. The summary of the effect factors are shown in Table 2.23 for the coarse aggregates Table 2.24 for the fine aggregates.

Table 2.19. Coarse and Fine Aggregate Factors and Limits Used in Experiment 4

Factor	Coarse and Fine Aggregate Factors:	Low Limit	High Limit
A	"Dummy Factor"	0	0
B	"Dummy Factor"	0	0
C	"Dummy Factor"	0	0
D	"Dummy Factor"	0	0
E	"Dummy Factor"	0	0
F	"Dummy Factor"	0	0
G	"Dummy Factor"	0	0

Table 2.20. Results of Dark 9.5 mm (0.35 in) Coarse Aggregates Used in Experiment 4

	Angularity	Texture	Sphericity	Flat or Elongated 3:1
Scan 1	2731.88	656.32	0.66	2.78
Scan 2	2751.49	657.16	0.66	2.79
Scan 3	2719.72	660.84	0.66	2.78
Scan 4	2722.21	657.90	0.67	2.73
Scan 5	2680.50	659.98	0.66	2.77
Scan 6	2697.37	658.39	0.67	2.75
Scan 7	2728.48	662.15	0.66	2.78
Scan 8	2747.92	661.14	0.66	2.77
Scan 9	2702.50	661.24	0.66	2.77
Scan 10	2747.12	663.30	0.66	2.76
Scan 11	2706.37	660.57	0.66	2.77
Scan 12	2719.17	657.08	0.66	2.75
Scan 13	2709.70	657.85	0.66	2.76
Scan 14	2677.41	661.83	0.66	2.76
Scan 15	2730.12	661.51	0.67	2.75
Scan 16	2660.21	658.07	0.67	2.73

Table 2.21. Results of Dark 0.60 mm (ASTM #30) Fine Aggregates Used in Experiment 4

	Angularity	2D Form
Scan 1	3841.29	7.83
Scan 2	3727.50	7.72
Scan 3	3900.22	7.74
Scan 4	3772.68	7.79
Scan 5	3761.00	7.80
Scan 6	3775.48	7.82
Scan 7	3712.38	7.73
Scan 8	3810.79	7.78
Scan 9	3737.36	7.76
Scan 10	3815.72	7.74
Scan 11	3897.90	7.82
Scan 12	3800.96	7.73
Scan 13	3845.72	7.73
Scan 14	3851.68	7.79
Scan 15	3884.05	7.76
Scan 16	3892.99	7.74

Table 2.22. Results of Light 0.60 mm (ASTM #30) Fine Aggregates Used in Experiment 4

	Angularity	2D Form
Scan 1	3330.09	6.91
Scan 2	3241.78	6.91
Scan 3	3293.31	6.94
Scan 4	3306.61	6.95
Scan 5	3318.89	6.96
Scan 6	3359.40	6.95
Scan 7	3351.62	6.95
Scan 8	3326.83	6.94
Scan 9	3324.90	6.95
Scan 10	3380.49	6.95
Scan 11	3376.37	6.95
Scan 12	3375.59	6.96
Scan 13	3362.93	6.95
Scan 14	3410.54	6.95
Scan 15	3334.68	6.93
Scan 16	3359.42	6.92

Table 2.23. Coarse Aggregates Summary of Results Used in Experiment 4

	Experiment 4	
	Dark	Factors
Angularity	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
Texture	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
Sphericity	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
Flat or Elongated 3:1	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"
	NS	"Dummy Factor"

Table 2.24. Fine Aggregates Summary of Results Used in Experiment 4

	Experiment 4		
	Dark	Light	Factors
Angularity	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
2D Form	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"
	NS	NS	"Dummy Factor"

All of the "dummy factors" for the coarse and fine aggregates showed no significance in the results of the system. It can be concluded that AIMS2 is able to control normal variation in the factors and this normal variation does not present a statistically significant influence on the results.

SUMMARY OF ASCE ASTM C 1067-00 RUGGEDNESS

The ASTM C 1067-00 ruggedness study has lead to identifying significant factors affecting the AIMS2 results. The AIMS2 transparent doors were not able to control effect of ambient lighting changes as originally predicted, so the doors were replaced with non-transparent doors. The new doors were designed to block any ambient light which was showed to be affecting the results. When all "dummy factors" were used and all of the limits were selected to their correct values, AIMS2 was able to control the normal variations in the system such that the AIMS2 controlled factors have no statistical significant effect on the results.

From the results of Experiments 1 and 2 discussed in this report, some factors were thought to be interacting with each other. This could cause factors effects to be artificially significant. ASTM C 1067-00 assumes that any interactions among factors tested are negligible and therefore not included in the test procedure. However, if the effect of the interactions are not negligible, the estimates of the effect could include be skewed due to interactions. Therefore, it was decided to conduct an additional ruggedness study using ASTM E 1169-07 to have a better understanding of the interaction of the factors.

RUGGEDNESS ANALYSIS USING ASTM E 1169-07

Another ruggedness study was conducted with a new set of ranges to identify factors that significantly influence the measurements provided by the AIMS2 and to estimate possible interaction between factors. The study was carried out in accordance with ASTM E 1169-07, "Standard Practice for Conducting Ruggedness Tests." ASTM E 1169-07 differs from the ASTM C 1067, since ASTM E 1169 is able to identify interactions which may arise from the interference of the individual factors.

Experimental Procedures

The ruggedness test requires 16 total scans of seven factors and specified high and low limits. The last eight scans (scans 9 through 16) are an inverse of the first eight scans (scans 1 through 8). This means that the low limits in scans 1 to 8 are used as the high limits in scans 9 to 16 and vice versa. Table 2.25 shows a template of the 16 scans and the limit levels (high or low) of each factor for all the scans.

Table 2.25. Template of Ruggedness Scans for ASTM E 1169-07

Replicate Scans Number 1

			Scan Number							
Factor	Low Limit	High Limit	1	2	3	4	5	6	7	8
A	a	A	A	a	a	A	a	A	A	a
B	b	B	B	B	b	b	B	b	B	b
C	c	C	C	C	C	c	c	C	c	c
D	d	D	d	D	D	D	d	d	D	d
E	e	E	E	e	E	E	E	e	e	e
F	f	F	f	F	f	F	F	F	f	f
G	g	G	g	g	G	g	G	G	G	g

Duplicate Scans

			Scan Number							
Factor	Low Limit	High Limit	9	10	11	12	13	14	15	16
A	a	A	a	A	A	a	A	a	a	A
B	b	B	b	b	B	B	b	B	b	B
C	c	C	c	c	c	C	C	c	C	C
D	d	D	D	d	d	d	D	D	d	D
E	e	E	E	E	e	e	e	E	E	E
F	f	F	F	f	F	f	f	f	F	F
G	g	G	G	G	g	G	g	g	g	G

The calculated effect of each factor as explained in ASTM E 1169-07 is used to determine the statistical significance of the factor on the results. As discussed earlier, the ASTM E 1169-07 method considers the interactions between factors in the test as oppose to the ASTM C 1067. If the effect of one factor depends on the level of another factor, then these two factors interacts. As a general rule, factors only interact when factors have large effects or statistical significance by themselves. The suffix –I is used to indicate the two factor interaction. For example, the position of the door and the intensity of the ambient light may be interacting in causing error in the test results or a false increase in a factor's effect. If an interaction is found, and both the door position and ambient light have large effects, then the interaction is mostly likely caused by these two factors. In this case, the door position and ambient light will typically be found to be statistically significant. If for the interaction, there are no possible factors with large individual effects, then the cause of the interaction may be unclear. The unclear interactions could be caused by more than one set of two factor interactions. The list of possible two factor interactions for each interaction effect is shown in Table 2.26. ASTM E 1169-07 contains the required details to calculate the effect factor and interaction for the different main factors.

Table 2.26. Possible Cause of Interactions for ASTM E 1169-07

Interaction	Possible Causes		
A-I	BF	CD	EG
B-I	AF	CG	DE
C-I	AD	BG	EF
D-I	AC	BE	FG
E-I	AG	BD	CF
F-I	AB	CE	DG
G-I	AE	BC	DF

In order to determine the significant factors and interaction, effect factors are plotted on a half-normal plot. A half-normal plot is an analytical test for revealing the presence of outliers by comparing the residuals from the data to the expected observed values from a normal distribution. Both the residuals and expected values are ordered. Points from the plot usually align along a straight line. The values that do not fall along the line and are in the top right of the plot are considered outliers. The half normal plot is much like a normal probably plot, except the outliers of the sample appear only in to upper right corner of the plot instead of at both ends.[4]

A linear line to represent the standard error for the estimates is drawn through the smallest effects, which are linearly orientated. Potential significant effect factors are those which fall farthest to the right of the standard error line. The statistical significance of factors that lie close, but are to the right of the standard error line were considered to be unclear.

Several experiments were conducted using both coarse and fine aggregates with different limits until the method was concluded to be rugged. Experiments 5 and 6 dealt with coarse aggregate, while Experiment 7 and 8 were for the fine aggregates. Experiment 9 was conducted to further investigate the influence of narrowing the limits of factors used in Experiment 6 on the aggregate height measurements. Replicate measurements of the aggregate height dimensions were compared to determine the ability of AIMS2 to

[4] Jay L. Devore (Ed.), *Probability and Statistics for Engineering and the Sciences*, 6th ed., 2004.

produce replicate measurements for different types and sizes of coarse aggregates in Experiment 10. A summary of the experiments is shown in Table 2.27.

Table 2.27. Summary of Ruggedness Experiments Using ASTM E 1169-07

Experiment	Purpose of the Experiment	Aggregate Sizes
5	Study to Determine the Appropriate Limits for a Rugged System	9.5 mm (0.375 in) and 4.75 mm (ASTM #4 sieve)
6	Based on Experiment 5, a Further Investigation of the Limits	9.5 mm (0.375 in) and 4.75 mm (ASTM #4 sieve)
7	Study to Determine the Appropriate Limits for a Rugged System	1.18 mm (ASTM #16 sieve) and 0.15 mm (ASTM #100 sieve)
8	Based on Experiment 7, a Further Investigation of the Limits	1.18 mm (ASTM #16 sieve) and 0.15 mm (ASTM #100 sieve)
9	Further Investigation of the Limits that Affect the Aggregate Height Measurements from Experiment 6	9.5 mm (0.375 in) and 4.75 mm (ASTM #4 sieve)
10	Comparison of Replicate Height Measurements Gather by AIMS2	25.0 mm (1.0 in) to 4.75 mm (ASTM #4 sieve)

Experiment 5

Experiment 5 was carried out on two different coarse aggregates (a dark-colored aggregate and a light-colored aggregate) with a size of 9.5 mm (0.375 in) (Figure 2.4). Table 2.28 lists the factors and limits chosen for this experiment.

Figure 2.4. Dark and light 9.5 mm (0.375 in) aggregates used in Experiment 5.

Table 2.28. Coarse Aggregate Factors and Limits Used in Experiment 5

Factor	Coarse Aggregate Study Factors:	Low Limit	High Limit
A	Light Illumination	-1	+1
B	Tray Height	-0.25 mm	+0.25 mm
C	Tray Size	4.75 mm	9.5 mm
D	Door Position	Open	Closed
E	Ambient Light	Off	On
F	Zoom Level	-1%	+1%
G	Focus (DOF)	1%	0%

The limits of the light illumination were selected as +1 and -1 light intensity from the operational setting which are used to decrease and increase light illumination setting of the system. The limits for the tray size were selected as the correct tray size, 9.5 mm, and one tray size below the correct tray size, 4.75 mm. The ambient light, either on or off, was included in order to consider the performance of the doors in eliminating the effect of changes in exterior lighting. The positions of the door limits were selected as completely closed or completely open. The focus, zoom level, and tray height limits were chosen to evaluate the acceptable variability for each factor.

Table 2.29 summarizes the texture, angularity, and sphericity results for the dark coarse aggregate. The light coarse aggregate results are summarized in Table 2.30.

Table 2.29. Results of Dark 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 5

	Angularity	Texture	Sphericity
Scan 1	2755.46	649.97	0.683
Scan 2	2634.78	650.33	0.673
Scan 3	2615.31	661.51	0.692
Scan 4	2680.15	667.60	0.702
Scan 5	2677.53	661.01	0.679
Scan 6	2703.25	658.79	0.699
Scan 7	2701.79	660.62	0.686
Scan 8	2649.91	659.61	0.700
Scan 9	2648.56	664.01	0.694
Scan 10	2693.35	657.70	0.702
Scan 11	2695.93	664.36	0.682
Scan 12	2623.58	654.00	0.677
Scan 13	2697.51	653.63	0.703
Scan 14	2647.31	657.26	0.681
Scan 15	2664.08	655.03	0.697
Scan 16	2714.22	658.51	0.672

Table 2.30. Results of Light 9.5 mm (0.375 in) Coarse Aggregates Used in Experiment 5

	Angularity	Texture	Sphericity
Scan 1	2369.09	108.08	0.663
Scan 2	2270.35	105.52	0.660
Scan 3	2319.58	108.62	0.682
Scan 4	2487.44	102.65	0.691
Scan 5	2407.35	100.73	0.668
Scan 6	2368.62	104.98	0.680
Scan 7	2467.20	102.23	0.676
Scan 8	2433.93	102.35	0.688
Scan 9	2420.17	101.37	0.684
Scan 10	2439.31	102.18	0.694
Scan 11	2493.94	101.67	0.673
Scan 12	2352.91	106.55	0.664
Scan 13	2366.58	107.07	0.688
Scan 14	2399.35	102.62	0.672
Scan 15	2353.66	106.14	0.677
Scan 16	2417.20	107.34	0.664

Figure 2.5, Figure 2.6, and Figure 2.7 show the half-normal plot for the dark aggregates angularity, texture, and sphericity, respectively, while the light aggregate plots are shown in Figure 2.8, Figure 2.9, and Figure 2.10.

From the half-normal plots of the dark aggregate, three factors show to be statistically significant, one for each of the shape characteristics. Light illumination, Factor A, appears to affect the angularity results (Figure 2.5); tray size, Factor C, appears to be statistically significant for the texture results (Figure 2.6); and the sphericity results are affected by tray height, Factor B (Figure 2.7).

The factors tested appear to affect the light coarse aggregate results more than the dark-colored aggregate results. The angularity results were affected by tray size (Factor C) and light illumination (Factor A), and by several interaction factors, Factor C-I, F-I, and B-I (Figure 2.8). The most likely cause for the large C-I interaction factor was the AD interaction since A (light illumination) and D (door position) have large main effects. The interaction AB (light illumination and tray height) or CE (tray size and ambient light) was most likely the cause for the large F-1 factor; the interaction AF (light illumination and zoom level) was most likely the cause of the large B-1 factor. The significance of Factors D (door position), F (zoom level), A-1 and E-1 were unclear. Factor C, tray size, appears to be statistically significant for the texture results (Figure 2.9). It was not clear whether the zoom level, Factor F, has a significant effect of the texture results or not. The sphericity results appears to be affected by Factors B, C, A, and F which were tray height, tray size, light illumination, and zoom level, respectively (Figure 2.10).

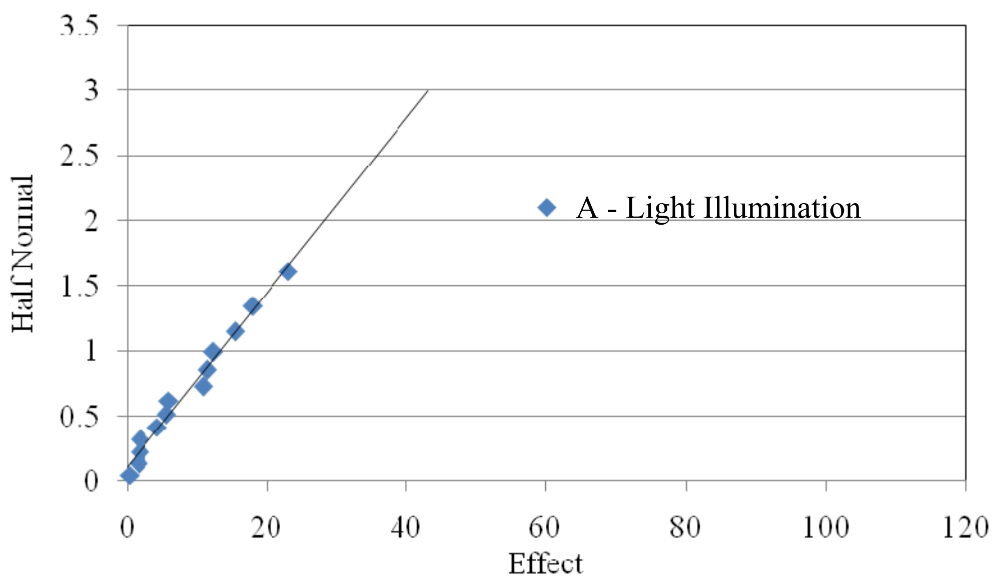

Figure 2.5. Half-normal plot of the angularity of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

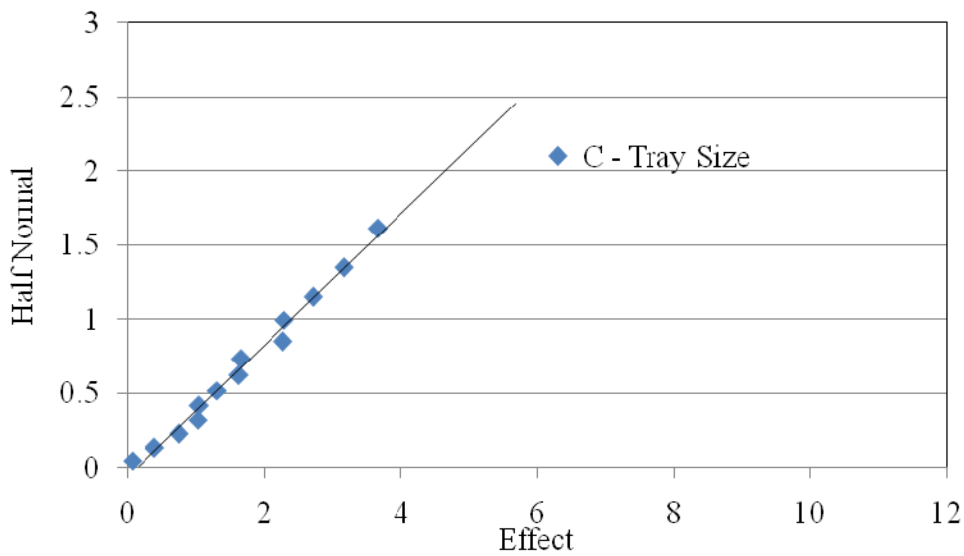

Figure 2.6. Half-normal plot of the texture of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

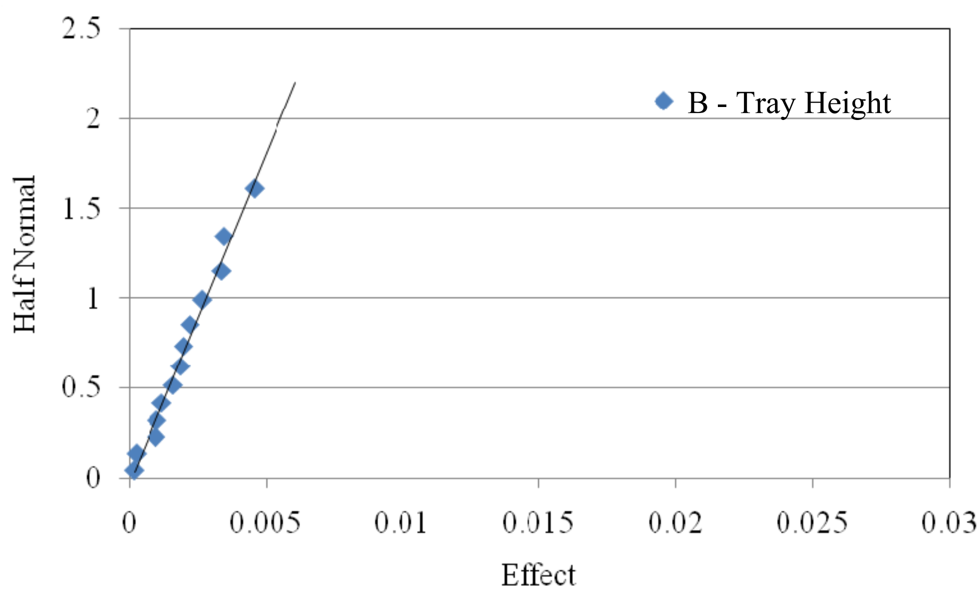

Figure 2.7. Half-normal plot of the sphericity of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

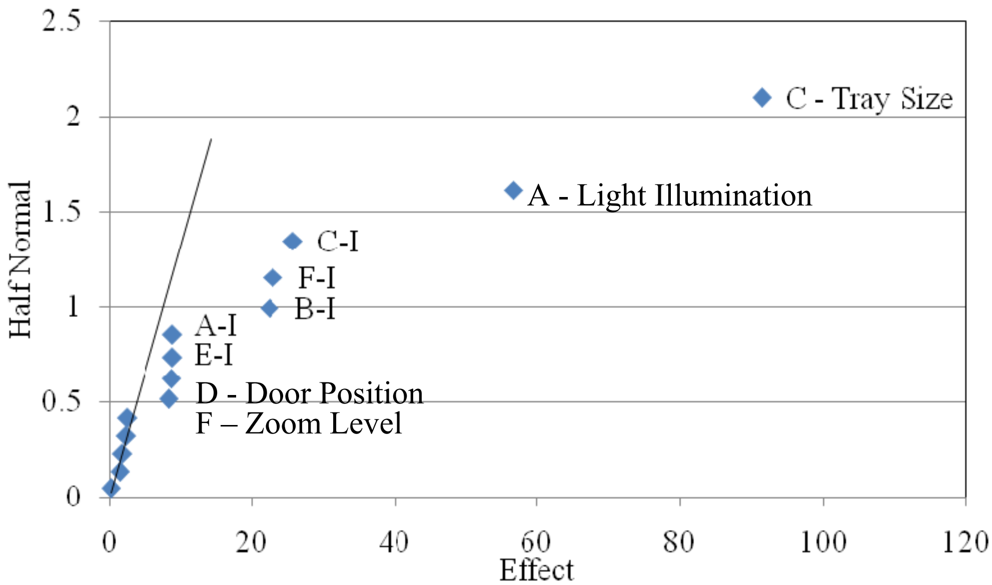

Figure 2.8. Half-normal plot of the angularity of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

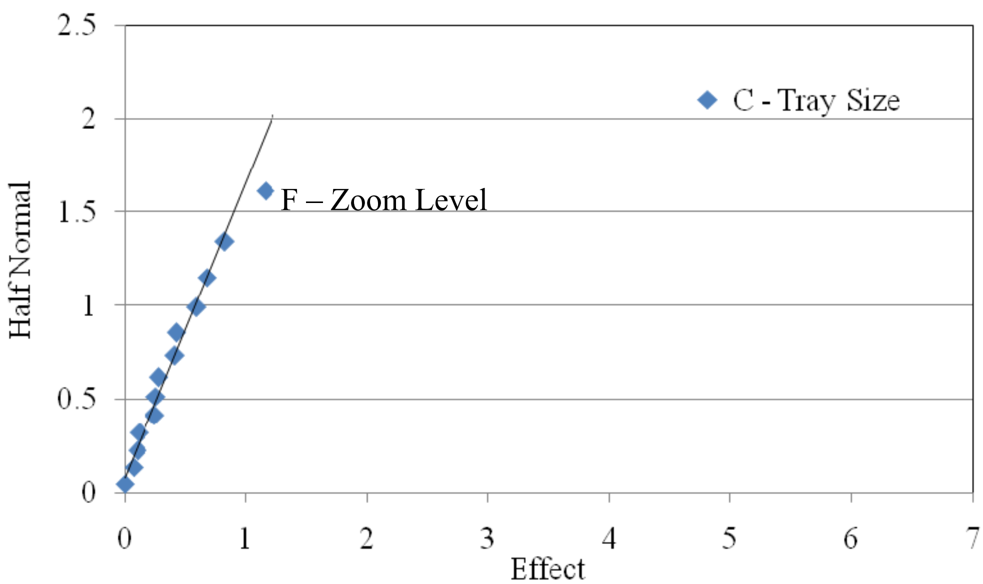

Figure 2.9. Half-normal plot of the texture of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

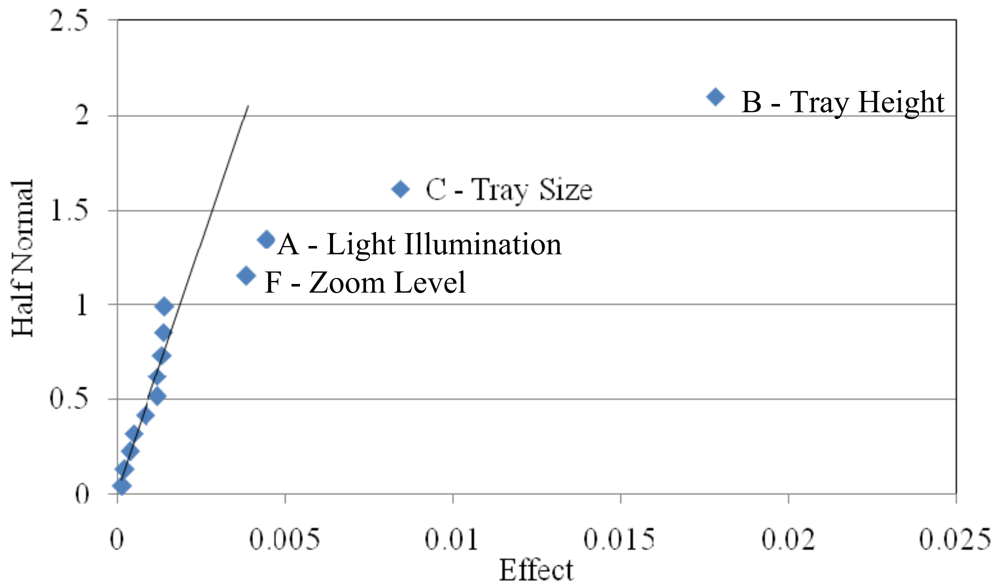

Figure 2.10. Half-normal plot of the sphericity of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 5.

An additional coarse size 4.75 mm (ASTM #4 sieve) was tested to confirm the results of the 9.5 mm size aggregate (0.375 in). Since more of the factors tested were significant for the light-colored aggregate than the dark-colored aggregate, only a light-colored aggregate was tested (Figure 2.11). The factors and limits were the same as the 9.5 mm (0.375 in) aggregates (Table 2.28). Since the aggregate size tested changed from 9.5 mm (0.375 in) to 4.75 mm (ASTM #4 sieve), the tray size limits with respect to the aggregate size were different. For the 9.5 mm (0.375 in) aggregate, the trays used were the correct size (9.5 mm) and one tray size smaller (4.75 mm). For the 4.7 5mm (ASTM #4 sieve), the trays used were the correct size (4.75 mm) and one tray size larger (9.5 mm). Table 2.31 shows a summary of the texture, angularity, and sphericity results.

Figure 2.11. Light 4.75 mm (ASTM #4 sieve) aggregates used in Experiment 5.

Table 2.31. Results of Light 4.75 mm (ASTM #4 sieve) Coarse Aggregate Used in Experiment 5

Scan	Angularity	Texture	Sphericity
Scan 1	2810.54	161.75	0.628
Scan 2	2688.51	160.94	0.619
Scan 3	2761.23	160.40	0.646
Scan 4	2775.79	163.57	0.602
Scan 5	2719.65	161.70	0.576
Scan 6	2744.61	157.84	0.654
Scan 7	2759.47	161.88	0.584
Scan 8	2620.12	162.98	0.596
Scan 9	2770.68	162.44	0.593
Scan 10	2788.08	163.88	0.605
Scan 11	2748.26	161.48	0.581
Scan 12	2695.06	162.04	0.615
Scan 13	2789.61	163.93	0.653
Scan 14	2678.55	164.21	0.577
Scan 15	2710.44	155.26	0.644
Scan 16	2805.75	155.61	0.625

The half-normal plots for the angularity, texture, and sphericity are shown in Figure 2.12, Figure 2.13, and Figure 2.14 respectively.

The light 4.75 mm (ASTM #4 sieve) aggregates were affected by several of the same factors that affected the light and dark 9.5 mm (0.375 in) aggregates. The light illumination (Factor A) was statistically significant for the angularity results (Figure 2.12). For the texture results (Figure 2.13), the main factors, tray size (Factor C) and zoom level (Factor F) were statistical significant. The interaction Factors F-I and E-I were statistically significant, which were caused most likely by the interactions CE (tray size and ambient light) and CF (tray size and zoom level), respectively. The sphericity results were affected by Factor C (tray size), Factor B (tray height), Factor A (light illumination), and G-I. The G-I interaction was probably caused be the interaction BC (tray size and tray height) (Figure 2.14).

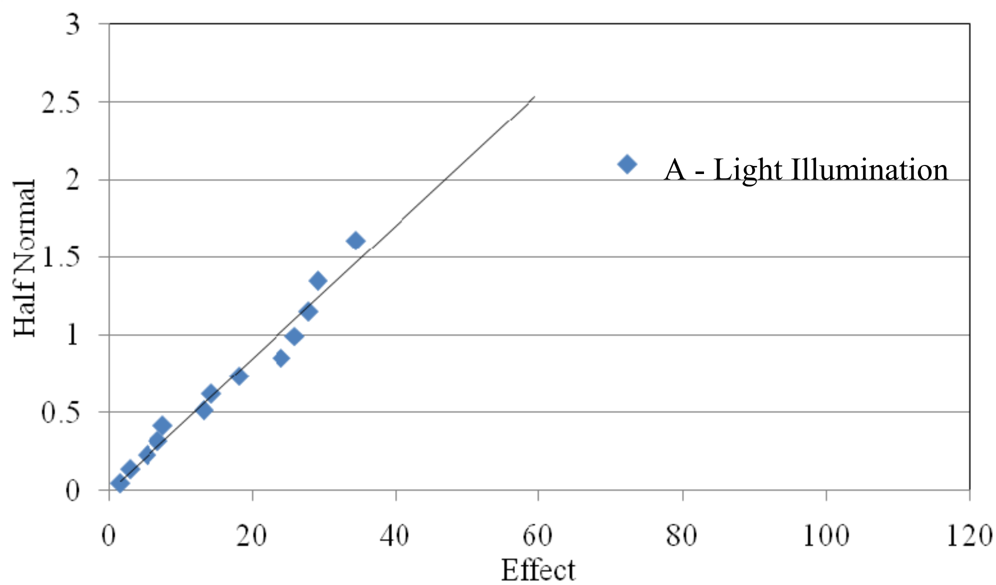

Figure 2.12. Half-normal plot of the angularity of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 5.

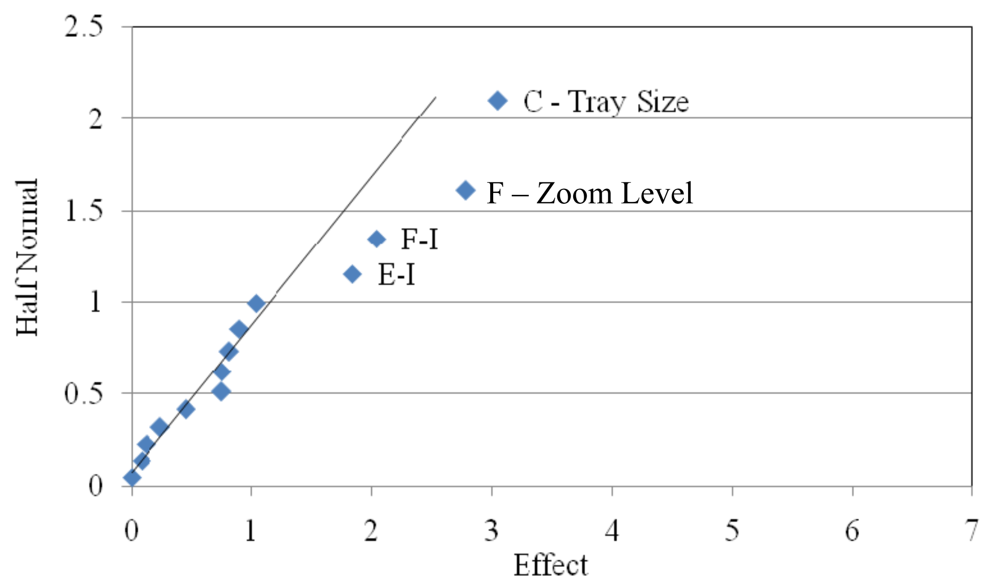

Figure 2.13. Half-normal plot of the texture of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 5.

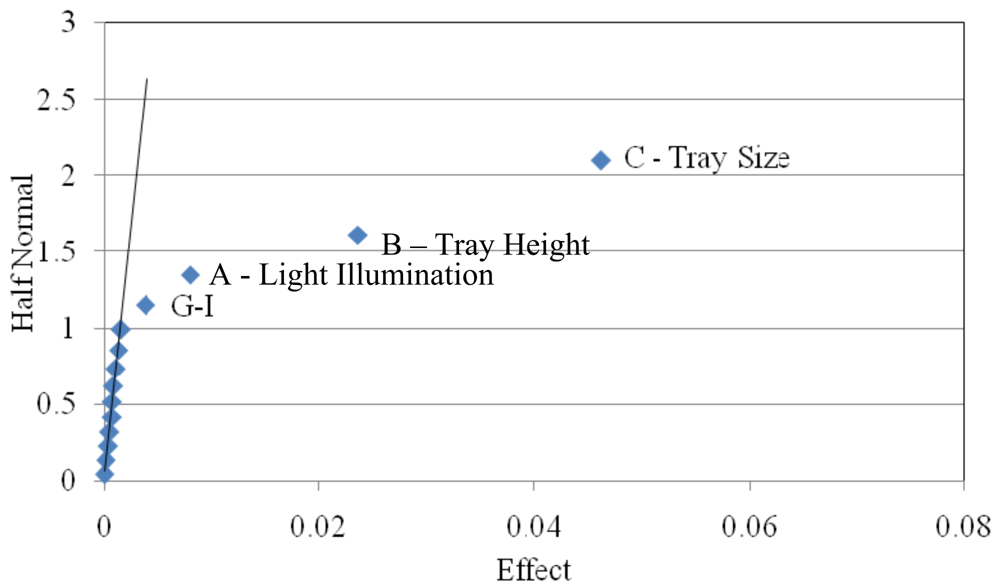

Figure 2.14. Half-normal plot of the sphericity of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 5.

Overall for the 9.5 mm (0.375 in) and 4.75 mm (ASTM #4 sieve) coarse aggregates, light illumination (Factor A), tray height (Factor B), tray size (Factor C), and zoom level (Factor F) were statistically significant using the limits tested. Other factors that appeared to be statistically significant were C-I (AD), F-I (AB or CE), B-I (AF), F-I (CE), D-I (CF), and G-I (BC).

Experiment 6

This experiment was carried out to further investigate acceptable ranges for the factors that were found to be statistically significant in affecting the coarse aggregates based on the results of Experiment 5. These factors are light illumination (Factor A), tray height (Factor B), and zoom level (Factor F). The new, tighter, factor ranges are shown in

Table 2.32. For Experiment 6, the same two aggregates as in Experiment 5 (Figure 2.4) were tested: a dark-colored 9.5 mm (0.375 in) and a light-colored 9.5 mm (0.375 in) size aggregate. The summary of the results for the angularity, texture, and sphericity are shown in Table 2.33 and Table 2.34.

Table 2.32. Coarse Aggregate Factors and Limits Used in Experiment 6

Factor	Coarse Aggregate Study Factors:	Low Limit	High Limit
A	Light illumination	-1	0
B	Tray Height	-0.10 mm	0.10 mm
C	Tray Size	4.75 mm	9.5 mm
D	Door Position	Open	Closed
E	Ambient Light	Off	On
F	Zoom Level	-0.5%	+0.5%
G	Focus (DOF)	1%	0%

Table 2.33. Results of Dark 9.5 mm (0.375 in) Coarse Aggregate Used in Experiment 6

	Angularity	Texture	Sphericity
Scan 1	2633.74	635.27	0.680
Scan 2	2679.19	639.65	0.678
Scan 3	2622.26	635.84	0.685
Scan 4	2655.28	631.71	0.687
Scan 5	2719.17	630.36	0.677
Scan 6	2669.10	633.06	0.684
Scan 7	2678.98	630.07	0.680
Scan 8	2678.43	624.20	0.689
Scan 9	2743.88	634.66	0.684
Scan 10	2637.89	620.24	0.688
Scan 11	2676.12	630.75	0.682
Scan 12	2660.87	634.31	0.679
Scan 13	2701.93	634.88	0.687
Scan 14	2709.30	632.69	0.681
Scan 15	2659.13	631.22	0.685
Scan 16	2689.69	635.59	0.677

Table 2.34. Results of Light 9.5 mm (0.375 in) Coarse Aggregate Used in Experiment 6

	Angularity	Texture	Sphericity
Scan 1	2462.38	106.35	0.666
Scan 2	2388.29	103.94	0.666
Scan 3	2417.29	105.75	0.670
Scan 4	2337.13	101.59	0.683
Scan 5	2444.97	100.00	0.676
Scan 6	2390.14	104.24	0.672
Scan 7	2379.26	100.83	0.677
Scan 8	2343.70	100.86	0.684
Scan 9	2358.73	100.76	0.682
Scan 10	2367.75	100.63	0.685
Scan 11	2364.89	100.46	0.677
Scan 12	2471.44	103.52	0.666
Scan 13	2482.36	105.35	0.674
Scan 14	2391.33	100.95	0.679
Scan 15	2357.64	103.94	0.671
Scan 16	2446.15	104.02	0.665

The half-normal plots for the 9.5 mm (0.375 in) dark aggregate are shown in Figure 2.15, Figure 2.16, and Figure 2.17 for angularity, texture, and sphericity, respectively. The 9.5 mm (0.375 in) light aggregate plots are shown in Figure 2.18, Figure 2.19, and Figure 2.20.

As result of using tighter ranges, the statistical significance of Factor A (light illumination), Factor B (tray height), and Factor F (zoom level) decreased or were no longer significant compared to Experiment 5. The texture and sphericity results were both affected by Factor C (tray size), as shown in Figure 2.16 and Figure 2.17. Factor D, door position, was also found to be statistically significant for the texture results (Figure 2.16).

The light-colored aggregates texture and sphericity results were affected by Factor C, (tray size) (Figure 2.19 and Figure 2.20), and sphericity results were affected by Factor B (tray height) (Figure 2.20). No interaction factors were found to be statistically significant in Experiment 6. This was most likely due to the decrease in the effects of the main factors.

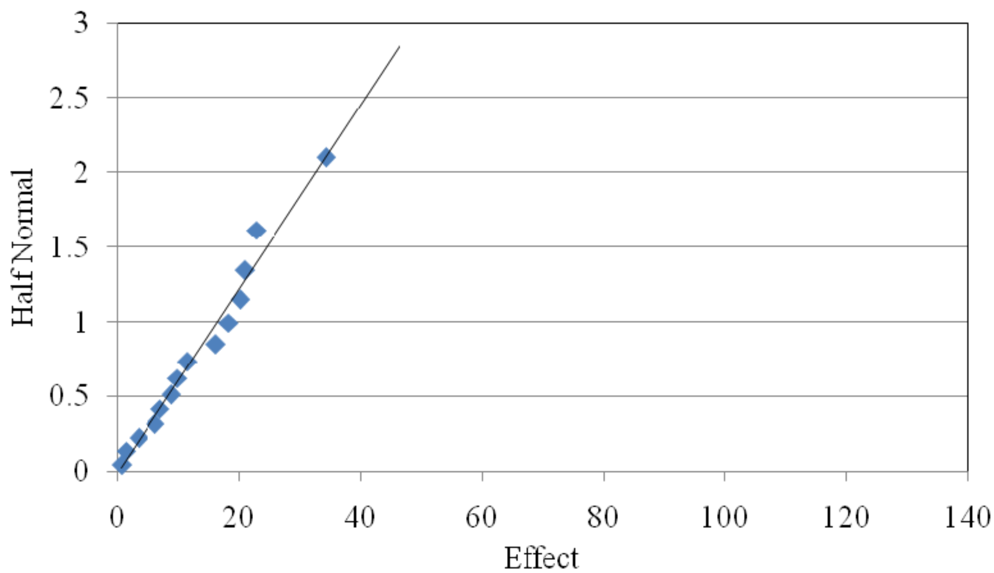

Figure 2.15. Half-normal plot of the angularity of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

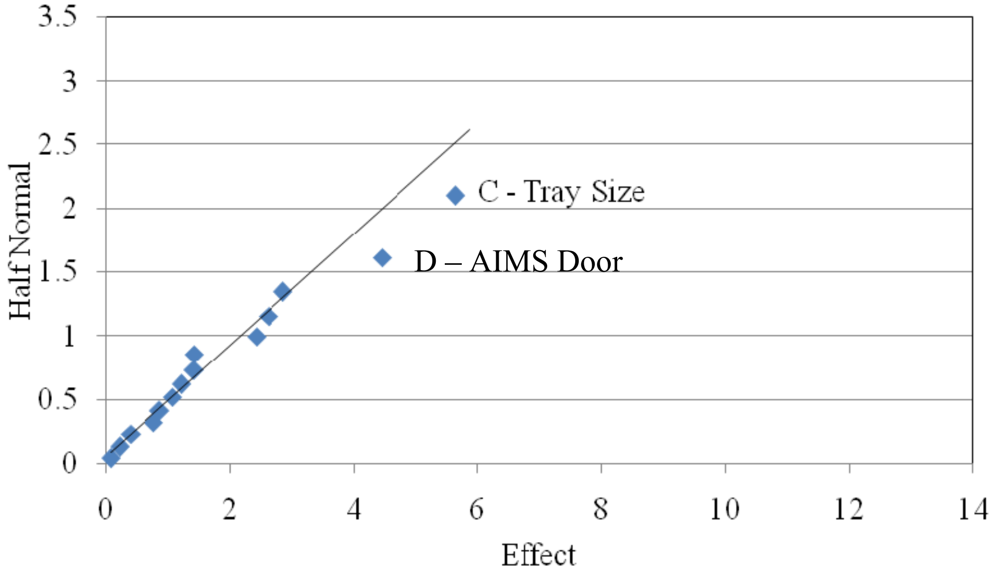

Figure 2.16. Half-normal plot of the texture of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

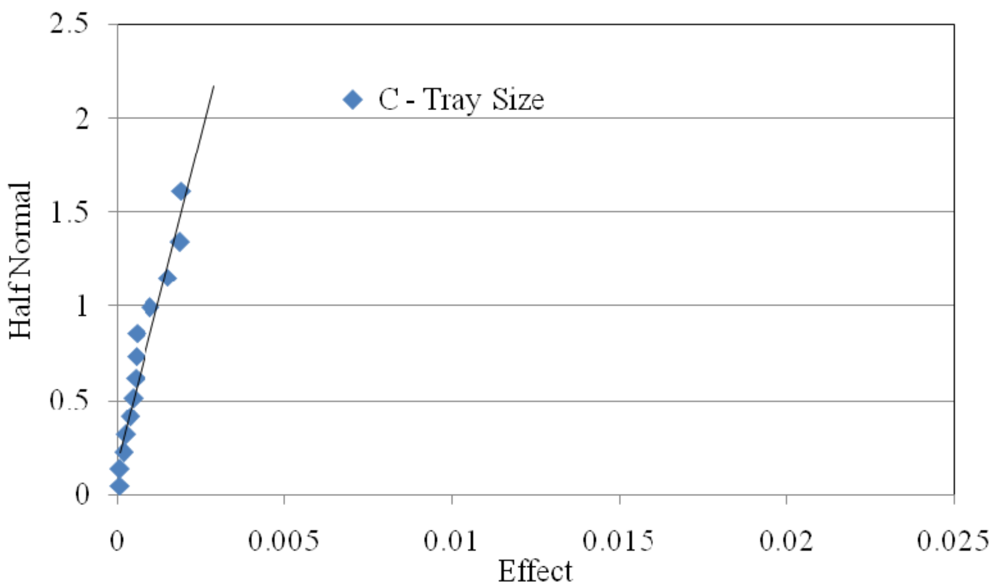

Figure 2.17. Half-normal plot of the sphericity of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

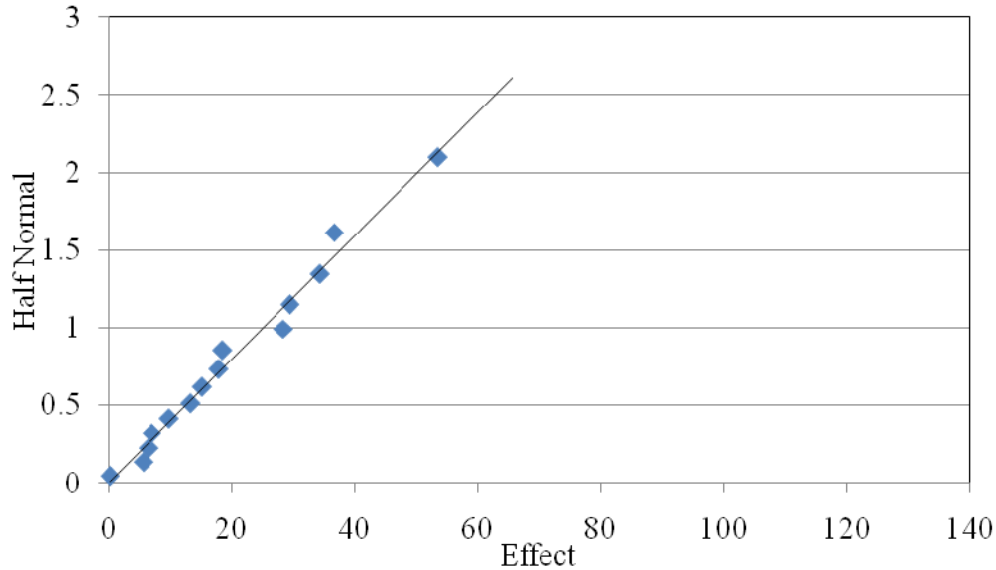

Figure 2.18. Half-normal plot of the angularity of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

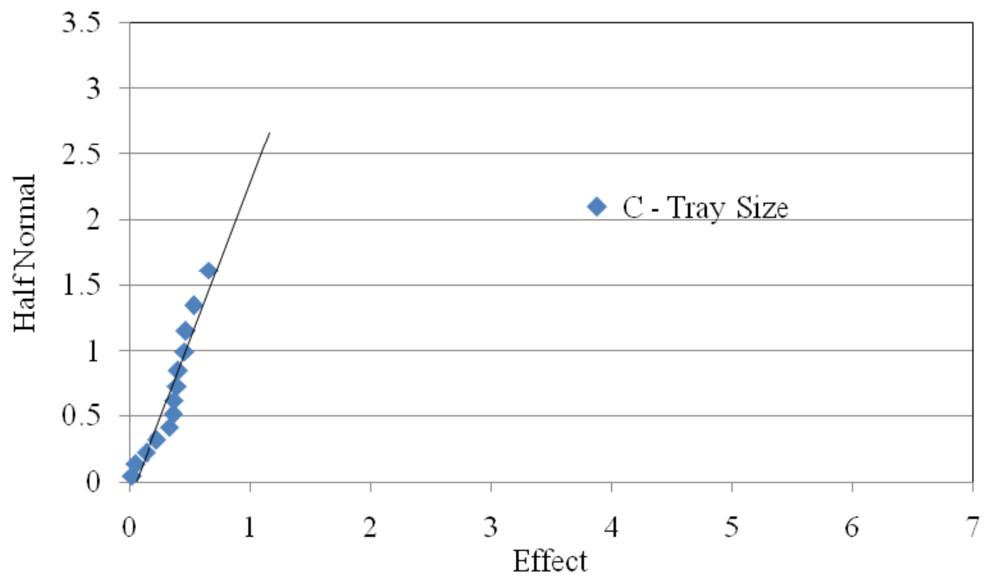

Figure 2.19. Half-normal plot of the texture of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

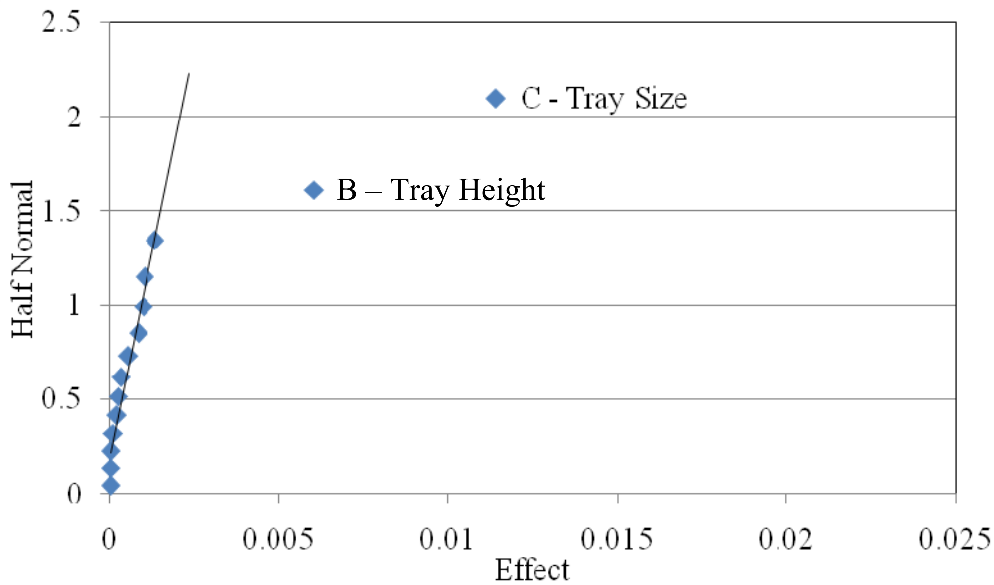

Figure 2.20. Half-normal plot of the sphericity of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 6.

The results from 9.5 mm (0.375 in) aggregates were confirmed using a light-colored 4.75 mm (ASTM #4 sieve) aggregate. All the factors remained the same as in Table 2.32. The same light-colored 4.75 mm (ASTM #4 sieve) aggregate used in Experiment 5, was used for Experiment 6 (Figure 2.11). A summary of the angularity, texture, and sphericity results are listed in Table 2.35.

Table 2.35. Results of Light 4.75 mm (ASTM #4 sieve) Coarse Aggregate Used in Experiment 6

	Angularity	Texture	Sphericity
Scan 1	2797.52	162.39	0.637
Scan 2	2818.41	158.53	0.629
Scan 3	2709.42	159.88	0.642
Scan 4	2861.97	161.43	0.592
Scan 5	2860.93	163.56	0.584
Scan 6	2785.88	158.19	0.645
Scan 7	2760.69	166.19	0.583
Scan 8	2779.38	162.63	0.595
Scan 9	2804.20	161.23	0.590
Scan 10	2851.35	163.00	0.597
Scan 11	2838.03	161.50	0.582
Scan 12	2757.61	159.12	0.634
Scan 13	2830.00	158.26	0.645
Scan 14	2801.37	162.29	0.583
Scan 15	2785.70	158.51	0.642
Scan 16	2777.80	157.08	0.635

Figure 2.21, Figure 2.22, and Figure 2.23 show the half-normal plots of the 4.75 mm (ASTM #4 sieve) light aggregates. The results for the 4.75 mm (ASTM #4 sieve) light aggregates were the same as the 9.5 mm (0.375 in) light aggregate. Factor C (tray size) was statistically significant for the texture results (Figure 2.22). The sphericity results were affected by Factor C (tray size) and Factor B (tray height) (Figure 2.23).

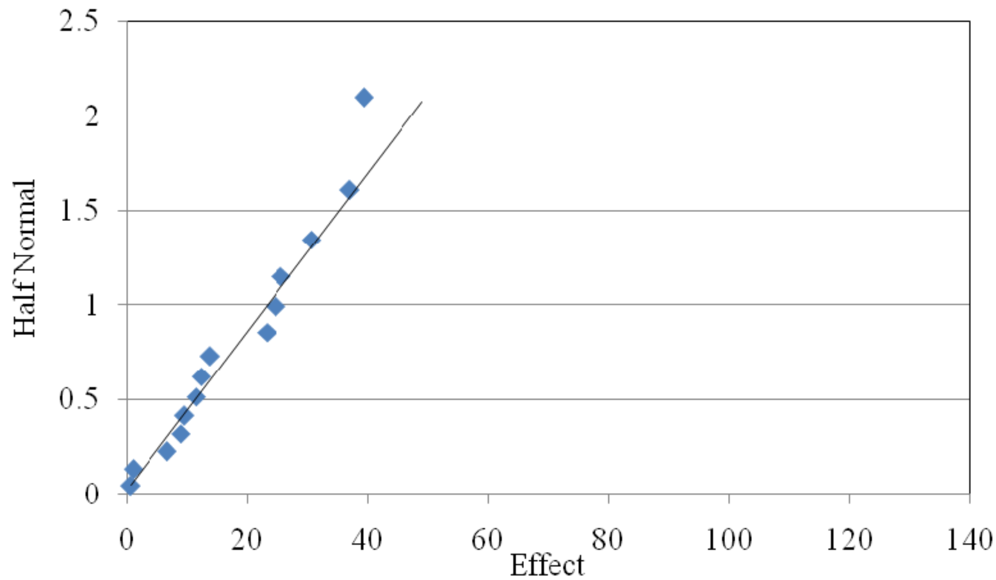

Figure 2.21. Half-normal plot of the angularity of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 6.

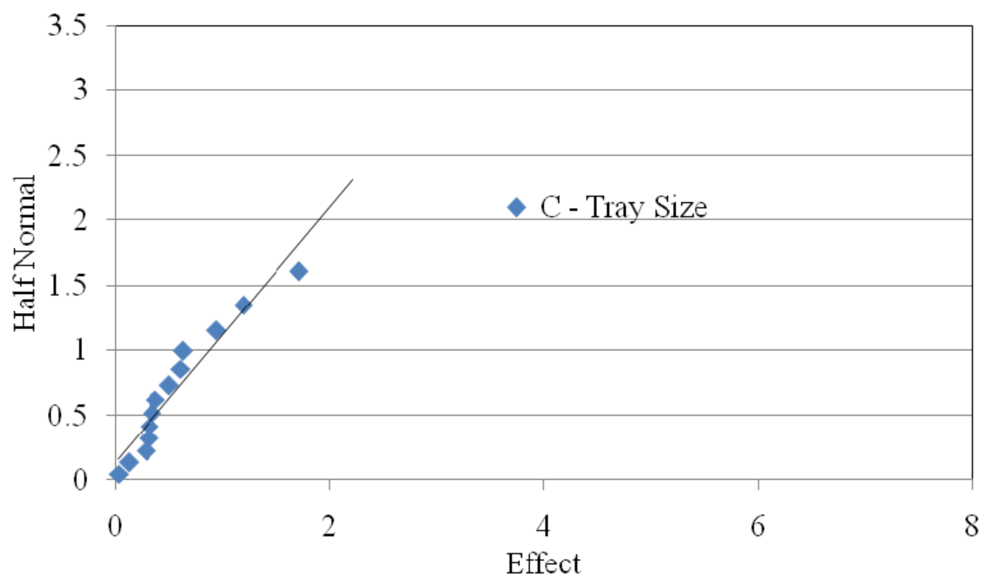

Figure 2.22. Half-normal plot of the texture of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 6.

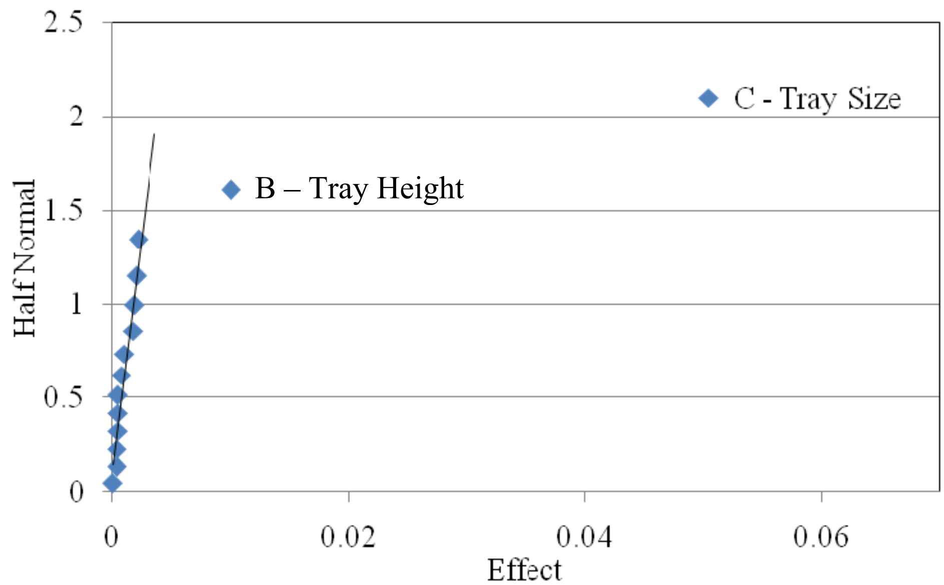

Figure 2.23. Half-normal plot of the sphericity of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 6.

Overall tray height (Factor B), tray size (Factor C), and door position (Factor D) were statistically significant using the limits tested. No interaction factors were found to be significant in Experiment 6.

Experiment 7

This experiment was conducted using 2 different fine aggregates, a dark-colored and light-colored 1.18 mm (ASTM #16 sieve) aggregate (Figure 2.24). The factors and limits chosen are listed in Table 2.36. Results from the 16 scans for 1.18 mm (ASTM #16 sieve) aggregates are shown in Table 2.37 and Table 2.38 for the dark- and light-colored aggregates.

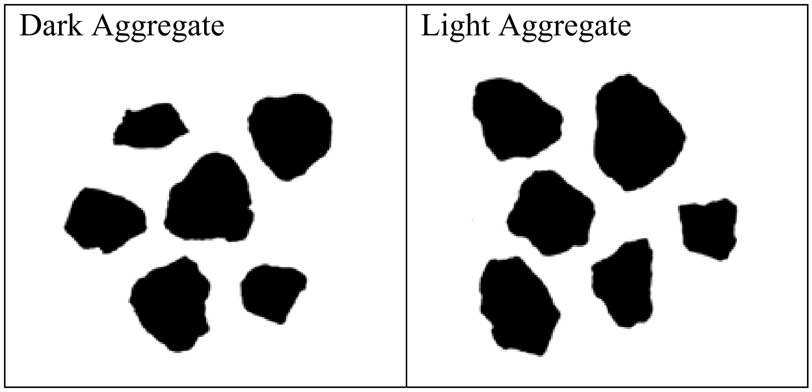

Figure 2.24. Dark and light 1.18 mm (ASTM #16 sieve) aggregates used in Experiment 7.

Table 2.36. Fine Aggregates Factors and Limits Used in Experiment 7

Factor	Fine Aggregate Factors:	Low Limit	High Limit
A	Light Illumination	-1	+1
B	CHPR	-0.01	0
C	Tray Color	Clear	Opaque
D	Door Position	Open	Closed
E	Ambient Light	Off	On
F	Zoom Level	-1%	+1%
G	Tray Height	-0.25	+0.25

Table 2.37. Results of Dark 1.18 mm (ASTM #16 sieve) Fine Aggregates Used in Experiment 7

	Angularity	Form 2D
Scan 1	3620.32	8.32
Scan 2	4187.16	8.39
Scan 3	4113.90	7.85
Scan 4	2781.27	7.54
Scan 5	2730.92	7.47
Scan 6	3769.39	8.20
Scan 7	2747.03	7.56
Scan 8	2768.94	7.51
Scan 9	2734.15	7.46
Scan 10	2803.33	7.54
Scan 11	2721.16	7.50
Scan 12	3936.83	8.25
Scan 13	3527.07	8.24
Scan 14	2804.73	7.47
Scan 15	3891.67	8.02
Scan 16	3698.28	8.29

Table 2.38. Results of Light 1.18 mm (ASTM #16 sieve) Fine Aggregates Used in Experiment 7

	Angularity	Form 2D
Scan 1	3301.83	7.43
Scan 2	3634.56	7.81
Scan 3	3552.14	7.67
Scan 4	3266.17	7.48
Scan 5	3242.04	7.47
Scan 6	3284.80	7.36
Scan 7	3304.95	7.49
Scan 8	3228.74	7.39
Scan 9	3237.06	7.44
Scan 10	3336.02	7.45
Scan 11	3314.50	7.52
Scan 12	3605.44	7.69
Scan 13	3290.79	7.33
Scan 14	3296.94	7.46
Scan 15	3589.77	7.75
Scan 16	3383.13	7.54

Figure 2.25 and Figure 2.26 show the half-normal plot of the angularity and 2D form, respectively, for the 1.18 mm (ASTM #16 sieve) dark aggregate. Similar plots for the 1.18 mm (ASTM #16 sieve) light aggregate are presented in Figure 2.27 and Figure 2.28.

The dark aggregate angularity results were affected by Factor C (tray color), Factor A (light illumination), and D-I (Figure 2.25). The most likely cause of D-I was the interaction between Factors A (tray color) and C (light illumination). Figure 2.26 shows that the 2D Form results were affected by Factor C (tray color).

For the 1.18 mm (ASTM #16 sieve) light aggregates, Factor C (tray color), Factor D-I, Factor A (light illumination), Factor B (CHPR), and Factor E-I appear to be statistical significant for the angularity results (Figure 2.27). The interaction between Factors A (light illumination) and C (tray color), most likely was the cause for D-I. The interaction AG (light illumination and tray height), BD (CHPR and door position), or CF (tray color and zoom level) could be the cause of the larger E-I interaction. The 2D Form results appear to be affected by Factor D-I, Factor A (light illumination), Factor C (tray color), Factor B (CHPR), and Factor F (zoom level) (Figure 2.28). Again the most likely cause for the large D-I interaction was the AC (light illumination and tray color) interaction.

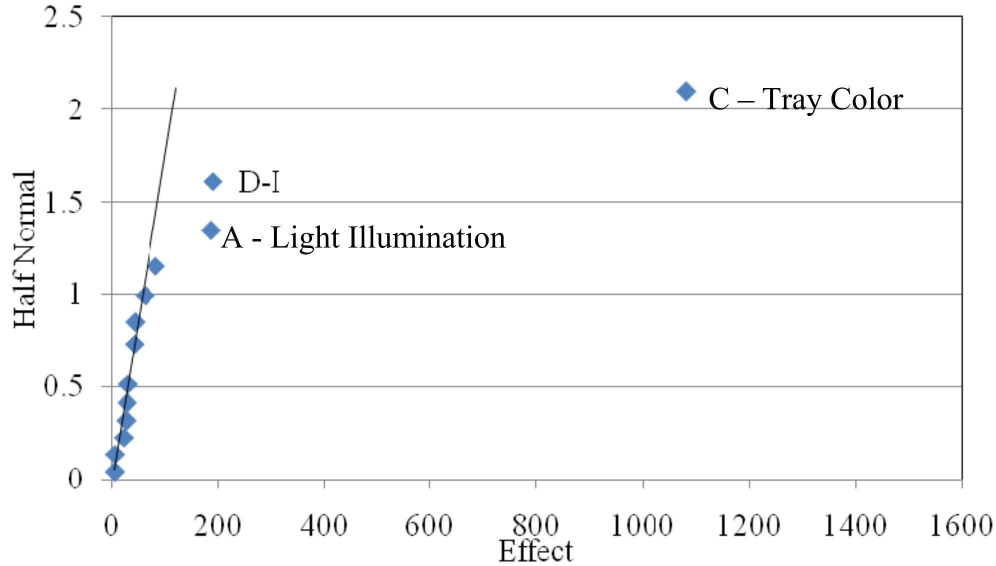

Figure 2.25. Half-normal plot of the angularity of the dark 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 7.

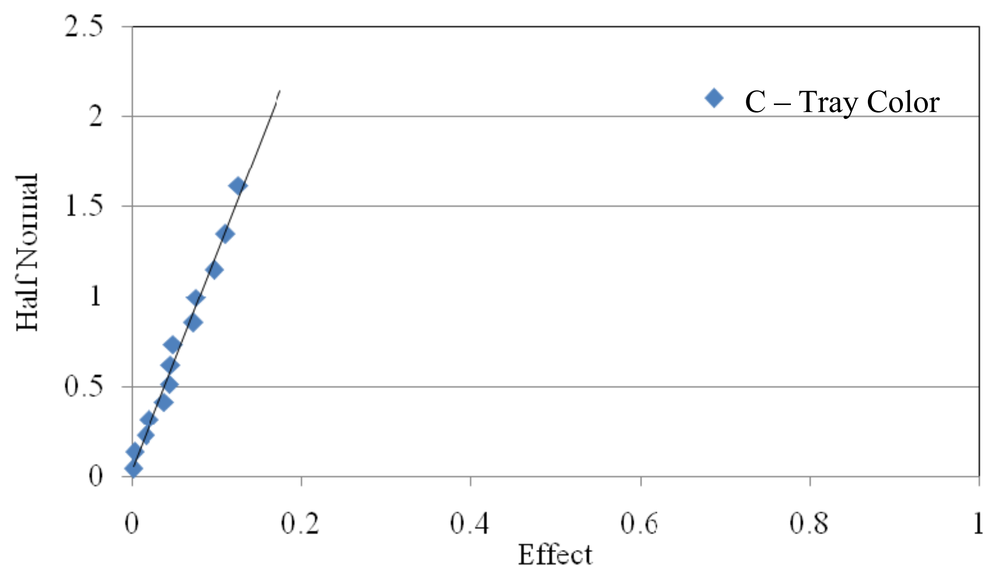

Figure 2.26. Half-normal plot of the 2D form of the dark 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 7.

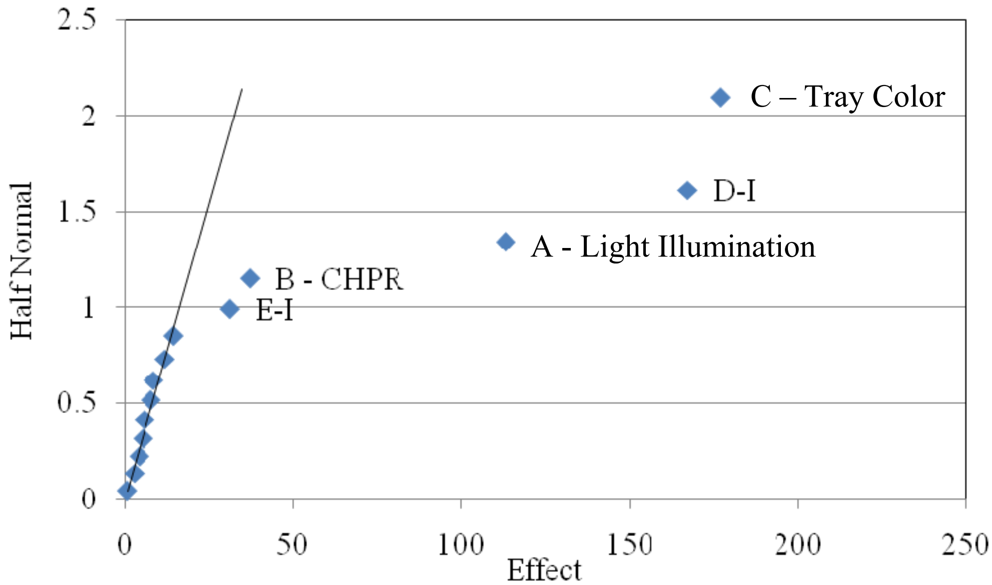

Figure 2.27. Half-normal plot of the angularity of the light 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 7.

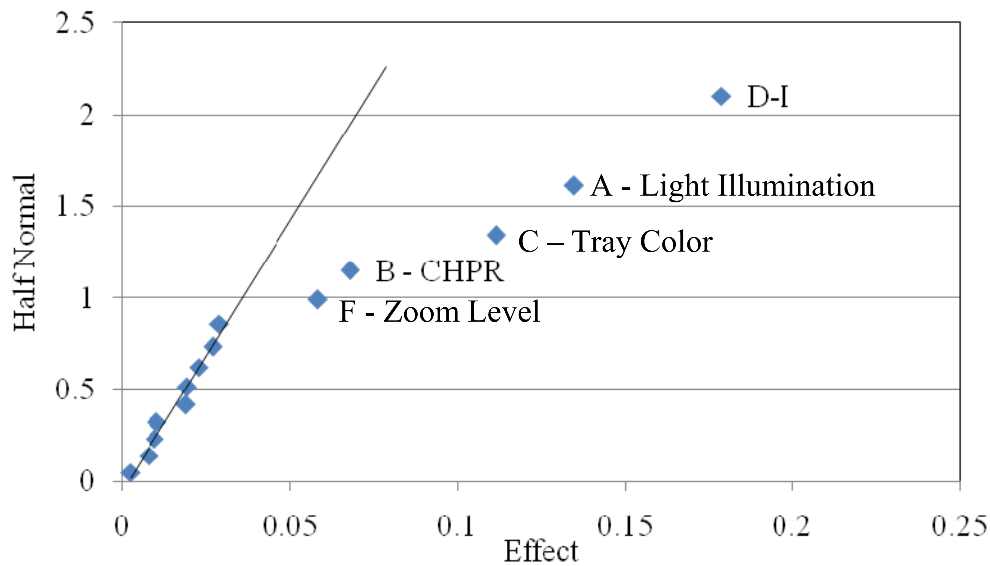

Figure 2.28. Half-normal plot of the 2D form of the light 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 7.

The factors and limits used for the 1.18 mm (ASTM #16 sieve) fine aggregates were tested on an additional fine aggregates size, 0.15 mm (ASTM #100 sieve), to confirm the results. For 0.15 mm (ASTM #100 sieve) aggregates, only a light-colored aggregate (Figure 2.29) was studied since the light-colored aggregates seemed to be more affected by the changes in the different factors. Table 2.39 summarizes the angularity and 2D form results.

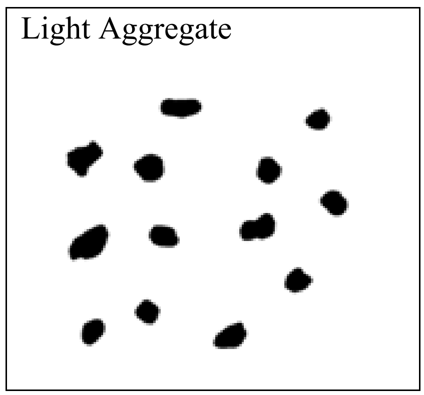

Figure 2.29. Light 0.15 mm (ASTM #100 sieve) aggregates used in Experiment 7.

Table 2.39. Results of Light 0.15 mm (ASTM #100 sieve) Fine Aggregates Used in Experiment 7

	Angularity	Form 2D
Scan 1	1877.54	6.13
Scan 2	2254.86	6.67
Scan 3	2235.24	6.61
Scan 4	2316.97	6.48
Scan 5	2670.46	6.61
Scan 6	1843.51	6.12
Scan 7	2569.78	6.67
Scan 8	2475.31	6.47
Scan 9	2566.89	6.50
Scan 10	2508.76	6.67
Scan 11	2371.79	6.59
Scan 12	2278.66	6.54
Scan 13	1863.52	6.09
Scan 14	2427.32	6.41
Scan 15	2344.11	6.67
Scan 16	1777.83	5.97

The half-normal plot for the angularity and 2D form for the 0.15 mm (ASTM #100 sieve) are shown in Figure 2.30 and Figure 2.31, respectively.

The plot in Figure 2.30 indicates that tray color (Factor C), light illumination (Factor A), tray height (Factor G), door position (Factor D), Factor D-I, and Factor B-I were statistically significant for the angularity results. The interaction D-I was most likely caused be the interaction AC (light illumination and tray color). The interaction between C and F (tray color and door position) were the most likely cause for the high B-I factor. The effects of Factors G-I and C-I were unclear. The 2D form results were affected by Factor A (light illumination), Factor C (tray color), Factor D-I, and Factor B-I

(Figure 2.31). The interactions D-I and B-I were most likely caused by AC (light illumination and tray color) and CF (tray color and door position), respectively. These interactions were the same as the angularity results. The statistically significance of Factor D (door position) and Factor G-I were unclear.

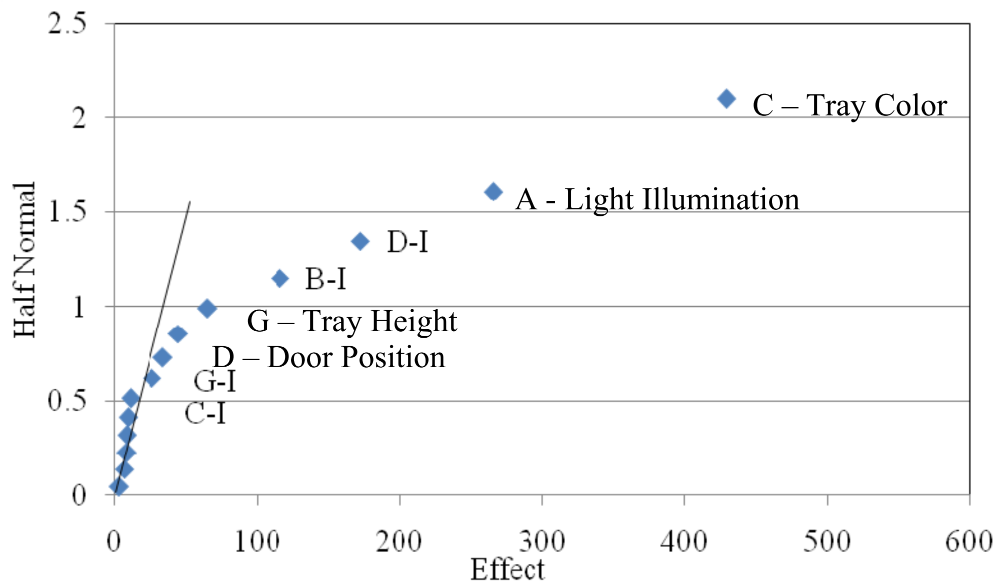

Figure 2.30. Half-normal plot of the angularity of the light 0.15 mm (ASTM #100 sieve) fine aggregate used in Experiment 7.

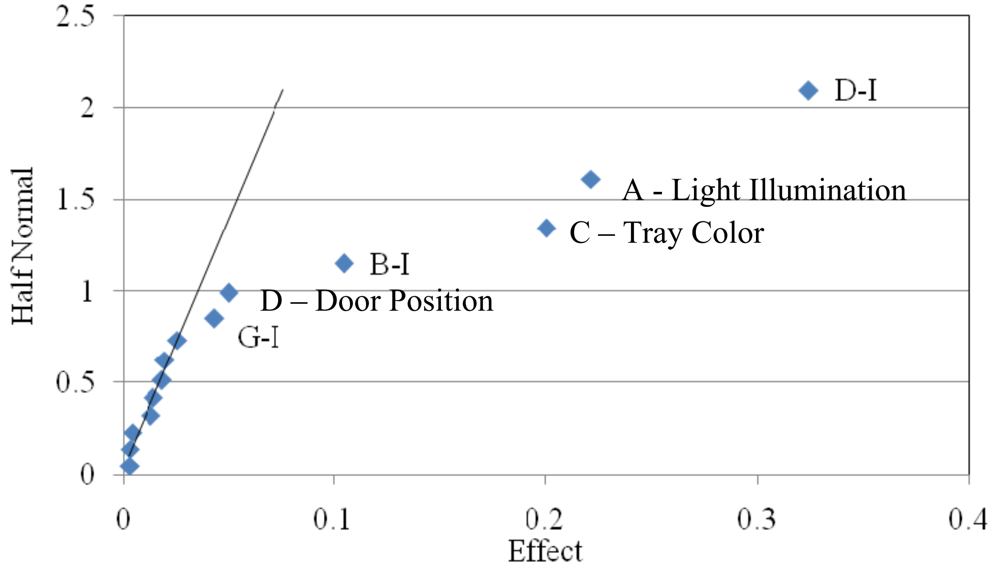

Figure 2.31. Half-normal plot of the 2D form of the light 0.15 mm (ASTM #100 sieve) fine aggregate used in Experiment 7.

In summary, for Experiment 7, Factors A, B, C, D, F, and G (light illumination, CHPR, tray color, door position, zoom level, and tray height) were statistical significant for the limits tested. Other factors that appeared to be significant due to interactions of the main factors were factors D-I (AC), E-I (AG, BD, or CF), and B-I (CG).

Experiment 8

The aim of this experiment was to investigate the effect of tightening the limits of the factors (A, B, F, and G) that showed statistical significance in Experiment 7. Table 2.40 lists the new limits for these factors. The tray color factor was removed and replaced with tray size for the analysis. The same aggregates used in Experiment 7 were used in this experiment, a dark- and light-colored 1.18 mm (ASTM #16 sieve) aggregate

(Figure 2.24). The results from these two aggregates are shown in Table 2.41 and Table 2.42.

Table 2.40. Fine Aggregates Factors and Limits Used in Experiment 8

Factor	Fine Aggregate Factors:	Low Limit	High Limit
A	Light illumination	-1	0
B	CHPR	-0.01	0
C	Tray Size	12.5 mm	19 mm
D	Door Position	Open	Closed
E	Ambient Light	Off	On
F	Zoom Level	-0.5%	+0.5%
G	Tray Height	-0.10 mm	+0.10 mm

Table 2.41. Results of Dark 1.18 mm (ASTM #16 sieve) Fine Aggregates Used in Experiment 8

	Angularity	Form 2D
Scan 1	2806.59	7.22
Scan 2	2757.55	7.17
Scan 3	2765.31	7.18
Scan 4	2897.77	7.56
Scan 5	2915.38	7.55
Scan 6	2798.36	7.20
Scan 7	2932.93	7.57
Scan 8	2902.82	7.64
Scan 9	2912.24	7.53
Scan 10	2924.59	7.61
Scan 11	2935.47	7.64
Scan 12	2787.75	7.24
Scan 13	2766.95	7.19
Scan 14	2896.07	7.63
Scan 15	2809.58	7.20
Scan 16	2810.88	7.22

Table 2.42. Results of Light 1.18 mm (ASTM #16 sieve) Fine Aggregates Used in Experiment 8

	Angularity	Form 2D
Scan 1	3271.76	7.37
Scan 2	3266.46	7.41
Scan 3	3256.10	7.34
Scan 4	3304.98	7.56
Scan 5	3337.61	7.57
Scan 6	3287.02	7.37
Scan 7	3275.73	7.56
Scan 8	3234.57	7.51
Scan 9	3330.38	7.49
Scan 10	3255.30	7.54
Scan 11	3307.82	7.60
Scan 12	3274.35	7.35
Scan 13	3261.85	7.40
Scan 14	3282.11	7.57
Scan 15	3263.61	7.37
Scan 16	3343.92	7.43

The half-normal plot for each shape characteristic parameter (Angularity and 2D Form) of the 1.18 mm (ASTM #16 sieve) dark aggregate are shown in Figure 2.32 and Figure 2.33. Figure 2.34 and Figure 2.35 show the half-normal plots for the 1.18 mm (ASTM #16 sieve) light aggregate.

The statistical significance of the factors decreased due to the tighter limits used in this experiment. For angularity and 2D form results of the dark aggregates (Figure 2.32 and Figure 2.33), the only statistically significant factor was Factor C (tray size).

The light-colored aggregate had similar factors as the dark-colored aggregate. Factor F (zoom level) appears to be statistically significant for the angularity (Figure 2.34). On the other hand, Factor C (tray size) was statistically significant for the 2D Form results (Figure 2.35). No interaction factors were found to be statistically significant in Experiment 8, which was most likely due to the decrease in the effects of the main factors.

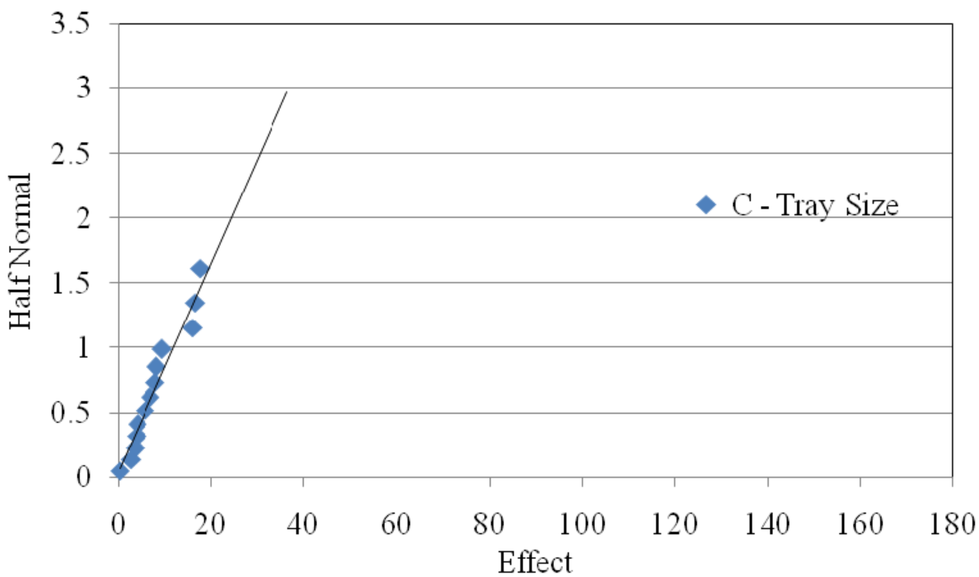

Figure 2.32. Half-normal plot of the angularity of the dark 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 8.

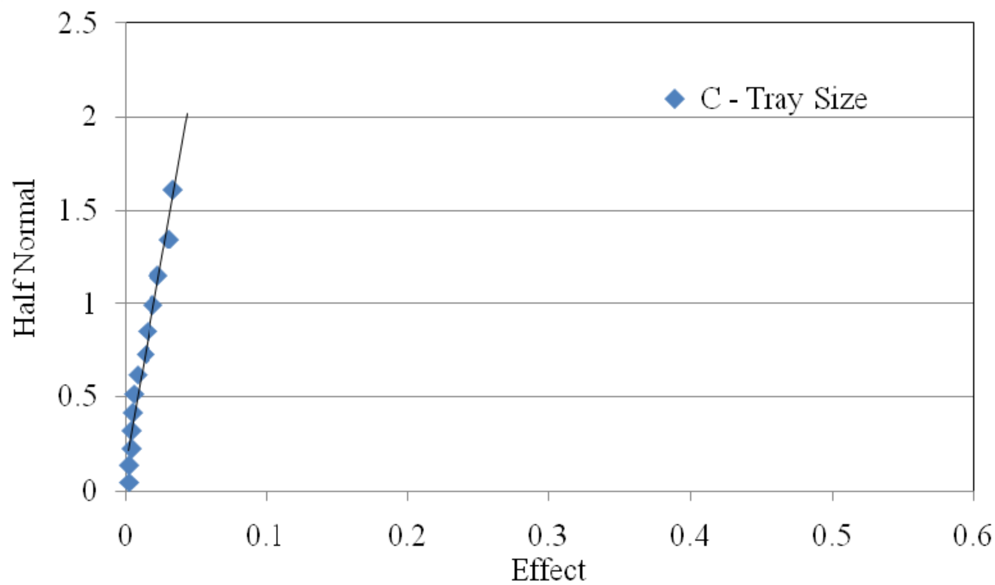

Figure 2.33. Half-normal plot of the 2D form of the dark 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 8.

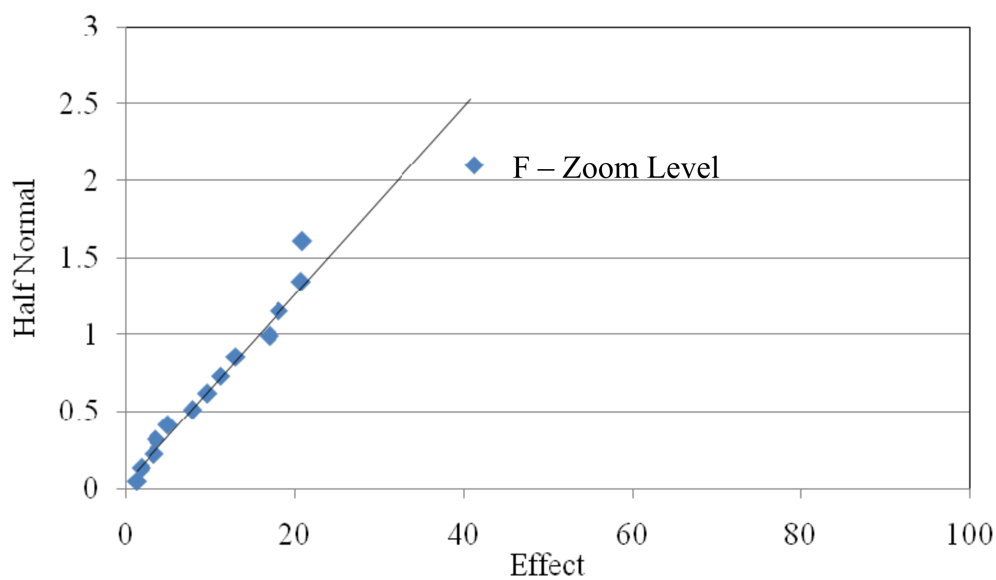

Figure 2.34. Half-normal plot of the angularity of the light 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 8.

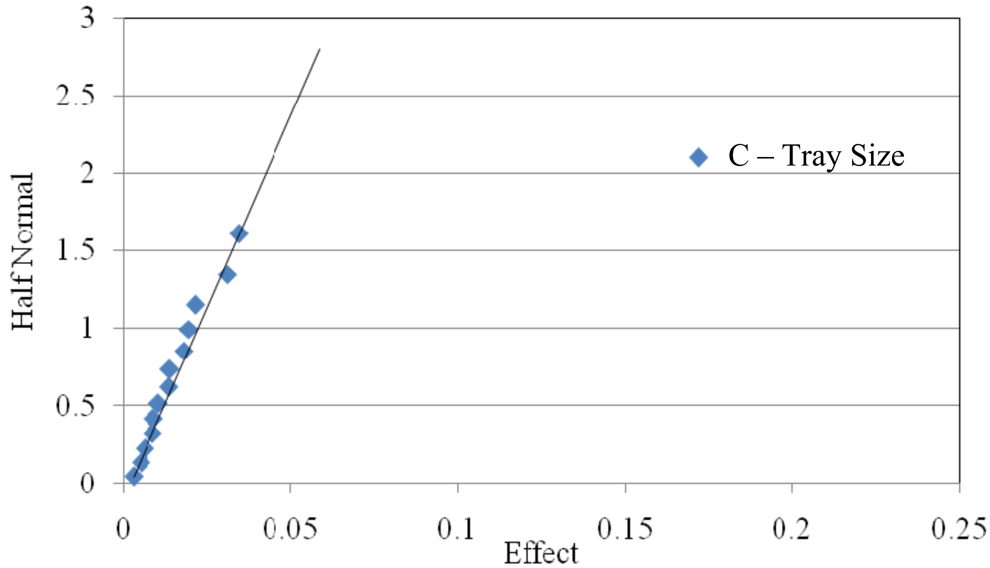

Figure 2.35. Half-normal plot of the 2D form of the light 1.18 mm (ASTM #16 sieve) fine aggregate used in Experiment 8.

The light 0.15 mm (ASTM #100 sieve) aggregate (Figure 2.29) were again used to confirm the result found using the 1.18 mm (ASTM #16 sieve) aggregate. The same factors and limits were used for both aggregate sizes (Table 2.40). The summary of the angularity and 2D form results are in Table 2.43.

Table 2.43. Results of Light 0.15 mm (ASTM #100 sieve) Fine Aggregate Used in Experiment 8

	Angularity	Form 2D
Scan 1	2442.63	6.59
Scan 2	2432.03	6.54
Scan 3	2457.91	6.47
Scan 4	2205.87	6.50
Scan 5	2296.71	6.60
Scan 6	2497.23	6.63
Scan 7	2309.90	6.41
Scan 8	2240.49	6.49
Scan 9	2379.27	6.53
Scan 10	2209.78	6.40
Scan 11	2187.52	6.41
Scan 12	2531.24	6.48
Scan 13	2358.65	6.59
Scan 14	2265.81	6.56
Scan 15	2355.22	6.39
Scan 16	2454.94	6.65

The statistical significance of the factors tested can be determined from the half-normal plots in Figure 2.36 and Figure 2.37. Factor C (tray size) and Factor G (tray height) were statistically significant for the angularity results in Figure 2.36. The 2D form results were affected by Factor C (tray size), Factor D-I, and Factor F-I (Figure 2.37). The interaction AC (light illumination and tray size) was the most likely cause for the high D-I factor. The interaction F-I was most likely caused be the interactions AB (light illumination and CHPR), CE (tray size and ambient light), or DG (door position and tray height). The statistical significance of Factors D, F, and B, which were door position, zoom level, and CHPR, were unclear.

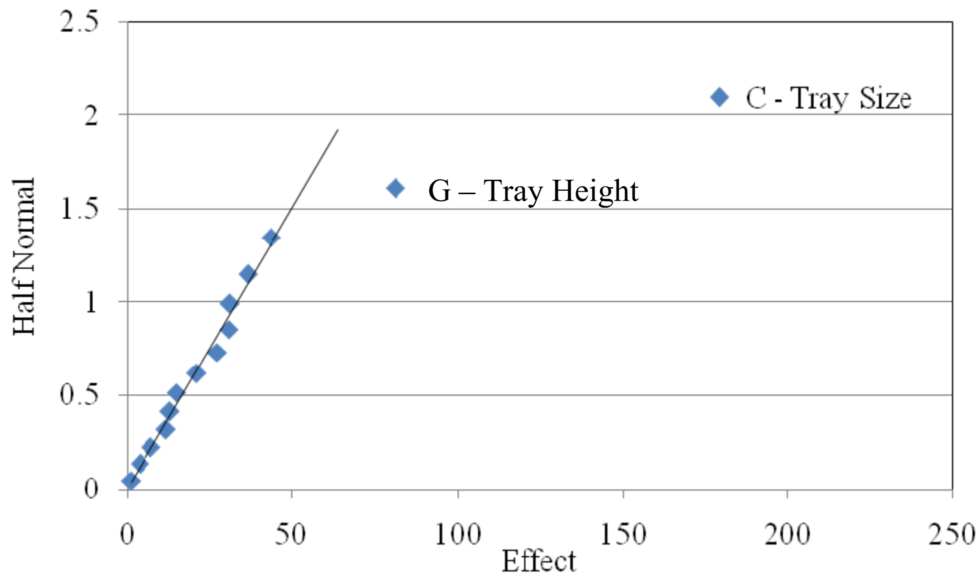

Figure 2.36. Half-normal plot of the angularity of the light 0.15 mm (ASTM #100 sieve) fine aggregate used in Experiment 8.

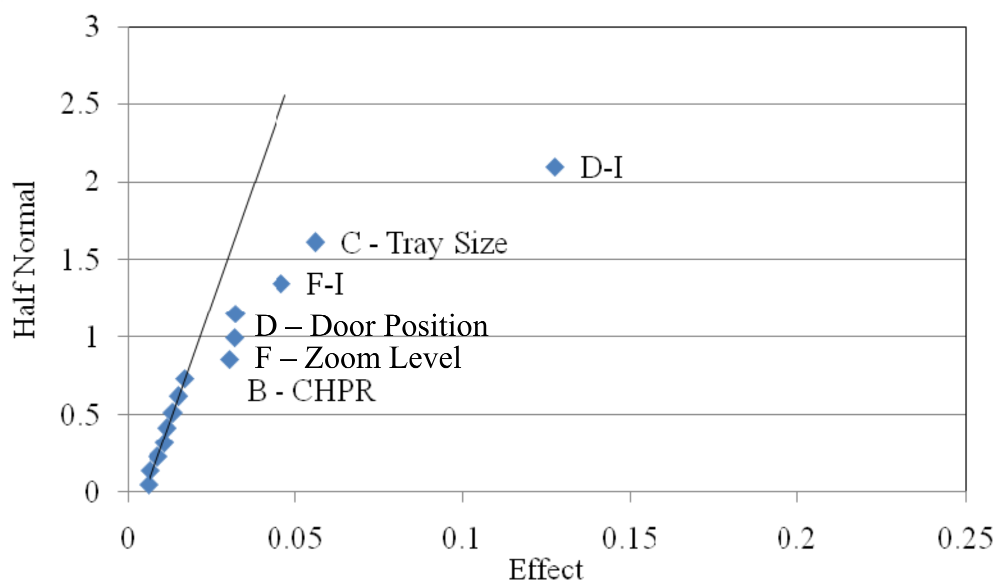

Figure 2.37. Half-normal plot of the 2D form of the light 0.15 mm (ASTM #100 sieve) fine aggregate used in Experiment 8.

Overall for Experiment 8, Factor C (tray size), Factor F (zoom level), and Factor G (tray height), were statistically significant for the limits tested. The other factors that appeared to be significant were Factor D-I (AC) and F-I (AB, CE, or DG).

Experiment 9

Since the tray height was found to affect the sphericity results in Experiment 6, the aggregate height dimension measurements were analyzed. The results of the three coarse aggregates from Experiment 6 were used to further investigate the impact of the tray height. Experiment 6 consisted of two coarse aggregates, one dark and one light, with a size of 9.5 mm (0.375in) (Figure 2.4) and one light-colored coarse aggregate with a size of 4.75 mm (ASTM #4 sieve) (Figure 2.11). Table 2.44 lists the factors and limits for Experiment 9, which are from Experiment 6. A list of the height measurement results of the three coarse aggregates are shown in Table 2.45.

Table 2.44. Coarse Aggregate Factors and Limits Used in Experiment 9

Factor	Coarse Aggregate Study Factors:	Low Limit	High Limit
A	Light illumination	-1	0
B	Tray Height	-0.10 mm	0.10 mm
C	Tray Size	4.75 mm	9.5 mm
D	Door Position	Open	Closed
E	Ambient Light	Off	On
F	Zoom Level	-0.5%	+0.5%
G	Focus (DOF)	1%	0%

Table 2.45. Results of Coarse Aggregate Used in Experiment 9

	Dark 9.5 mm (0.375 in) Aggregate	Light 9.5 mm (0.375 in) Aggregate	Light 4.75 mm (ASTM #4 sieve) Aggregate
Scan 1	7.06	6.64	4.55
Scan 2	7.16	6.68	4.47
Scan 3	7.23	6.83	4.69
Scan 4	7.67	6.87	3.76
Scan 5	7.47	6.61	3.66
Scan 6	7.28	6.83	4.75
Scan 7	7.44	6.61	3.58
Scan 8	7.69	6.9	3.82
Scan 9	7.66	6.83	3.77
Scan 10	7.69	6.81	3.83
Scan 11	7.47	6.70	3.59
Scan 12	7.09	6.65	4.52
Scan 13	7.31	6.85	4.71
Scan 14	7.51	6.66	3.62
Scan 15	7.29	6.86	4.70
Scan 16	7.06	6.62	4.54

The half-normal plots for the dark and light 9.5 mm (0.375 in) aggregates are shown in Figure 2.38 and Figure 2.39, respectively. The 4.75 mm (ASTM #4 sieve) half-normal plot is in Figure 2.40.

The measured aggregate heights for the dark 9.5 mm (0.375 in) aggregates are affected by Factor B (tray height) and Factor G (focus) (Figure 2.38). Factor B (tray height) and Factor C (tray size) are statistically significant for the measured aggregate height for the light 9.5 mm (0.375 in) and light 4.75 mm (ASTM #4 sieve) aggregates (Figure 2.39 and Figure 2.40). From Experiment 9, the tray height was found to still be statistically significant for the height measurements of the aggregates.

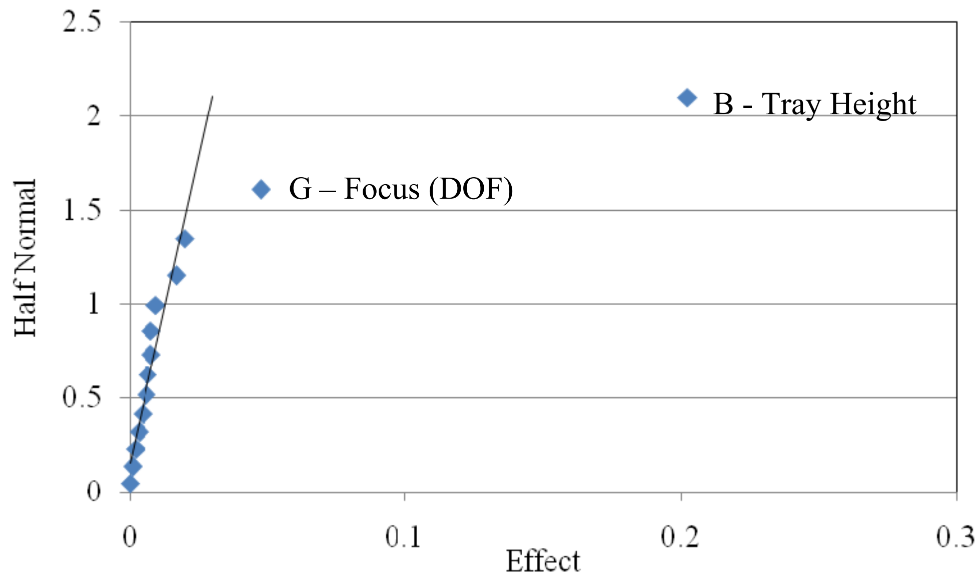

Figure 2.38. Half-normal plot of the aggregate height of the dark 9.5 mm (0.375 in) coarse aggregate used in Experiment 9.

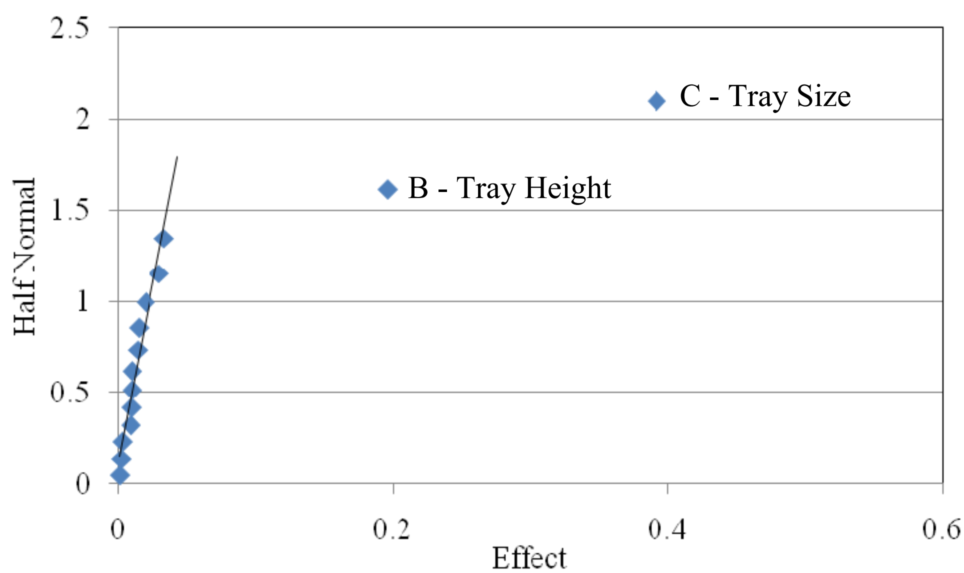

Figure 2.39. Half-normal plot of the aggregate height of the light 9.5 mm (0.375 in) coarse aggregate used in Experiment 9.

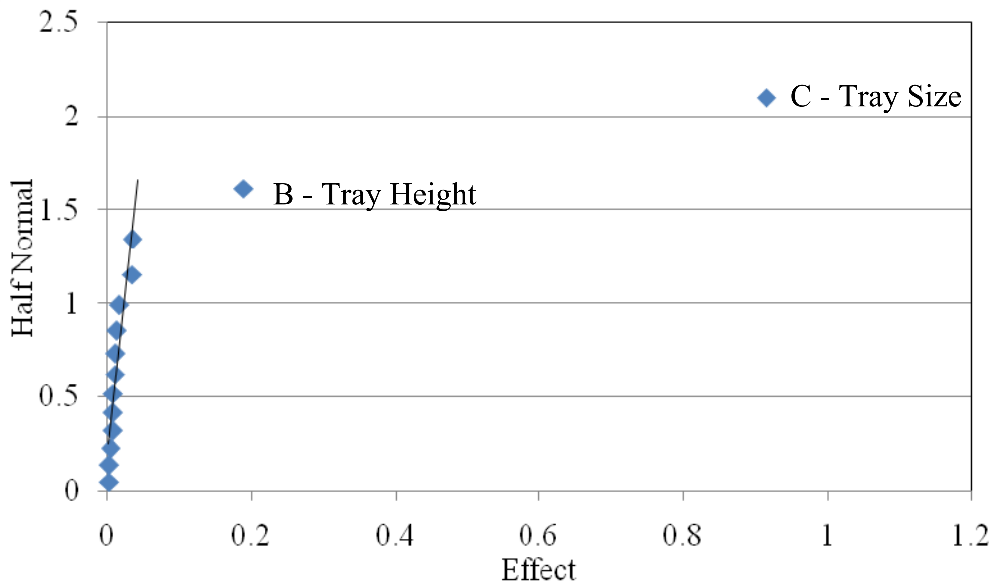

Figure 2.40. Half-normal plot of the aggregate height of the light 4.75 mm (ASTM #4 sieve) coarse aggregate used in Experiment 9.

Experiment 10

Although the tray height was shown to be statistically significant for the sphericity and the aggregate height results, this factor might be considered insignificant from an engineering standpoint. It is important to investigate the impact of the significance on the AIMS2 results and the engineering interpretation of these results. In order to investigate this issue, a set of 50 aggregate particles containing a mix of gravel, granite and limestone were scanned three times to determine the difference in AIMS2 results between the three scans of each set. Examples of the comparisons of the height measurements for the 25.0 mm (1.0 in) aggregate are shown in Figure 2.41, Figure 2.42, and Figure 2.43 of the three replicate scans. A list of all of the equations of the fitted line equations and R^2 values for the all of the coarse aggregate sizes are shown in Table 2.46. The data in Table 2.46 show that the measurements are close to the line of equality with very small biases. The values of the confidence interval for the slope either contain or are very close to one and the values of the confidence interval for the intercepts either contain or are very close to zero (Table 2.47). The high R^2 values show the minimal spread in the data.

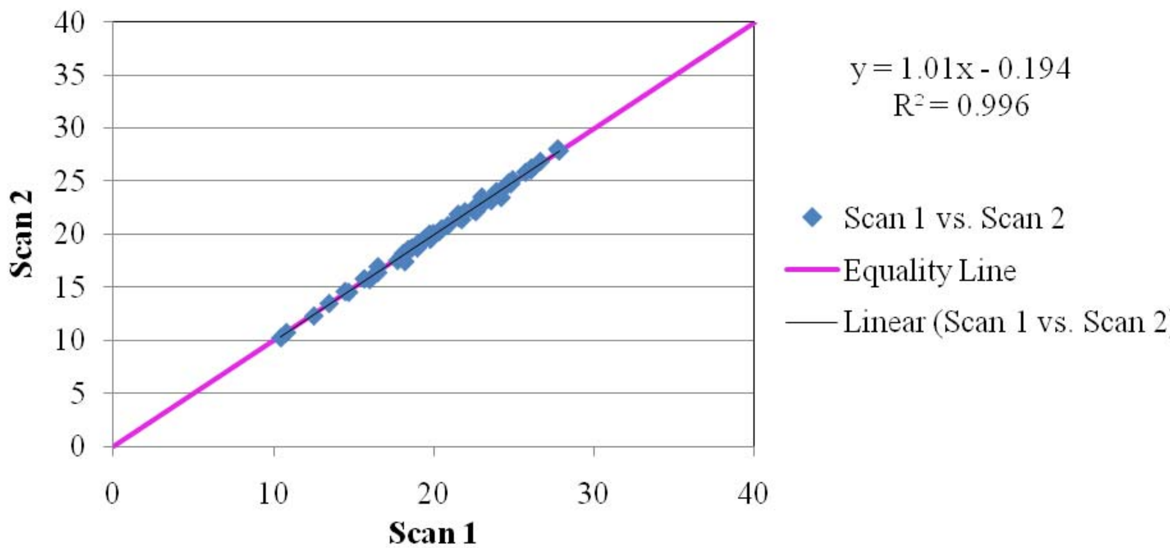

Figure 2.41. 25.0 mm (1.0 in) aggregate height measurement for Replicate Scan 1 vs. Scan 2.

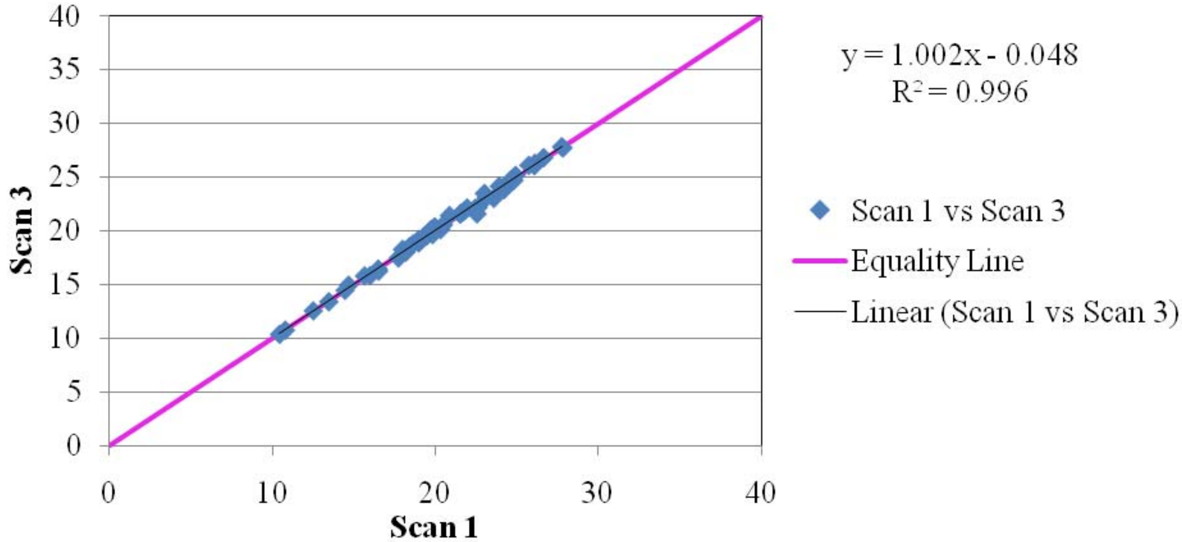

Figure 2.42. 25.0 mm (1.0 in) aggregate height measurement for Replicate Scan 1 vs. Scan 3.

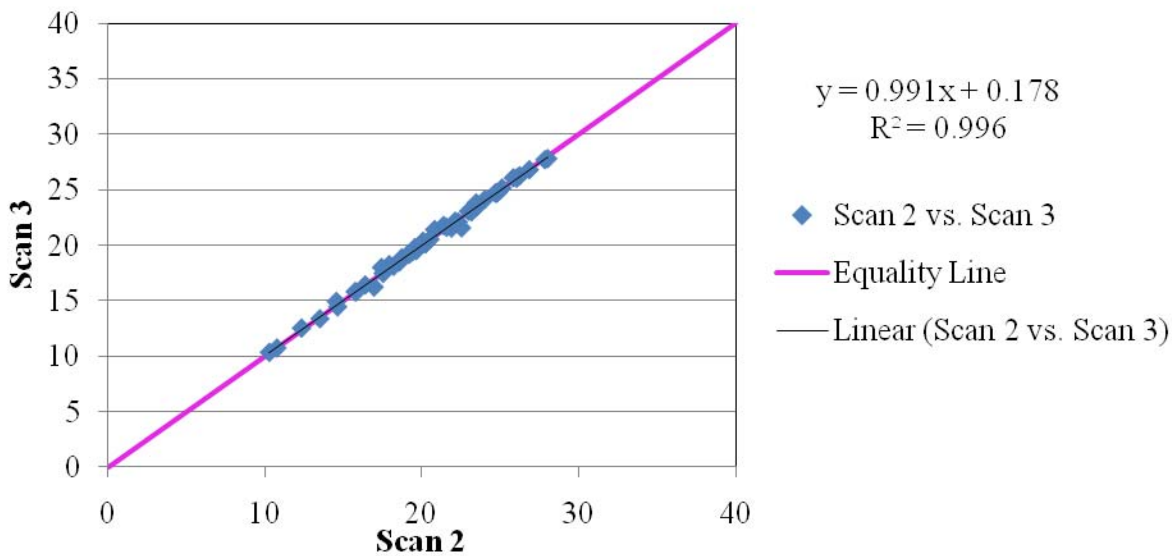

Figure 2.43. 25.0 mm (1.0 in) aggregate height measurement for Replicate Scan 2 vs. Scan 3.

Table 2.46. Linear Model Results for Aggregates Height Measurements

Aggregate Size	Scans Plotted	Best-fit Linear Equation	R^2 Value
25.0 mm (1.0 in)	S1* vs. S2*	S1* = 1.01 × S2* - 0.194	0.996
	S1 vs. S3*	S1 = 1.002 × S3* - 0.048	0.996
	S2 vs. S3	S2 = 0.991 × S3 + 0.178	0.996
19.0 mm (.75in)	S1 vs. S2	S1 = 0.99 × S2 + 0.132	0.992
	S1 vs. S3	S1 = 0.98 × S3 + 0.297	0.989
	S2 vs. S3	S2 = 0.989 × S3 + 0.172	0.996
12.5 mm (.50in)	S1 vs. S2	S1 = 0.973 × S2 + 0.292	0.995
	S1 vs. S3	S1 = 0.969 × S3 + 0.287	0.996
	S2 vs. S3	S2 = 0.993 × S3 + 0.025	0.995
9.5 mm (.375in)	S1 vs. S2	S1 = 0.993 × S2 + 0.094	0.986
	S1 vs. S3	S1 = 0.99 × S3 + 0.064	0.97
	S2 vs. S3	S2 = 0.994 × S3 - 0.002	0.976
4.75 mm (#4 sieve)	S1 vs. S2	S1 = 0.98 × S2 + 0.033	0.958
	S1 vs. S3	S1 = 0.968 × S3 + 0.104	0.961
	S2 vs. S3	S2 = 0.974 × S3 + 0.132	0.975

*S1 = Scan 1, S2 = Scan 2, and S3 = Scan 3

Table 2.47. Confidence Intervals of the Linear Model Results

Aggregate Size	Scans Plotted	Slope CI	Intercept CI
25.0 mm (1.0 in)	S1* vs. S2*	(1.001, 1.018)	(-0.375, -0.012)
	S1 vs. S3*	(0.993, 1.012)	(-0.24, 0.144)
	S2 vs. S3	(0.982, 1)	(-0.005, 0.361)
19.0 mm (.75 in)	S1 vs. S2	(0.977, 1.003)	(-0.076, 0.339)
	S1 vs. S3	(0.965, 0.995)	(0.055, 0.54)
	S2 vs. S3	(0.98, 0.998)	(0.032, 0.311)
12.5 mm (.50 in)	S1 vs. S2	(0.963, 0.983)	(0.182, 0.402)
	S1 vs. S3	(0.96, 0.978)	(0.187, 0.386)
	S2 vs. S3	(0.984, 1.003)	(-0.083, 0.132)
9.5 mm (.375 in)	S1 vs. S2	(0.976, 1.01)	(-0.032, 0.22)
	S1 vs. S3	(0.965, 1.016)	(-0.124, 0.252)
	S2 vs. S3	(0.971, 1.016)	(-0.172, 0.168)
4.75 mm (#4 sieve)	S1 vs. S2	(0.95, 1.01)	(-0.103, 0.169)
	S1 vs. S3	(0.94, 0.996)	(-0.025, 0.232)
	S2 vs. S3	(0.951, 0.996)	(0.029, 0.234)

*S1 = Scan 1, S2 = Scan 2, and S3 = Scan 3

Although the tray height was statistically significant based on the results of Experiments 5 and 6; Experiment 9 showed that the differences in replicate measurements of the same aggregate is minimal. The tray height factor therefore appears not to be affecting the results from the practical aspect and AIMS2 is able to control normal variations in the height dimension measurement of the aggregates.

CONCLUSIONS

The ruggedness study following ASTM C 1067-00 identified several factors that were found to be statistically significant in affecting the AIMS2 results. The transparent doors were not able to control the changes in ambient lighting, therefore these were replaced with non-transparent doors. The non-transparent doors were found to block the ambient light completely. There was concern that the results of the factors may be skewed due to the effect of interactions between the factors. Therefore, the ruggedness analysis was also conducted using the ASTM E 1169-07 procedure, which allows for the identification of the effects of the main factors and interactions between these factors. The ruggedness study following ASTM E 1169-07 lead to the identification of several significant factors that could affect the AIMS2 shape characteristics. Consequently, limits were proposed for these factors in order to eliminate their influence on the measured characteristics. The factors and limits listed in Table 2.48 are the recommended controls for the factors in order to ensure the ruggedness of the AIMS2 measurements. As long as these limits are achieved by the system, AIMS2 can control normal variations related to the factors without significantly changing the results.

Table 2.48. Recommendations for AIMS2 To Be Rugged

Aggregate Factors	Recommended Limits
Light Illumination	-1 and 0.
Tray Size	Use tray size specified for each aggregate size.
Tray Color	Use opaque tray for #50, #100, and #200 aggregates.
Door Position	Door must be closed.
Ambient Light	Not significant with doors closed.
Focus (DOF)	A maximum variation of 1% from the settings.
CHPR	Nonchangeable parameter (1.07).
Zoom Level	A variation ±0.5% of nominal setting.
Tray Height	Height calibration must follow the Operation Manual procedure.

CHRP = convex hull perimeter ratio

CHAPTER 3

INTERLABORATORY STUDY

INTRODUCTION

The Interlaboratory Study (ILS) was conducted to determine the repeatability and reproducibility of AIMS2 for multiple users and laboratories. The ILS was carried out in accordance with ASTM C 802 – 96, "Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials." The ILS results were used to develop a precision statement for the test method using ASTM C 670 – 03, "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials."

ILS provides two different precision estimates of the test method; single-operator precision (within-laboratory precision) and multi-laboratory precision (between-laboratory precision). The single-operator precision provides an estimate of the variance that may be expected between duplicate measurements of the same sample made by the same operator in the same laboratory. The multi-laboratory precision gives an estimate of the differences that may be expected between measurements of the same material made in different laboratories by different users. The single-operator and multi-laboratory precision statements were determined in this study for the outputs of the AIM2S system: angularity, texture, 2D Form, sphericity, flat or elongated 3:1 ratio.

AGGREGATE SOURCES AND SIZES

Three different aggregates (Crushed Gravel, Limestone, and Granite) were used for all sizes except that a sandstone source was used instead of granite for the size passing the 0.15 mm sieve (ASTM #100 sieve) and retained on the 0.075 mm (ASTM #200 sieve). Based on previous characterization of these aggregates, the Crushed Gravel (CG) has the lowest angularity and texture among the three aggregates, the Granite (GR) has the highest angularity and texture, while the Limestone (LS) is in the middle. A list of the materials and sources used in this study are shown in Table 3.1. The coarse and fine aggregates sizes are listed in Table 3.2. Coarse aggregates are defined as those retained on 4.75 mm sieve (ASTM #4 sieve), while fine aggregates are those passing the 4.75 mm sieve (ASTM #4 sieve). In Table 3.2, the aggregate size range gives the sieve size that all particles pass through and the sieve size that all aggregates are retained on.

Table 3.1. Aggregates Source and Sizes for ILS

Label	Source	Aggregate Description	Aggregate Size Range
CG	Texas	Crushed Gravel	38.0 mm (1.5 in) – 0.15 mm (ASTM #100 sieve)
LS	Texas	Limestone	
GR	Oklahoma	Granite	
CG*	Georgia	Gravel	0.15 mm (ASTM #100 sieve) – 0.075 mm (ASTM #200 sieve)
LS*	Texas	Limestone	
GR*	Texas	Sandstone	

Table 3.2. Aggregates Size Ranges Used in the ILS

Aggregate Type	Aggregates Size Range
Coarse Aggregate	37.5 mm (1.5 in) – 25.0 mm (1 in)
	25.0 mm (1 in) – 19.0 mm (0.75 in)
	19.0 mm (0.75 in) – 12.5 mm (0.5 in)
	12.5 mm (0.5 in) – 9.5 mm (0.37 5in)
	9.5 mm (0.375 in) – 4.75 mm (ASTM #4 sieve)
Fine Aggregate	4.75 mm (ASTM #4 sieve) – 2.36 mm (ASTM #8 sieve)
	2.36 mm (ASTM #8 sieve) – 1.18 mm (ASTM #16 sieve)
	1.18 mm (ASTM #16 sieve) – 0.6 mm(ASTM #30 sieve)
	0.6 mm(ASTM #30 sieve) – 0.3 mm (ASTM #50 sieve)
	0.3 mm (ASTM #50 sieve) – 0.15 mm (ASTM #100 sieve)
	0.15 mm (ASTM #100 sieve) – 0.075 mm (ASTM #200 sieve)

As discussed, different aggregates sources were used for the 0.075 mm size (ASTM #200 sieve). These were Crushed Gravel, Limestone, and Sandstone. For simplicity in this study the 0.075 mm (ASTM #200 sieve) sandstone will be grouped with the granite.

In addition to the average shape characteristics for each sieve range, the AIMS2 software includes a method to determine the weighted average of a certain property of an aggregate blend. The weighing averaging factors are determined based on aggregate size (see Appendix A). The hypothetical gradation shown in Table 3.3 was used in determining the shape characteristics of the blend. Since the 0.075 mm (ASTM #200 sieve) fine aggregates were not from the same sources as the other aggregates sizes, it was not included in the combined results.

Table 3.3. Gradation used for Combined Properties

Retained Size	Percent Passing	Percent Retained
37.5 mm (1.5 in)	100.0%	0.0%
25.0 mm (1 in)	93.0%	7.0%
19.0 mm (0.75 in)	85.0%	8.0%
12.5 mm (0.5 in)	70.0%	15.0%
9.5 mm (0.375 in)	55.0%	15.0%
4.75 mm (ASTM #4 sieve)	35.0%	20.0%
2.36 mm (ASTM #8 sieve)	25.0%	10.0%
1.18 mm (ASTM #16 sieve)	15.0%	10.0%
0.6 mm(ASTM #30 sieve)	10.0%	5.0%
0.3 mm (ASTM #50 sieve)	5.0%	5.0%
0.15 mm (ASTM #100 sieve)	0.0%	5.0%
0.075 mm (ASTM #200 sieve)	0.0%	0.0%

Each aggregate source was sieved according to the size ranges and randomly separated into samples which were shipped with each AIMS2 machine to the participating laboratories. Each coarse aggregate sample consisted of 60. All of the particles were placed on the tray and 50 of them were used in the analysis. Approximately 150 grams of each fine aggregate size, 2.36 mm (ASTM #8 sieve) to 0.15 mm (ASTM #100 sieve), and 50 grams of 0.075 mm (ASTM #200 sieve) aggregate were sent to the laboratories. A fine aggregate sample was spread onto the tray and 150 aggregate particles were used for the analysis.

Eight AIMS2 machines were used in this study. Given the number of participating laboratories (32 labs), three to four laboratories used the same exact machine and tested the same samples. This procedure satisfied the number of materials and participating laboratory requirements of ASTM C 802-96. Testing began with successfully calibrating the machines according to manufacture instructions. The user was instructed to scan the two replicate measurements on different days to provide meaningful replicate values. Data from each test was automatically saved into computer files.

DATA ANALYSIS

Following careful examination of the procedure followed to conduct measurements, three laboratories' data were removed from the ILS study due to user error by not following manufacture and procedure instructions. The within-laboratory and between-laboratory variances were calculated using data from the remaining 29 laboratories. A list of the raw data is show in Appendix B.

With an additional analysis of the raw data images, several 4.75 mm (ASTM #4 sieve) texture images were found to be of the aggregate edge instead of the aggregate surface. Figure 3.1 shows two texture images, one image including the aggregate edge and one image of the aggregate surface. The image of the edge of the aggregate contains both the surface of the aggregate and the surface of the tray. If several images are of the aggregate edge are within a sample data, these images can affect the AIMS2 results, in particularly the texture values. The images with aggregate edges were removed manually and the results were recalculated for the remaining images. The remaining coarse aggregate sizes were checked and the images did not have the same problems as the 4.75 mm (ASTM #4 sieve) aggregates.

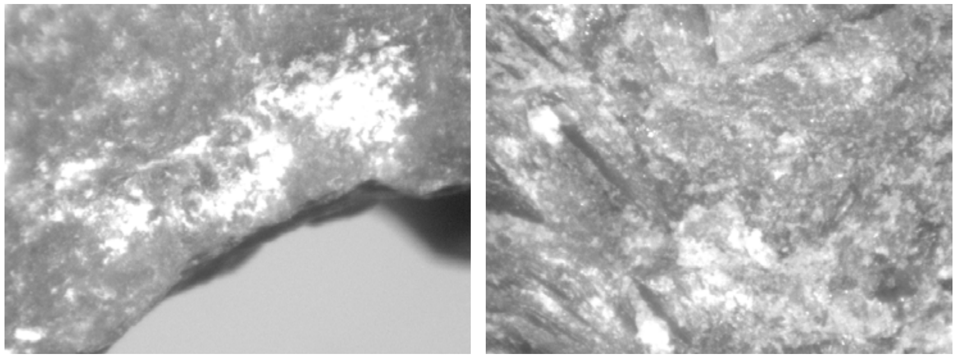

Figure 3.1. Texture image with and without aggregate edge.

The data was checked for agreement of variances and interactions between material and laboratories. ASTM C 802-96 assumes that different laboratories have the same within-laboratory variances. The variance of the each laboratory was checked for an agreement of variances based on the ratio of the largest variance to the sum of variances. The laboratories with the variances above the upper 5% level were eliminated to bring the variances into agreement. The interactions between laboratory and material were checked by plotting the averages values obtained by each laboratory to aggregate type. A similar pattern of change was found from one material to another which indicated little to no interaction between laboratory and materials. An example of the analysis results of all 29 laboratory data is shown in Figure 3.2 for the angularity measurement of 25.0 mm (1in) size aggregates.

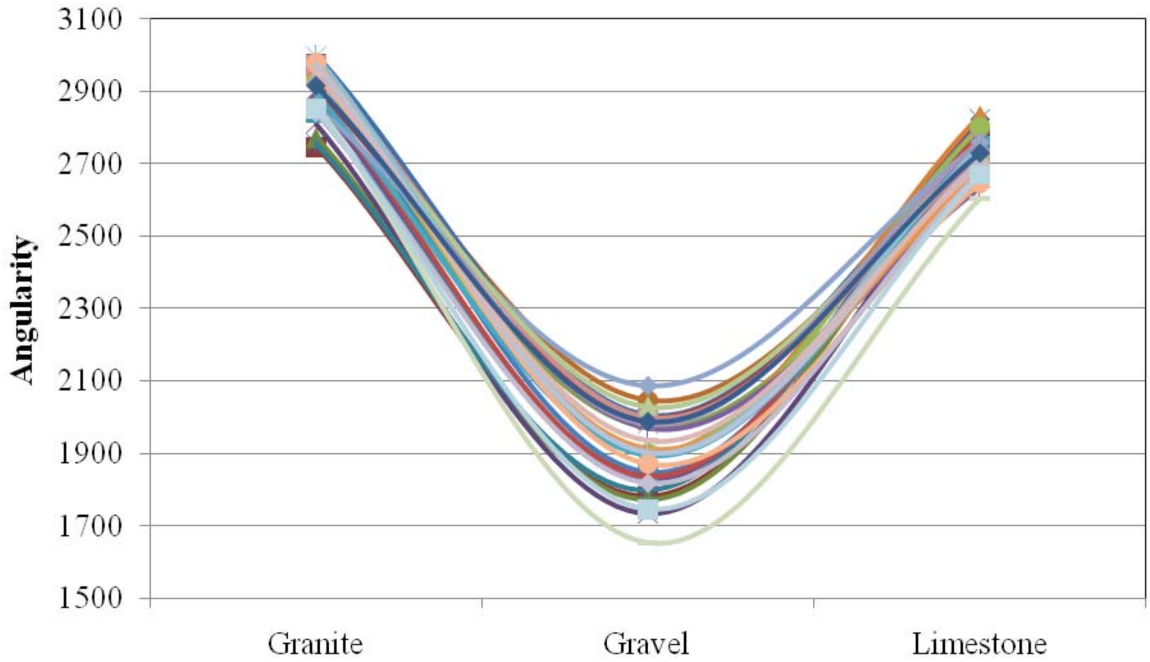

Figure 3.2. Interaction check for angularity versus material for 25.0 mm (1 in) aggregates.

The components of variance, variances, standard deviations, and coefficient of variations were calculated for each shape property for each aggregate type. The components of variance are the estimated amount of variation that can be attributed to the effects of the experiment from the factor.[5] The averages, components of variance, and variances of the Gravel, Limestone, and Granite are shown in Table 3.4, Table 3.5, and Table 3.6, respectively. The standard deviation and coefficient of variation of the Gravel, Limestone, and Granite are shown in Table 3.7, Table 3.8, and Table 3.9 respectively. The combined data results for the weighted aggregate blend are listed in Table 3.10 and Table 3.11.

[5] Jay L. Devore (Ed.), *Probability and Statistics for Engineering and the Sciences*, 6th ed., 2004.

It should be noted that the analysis was conducted on the flat or elongated 3:1 ratio instead of the 5:1 ratio because the aggregate samples had a few or no particles that exceeded the 5:1 ratio. For example, the 25.0 mm (1 in) and 4.75 mm (ASTM #4 sieve) aggregates, it was found during the analysis that any small variation in measurements even by one particle would translate to a very high coefficient of variation if the 5:1 ratio was used. The coefficient of variation reported for the flat or elongated 3:1 ratio were calculated based on the average percent of particles that have a ratio less than (not more than) 3:1.

Table 3.4. Averages, Components of Variance, and Variances of Gravel for All Aggregate Sizes.

Aggregate Shape Characteristic	Aggregate Size	Average	Components of Variance Within-Laboratory	Components of Variance Between-Laboratory	Variance Within-Laboratory	Variance Between-Laboratory
Angularity	25 (1.0")	1895.6	3795.7	9033.3	3795.7	12829.0
	19 (3/4")	2609.1	7630.1	8597.4	7630.1	16227.5
	12.5 (1/2")	2777.9	5511.7	8718.2	5511.7	14229.9
	9.5 (3/8")	2563.5	3038.2	20105.9	3038.2	23144.1
	4.75 (#4)	2275.5	4403.8	14193.3	4403.8	18597.2
	2.36 (#8)	2667.3	7588.7	1311.3	7588.7	8900.0
	1.18 (#16)	3076.3	3482.6	1894.0	3482.6	5376.6
	0.6 (#30)	3237.1	8033.0	824.2	8033.0	8857.2
	0.3 (#50)	3179.5	12085.8	10815.3	12085.8	22901.1
	0.15 (#100)	2735.1	13011.2	10529.8	13011.2	23541.0
	0.075 (#200)	2251.8	31135.2	12453.6	31135.2	43588.8
Texture	25 (1.0")	224.7	78.1	155.4	78.1	233.5
	19 (3/4")	249.8	221.8	165.4	221.8	387.3
	12.5 (1/2")	233.6	161.4	103.6	161.4	264.9
	9.5 (3/8")	227.5	143.6	213.2	143.6	356.8
	4.75 (#4)	180.8	185.0	173.0	185.0	358.1
Sphericity	25 (1.0")	0.7	0.0	0.0	0.0	0.0
	19 (3/4")	0.7	0.0	0.0	0.0	0.0
	12.5 (1/2")	0.7	0.0	0.0	0.0	0.0
	9.5 (3/8")	0.68	0.0000	0.0001	0.0000	0.0001
	4.75 (#4)	0.70	0.0001	0.0003	0.0001	0.0004
Flat or Elongated 3:1	25 (1.0")	0.58%	0.0000	0.0002	0.0000	0.0002
	19 (3/4")	0.76%	0.0001	0.0001	0.0001	0.0002
	12.5 (1/2")	1.12%	0.0001	0.0002	0.0001	0.0003
	9.5 (3/8")	3.83%	0.0003	0.0014	0.0003	0.0016
	4.75 (#4)	3.22%	0.0005	0.0007	0.0005	0.0012
2D Form	2.36 (#8)	6.7	0.0264	0.0043	0.0264	0.0307
	1.18 (#16)	7.4	0.0289	0.0067	0.0289	0.0357
	0.6 (#30)	7.8	0.0335	0.0097	0.0335	0.0432
	0.3 (#50)	7.6	0.0440	0.0334	0.0440	0.0774
	0.15 (#100)	7.4	0.0462	0.0264	0.0462	0.0727
	0.075 (#200)	8.5	0.1465	0.0799	0.1465	0.2265

Table 3.5. Averages, Components of Variance, and Variances of Limestone for All Aggregate Sizes.

Aggregate Shape Characteristic	Aggregate Size	Average	Components of Variance		Variance	
			Within-Laboratory	Between-Laboratory	Within-Laboratory	Between-Laboratory
Angularity	25 (1.0")	2730.7	3746.2	1704.9	3746.2	5451.1
	19 (3/4")	2746.4	5320.3	2813.7	5320.3	8134.0
	12.5 (1/2")	2702.3	4158.7	4364.5	4158.7	8523.2
	9.5 (3/8")	2705.6	4695.5	1237.7	4695.5	5933.1
	4.75 (#4)	2706.5	4656.6	1643.3	4656.6	6299.8
	2.36 (#8)	2913.9	5244.4	-155.9	5244.4	5088.5
	1.18 (#16)	2948.6	3762.9	5953.5	3762.9	9716.4
	0.6 (#30)	3006.6	3610.8	5327.9	3610.8	8938.6
	0.3 (#50)	2914.5	10183.6	8965.8	10183.6	19149.4
	0.15 (#100)	2412.9	11688.2	17729.0	11688.2	29417.2
	0.075 (#200)	2798.3	124617.2	209763.9	124617.2	334381.0
Texture	25 (1.0")	275.4	143.7	198.9	143.7	342.6
	19 (3/4")	268.6	84.4	157.5	84.4	241.8
	12.5 (1/2")	257.3	103.0	108.1	103.0	211.2
	9.5 (3/8")	225.6	93.1	93.2	93.1	186.3
	4.75 (#4)	139.1	31.4	86.3	31.4	117.7
Sphericity	25 (1.0")	0.7	0.0	0.0	0.0	0.0
	19 (3/4")	0.7	0.0	0.0	0.0	0.0
	12.5 (1/2")	0.68	0.0001	0.0001	0.0001	0.0002
	9.5 (3/8")	0.68	0.0001	0.0001	0.0001	0.0002
	4.75 (#4)	0.67	0.0001	0.0002	0.0001	0.0003
Flat or Elongated 3:1	25 (1.0")	0.83%	0.0001	0.0001	0.0001	0.0002
	19 (3/4")	0.31%	0.0000	0.0000	0.0000	0.0001
	12.5 (1/2")	0.97%	0.0002	0.0000	0.0002	0.0002
	9.5 (3/8")	2.04%	0.0003	0.0003	0.0003	0.0006
	4.75 (#4)	4.11%	0.0005	0.0006	0.0005	0.0011
2D Form	2.36 (#8)	7.3	0.0294	0.0134	0.0294	0.0428
	1.18 (#16)	7.5	0.0436	0.0088	0.0436	0.0524
	0.6 (#30)	7.4	0.0208	0.0279	0.0208	0.0487
	0.3 (#50)	7.2	0.0377	0.0376	0.0377	0.0753
	0.15 (#100)	7.0	0.0715	0.0131	0.0715	0.0846
	0.075 (#200)	8.8	0.1805	0.1919	0.1805	0.3724

Table 3.6. Averages, Components of Variance, and Variances of Granite (Sandstone for 0.075 mm size) for All Aggregate Sizes.

Aggregate Shape Characteristic	Aggregate Size	Average	Components of Variance		Variance	
			Within-Laboratory	Between-Laboratory	Within-Laboratory	Between-Laboratory
Angularity	25 (1.0")	2901.4	3012.5	3479.6	3012.5	6492.2
	19 (3/4")	2985.9	5617.4	3750.5	5617.4	9367.9
	12.5 (1/2")	3117.7	3003.9	5429.6	3003.9	8433.5
	9.5 (3/8")	3193.4	3916.6	6345.0	3916.6	10261.6
	4.75 (#4)	3061.0	8969.4	2738.1	8969.4	11707.5
	2.36 (#8)	3330.8	4573.7	331.6	4573.7	4905.3
	1.18 (#16)	3373.1	6988.0	1074.0	6988.0	8062.0
	0.6 (#30)	3428.1	8080.1	9902.4	8080.1	17982.5
	0.3 (#50)	3436.1	9438.5	47278.8	9438.5	56717.2
	0.15 (#100)	3182.0	14401.6	15384.8	14401.6	29786.3
	0.075 (#200)	2845.4	115989.5	14255.0	115989.5	130244.5
Texture	25 (1.0")	471.8	100.4	132.3	100.4	232.7
	19 (3/4")	476.5	68.6	246.7	68.6	315.3
	12.5 (1/2")	465.0	169.6	205.2	169.6	374.8
	9.5 (3/8")	463.2	97.4	381.4	97.4	478.8
	4.75 (#4)	363.5	120.8	276.5	120.8	397.3
Sphericity	25 (1.0")	0.7	0.0	0.0	0.0	0.0
	19 (3/4")	0.6	0.0	0.0	0.0	0.0
	12.5 (1/2")	0.6	0.0	0.0	0.0	0.0
	9.5 (3/8")	0.62	0.0000	0.0002	0.0000	0.0002
	4.75 (#4)	0.68	0.0000	0.0002	0.0000	0.0002
Flat or Elongated 3:1	25 (1.0")	6.81%	0.0005	0.0025	0.0005	0.0030
	19 (3/4")	9.66%	0.0004	0.0027	0.0004	0.0032
	12.5 (1/2")	7.91%	0.0006	0.0008	0.0006	0.0013
	9.5 (3/8")	5.72%	0.0007	0.0010	0.0007	0.0017
	4.75 (#4)	5.19%	0.0011	0.0001	0.0011	0.0012
2D Form	2.36 (#8)	7.6	0.0169	0.0152	0.0169	0.0321
	1.18 (#16)	7.7	0.0258	0.0329	0.0258	0.0587
	0.6 (#30)	7.9	0.0302	0.0238	0.0302	0.0540
	0.3 (#50)	8.0	0.0147	0.0563	0.0147	0.0710
	0.15 (#100)	7.9	0.0401	0.0266	0.0401	0.0667
	0.075 (#200)	9.5	0.2947	0.0373	0.2947	0.3320

Table 3.7. Averages, Standard Deviation, and Coefficient of Variation of Gravel

Aggregate Shape Characteristic	Aggregate Size	Average	Standard Deviations Within-Laboratory	Standard Deviations Between-Laboratory	Coefficients of Variation Within-Laboratory	Coefficients of Variation Between-Laboratory
Angularity	25 (1.0")	1895.6	61.6	113.3	3.3	6.0
	19 (3/4")	2609.1	87.4	127.4	3.3	4.9
	12.5 (1/2")	2777.9	74.2	119.3	2.7	4.3
	9.5 (3/8")	2563.5	55.1	152.1	2.2	5.9
	4.75 (#4)	2275.5	66.4	136.4	2.9	6.0
	2.36 (#8)	2667.3	87.1	94.3	3.3	3.5
	1.18 (#16)	3076.3	59.0	73.3	1.9	2.4
	0.6 (#30)	3237.1	89.6	94.1	2.8	2.9
	0.3 (#50)	3179.5	109.9	151.3	3.5	4.8
	0.15 (#100)	2735.1	114.1	153.4	4.2	5.6
	0.075 (#200)	2251.8	176.5	208.8	7.8	9.3
Texture	25 (1.0")	224.7	8.8	15.3	3.9	6.8
	19 (3/4")	249.8	14.9	19.7	6.0	7.9
	12.5 (1/2")	233.6	12.7	16.3	5.4	7.0
	9.5 (3/8")	227.5	12.0	18.9	5.3	8.3
	4.75 (#4)	180.8	13.6	18.9	7.5	10.5
Sphericity	25 (1.0")	0.7	0.0	0.0	1.1	2.4
	19 (3/4")	0.7	0.0	0.0	1.0	2.3
	12.5 (1/2")	0.69	0.0066	0.0133	0.9574	1.9202
	9.5 (3/8")	0.68	0.0069	0.0114	1.0096	1.6730
	4.75 (#4)	0.70	0.0107	0.0205	1.5294	2.9281
Flat or Elongated 3:1	25 (1.0")	0.58%	0.0066	0.0148	0.6631	1.4909
	19 (3/4")	0.76%	0.0099	0.0124	0.9989	1.2523
	12.5 (1/2")	1.12%	0.0099	0.0167	1.0057	1.6901
	9.5 (3/8")	3.83%	0.0161	0.0406	1.6777	4.2236
	4.75 (#4)	3.22%	0.0232	0.0346	2.3940	3.5730
2D Form	2.36 (#8)	6.7	0.1624	0.1752	2.4326	2.6235
	1.18 (#16)	7.4	0.1701	0.1888	2.2868	2.5379
	0.6 (#30)	7.8	0.1830	0.2079	2.3469	2.6666
	0.3 (#50)	7.6	0.2098	0.2783	2.7553	3.6536
	0.15 (#100)	7.4	0.2150	0.2696	2.8944	3.6288
	0.075 (#200)	8.5	0.3828	0.4759	4.5283	5.6292

Table 3.8. Averages, Standard Deviation, and Coefficient of Variation of Limestone

Aggregate Shape Characteristic	Aggregate Size	Average	Standard Deviations Within-Laboratory	Standard Deviations Between-Laboratory	Coefficients of Variation Within-Laboratory	Coefficients of Variation Between-Laboratory
Angularity	25 (1.0")	2730.7	61.2	73.8	2.2	2.7
	19 (3/4")	2746.4	72.9	90.2	2.7	3.3
	12.5 (1/2")	2702.3	64.5	92.3	2.4	3.4
	9.5 (3/8")	2705.6	68.5	77.0	2.5	2.8
	4.75 (#4)	2706.5	68.2	79.4	2.5	2.9
	2.36 (#8)	2913.9	72.4	71.3	2.5	2.4
	1.18 (#16)	2948.6	61.3	98.6	2.1	3.3
	0.6 (#30)	3006.6	60.1	94.5	2.0	3.1
	0.3 (#50)	2914.5	100.9	138.4	3.5	4.7
	0.15 (#100)	2412.9	108.1	171.5	4.5	7.1
	0.075 (#200)	2798.3	353.0	578.3	12.6	20.7
Texture	25 (1.0")	275.4	12.0	18.5	4.4	6.7
	19 (3/4")	268.6	9.2	15.6	3.4	5.8
	12.5 (1/2")	257.3	10.2	14.5	3.9	5.6
	9.5 (3/8")	225.6	9.6	13.7	4.3	6.1
	4.75 (#4)	139.1	5.6	10.8	4.0	7.8
Sphericity	25 (1.0")	0.72	0.0054	0.0155	0.7598	2.1676
	19 (3/4")	0.68	0.0057	0.0165	0.8326	2.4187
	12.5 (1/2")	0.68	0.0074	0.0142	1.0887	2.0887
	9.5 (3/8")	0.68	0.0076	0.0133	1.1196	1.9515
	4.75 (#4)	0.67	0.0100	0.0164	1.5023	2.4658
Flat or Elongated 3:1	25 (1.0")	0.83%	0.0071	0.0127	0.7173	1.2764
	19 (3/4")	0.31%	0.0070	0.0073	0.6990	0.7350
	12.5 (1/2")	0.97%	0.0124	0.0137	1.2473	1.3826
	9.5 (3/8")	2.04%	0.0159	0.0240	1.6281	2.4467
	4.75 (#4)	4.11%	0.0225	0.0326	2.3424	3.4007
2D Form	2.36 (#8)	7.3	0.1715	0.2069	2.3464	2.8304
	1.18 (#16)	7.5	0.2089	0.2289	2.8027	3.0717
	0.6 (#30)	7.4	0.1442	0.2206	1.9395	2.9662
	0.3 (#50)	7.2	0.1941	0.2743	2.6878	3.7988
	0.15 (#100)	7.0	0.2675	0.2909	3.8203	4.1550
	0.075 (#200)	8.8	0.4249	0.6103	4.8284	6.9350

Table 3.9. Averages, Standard Deviation, and Coefficient of Variation of Granite

(Sandstone for 0.075 mm size)

Aggregate Shape Characteristic	Aggregate Size	Average	Standard Deviations Within-Laboratory	Standard Deviations Between-Laboratory	Coefficients of Variation Within-Laboratory	Coefficients of Variation Between-Laboratory
Angularity	25 (1.0")	2901.4	54.9	80.6	1.9	2.8
	19 (3/4")	2985.9	74.9	96.8	2.5	3.2
	12.5 (1/2")	3117.7	54.8	91.8	1.8	2.9
	9.5 (3/8")	3193.4	62.6	101.3	2.0	3.2
	4.75 (#4)	3061.0	94.7	108.2	3.1	3.5
	2.36 (#8)	3330.8	67.6	70.0	2.0	2.1
	1.18 (#16)	3373.1	83.6	89.8	2.5	2.7
	0.6 (#30)	3428.1	89.9	134.1	2.6	3.9
	0.3 (#50)	3436.1	97.2	238.2	2.8	6.9
	0.15 (#100)	3182.0	120.0	172.6	3.8	5.4
	0.075 (#200)	2845.4	340.6	360.9	12.0	12.7
Texture	25 (1.0")	471.8	10.0	15.3	2.1	3.2
	19 (3/4")	476.5	8.3	17.8	1.7	3.7
	12.5 (1/2")	465.0	13.0	19.4	2.8	4.2
	9.5 (3/8")	463.2	9.9	21.9	2.1	4.7
	4.75 (#4)	363.5	11.0	19.9	3.0	5.5
Sphericity	25 (1.0")	0.7	0.0	0.0	0.8	2.9
	19 (3/4")	0.64	0.0054	0.0180	0.8389	2.8273
	12.5 (1/2")	0.62	0.0078	0.0126	1.2580	2.0376
	9.5 (3/8")	0.62	0.0064	0.0148	1.0388	2.3872
	4.75 (#4)	0.68	0.0065	0.0153	0.9542	2.2500
Flat or Elongated 3:1	25 (1.0")	6.81%	0.0222	0.0550	2.3831	5.9008
	19 (3/4")	9.66%	0.0208	0.0562	2.3017	6.2250
	12.5 (1/2")	7.91%	0.0241	0.0366	2.6180	3.9717
	9.5 (3/8")	5.72%	0.0257	0.0407	2.7262	4.3195
	4.75 (#4)	5.19%	0.0332	0.0345	3.4992	3.6437
2D Form	2.36 (#8)	7.6	0.1299	0.1791	1.7012	2.3456
	1.18 (#16)	7.7	0.1606	0.2422	2.0854	3.1457
	0.6 (#30)	7.9	0.1739	0.2325	2.1978	2.9387
	0.3 (#50)	8.0	0.1212	0.2665	1.5243	3.3506
	0.15 (#100)	7.9	0.2003	0.2583	2.5197	3.2500
	0.075 (#200)	9.5	0.5429	0.5762	5.7193	6.0704

Table 3.10. Averages, Components of Variance, and Variances of Combined Properties for the Blend

Aggregate Material	Aggregate Size	Average	Components of Variance		Variance	
			Within-Laboratory	Between-Laboratory	Within-Laboratory	Between-Laboratory
Gravel	Angularity	2878.1	3400.8	4697.5	3400.8	8098.3
	Texture	203.4	44.7	123.9	44.7	168.6
	Sphericity	0.70	0.0001	0.0003	0.0001	0.0003
	Flat or Elongated 3:1	1.52%	0.0000	0.0001	0.0000	0.0002
	2D Form	7.5	0.0124	0.0093	0.0124	0.0217
Limestone	Angularity	2689.8	2715.7	6833.3	2715.7	9549.0
	Texture	183.4	11.0	58.0	11.0	69.0
	Sphericity	0.67	0.0001	0.0001	0.0001	0.0002
	Flat or Elongated 3:1	1.46%	0.0000	0.0000	0.0000	0.0001
	2D Form	7.2	0.0213	0.0109	0.0213	0.0322
Granite	Angularity	3262.2	5341.0	12882.9	5341.0	18223.9
	Texture	399.5	75.2	167.8	75.2	243.0
	Sphericity	0.67	0.0001	0.0001	0.0001	0.0002
	Flat or Elongated 3:1	4.36%	0.0001	0.0001	0.0001	0.0002
	2D Form	7.9	0.0131	0.0109	0.0131	0.0241

Table 3.11. Averages, Standard Deviation, and Coefficient of Variation of Combined Properties for the Blend

Aggregate Material	Aggregate Size	Average	Standard Deviations Within-Laboratory	Standard Deviations Between-Laboratory	Coefficients of Variation Within-Laboratory	Coefficients of Variation Between-Laboratory
Gravel	Angularity	2878.1	58.3	90.0	2.0	3.1
	Texture	203.4	6.7	13.0	3.3	6.4
	Sphericity	0.70	0.0083	0.0183	1.1981	2.6291
	Flat or Elongated 3:1	1.52%	0.0066	0.0138	0.6733	1.4002
	2D Form	7.5	0.1112	0.1472	1.4885	1.9700
Limestone	Angularity	2689.8	52.1	97.7	1.9	3.6
	Texture	183.4	3.3	8.3	1.8	4.5
	Sphericity	0.67	0.0090	0.0151	1.3578	2.2602
	Flat or Elongated 3:1	1.46%	0.0052	0.0084	0.5295	0.8491
	2D Form	7.2	0.1459	0.1794	2.0338	2.4999
Granite	Angularity	3262.2	73.1	135.0	2.2	4.1
	Texture	399.5	8.7	15.6	2.2	3.9
	Sphericity	0.67	0.0092	0.0151	1.3633	2.2521
	Flat or Elongated 3:1	4.36%	0.0103	0.0141	1.0753	1.4739
	2D Form	7.9	0.1146	0.1551	1.4509	1.9645

The standard deviations and coefficient of variations were plotted against the average of each materials source. Figure 3.3 and Figure 3.4 are examples of the standard deviation and coefficient of variations relationships for the angularity measurement of 25.0 mm (1 in) aggregates.

The precision statement of the data was established by analyzing the relationships of the standard deviations and/or coefficient of variations. The ASTM C 670-96 procedure includes two provisions for the data analysis. One provision is for a constant standard deviation case and the second provision is for a constant coefficient of variation case.

The constant standard deviation case is where pooled within-laboratory standard deviation over all the materials becomes the single-operator standard deviation and the pooled between-laboratory standard deviation becomes the multi-laboratory standard deviation. In the case of a constant coefficient of variation, the average within-laboratory and between-laboratory coefficient of variation becomes the single-operator and the multi-laboratory coefficient of variation, respectively.

Neither of the constant standard deviation or constant coefficient of variation conditions was strictly satisfied in the analysis results. However, from an engineering perspective, the variation of the standard deviation and coefficient of variation is considered small. Therefore, it was decided to determine the precision statements for both a constant standard deviation and a constant coefficient of variation for the single-operator (within-laboratory) and multi-laboratory (between-laboratory) precision.

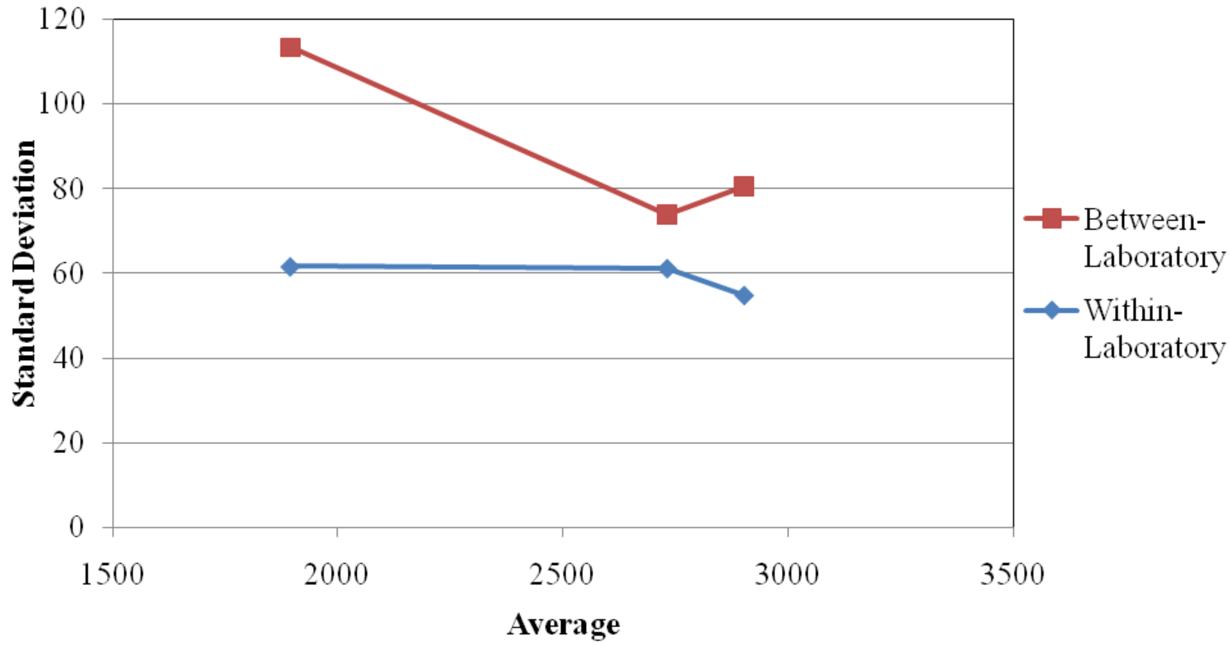

Figure 3.3. Standard deviation versus average angularity of 25.0 mm (1 in).

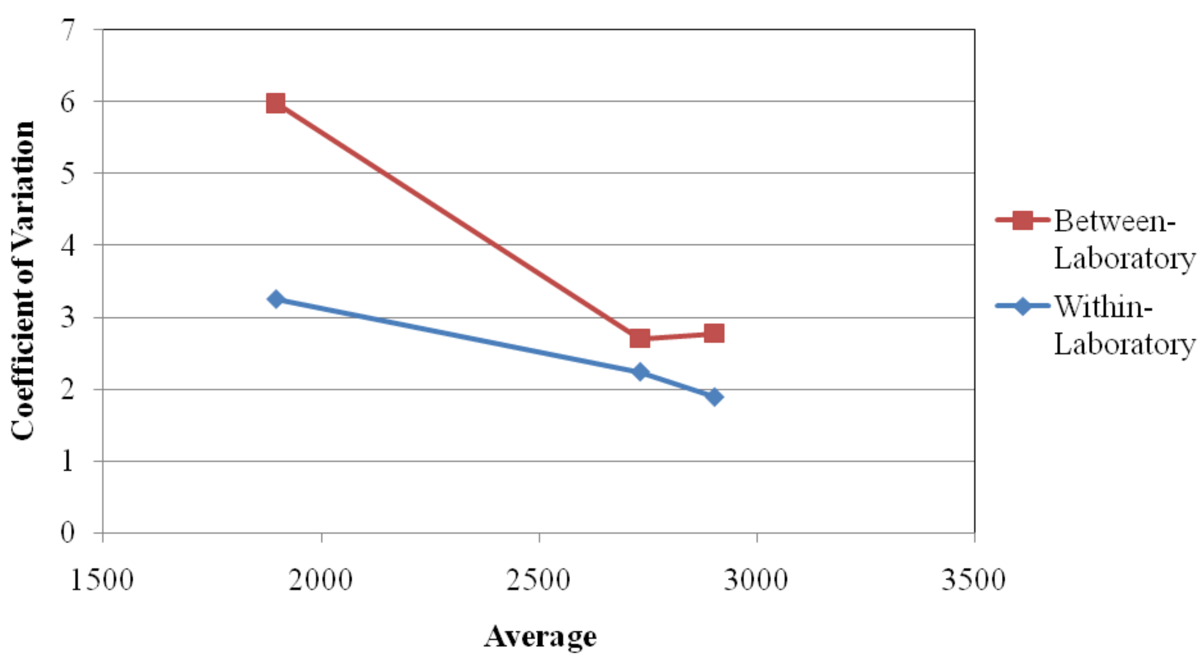

Figure 3.4. Coefficient of variation versus average angularity of 25.0 mm (1 in).

The precision statements (1s%) based on the assumption of constant standard deviation are shown in Table 3.12 for the single-operator and multi-laboratory results. The precision statements (1s%) based on the assumption of constant coefficient of variation are shown in Table 3.13. The combined results precision statements (1s%) based on the assumptions of constant standard deviation and constant coefficient of variation are shown in Table 3.14 and 3.15, respectively.

Table 3.12. Precision Statements (1s%) for Constant Standard Deviation

Aggregate Shape Characteristic	Aggregate Size	Standard Deviation	
		Single-Operator	Multi-Laboratory
Angularity	25 (1.0")	59.3	90.9
	19 (3/4")	78.7	106.0
	12.5 (1/2")	65.0	102.0
	9.5 (3/8")	62.3	114.5
	4.75 (#4)	77.5	110.5
	2.36 (#8)	76.2	79.4
	1.18 (#16)	68.9	87.9
	0.6 (#30)	81.1	109.2
	0.3 (#50)	102.8	181.4
	0.15 (#100)	114.2	166.1
	0.075 (#200)	301.0	411.6
Texture	25 (1.0")	10.4	16.4
	19 (3/4")	11.2	17.7
	12.5 (1/2")	12.0	16.8
	9.5 (3/8")	10.6	18.5
	4.75 (#4)	10.6	17.1
Sphericity	25 (1.0")	0.0066	0.0178
	19 (3/4")	0.0061	0.0171
	12.5 (1/2")	0.0073	0.0134
	9.5 (3/8")	0.0070	0.0132
	4.75 (#4)	0.0092	0.0175
Flat or Elongated 3:1	25 (1.0")	0.0140	0.0337
	19 (3/4")	0.0139	0.0335
	12.5 (1/2")	0.0167	0.0245
	9.5 (3/8")	0.0198	0.0360
	4.75 (#4)	0.0271	0.0331
2D Form	2.36 (#8)	0.1556	0.1876
	1.18 (#16)	0.1811	0.2212
	0.6 (#30)	0.1679	0.2206
	0.3 (#50)	0.1793	0.2731
	0.15 (#100)	0.2294	0.2733
	0.075 (#200)	0.4553	0.5570

Table 3.13. Precision Statements (1s%) for Constant Coefficient of Variation

Aggregate Shape Characteristic	Aggregate Size	Coefficient of Variation	
		Single-Operator	Multi-Laboratory
Angularity	25 (1.0")	2.5%	3.8%
	19 (3/4")	2.8%	3.8%
	12.5 (1/2")	2.3%	3.6%
	9.5 (3/8")	2.2%	4.0%
	4.75 (#4)	2.8%	4.2%
	2.36 (#8)	2.6%	2.7%
	1.18 (#16)	2.2%	2.8%
	0.6 (#30)	2.5%	3.3%
	0.3 (#50)	3.2%	5.5%
	0.15 (#100)	4.1%	6.0%
	0.075 (#200)	10.8%	14.2%
Texture	25 (1.0")	3.5%	5.6%
	19 (3/4")	3.7%	5.8%
	12.5 (1/2")	4.1%	5.6%
	9.5 (3/8")	3.9%	6.4%
	4.75 (#4)	4.9%	7.9%
Sphericity	25 (1.0")	0.9%	2.5%
	19 (3/4")	0.9%	2.5%
	12.5 (1/2")	1.1%	2.0%
	9.5 (3/8")	1.1%	2.0%
	4.75 (#4)	1.3%	2.5%
Flat or Elongated 3:1	25 (1.0")	1.3%	2.9%
	19 (3/4")	1.3%	2.7%
	12.5 (1/2")	1.6%	2.3%
	9.5 (3/8")	2.0%	3.7%
	4.75 (#4)	2.8%	3.5%
2D Form	2.36 (#8)	2.2%	2.6%
	1.18 (#16)	2.4%	2.9%
	0.6 (#30)	2.2%	2.9%
	0.3 (#50)	2.3%	3.6%
	0.15 (#100)	3.1%	3.7%
	0.075 (#200)	5.0%	6.2%

Table 3.14. Combined Properties Precision Statements (1s%) for Standard Deviation for the Blend

Aggregate Shape Characteristic	Constant Standard Deviation	
	Single-Operator	Multi-Laboratory
Angularity	61.8	109.3
Texture	6.6	12.7
Sphericity	0.0089	0.0162
Flat or Elongated 3:1	0.0077	0.0124
2D Form	0.1249	0.1612

Table 3.15. Combined Properties Precision Statements (1s%) for Constant Coefficient of Variation for the Blend

Aggregate Shape Characteristic	Coefficient of Variation	
	Single-Operator	Multi-Laboratory
Angularity	2.1%	3.6%
Texture	2.4%	4.9%
Sphericity	1.3%	2.4%
Flat or Elongated 3:1	0.8%	1.2%
2D Form	1.7%	2.1%

Based on these precisions statements, the results of two properly conducted tests (d2s%) which are tested either by a single-operator or multi-laboratory are not expected to differ more than the values shown in Table 3.16, Table 3.17, Table 3.18, and Table 3.19. These numbers are based on the calculations described in ASTM C 670-96.

Table 3.16. Precision Statements of Two Tests (d2s%) for Constant Standard Deviation

Aggregate Shape Characteristic	Aggregate Size	Standard Deviation	
		Single-Operator	Multi-Laboratory
Angularity	25 (1.0")	167.8	257.0
	19 (3/4")	222.5	299.9
	12.5 (1/2")	183.8	288.4
	9.5 (3/8")	176.3	323.9
	4.75 (#4)	219.3	312.4
	2.36 (#8)	215.4	224.5
	1.18 (#16)	194.8	248.5
	0.6 (#30)	229.3	308.9
	0.3 (#50)	290.8	513.2
	0.15 (#100)	322.9	469.7
	0.075 (#200)	851.3	1164.1
Texture	25 (1.0")	29.3	46.4
	19 (3/4")	31.6	50.2
	12.5 (1/2")	34.0	47.6
	9.5 (3/8")	29.8	52.2
	4.75 (#4)	30.0	48.2
Sphericity	25 (1.0")	0.0186	0.0504
	19 (3/4")	0.0172	0.0483
	12.5 (1/2")	0.0206	0.0379
	9.5 (3/8")	0.0198	0.0374
	4.75 (#4)	0.0261	0.0496
Flat or Elongated 3:1	25 (1.0")	0.0396	0.0953
	19 (3/4")	0.0393	0.0948
	12.5 (1/2")	0.0471	0.0694
	9.5 (3/8")	0.0560	0.1018
	4.75 (#4)	0.0765	0.0938
2D Form	2.36 (#8)	0.4402	0.5306
	1.18 (#16)	0.5122	0.6255
	0.6 (#30)	0.4748	0.6238
	0.3 (#50)	0.5070	0.7724
	0.15 (#100)	0.6488	0.7729
	0.075 (#200)	1.2877	1.5756

Table 3.17. Precision Statements of Two Tests (d2s%) for Constant Coefficient of Variation

Aggregate Shape Characteristic	Aggregate Size	Coefficient of Variation	
		Single-Operator	Multi-Laboratory
Angularity	25 (1.0")	7.0%	10.8%
	19 (3/4")	8.0%	10.8%
	12.5 (1/2")	6.4%	10.0%
	9.5 (3/8")	6.3%	11.3%
	4.75 (#4)	8.0%	11.7%
	2.36 (#8)	7.3%	7.6%
	1.18 (#16)	6.1%	7.9%
	0.6 (#30)	7.0%	9.4%
	0.3 (#50)	9.2%	15.5%
	0.15 (#100)	11.7%	17.1%
	0.075 (#200)	30.6%	40.2%
Texture	25 (1.0")	9.8%	15.8%
	19 (3/4")	10.5%	16.4%
	12.5 (1/2")	11.5%	15.8%
	9.5 (3/8")	11.0%	18.0%
	4.75 (#4)	13.7%	22.4%
Sphericity	25 (1.0")	2.5%	7.1%
	19 (3/4")	2.5%	7.1%
	12.5 (1/2")	3.1%	5.7%
	9.5 (3/8")	3.0%	5.7%
	4.75 (#4)	3.8%	7.2%
Flat or Elongated 3:1	25 (1.0")	3.5%	8.2%
	19 (3/4")	3.8%	7.7%
	12.5 (1/2")	4.6%	6.6%
	9.5 (3/8")	5.7%	10.4%
	4.75 (#4)	7.8%	9.8%
2D Form	2.36 (#8)	6.1%	7.4%
	1.18 (#16)	6.8%	8.3%
	0.6 (#30)	6.1%	8.1%
	0.3 (#50)	6.6%	10.2%
	0.15 (#100)	8.7%	10.4%
	0.075 (#200)	14.2%	17.6%

Table 3.18. Combined Properties Precision Statements of Two Tests (d2s%) for Constant Standard Deviation for the Blend

Aggregate Shape Characteristic	Standard Deviation	
	Single-Operator	Multi-Laboratory
Angularity	174.8	309.3
Texture	18.7	35.8
Sphericity	0.0250	0.0459
Flat or Elongated 3:1	0.0217	0.0350
2D Form	0.3533	0.4558

Table 3.19. Combined Properties Precision Statements of Two Tests (d2s%) for Constant Coefficient of Variation for the Blend

Aggregate Shape Characteristic	Coefficient of Variation	
	Single-Operator	Multi-Laboratory
Angularity	5.8%	10.3%
Texture	6.8%	14.0%
Sphericity	3.7%	6.7%
Flat or Elongated 3:1	2.1%	3.5%
2D Form	4.7%	6.1%

The machines were calibrated before each laboratory scanned the materials to eliminate possible sources of error. The 0.075 mm (ASTM #200 sieve) has larger than expected single-operator and multi-laboratory standard deviation. After investigation into the possible sources of error, the CHPR value, which is used to eliminate touching particles from the data before it is analyzed, was found to be the source of error.[6] The limits of the CHPR value were believed allow several touching particles to be analyzed. This was determined by an inspection of the number of touching particles in the images from the

[6] E. Mahmoud, L. Gates, E. Masad, S. Erdogafan, and E. Garboczi, "Comprehensive Evaluation of AIMS Texture, Angularity, and Dimension Measurements," *Journal of Materials in Civil Engineering,* vol. 22, no. 4, pp. 369–79, 2010.

analyzed data. Therefore, the 0.075 mm (ASTM #200 sieve) results should be further examined after developing a more robust method to eliminate touching particles. Once such a method is developed, precision statements for the standard deviation and coefficient of variation results will be developed for this size.

CONCLUSIONS

The analysis conducted in this chapter lead to the development of precision statements for the different shape indices and parameters given by AIMS2. In general, the experiments gave very reasonable coefficient of variation for the various indices for all sizes except the 0.075 mm size. The results from the constant coefficient of variation should be used to describe the precision statement since the standard deviation results have a slight trend of increase with an increase in average. Therefore, a precision statement based on constant standard deviation will be biased against materials with low average and work in favor of materials with high average. Overall, the maximum coefficient of variation was less than 5% for a single operator and less than 8% for multi laboratories when individual sizes were analyzed. The maximum coefficient of variation for the combined results of a blend was less than 3% for a single operator and less than 5% for multi laboratories. These are considered acceptable coefficient of variation values given the natural variation in aggregate samples from the same source.

Further tests will be necessary to determine the proper CHRP calibrated value for the 0.075 mm (ASTM #200 sieve) in order to remove touching particles in the analysis. The determination of this value is expected to reduce the variations in the measurements conducted on the 0.075 mm sieve, and reduce the precision coefficient of variation reported for this size.

The precision statements from the constant coefficient of variations were combined for aggregates sizes, excluding 0.075 mm (ASTM #200 sieve), for each aggregate shape characteristic. The was done by taking the square root of the sum divided by n-1 of the squares of all sizes except 0.075 mm (ASTM #200 sieve) for each aggregate shape property. Where n is the number of values sum. The precision statements for the single limit (1s%) and difference of two results (d2s%) are shown in Table 3.20 and Table 3.21, respectively.

Table 3.20. Precision Statement (1s%) for Each Shape Characteristic

Aggregate Shape Characteristic	Constant Coefficient of Variation	
	Within-Laboratory	Between-Laboratory
Angularity	2.9%	4.3%
Texture	4.5%	7.1%
Sphericity	1.2%	2.6%
Flat or Elongated 3:1	2.1%	3.4%
2D Form	2.7%	3.5%

Table 3.21. Precision Statement (d2s%) for Each Shape Characteristic

Aggregate Shape Characteristic	Constant Coefficient of Variation	
	Within-Laboratory	Between-Laboratory
Angularity	8.3%	12.2%
Texture	12.7%	20.0%
Sphericity	3.4%	7.4%
Flat or Elongated 3:1	5.9%	9.7%
2D Form	7.7%	10.0%

APPENDIX B

ILS Data & ILS Lab Participants

<u>Texas A&M University Report</u>

A Report Submitted to Pine Instruments as Part of FHWA Grant Number DTFH61-08-G-00003

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December 31, 2009

Pine Instrument Company
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Alaska Department of Transportation Central

Alaska Department of Transportation North

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Federal Highway Administration Central Federal Lands

Federal Highway Administration Technology Trailer

Federal Highway Administration Turner-Fairbank Highway Research Center

Florida Department of Transportation

Illinois Department of Transportation

Indiana Department of Transportation

Iowa Department of Transportation

Kansas Department of Transportation

Maine Department of Transportation

Michigan Department of Transportation

Minnesota Department of Transportation

Mississippi Department of Transportation

Nebraska Department of Transportation

New Mexico Department of Transportation

New York Department of Transportation

North Carolina State University

North Dakota Department of Transportation

Ohio Department of Transportation

Oklahoma Department of Transportation

Oregon Department of Transportation

Saskatchewan Ministry of Highways and Infrastructure

South Carolina Department of Transportation

South Dakota Department of Transportation

Texas A&M (Principle Research Laboratory)

Texas Department of Transportation(Texas Transportation Institute)

University of Texas, Austin

Vermont Department of Transportation

Washington Department of Transportation

Gravel		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	1794.4	2778.9	2620.1	2743.5	2122.4	2462.7	3135.1	3218.7	3014.1	2633.3	2121.6
	2	1770.1	2717.2	2784.8	2650.4	2120.8	2668.3	3130.6	3348.8	2855.4	2899.1	2046.7
2	1	1755.8	2705.0	2751.5	2647.5	2197.2	2594.2	3075.8	3266.9	3275.2	2879.5	2226.9
	2	1788.7	2644.3	2801.8	2611.4	2213.7	2726.8	3024.3	3400.4	3148.2	2825.1	2242.0
3	1	1604.0	2857.6	2740.1	2641.4	2129.6	2731.6	3057.2	3284.1	3127.2	2725.6	2362.0
	2	1861.3	2597.3	2732.2	2559.4	2273.2	2614.9	3045.6	3276.4	3127.0	2657.7	2260.0
4	1	1856.4	2499.3	2918.8	2674.2	2215.2	2770.0	2987.0	3226.6	3186.9	2705.4	2432.6
	2	1742.3	2751.0	2735.1	2607.5	2133.1	2737.0	3113.3	3261.8	3069.5	2539.3	2220.3
5	1	2090.9	2662.6	2897.1	2510.2	2462.3	2826.7	3193.4	3186.6	3125.1	2586.4	2291.3
	2	2004.6	2483.3	2867.7	2467.3	2386.1	2803.0	3300.4	3289.9	3026.6	2744.7	2554.9
6	1	2046.9	2599.0	2667.9	2461.5	2225.2	2876.3	3105.5	3168.8	3386.2	2943.0	2263.7
	2	1968.9	2585.9	2854.7	2457.8	2242.4	2611.1	3002.3	3348.8	3353.3	2807.7	2297.7
7	1	2013.4	2604.8	2897.9	2597.8	2275.7	2691.6	3033.9	3262.4	3211.0	2663.3	2347.2
	2	1987.2	2519.6	2845.9	2462.4	2293.5	2700.7	3093.4	3013.2	2912.0	2841.4	2417.4
8	1	2000.8	2598.1	2912.8	2409.9	2321.5	2763.2	3046.2	3273.5	3181.2	2817.1	2504.8
	2	1941.3	2552.4	2912.8	2530.6	2243.0	2642.5	3071.0	3058.3	3337.2	2964.3	2505.9
9	1	1782.4	2635.9	2901.0	2418.9	2036.7	2668.9	3058.6	3269.0	2956.8	2670.4	2164.6
	2	1869.0	2738.9	3079.1	2410.4	1951.8	2662.1	3093.1	3239.1	3036.5	2650.2	2742.0
10	1	1817.0	2599.3	2895.2	2710.6	2173.3	2549.7	3104.7	3350.7	3231.6	2705.6	2374.6
	2	1868.3	2551.9	2870.4	2401.7	2074.9	2713.4	3015.4	3358.2	3173.1	2835.6	2002.8
11	1	1890.2	2543.2	2795.7	2520.4	2027.5	2648.5	3040.8	3228.4	3248.0	2135.6	1639.6
	2	1916.1	2564.0	2806.3	2468.5	2179.8	2572.5	3212.3	3293.3	3233.9	2598.1	2031.3
12	1	1875.2	2580.9	2828.5	2568.4	2034.1	2481.5	2971.3	3208.7	3164.6	2825.1	2268.1
	2	1823.3	2526.0	2875.6	2606.7	2090.6	2670.9	3085.8	3256.4	3335.4	2878.6	2360.2
13	1	1924.2	2392.0	2806.2	2376.3	2203.2	2594.5	3078.0	3306.1	3341.1	2633.9	2596.8
	2	1747.9	2495.4	2971.7	2445.6	2417.9	2735.7	3070.3	3330.2	3275.6	2639.9	2045.4
14	1	1905.6	2416.4	2623.1	2503.0	2382.7	2614.4	3091.6	3190.0	3181.8	2835.6	2257.2
	2	1899.6	2443.4	2813.2	2476.9	2382.1	2679.7	3197.1	3350.3	3120.2	2943.3	2196.2
15	1	1962.3	2625.0	2729.9	2468.8	2254.3	2735.5	3108.5	3296.9	3401.1	2855.4	1970.8

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Gravel		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	1979.0	2781.0	2710.9	2427.4	2289.8	2647.6	3086.1	3267.2	3349.1	2819.6	2405.2
16	1	1880.5	2847.1	2617.1	2322.1	2279.4	2724.4	3024.6	3116.6	3240.7	2689.8	2229.6
	2	1912.2	2818.4	2589.8	2376.1	2224.2	2627.6	3001.0	3181.4	3393.9	2649.8	2381.1
17	1	1936.3	2735.9	2580.7	2351.5	2259.5	2519.7	3050.1	3166.9	3226.6	2938.8	2523.0
	2	1888.8	2818.5	2537.7	2495.3	2291.5	2594.0	3145.2	3236.4	3150.8	2650.8	2584.0
18	1	1979.3	2666.9	2583.5	2395.0	2299.7	2557.0	3070.4	3214.5	3375.0	2671.9	1960.2
	2	2193.3	2868.0	2707.0	2360.0	2415.6	2763.2	3152.9	3209.2	3225.1	2720.2	2007.3
19	1	2048.8	2421.1	2908.7	2528.8	2489.5	2601.8	3153.2	3253.0	3149.4	2602.4	1966.4
	2	1952.4	2511.6	2834.8	2455.0	2513.6	2739.0	3190.9	3309.5	3001.7	2597.4	2293.1
20	1	2014.1	2505.9	2763.4	2466.0	2399.7	2709.4	3157.9	3258.5	3131.9	2594.0	2177.6
	2	2043.2	2384.2	2835.9	2487.2	2370.4	2627.5	3124.2	3415.5	3260.8	2625.0	2162.5
21	1	1951.3	2359.2	2868.9	2446.9	2421.4	2758.8	3093.7	3304.1	3243.9	2817.0	2168.3
	2	2013.1	2491.9	2816.9	2388.4	2548.2	2673.4	3165.4	3277.0	3266.8	2766.2	2565.0
22	1	1900.3	2651.8	2887.1	2938.1	2179.0	2711.2	2891.2	3182.0	3355.2	2861.0	2309.2
	2	1904.7	2598.7	2872.2	2834.4	2347.6	2495.1	3081.0	3167.0	3294.7	2896.6	2195.5
23	1	1844.7	2519.8	2885.9	2700.7	2258.5	2587.7	3148.7	3363.2	3189.8	2588.3	2008.9
	2	1899.9	2593.6	2752.4	2858.0	2346.3	2384.4	3086.0	3231.5	2996.1	2446.6	1826.1
24	1	1871.7	2667.2	2741.1	2706.0	2312.7	2831.8	2962.5	3277.3	3326.2	2678.1	2451.2
	2	1933.2	2399.3	2782.4	2774.6	2211.6	2761.5	2974.4	3272.3	3257.2	2772.4	2427.6
25	1	1953.1	2603.1	2766.3	2728.2	2371.7	2631.4	2995.7	3119.7	3347.4	2967.4	2209.8
	2	1920.6	2605.1	2826.4	2775.6	2210.1	2621.1	3006.0	3114.1	3211.9	2703.6	2230.8
26	1	1632.7	2711.4	2666.2	2819.7	2241.4	2650.9	2977.1	3155.1	3152.4	2798.8	2299.4
	2	1675.8	2692.9	2709.4	2703.2	2242.5	2688.1	3113.0	3035.3	2801.5	2521.3	2084.7
27	1	1788.0	2718.8	2594.1	2831.0	2225.5	2546.1	3084.8	3323.3	2949.9	2308.5	1719.3
	2	1848.6	2680.5	2575.5	2757.6	2182.7	2638.8	3053.5	2953.7	3014.8	2329.6	1717.6
28	1	1751.1	2779.1	2501.0	2630.2	2268.6	2602.4	2974.9	3304.6	2739.9	2726.1	2151.7
	2	1740.1	2586.6	2743.5	2701.0	2351.0	2714.5	3033.9	3139.0	3173.5	2701.2	2341.3
29	1	1993.0	2547.3	2791.7	2523.3	2388.7	2757.9	3003.0	3120.1	3290.6	3012.8	2253.2
	2	1985.0	2496.5	2731.5	2475.4	2299.2	2786.8	3082.8	3220.7	3256.8	2907.6	2269.3

Limestone		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	2749.0	2826.6	2802.1	2625.7	2786.4	3356.8	3271.3	3198.1	2905.3	2226.3	2451.3
	2	2802.5	2837.1	2803.7	2695.9	2777.1	3336.6	3263.0	3230.1	2888.6	2146.8	1952.0
2	1	2718.0	2817.4	2968.7	2687.6	2712.8	2917.3	3031.4	3147.8	2927.4	2313.0	2697.2
	2	2861.8	2849.4	2879.3	2596.5	2717.5	2881.7	2884.6	2974.2	2856.4	2417.6	3057.0
3	1	2718.5	2741.6	2762.8	2621.3	2723.6	2949.1	2985.2	2972.5	2893.8	2268.5	3192.5
	2	2781.1	2775.4	2801.1	2567.5	2536.1	2848.9	2930.6	2893.3	2925.9	2469.4	3381.3
4	1	2823.5	2766.0	2793.8	2611.3	2740.2	2855.1	2969.7	3158.7	2969.9	2350.6	2177.6
	2	2824.2	2795.4	2782.4	2592.9	2623.9	2791.7	2928.2	3005.8	2866.1	2358.1	3113.3
5	1	2665.5	2741.6	2702.9	2835.6	2763.5	2874.6	2930.7	3202.9	2947.9	2462.2	4138.6
	2	2748.9	2797.1	2691.7	2667.3	2725.3	2998.1	3108.5	3234.0	3302.8	2412.6	3391.5
6	1	2828.5	2815.8	2727.9	2761.8	2732.5	2747.2	3060.7	2942.4	3011.4	2566.1	2780.3
	2	2707.6	2772.5	2675.9	2669.7	2608.7	2906.7	2894.8	2972.4	2942.5	2439.0	3086.9
7	1	2736.7	2824.9	2637.5	2720.7	2759.0	2878.9	3019.6	3016.5	2959.6	2680.4	3178.9
	2	2718.6	2722.9	2573.1	2670.6	2740.6	3017.1	2936.3	3002.7	2929.3	2948.5	2544.5
8	1	2659.6	2767.8	2804.1	2835.3	2557.6	2847.6	3164.8	2874.8	2664.6	2419.7	3121.5
	2	2638.0	2874.4	2888.2	2835.5	2729.9	2977.8	3034.6	2884.2	2966.3	2500.2	3629.0
9	1	2829.7	2765.6	2538.4	2672.0	2656.8	2922.9	3033.7	3085.1	2789.8	2468.4	3536.3
	2	2813.8	2719.1	2583.5	2718.5	2705.7	2942.4	3007.4	3093.3	2678.1	2338.6	3447.9
10	1	2735.5	2786.3	2644.4	2650.5	2712.1	2923.1	2902.1	3023.1	2851.0	2348.4	2674.7
	2	2761.7	2651.5	2699.7	2785.5	2751.3	2990.8	2910.0	2982.3	2946.8	2420.9	2199.1
11	1	2829.2	2753.4	2685.4	2609.0	2798.1	2898.5	2977.1	2975.3	2981.3	2106.0	3090.4
	2	2838.3	2820.0	2642.8	2742.8	2722.9	2893.2	2917.6	3125.2	3055.7	2482.7	3193.8
12	1	2800.1	2750.8	2640.4	2672.6	2780.3	2794.4	2921.0	3013.0	2931.5	2464.4	2785.2
	2	2748.3	2758.6	2633.3	2680.9	2787.4	3037.3	3004.3	3005.8	3023.0	2536.1	3187.7
13	1	2743.5	2626.3	2728.8	2786.7	2823.2	2900.3	2960.5	3174.7	2953.7	2652.2	2485.8
	2	2825.1	2635.2	2714.8	2686.8	2859.6	3029.8	2917.7	2991.5	2910.3	1759.9	1584.7
14	1	2836.7	2650.2	2670.4	2867.1	2738.9	2862.0	2920.7	2943.4	3046.0	2584.9	2860.7
	2	2767.0	2703.5	2731.9	2659.1	2721.9	3052.4	2987.8	3011.1	2985.0	2637.8	3261.4
15	1	2740.8	2811.3	2805.2	2807.9	2792.2	2938.9	3042.6	2878.2	3007.3	2563.6	2908.2

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Limestone		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	2525.0	2847.7	2825.4	2672.8	2726.1	2897.3	2958.3	2984.7	2951.7	2430.9	3106.1
16	1	2749.5	2724.9	2722.7	2657.0	2774.8	2895.4	2912.4	2988.7	3046.8	2422.0	2632.4
	2	2628.0	2848.4	2659.6	2787.2	2624.7	2859.7	2936.4	2967.2	2862.6	2371.1	2861.1
17	1	2656.2	2802.8	2788.1	2730.3	2718.0	3065.4	2868.2	2987.8	3030.1	2571.0	3865.4
	2	2702.2	2840.9	2682.0	2691.1	2788.9	2996.3	2970.1	2982.8	2920.1	2679.2	3594.3
18	1	2719.4	3058.2	2521.8	2796.8	2768.6	2809.6	2793.7	3031.4	2769.2	2190.5	2220.2
	2	2799.7	2760.9	2782.2	2729.9	2684.9	2930.0	2897.3	3121.4	2850.6	2232.9	2222.4
19	1	2652.0	2499.2	2726.5	2674.7	2724.6	2742.2	2837.7	3074.0	2974.7	2275.9	2932.0
	2	2776.3	2725.6	2632.4	2590.7	2667.6	2859.3	2887.6	3056.4	2937.3	2200.0	2337.6
20	1	2709.3	2629.3	2719.1	2727.5	2738.9	2947.4	2979.5	3049.2	2968.5	2205.3	2238.8
	2	2745.2	2658.1	2644.6	2772.9	2642.1	2848.3	2972.7	2975.0	2740.7	2360.3	1873.5
21	1	2828.8	2559.8	2772.2	2629.7	2672.0	2931.0	2911.9	2919.7	3017.2	2528.6	2895.5
	2	2697.9	2700.1	2698.7	2790.5	2605.9	2874.5	2967.9	3008.3	3062.5	2446.5	2552.5
22	1	2669.1	2683.9	2616.9	2766.1	2522.2	2935.9	2877.8	2937.8	2505.8	2382.5	1752.1
	2	2820.9	2659.1	2746.9	2847.2	2734.6	2891.6	2940.1	2886.1	2851.6	2288.4	3002.5
23	1	2692.7	2821.0	2565.3	2697.7	2670.9	2893.9	2899.4	2942.2	3036.0	2046.4	2026.8
	2	2602.3	2727.1	2707.7	2595.0	2676.8	2969.2	2923.2	3075.5	2888.6	2101.5	1861.6
24	1	2646.2	2707.5	2690.7	2765.3	2807.7	2943.9	2961.7	2920.3	3130.9	2462.9	3144.0
	2	2763.1	2799.4	2576.1	2738.9	2718.3	2948.9	2912.6	2939.3	3034.1	2614.0	3048.4
25	1	2686.2	2732.2	2647.1	2865.8	2643.8	2795.0	2879.3	2916.6	2896.7	2346.2	2945.6
	2	2702.9	2812.7	2753.4	2744.2	2608.5	2941.6	2851.6	2984.7	2755.5	2638.9	3349.7
26	1	2587.0	2768.3	2649.1	2653.5	2617.0	2981.3	2742.3	2869.0	2959.7	2180.8	1932.0
	2	2623.7	2687.2	2630.7	2694.7	2528.7	2945.5	2862.5	2942.9	2884.8	2475.5	1888.8
27	1	2678.0	2637.6	2596.5	2662.0	2627.8	2886.7	2727.4	2852.0	2519.0	1984.0	1782.6
	2	2672.0	2815.7	2770.1	2664.2	2580.4	2889.5	2887.8	2912.2	2596.0	2148.1	2221.4
28	1	2662.9	2685.1	2577.0	2633.7	2608.5	2896.5	2920.3	2922.8	2799.1	2424.2	3212.9
	2	2675.4	2609.9	2563.4	2738.9	2642.7	2957.2	2840.1	3024.1	2914.6	2359.2	2785.2
29	1	2750.0	2630.8	2779.0	2665.8	2828.8	2964.4	2966.7	3012.2	3039.3	2490.2	3064.0
	2	2707.9	2697.8	2673.5	2607.3	2728.3	3002.3	3018.0	3087.2	2982.8	2641.3	2625.5

Granite		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	2740.5	2823.7	3343.8	3301.6	3261.3	3288.7	3432.4	3396.6	3215.6	3068.5	2266.4
	2	2751.9	2889.6	3191.3	3225.9	3106.5	3391.0	3335.6	3457.5	3375.7	3017.6	2677.1
2	1	2815.5	2913.1	3270.8	3228.2	3086.6	3367.7	3370.2	3488.5	3404.7	2975.0	2525.3
	2	2728.3	3000.4	3322.3	3245.4	3114.2	3429.3	3409.1	3427.1	3371.0	3276.9	2366.3
3	1	2848.5	2914.9	3143.1	3283.8	3127.0	3281.1	3468.5	3402.2	3278.9	3103.6	3127.0
	2	2772.8	2943.2	3229.9	3249.8	3170.7	3332.2	3379.4	3401.7	3245.5	3227.9	2908.6
4	1	2720.5	2933.0	3322.6	3427.0	3183.9	3300.0	3394.1	3588.0	3409.2	3077.2	2666.4
	2	2791.0	2975.4	3286.6	3380.0	3115.9	3274.8	3408.3	3537.9	3432.5	3098.0	3174.9
5	1	2984.5	3308.7	3231.7	3194.4	3066.0	3284.1	3358.5	3965.3	4090.7	3668.5	3323.1
	2	2917.6	2996.5	3136.2	3368.6	3030.6	3361.9	3438.4	3754.3	4087.0	3224.4	3467.2
6	1	2982.2	2995.5	3140.3	3123.7	3137.8	3285.0	3465.7	3335.8	3208.5	3214.2	3338.9
	2	3021.1	3015.8	3183.4	3130.2	3004.5	3297.3	3508.0	3365.0	3235.2	3256.3	2694.6
7	1	2851.2	2996.4	3080.5	3120.8	2928.7	3422.9	3409.2	3320.9	3252.2	3144.9	2836.4
	2	2958.8	2962.4	3048.1	3100.5	3019.0	3263.4	3570.3	3304.5	3287.2	3425.5	3550.4
8	1	2867.4	2935.9	3139.3	3245.1	2982.8	3449.4	3396.8	3329.3	3170.0	3141.1	2776.9
	2	2871.5	2967.9	3154.3	3504.7	3053.0	3368.3	3455.6	3298.4	3165.9	3189.3	3337.8
9	1	2892.1	2890.2	3067.9	3203.9	3100.3	3389.9	3325.9	3525.9	3686.5	3367.5	3017.5
	2	2860.4	3019.0	3142.4	3163.8	3058.9	3331.0	3334.7	3503.7	3551.9	3127.5	3173.6
10	1	2832.1	2926.0	3192.6	3150.6	3183.0	3275.8	3444.1	3443.1	3368.0	3102.6	2942.8
	2	2849.7	2876.2	2983.1	3049.1	3121.2	3189.1	3307.2	3371.3	3512.9	3102.6	2870.5
11	1	2930.0	2955.5	3148.0	3162.9	3006.1	3410.5	3379.4	3397.7	3642.6	3039.1	3065.9
	2	2988.7	2889.7	3134.7	3114.0	3147.8	3289.0	3436.3	3541.3	3477.6	2898.8	2283.0
12	1	2968.9	2912.9	3124.2	3014.8	3184.6	3249.5	3356.5	3437.9	3397.7	2650.2	2474.1
	2	2931.7	2978.8	3105.3	3012.7	3158.3	3253.7	3296.3	3512.9	3329.7	2042.7	1285.7
13	1	2885.2	2901.2	3181.9	3269.6	3063.7	3320.3	3415.7	3443.1	3681.5	3158.3	2453.0
	2	2900.8	2926.0	3201.2	3257.7	3120.1	3300.9	3379.0	3526.4	3604.2	3072.0	3297.1
14	1	3014.1	2927.9	3118.7	3244.5	3138.2	3367.3	3472.8	3392.4	3458.3	3295.6	3470.3
	2	2873.1	2870.2	3112.4	3242.6	3136.5	3251.1	3325.9	3430.1	3490.6	3450.7	3101.6
15	1	2973.0	3087.7	3121.6	3166.8	2937.5	3477.7	3473.9	3498.6	3371.9	2958.1	3059.0

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Granite		Angularity										
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	2913.7	3025.9	3202.3	3229.6	2903.9	3247.2	3230.1	3611.8	3436.9	2802.6	2752.8
16	1	2928.3	2965.0	3051.7	3217.7	2753.9	3339.6	3557.1	3372.7	3403.9	3403.2	2797.7
	2	2851.1	3055.2	3063.8	3360.1	2960.3	3328.1	3386.5	3344.5	3332.3	3108.3	2305.5
17	1	3026.0	2924.6	3018.9	3295.3	2921.2	3229.9	3331.3	3074.4	3332.1	3324.0	2763.3
	2	2865.4	2983.8	3085.6	3250.4	2968.5	3327.8	3512.6	3527.6	3402.2	3454.1	2794.4
18	1	2869.0	3017.8	3055.1	3207.0	3037.2	3231.5	3446.9	3539.1	3359.1	2929.9	2464.5
	2	2851.8	2970.1	3190.2	3224.8	2918.9	3367.7	3243.8	3356.8	2967.0	2993.8	2378.7
19	1	2935.3	2968.9	3049.5	3111.3	3086.4	3352.0	3409.0	3484.9	3363.0	3195.6	2478.7
	2	3007.4	3014.2	2995.8	3281.8	2904.5	3271.4	3344.9	3430.7	3468.8	3240.2	2949.3
20	1	3019.2	2934.4	2962.6	3088.5	3024.8	3325.4	3341.0	3426.0	3395.5	3052.6	2454.8
	2	2864.9	2854.1	2973.5	3107.6	2963.8	3335.3	3386.0	3507.6	3340.9	3011.2	2548.1
21	1	2973.2	2958.6	3035.5	3116.8	3045.1	3504.3	3277.0	3427.0	3298.3	3289.0	2750.1
	2	2921.6	2995.7	3009.0	3234.2	3122.5	3365.4	3478.7	3356.5	3424.8	3265.6	2807.0
22	1	2962.2	3171.9	3027.1	2967.1	3054.1	3325.6	3307.2	3319.9	3252.2	3108.3	2244.3
	2	3030.4	2891.8	2974.8	3096.1	3140.9	3298.3	3433.7	3317.2	3205.0	3171.1	3082.8
23	1	2989.9	3142.9	3056.5	3106.9	3126.0	3381.6	3392.9	3486.1	3437.6	3310.4	2665.6
	2	2969.7	3080.6	3091.4	3182.7	3171.0	3439.6	3351.7	3470.7	3458.1	3147.8	2717.6
24	1	2950.2	3035.3	3022.6	3198.4	3078.3	3402.5	3428.9	3278.2	4017.5	3349.4	3122.4
	2	2990.5	3115.7	3105.4	3165.9	3128.9	3322.0	3286.6	3474.8	3962.3	3384.2	3440.4
25	1	2863.2	3108.2	3010.2	3110.3	2904.8	3307.6	3111.8	3240.6	3178.6	3328.5	3221.7
	2	3030.5	2926.4	3108.9	3169.4	3240.6	3166.9	3256.8	3393.8	3144.7	3148.7	2328.3
26	1	2853.0	3183.3	3173.5	3222.8	2933.3	3406.7	3298.4	3343.6	3242.5	2965.0	2298.2
	2	2873.9	3146.3	3067.2	3188.2	3123.7	3292.4	3269.1	3324.6	3250.4	2896.2	3197.8
27	1	2825.9	2968.3	3092.5	3105.5	3028.4	3312.3	3356.8	3049.8	3459.6	2673.1	1957.8
	2	2857.1	3105.7	3048.6	3126.3	2951.8	3315.3	3312.7	3357.1	3763.5	2775.3	1850.1
28	1	2828.9	3048.9	3062.4	3067.8	2975.0	3396.2	3235.0	3260.2	3734.5	3109.7	2967.8
	2	2874.1	3143.8	3055.9	3139.8	3120.1	3324.1	3171.9	3442.2	3896.9	3360.5	3090.9
29	1	2873.0	2841.5	3138.7	3251.6	2963.7	3454.8	3288.5	3642.0	3650.0	3451.5	2595.7
	2	2957.1	2870.0	3238.3	3211.8	3079.6	3331.1	3446.2	3319.6	3310.6	3345.5	2663.9

Gravel

Laboratory	Scan #	Texture 25.0 (1.0")	Texture 19.0 (3/4")	Texture 12.5 (1/2")	Texture 9.5 (3/8")	Texture 4.75 (#4)	Sphericity 25.0 (1.0")	Sphericity 19.0 (3/4")	Sphericity 12.5 (1/2")	Sphericity 9.5 (3/8")	Sphericity 4.75 (#4)
1	1	205.9	269.9	209.3	236.8	201.3	0.76	0.72	0.69	0.68	0.71
	2	207.2	266.7	218.6	226.4	219.9	0.77	0.71	0.69	0.68	0.71
2	1	201.0	252.9	226.1	244.3	197.9	0.75	0.71	0.69	0.70	0.70
	2	221.0	240.3	220.5	237.8	222.5	0.76	0.71	0.69	0.68	0.72
3	1	210.9	239.2	235.7	242.7	189.3	0.76	0.71	0.69	0.69	0.72
	2	215.4	264.1	242.6	215.0	202.4	0.75	0.71	0.69	0.68	0.70
4	1	221.1	229.5	243.5	234.9	198.6	0.74	0.72	0.68	0.68	0.69
	2	230.7	227.9	206.8	236.7	214.4	0.77	0.71	0.69	0.69	0.70
5	1	196.6	264.1	245.3	204.5	153.2	0.74	0.75	0.68	0.67	0.66
	2	195.2	284.3	202.6	209.6	168.2	0.74	0.73	0.69	0.68	0.65
6	1	211.7	275.5	219.8	218.7	155.5	0.74	0.75	0.68	0.67	0.66
	2	211.2	295.7	220.4	231.8	171.1	0.74	0.73	0.67	0.68	0.67
7	1	207.7	256.5	227.8	218.4	169.8	0.72	0.75	0.68	0.69	0.68
	2	203.8	265.5	221.8	219.2	152.8	0.75	0.74	0.68	0.68	0.68
8	1	208.8	272.3	230.4	222.2	180.6	0.75	0.75	0.67	0.67	0.67
	2	215.2	284.7	217.0	218.2	163.0	0.74	0.74	0.67	0.68	0.68
9	1	232.9	248.4	236.8	257.9	176.6	0.76	0.70	0.69	0.68	0.72
	2	231.6	209.4	243.2	226.9	166.1	0.76	0.69	0.71	0.70	0.70
10	1	249.4	226.7	232.7	241.0	171.4	0.75	0.70	0.71	0.71	0.70
	2	235.6	259.8	223.7	222.9	155.1	0.76	0.71	0.70	0.69	0.71
11	1	213.3	226.2	229.8	241.6	174.6	0.75	0.70	0.69	0.69	0.70
	2	224.4	224.2	236.5	239.5	164.8	0.76	0.69	0.71	0.70	0.73
12	1	225.8	199.2	222.3	235.9	150.8	0.75	0.70	0.71	0.70	0.71
	2	219.9	230.5	216.3	203.9	151.9	0.76	0.70	0.71	0.69	0.70
13	1	219.7	248.0	200.2	233.2	209.0	0.73	0.73	0.69	0.67	0.75
	2	230.9	260.2	216.5	209.8	191.8	0.73	0.73	0.69	0.67	0.73
14	1	224.6	255.7	224.4	200.1	177.0	0.74	0.73	0.69	0.68	0.71
	2	235.1	227.6	233.6	204.9	180.8	0.75	0.72	0.68	0.69	0.72
15	1	220.8	275.8	236.5	249.9	183.5	0.71	0.74	0.69	0.68	0.68

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Gravel		Texture					Sphericity				
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)
	2	210.2	271.9	233.4	214.5	182.9	0.72	0.73	0.68	0.68	0.69
16	1	229.1	246.0	243.5	231.6	165.3	0.71	0.73	0.68	0.67	0.67
	2	227.1	265.7	243.3	233.9	180.4	0.71	0.75	0.69	0.66	0.68
17	1	241.9	250.1	229.4	229.3	170.3	0.71	0.74	0.69	0.65	0.70
	2	213.7	243.8	232.0	215.0	162.2	0.72	0.73	0.67	0.66	0.68
18	1	202.1	277.6	221.1	223.0	160.6	0.73	0.74	0.68	0.67	0.68
	2	209.1	247.1	232.8	225.5	130.6	0.72	0.75	0.68	0.67	0.68
19	1	223.4	249.8	257.6	211.3	182.4	0.73	0.74	0.71	0.69	0.69
	2	236.3	277.2	235.8	201.7	183.8	0.74	0.75	0.71	0.69	0.68
20	1	231.4	257.3	229.0	200.8	197.4	0.74	0.73	0.71	0.68	0.69
	2	241.2	258.5	219.6	212.6	190.0	0.72	0.74	0.72	0.69	0.69
21	1	217.8	227.5	257.0	196.3	189.0	0.72	0.74	0.72	0.69	0.68
	2	221.9	257.1	262.7	198.6	185.6	0.71	0.73	0.70	0.69	0.68
22	1	238.3	246.6	244.7	262.6	200.9	0.75	0.72	0.68	0.68	0.69
	2	236.4	254.8	273.4	257.2	189.6	0.76	0.73	0.68	0.68	0.70
23	1	251.0	222.5	234.6	262.4	185.6	0.75	0.70	0.68	0.67	0.70
	2	243.7	255.5	271.5	264.7	218.1	0.75	0.71	0.68	0.68	0.69
24	1	250.2	245.8	235.7	244.2	198.5	0.76	0.72	0.69	0.68	0.69
	2	256.1	236.4	238.2	252.8	199.6	0.76	0.73	0.68	0.68	0.70
25	1	227.6	235.0	274.7	240.6	196.3	0.78	0.73	0.69	0.69	0.73
	2	258.5	234.4	253.3	227.0	195.2	0.78	0.73	0.69	0.67	0.71
26	1	235.7	231.0	242.5	251.9	169.8	0.76	0.71	0.69	0.66	0.70
	2	215.0	265.1	241.1	218.8	187.6	0.75	0.71	0.71	0.68	0.71
27	1	235.9	228.3	243.8	220.3	194.7	0.76	0.72	0.70	0.66	0.73
	2	250.9	251.5	234.8	236.4	177.3	0.73	0.72	0.71	0.67	0.72
28	1	230.3	232.1	243.8	236.9	179.9	0.75	0.71	0.70	0.67	0.68
	2	217.2	255.3	220.7	251.1	175.9	0.75	0.73	0.70	0.67	0.70
29	1	233.6	242.1	211.8	182.1	189.5	0.75	0.72	0.69	0.67	0.72
	2	217.3	240.8	247.0	209.7	186.4	0.75	0.73	0.70	0.68	0.73

Limestone

Laboratory	Scan #	Texture 25.0 (1.0")	Texture 19.0 (3/4")	Texture 12.5 (1/2")	Texture 9.5 (3/8")	Texture 4.75 (#4)	Sphericity 25.0 (1.0")	Sphericity 19.0 (3/4")	Sphericity 12.5 (1/2")	Sphericity 9.5 (3/8")	Sphericity 4.75 (#4)
1	1	300.0	278.5	267.2	221.7	132.4	0.72	0.66	0.68	0.69	0.65
	2	321.2	261.8	260.6	206.4	131.3	0.72	0.68	0.66	0.68	0.65
2	1	275.7	250.1	262.6	207.7	121.0	0.73	0.67	0.67	0.69	0.67
	2	280.3	268.2	252.3	228.4	121.0	0.71	0.66	0.66	0.69	0.68
3	1	297.9	254.0	262.8	221.8	131.6	0.72	0.66	0.68	0.70	0.68
	2	282.9	256.6	277.3	224.2	131.2	0.72	0.66	0.68	0.68	0.67
4	1	277.9	286.3	263.7	216.0	123.8	0.72	0.66	0.65	0.69	0.65
	2	249.6	247.9	270.8	205.8	129.8	0.72	0.66	0.67	0.69	0.64
5	1	279.6	280.3	272.2	244.6	157.1	0.72	0.67	0.65	0.66	0.68
	2	271.0	280.5	273.9	235.9	148.8	0.72	0.69	0.67	0.67	0.66
6	1	293.5	279.8	261.9	242.2	158.1	0.73	0.70	0.67	0.67	0.65
	2	256.6	283.7	265.6	242.9	155.6	0.72	0.70	0.67	0.68	0.65
7	1	274.1	261.6	253.8	244.4	149.4	0.72	0.70	0.66	0.67	0.66
	2	292.5	265.6	266.3	256.4	140.3	0.72	0.70	0.66	0.68	0.67
8	1	282.3	285.9	300.5	241.3	136.9	0.73	0.69	0.65	0.67	0.65
	2	276.5	268.9	268.5	253.9	136.2	0.73	0.70	0.66	0.67	0.65
9	1	258.7	278.5	243.9	216.4	139.1	0.73	0.68	0.67	0.71	0.65
	2	254.6	293.9	249.0	221.3	148.4	0.72	0.67	0.68	0.70	0.65
10	1	265.6	272.9	239.8	211.6	140.1	0.74	0.68	0.68	0.70	0.64
	2	247.4	280.9	261.5	208.6	123.4	0.72	0.68	0.67	0.71	0.64
11	1	279.7	293.5	257.2	236.4	126.3	0.73	0.69	0.67	0.70	0.67
	2	266.6	283.0	255.1	217.2	132.2	0.73	0.69	0.67	0.70	0.65
12	1	253.0	265.7	246.2	207.7	132.2	0.72	0.69	0.67	0.70	0.66
	2	245.9	258.3	236.7	216.3	132.9	0.73	0.68	0.67	0.70	0.64
13	1	249.7	241.4	278.8	230.8	128.8	0.71	0.68	0.69	0.69	0.67
	2	258.1	236.3	263.5	230.9	137.5	0.71	0.69	0.68	0.69	0.67
14	1	256.8	249.1	252.3	224.0	128.8	0.71	0.70	0.69	0.69	0.67
	2	245.2	250.5	259.7	232.3	124.7	0.71	0.68	0.69	0.69	0.68
15	1	281.7	283.8	265.5	212.9	137.9	0.70	0.65	0.69	0.69	0.66

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Limestone		Texture					Sphericity				
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)
	2	294.1	275.9	274.5	209.2	126.6	0.70	0.66	0.68	0.68	0.65
16	1	292.5	283.1	260.5	221.0	134.0	0.70	0.65	0.67	0.67	0.64
	2	279.6	277.3	239.2	222.8	134.6	0.69	0.65	0.69	0.68	0.65
17	1	312.2	282.9	255.5	220.8	122.8	0.69	0.66	0.68	0.67	0.65
	2	292.8	295.0	258.2	214.4	126.5	0.69	0.66	0.68	0.69	0.66
18	1	272.7	262.4	233.5	212.5	131.9	0.69	0.67	0.65	0.68	0.67
	2	264.6	268.5	223.2	203.1	131.0	0.70	0.66	0.67	0.69	0.65
19	1	301.9	280.0	274.2	206.3	168.9	0.70	0.71	0.69	0.65	0.66
	2	291.6	279.1	289.8	230.0	146.5	0.71	0.72	0.69	0.66	0.67
20	1	266.1	305.9	257.1	241.8	158.8	0.72	0.71	0.69	0.67	0.67
	2	264.1	292.3	246.3	219.9	156.2	0.71	0.71	0.68	0.66	0.66
21	1	263.4	254.2	265.0	230.6	149.5	0.69	0.70	0.68	0.69	0.67
	2	285.4	253.9	251.5	205.5	145.9	0.70	0.70	0.68	0.66	0.66
22	1	267.2	253.5	238.4	230.3	137.9	0.73	0.68	0.70	0.70	0.69
	2	293.6	260.2	262.7	241.1	130.4	0.73	0.67	0.69	0.70	0.68
23	1	283.6	259.0	229.0	219.7	134.4	0.72	0.66	0.69	0.68	0.68
	2	303.9	262.5	258.9	253.3	142.3	0.73	0.67	0.69	0.68	0.66
24	1	302.6	264.4	250.7	251.3	128.8	0.73	0.68	0.68	0.67	0.70
	2	277.0	267.1	255.2	235.6	131.6	0.75	0.68	0.69	0.68	0.68
25	1	270.9	255.4	245.4	237.9	139.1	0.76	0.69	0.70	0.67	0.69
	2	277.5	246.2	253.6	226.4	129.1	0.75	0.70	0.70	0.67	0.70
26	1	291.0	270.0	257.2	217.5	144.5	0.71	0.68	0.69	0.67	0.65
	2	282.5	273.6	239.0	221.2	139.9	0.70	0.68	0.70	0.67	0.67
27	1	279.8	278.2	237.4	228.0	138.8	0.71	0.68	0.70	0.69	0.71
	2	255.5	251.5	236.6	227.2	140.0	0.71	0.68	0.71	0.68	0.67
28	1	263.2	251.9	264.2	216.1	134.9	0.72	0.68	0.72	0.68	0.65
	2	283.5	273.7	260.4	226.7	140.6	0.71	0.70	0.69	0.68	0.64
29	1	244.0	243.7	267.1	222.2	124.4	0.73	0.69	0.68	0.68	0.67
	2	241.2	257.1	247.3	233.9	132.4	0.72	0.69	0.68	0.68	0.69

Granite		Texture					Sphericity				
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)
1	1	493.3	474.7	485.3	460.4	375.6	0.71	0.66	0.61	0.61	0.66
	2	484.7	457.9	456.5	444.9	350.3	0.71	0.65	0.62	0.59	0.66
2	1	470.5	456.2	470.7	439.3	354.8	0.70	0.65	0.63	0.61	0.68
	2	471.6	459.1	473.6	449.0	351.6	0.71	0.64	0.62	0.60	0.69
3	1	462.8	466.2	473.4	443.7	347.6	0.69	0.64	0.63	0.59	0.70
	2	465.3	452.0	473.4	446.5	356.8	0.70	0.64	0.61	0.60	0.66
4	1	477.7	446.5	443.8	458.7	335.8	0.69	0.65	0.61	0.60	0.66
	2	453.3	473.2	458.6	446.7	368.4	0.70	0.66	0.62	0.61	0.65
5	1	472.6	482.0	474.0	451.3	316.9	0.69	0.64	0.62	0.62	0.69
	2	475.9	477.9	508.7	437.5	338.4	0.70	0.65	0.62	0.61	0.68
6	1	482.2	506.4	490.2	460.9	340.1	0.69	0.66	0.62	0.63	0.68
	2	475.9	518.3	486.1	456.6	347.8	0.69	0.67	0.63	0.64	0.68
7	1	465.4	483.8	481.5	451.1	348.4	0.68	0.67	0.62	0.61	0.69
	2	469.4	476.1	496.6	460.2	351.1	0.69	0.68	0.62	0.63	0.69
8	1	460.3	507.5	476.7	470.4	327.8	0.68	0.66	0.61	0.61	0.65
	2	463.1	507.1	467.1	449.3	347.6	0.69	0.67	0.63	0.63	0.67
9	1	471.0	474.4	451.7	473.1	297.9	0.69	0.62	0.64	0.63	0.68
	2	449.9	474.7	454.1	442.1	341.3	0.68	0.63	0.63	0.64	0.67
10	1	439.4	488.2	460.6	458.9	302.0	0.69	0.62	0.63	0.63	0.67
	2	475.3	493.1	451.3	447.9	342.6	0.69	0.62	0.64	0.64	0.68
11	1	475.0	467.1	462.6	443.5	331.5	0.69	0.61	0.64	0.64	0.68
	2	480.2	491.7	463.0	436.4	327.7	0.70	0.62	0.64	0.63	0.68
12	1	454.2	483.8	448.9	452.0	320.4	0.69	0.61	0.62	0.64	0.70
	2	453.4	492.2	458.4	433.7	348.1	0.70	0.62	0.64	0.63	0.67
13	1	484.7	502.4	474.3	445.1	370.5	0.67	0.62	0.63	0.61	0.67
	2	479.2	488.6	454.6	440.3	346.8	0.66	0.63	0.63	0.61	0.69
14	1	468.0	494.7	457.4	441.9	350.0	0.67	0.61	0.63	0.63	0.68
	2	488.8	508.5	473.6	444.8	367.1	0.66	0.62	0.64	0.63	0.70
15	1	497.5	451.5	445.5	494.0	359.0	0.65	0.63	0.61	0.61	0.67

Continued next page

Granite		Texture					Sphericity				
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)
	2	484.1	471.3	439.8	468.4	350.7	0.65	0.63	0.59	0.60	0.65
16	1	471.5	448.1	440.9	497.6	348.2	0.64	0.63	0.60	0.61	0.66
	2	478.8	444.5	440.0	481.5	360.7	0.65	0.63	0.62	0.59	0.66
17	1	479.5	441.5	454.8	484.0	340.7	0.63	0.63	0.59	0.61	0.64
	2	491.4	455.6	433.0	490.6	337.8	0.64	0.64	0.60	0.60	0.67
18	1	505.9	456.4	442.0	474.5	331.3	0.66	0.65	0.60	0.61	0.67
	2	481.6	435.5	441.3	469.7	348.7	0.66	0.64	0.61	0.61	0.68
19	1	461.7	484.5	471.4	501.5	359.2	0.66	0.65	0.62	0.62	0.68
	2	475.0	474.8	458.7	499.5	362.0	0.66	0.65	0.62	0.64	0.68
20	1	456.1	488.3	495.8	471.4	367.3	0.66	0.63	0.61	0.62	0.68
	2	460.7	476.0	476.9	453.0	363.6	0.66	0.64	0.60	0.62	0.66
21	1	431.4	470.6	454.8	492.3	352.4	0.64	0.64	0.60	0.62	0.65
	2	443.2	464.9	461.9	468.6	355.4	0.65	0.63	0.61	0.62	0.67
22	1	477.0	480.1	460.9	476.6	345.1	0.67	0.65	0.63	0.64	0.69
	2	456.7	478.6	504.7	480.9	377.3	0.68	0.65	0.63	0.64	0.68
23	1	496.9	490.8	477.6	499.7	400.7	0.66	0.63	0.63	0.65	0.69
	2	481.6	484.3	490.7	509.5	384.6	0.66	0.62	0.62	0.64	0.69
24	1	487.9	472.0	500.6	519.6	374.2	0.68	0.64	0.63	0.62	0.69
	2	467.3	476.1	460.3	492.5	376.1	0.67	0.65	0.62	0.62	0.69
25	1	457.0	474.1	487.1	486.0	382.7	0.69	0.67	0.62	0.63	0.72
	2	443.6	477.5	495.1	480.7	380.6	0.69	0.67	0.63	0.64	0.71
26	1	472.5	480.8	479.2	460.2	331.7	0.67	0.62	0.61	0.61	0.67
	2	474.2	476.6	461.3	454.8	320.5	0.68	0.62	0.61	0.61	0.69
27	1	482.9	477.2	447.9	447.3	330.0	0.68	0.61	0.61	0.72	0.70
	2	469.0	470.0	432.0	454.8	319.9	0.69	0.61	0.62	0.62	0.71
28	1	493.6	487.5	451.9	447.6	305.7	0.69	0.63	0.63	0.61	0.67
	2	489.3	486.7	458.5	454.0	334.7	0.68	0.62	0.62	0.61	0.67
29	1	461.0	480.4	455.5	430.5	342.5	0.68	0.62	0.62	0.61	0.67
	2	469.9	475.8	425.1	436.1	375.2	0.68	0.62	0.62	0.62	0.68

Gravel		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	100.0%	100.0%	100.0%	100.0%	95.8%	6.4	7.5	8.0	7.2	7.3	8.1
	2	100.0%	100.0%	95.9%	98.0%	95.8%	6.6	7.3	8.2	6.9	7.7	8.1
2	1	100.0%	100.0%	98.0%	100.0%	95.8%	6.7	7.5	7.9	7.6	7.5	8.4
	2	100.0%	100.0%	97.9%	100.0%	98.0%	6.7	7.3	8.0	7.5	7.5	8.2
3	1	100.0%	100.0%	100.0%	100.0%	100.0%	6.6	7.7	7.9	7.7	7.3	8.5
	2	100.0%	100.0%	98.0%	98.0%	95.7%	6.8	7.3	8.0	7.4	7.3	8.6
4	1	100.0%	100.0%	98.0%	95.9%	89.6%	6.8	7.5	7.8	7.6	7.7	9.0
	2	100.0%	100.0%	98.0%	100.0%	95.9%	6.8	7.4	7.7	7.5	7.3	8.2
5	1	100.0%	100.0%	100.0%	96.0%	91.7%	6.7	7.8	8.2	7.5	7.5	8.9
	2	100.0%	100.0%	100.0%	98.0%	91.7%	7.2	7.6	8.0	7.3	7.2	9.4
6	1	98.0%	100.0%	100.0%	96.0%	93.8%	6.9	7.5	7.8	7.6	7.7	8.2
	2	100.0%	100.0%	100.0%	96.0%	100.0%	6.6	7.4	7.9	7.8	7.4	8.3
7	1	100.0%	100.0%	100.0%	98.0%	95.8%	6.7	7.7	8.0	7.8	7.3	8.9
	2	100.0%	100.0%	100.0%	100.0%	100.0%	6.7	7.5	7.5	7.3	7.6	9.0
8	1	100.0%	100.0%	100.0%	98.0%	97.9%	6.9	7.4	8.0	7.3	7.2	8.4
	2	100.0%	100.0%	100.0%	96.0%	100.0%	6.6	7.7	7.5	8.0	7.6	8.6
9	1	100.0%	98.0%	100.0%	100.0%	97.9%	6.6	7.4	7.7	7.4	7.2	8.0
	2	100.0%	100.0%	100.0%	98.0%	98.0%	6.6	7.3	7.8	7.4	7.2	9.5
10	1	100.0%	100.0%	100.0%	100.0%	97.8%	6.6	7.4	7.8	7.8	7.6	9.0
	2	100.0%	100.0%	100.0%	98.0%	97.9%	6.8	7.2	8.0	7.6	7.7	8.6
11	1	100.0%	98.0%	100.0%	98.0%	91.1%	6.6	7.4	8.0	7.7	6.5	7.6
	2	100.0%	100.0%	100.0%	100.0%	97.9%	6.4	7.7	7.9	7.6	7.3	8.1
12	1	100.0%	100.0%	100.0%	100.0%	95.7%	6.4	7.3	7.6	7.7	7.6	8.2
	2	100.0%	100.0%	100.0%	98.0%	95.7%	6.8	7.7	7.9	8.0	7.8	8.3
13	1	100.0%	98.0%	100.0%	98.0%	100.0%	6.4	7.3	7.8	8.1	7.4	9.3
	2	98.0%	96.0%	100.0%	96.0%	95.8%	6.7	7.4	7.9	7.9	7.2	8.0
14	1	100.0%	100.0%	98.0%	98.0%	100.0%	6.9	7.3	7.5	7.5	7.5	7.8
	2	100.0%	98.0%	98.0%	100.0%	97.9%	6.5	7.6	8.0	7.3	7.5	8.3
15	1	94.0%	100.0%	95.9%	91.7%	89.6%	6.8	7.8	7.9	7.7	7.4	7.8

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Gravel		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	98.0%	100.0%	95.9%	87.8%	93.6%	6.4	7.6	7.7	7.6	7.4	8.6
16	1	94.0%	100.0%	93.9%	88.0%	91.1%	6.9	7.3	7.9	7.4	7.6	8.6
	2	96.0%	100.0%	96.0%	84.0%	91.8%	6.8	7.3	7.8	7.9	7.3	8.6
17	1	94.0%	100.0%	96.0%	83.7%	91.8%	6.6	7.6	7.8	8.2	7.9	9.7
	2	95.9%	100.0%	96.0%	83.7%	91.8%	6.9	7.7	8.1	8.1	7.3	9.1
18	1	98.0%	100.0%	95.8%	81.6%	91.8%	6.6	7.6	7.7	8.0	7.7	7.9
	2	95.9%	100.0%	96.0%	95.9%	93.5%	7.0	7.5	7.8	7.6	7.3	8.1
19	1	100.0%	98.0%	100.0%	98.0%	100.0%	6.7	7.7	7.6	7.4	7.4	8.0
	2	100.0%	100.0%	98.0%	95.9%	100.0%	6.7	7.4	7.6	7.3	7.3	8.7
20	1	100.0%	100.0%	98.0%	98.0%	100.0%	6.8	7.4	8.1	7.5	7.4	8.6
	2	100.0%	100.0%	100.0%	98.0%	100.0%	6.6	7.5	7.8	7.9	7.2	8.7
21	1	100.0%	100.0%	100.0%	100.0%	100.0%	6.7	7.2	7.6	8.2	7.5	8.1
	2	100.0%	100.0%	96.0%	98.0%	100.0%	6.6	7.4	7.8	7.6	7.5	8.9
22	1	100.0%	100.0%	100.0%	98.0%	95.9%	6.7	7.4	7.7	7.8	7.9	8.2
	2	100.0%	98.0%	100.0%	93.9%	100.0%	6.5	7.2	8.1	7.5	7.9	8.3
23	1	100.0%	96.0%	100.0%	98.0%	98.0%	6.3	7.6	7.9	7.4	6.9	8.3
	2	100.0%	98.0%	100.0%	94.0%	95.8%	6.3	7.2	7.8	7.4	7.1	7.8
24	1	100.0%	96.0%	98.0%	92.0%	98.0%	6.9	7.1	7.9	7.6	7.3	8.9
	2	100.0%	98.0%	100.0%	94.0%	100.0%	6.8	7.2	7.7	7.9	7.5	8.8
25	1	100.0%	98.0%	100.0%	96.0%	100.0%	6.6	7.3	7.5	7.9	7.7	8.2
	2	100.0%	98.0%	100.0%	96.0%	100.0%	6.5	7.0	7.2	8.2	7.1	8.1
26	1	100.0%	100.0%	100.0%	93.9%	97.9%	6.7	7.2	7.7	7.6	7.5	8.3
	2	100.0%	95.9%	100.0%	95.9%	100.0%	6.7	7.5	7.7	7.4	7.9	8.8
27	1	100.0%	98.0%	98.0%	95.8%	100.0%	6.9	7.9	7.9	7.5	6.8	7.6
	2	100.0%	98.0%	100.0%	93.9%	100.0%	6.8	7.4	7.5	7.3	7.2	7.8
28	1	100.0%	98.0%	100.0%	95.9%	96.0%	6.7	7.5	7.8	7.3	7.5	8.8
	2	98.0%	100.0%	100.0%	96.0%	100.0%	6.9	7.2	7.4	7.6	7.5	9.1
29	1	100.0%	98.0%	100.0%	96.0%	98.0%	6.7	7.3	7.4	7.6	7.7	8.3
	2	100.0%	100.0%	100.0%	96.0%	98.0%	6.6	7.3	7.5	7.4	7.8	8.2

Limestone		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	98.0%	100.0%	98.0%	100.0%	90.0%	7.7	8.1	7.8	7.3	6.8	8.3
	2	100.0%	100.0%	98.0%	100.0%	92.0%	7.8	7.7	7.7	7.3	6.9	7.4
2	1	98.0%	100.0%	98.0%	100.0%	94.0%	7.3	7.6	7.6	7.2	6.9	8.3
	2	98.0%	100.0%	98.0%	100.0%	96.0%	7.4	7.4	7.5	7.1	7.3	8.7
3	1	100.0%	100.0%	100.0%	100.0%	98.0%	7.4	7.3	7.4	7.2	6.8	9.2
	2	98.0%	100.0%	100.0%	100.0%	94.0%	7.2	7.3	7.2	7.4	7.2	9.5
4	1	100.0%	98.0%	98.0%	100.0%	90.0%	7.2	7.3	7.5	7.1	7.0	8.1
	2	98.0%	100.0%	100.0%	100.0%	88.0%	7.1	7.3	7.2	7.0	7.0	9.3
5	1	100.0%	100.0%	100.0%	100.0%	95.9%	7.3	7.4	8.3	7.8	7.3	9.5
	2	100.0%	100.0%	100.0%	96.0%	95.7%	7.8	7.9	8.0	8.0	6.9	9.5
6	1	100.0%	100.0%	100.0%	100.0%	92.0%	7.2	7.3	7.6	7.4	7.1	9.0
	2	100.0%	100.0%	98.0%	98.0%	98.0%	7.4	7.5	7.7	7.3	6.8	9.7
7	1	100.0%	100.0%	96.0%	100.0%	96.0%	7.2	7.5	7.4	7.2	7.3	9.2
	2	100.0%	100.0%	100.0%	100.0%	98.0%	7.4	7.5	7.6	6.9	7.5	8.2
8	1	100.0%	100.0%	100.0%	100.0%	94.0%	7.1	7.4	7.5	6.9	6.9	9.3
	2	100.0%	100.0%	100.0%	100.0%	94.0%	7.3	8.0	7.3	7.2	7.0	9.7
9	1	100.0%	100.0%	100.0%	98.0%	96.0%	7.5	7.6	7.2	7.2	6.9	9.4
	2	100.0%	100.0%	100.0%	98.0%	96.0%	7.5	7.6	7.5	7.1	7.0	9.3
10	1	100.0%	100.0%	100.0%	98.0%	92.0%	7.5	7.4	7.5	7.1	7.1	8.9
	2	100.0%	98.0%	100.0%	98.0%	91.8%	7.5	7.6	7.5	7.3	7.3	8.4
11	1	100.0%	100.0%	100.0%	100.0%	98.0%	7.1	7.5	7.3	7.5	6.5	9.0
	2	100.0%	100.0%	98.0%	98.0%	94.0%	7.3	7.4	7.6	7.3	7.0	9.2
12	1	100.0%	100.0%	98.0%	98.0%	96.0%	7.2	7.3	7.3	7.2	7.0	8.1
	2	100.0%	100.0%	100.0%	98.0%	94.0%	7.5	7.8	7.5	7.5	7.4	8.8
13	1	100.0%	100.0%	96.0%	98.0%	98.0%	7.3	7.5	7.5	7.3	7.5	8.3
	2	98.0%	98.0%	98.0%	98.0%	94.0%	7.7	7.2	7.3	7.3	6.6	8.0
14	1	100.0%	100.0%	98.0%	100.0%	96.0%	7.2	7.4	7.2	7.2	7.0	9.4
	2	100.0%	100.0%	98.0%	100.0%	98.0%	7.4	7.5	7.3	7.0	7.7	9.5
15	1	96.0%	98.0%	100.0%	98.0%	93.9%	7.1	7.4	7.1	7.3	7.2	8.9

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Limestone		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	98.0%	100.0%	100.0%	92.0%	96.0%	7.3	7.5	7.3	7.2	7.4	9.2
16	1	100.0%	98.0%	98.0%	94.0%	86.0%	7.3	7.5	7.6	7.7	6.9	8.9
	2	96.0%	100.0%	100.0%	92.0%	92.0%	7.1	7.7	7.6	7.8	6.8	9.0
17	1	98.0%	100.0%	100.0%	92.0%	88.0%	7.7	7.5	7.3	7.0	7.0	9.8
	2	96.0%	100.0%	100.0%	94.0%	94.0%	7.3	7.6	7.5	7.7	7.4	9.4
18	1	98.0%	100.0%	96.0%	98.0%	98.0%	7.3	7.3	7.3	7.1	6.5	7.8
	2	100.0%	100.0%	100.0%	92.0%	90.0%	7.3	7.1	7.5	7.2	6.6	8.3
19	1	100.0%	100.0%	100.0%	98.0%	93.9%	6.8	6.9	7.6	7.2	7.0	9.3
	2	100.0%	100.0%	100.0%	96.0%	98.0%	7.1	7.3	7.3	6.9	6.8	8.9
20	1	100.0%	100.0%	100.0%	98.0%	93.9%	7.2	7.4	7.4	7.0	6.7	8.2
	2	100.0%	100.0%	100.0%	100.0%	96.0%	7.3	7.5	7.3	6.9	6.9	7.7
21	1	98.0%	100.0%	100.0%	98.0%	96.0%	7.3	7.4	7.5	7.6	7.0	8.9
	2	98.0%	98.0%	98.0%	98.0%	98.0%	7.1	7.7	7.5	7.3	7.2	8.6
22	1	100.0%	98.0%	100.0%	100.0%	100.0%	7.2	7.2	7.3	6.6	6.9	7.5
	2	100.0%	98.0%	100.0%	100.0%	96.0%	7.1	7.8	7.5	7.3	6.7	8.9
23	1	100.0%	98.0%	100.0%	94.0%	98.0%	7.2	7.3	7.2	7.2	6.3	8.6
	2	100.0%	100.0%	100.0%	96.0%	98.0%	7.4	7.3	7.6	7.3	6.5	8.1
24	1	100.0%	100.0%	100.0%	98.0%	98.0%	7.3	7.5	7.6	7.3	6.8	9.2
	2	100.0%	100.0%	100.0%	98.0%	98.0%	7.4	7.3	7.7	7.4	7.4	9.1
25	1	100.0%	100.0%	100.0%	100.0%	100.0%	7.5	7.7	7.3	7.0	7.0	8.5
	2	100.0%	100.0%	100.0%	97.9%	100.0%	7.2	7.2	7.3	7.1	7.1	9.6
26	1	98.0%	100.0%	95.9%	100.0%	94.0%	7.2	7.1	7.0	7.4	6.6	8.1
	2	98.0%	100.0%	98.0%	98.0%	98.0%	7.3	7.3	7.3	7.2	7.5	8.1
27	1	95.9%	100.0%	98.0%	98.0%	100.0%	6.9	7.0	7.0	6.6	6.6	7.9
	2	96.0%	100.0%	100.0%	100.0%	100.0%	7.1	7.4	7.4	6.7	7.0	8.5
28	1	98.0%	100.0%	100.0%	96.0%	98.0%	7.4	7.3	7.1	6.7	7.1	9.6
	2	98.0%	100.0%	96.0%	100.0%	94.0%	7.2	7.2	7.3	7.4	6.7	9.0
29	1	100.0%	100.0%	96.0%	94.0%	98.0%	7.1	7.5	7.6	7.1	7.4	9.2
	2	100.0%	100.0%	98.0%	95.9%	98.0%	7.7	7.7	7.4	7.3	7.0	8.5

Granite		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
1	1	96.0%	94.0%	98.0%	88.0%	89.8%	7.6	7.9	7.9	7.6	7.7	8.9
	2	95.9%	95.9%	91.8%	93.9%	96.0%	7.5	7.9	7.6	7.9	7.9	9.6
2	1	96.0%	96.0%	96.0%	94.0%	94.1%	7.7	7.7	7.9	7.8	7.7	9.1
	2	98.0%	94.0%	96.0%	90.0%	96.1%	7.8	7.9	8.2	7.9	8.1	9.4
3	1	91.8%	91.8%	93.9%	94.0%	98.0%	7.3	7.4	8.0	7.4	8.0	10.2
	2	96.0%	96.0%	93.9%	86.0%	94.0%	7.6	7.7	7.7	7.7	8.2	9.9
4	1	92.0%	96.0%	96.0%	86.0%	92.0%	7.7	7.8	8.2	7.8	7.7	9.2
	2	94.0%	93.9%	92.0%	90.0%	96.0%	7.7	7.6	7.9	8.1	7.9	10.0
5	1	94.0%	96.3%	90.0%	100.0%	91.8%	7.8	8.0	8.8	8.6	8.1	10.2
	2	95.9%	94.0%	84.0%	96.0%	93.9%	7.8	8.4	8.3	8.5	8.1	9.5
6	1	94.0%	96.0%	87.2%	98.0%	94.0%	7.9	7.9	7.8	7.7	7.7	10.1
	2	93.9%	96.0%	88.0%	100.0%	95.9%	7.7	7.9	7.9	7.6	8.2	9.4
7	1	94.0%	98.0%	88.0%	100.0%	100.0%	7.8	8.0	7.5	7.9	8.0	9.6
	2	93.9%	100.0%	87.8%	100.0%	94.0%	7.7	8.5	7.9	7.9	8.2	9.8
8	1	93.9%	98.0%	88.0%	100.0%	84.0%	8.0	7.9	8.0	7.8	7.9	9.6
	2	95.9%	98.0%	88.0%	100.0%	93.6%	8.0	8.1	7.7	7.8	7.8	9.5
9	1	91.8%	84.0%	91.8%	93.9%	86.0%	7.8	7.8	8.2	8.4	8.4	10.4
	2	94.0%	86.0%	90.0%	93.9%	92.0%	7.5	7.7	8.3	8.1	8.1	10.2
10	1	96.0%	84.0%	96.0%	90.0%	93.9%	7.6	7.6	8.1	7.8	7.9	9.9
	2	98.0%	88.0%	94.0%	91.8%	96.0%	7.4	7.4	8.0	7.9	8.1	9.8
11	1	96.0%	84.0%	93.9%	90.0%	92.0%	8.1	7.5	8.0	8.2	7.6	10.1
	2	96.0%	86.0%	95.9%	94.0%	94.0%	7.4	7.7	8.1	7.8	7.7	9.2
12	1	94.0%	84.0%	98.0%	94.0%	100.0%	7.6	7.6	8.1	8.2	7.4	9.5
	2	98.0%	89.8%	96.0%	90.0%	90.0%	7.5	7.8	8.3	8.2	7.1	7.4
13	1	89.8%	90.0%	94.0%	92.0%	97.9%	7.7	8.0	8.0	8.2	7.9	8.8
	2	94.0%	90.0%	92.0%	90.0%	96.0%	7.6	7.6	8.2	8.1	8.1	10.5
14	1	98.0%	93.9%	90.0%	98.0%	94.0%	7.7	7.9	8.0	7.8	8.1	9.9
	2	98.0%	89.8%	91.7%	98.0%	94.0%	7.7	7.6	7.7	7.8	8.1	9.8
15	1	81.6%	85.7%	94.0%	86.0%	93.8%	7.8	7.8	7.7	7.7	7.9	10.5

Continued next page

Granite		Flat or Elongated 3:1					2D Form					
Laboratory	Scan #	25.0 (1.0")	19.0 (3/4")	12.5 (1/2")	9.5 (3/8")	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
	2	78.0%	86.0%	92.0%	94.0%	90.0%	7.6	7.5	8.0	7.7	7.8	10.2
16	1	80.0%	88.0%	90.0%	96.0%	95.9%	7.8	7.8	7.9	8.0	8.5	9.5
	2	83.7%	86.0%	90.0%	92.0%	87.8%	7.5	7.7	8.0	7.9	7.8	9.0
17	1	83.7%	90.0%	88.0%	89.6%	87.0%	7.6	7.7	7.8	8.2	8.1	9.6
	2	80.0%	94.0%	88.0%	94.0%	97.9%	7.5	7.8	7.7	8.2	8.0	9.5
18	1	86.0%	93.9%	87.8%	85.7%	91.8%	7.4	7.6	7.7	7.8	7.9	9.7
	2	88.0%	96.0%	94.0%	90.0%	96.0%	7.5	7.8	7.6	7.4	7.6	9.1
19	1	92.0%	93.8%	96.0%	98.0%	98.0%	7.5	7.5	8.0	8.3	8.2	9.0
	2	83.7%	88.0%	90.0%	92.0%	96.0%	7.4	7.4	8.1	8.2	7.9	9.6
20	1	90.0%	96.0%	86.0%	96.0%	96.0%	7.6	7.8	7.9	7.8	7.9	8.7
	2	93.9%	92.0%	90.0%	92.0%	94.0%	7.4	7.7	7.8	7.8	7.9	9.2
21	1	84.0%	88.0%	86.0%	91.8%	96.0%	7.5	7.4	8.0	7.7	8.0	9.1
	2	89.8%	91.8%	86.0%	90.0%	98.0%	7.4	7.5	7.7	7.8	8.2	9.6
22	1	96.0%	90.0%	98.0%	94.0%	98.0%	7.8	7.9	7.8	7.7	7.8	8.4
	2	100.0%	90.0%	96.0%	96.0%	96.0%	7.9	7.8	8.0	7.8	7.8	10.0
23	1	100.0%	80.0%	87.5%	98.0%	98.0%	8.1	7.7	8.0	7.7	8.5	8.9
	2	96.0%	78.0%	100.0%	96.0%	94.0%	7.7	7.5	7.8	8.4	8.0	9.1
24	1	100.0%	96.0%	98.0%	95.9%	98.0%	7.9	7.5	7.7	8.4	8.1	9.5
	2	100.0%	92.0%	92.0%	96.0%	94.0%	7.8	7.7	8.0	8.3	8.0	10.1
25	1	100.0%	96.0%	95.8%	100.0%	100.0%	7.5	7.7	7.6	7.8	8.2	9.9
	2	98.0%	94.0%	91.7%	98.0%	100.0%	7.5	7.5	7.8	7.8	8.1	8.7
26	1	93.9%	82.0%	96.0%	95.9%	96.0%	7.4	7.6	8.0	7.9	7.9	9.3
	2	94.0%	78.0%	92.0%	96.0%	95.9%	7.5	7.3	7.6	8.0	7.8	9.9
27	1	94.0%	80.0%	90.0%	100.0%	96.0%	7.6	7.6	7.1	8.2	7.6	9.1
	2	96.0%	82.0%	96.0%	98.0%	96.0%	7.5	7.5	8.1	8.2	7.7	8.5
28	1	96.0%	84.0%	96.0%	98.0%	94.0%	7.6	7.3	7.6	8.2	7.9	9.6
	2	94.0%	83.7%	94.0%	98.0%	100.0%	7.8	7.3	7.6	8.3	8.3	9.9
29	1	95.9%	91.8%	91.8%	96.0%	90.0%	7.7	7.5	8.0	8.0	8.1	8.9
	2	98.0%	89.6%	89.8%	94.0%	96.0%	7.2	7.7	7.9	7.7	7.8	9.0

Addendum 1:
Project Questions and Responses

Highways for Life Final Report
Grant #DTFH61-08-G-00003

Aggregate Image Measurement System (AIMS2)

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This section is intended to respond to questions or comments that may arise from readers of this report. It will be appended as needed to provide clarification. Readers may submit these inquiries to Pine Instrument Company per the contact information above.

1. **The AIMS2 values are forced to fit the AIMS1 values in order to allow continued usage of the data collected with the previous AIMS1 device.**

- What is the value of shifting the AIMS2 data to the AIMS1 data? If the AIMS1 data have ambient light effects and less effective/accurate optics, why do we want to preserve these historic values?

Response:

AIMS1 to AIMS2 2D-Form, Angularity, and Dimensional ratios required no adjustments. The AIMS2 texture value required adjustment to match the AIMS1 texture. A linear fit was determined to be an appropriate correlation correction and a multiplier was determined which provided a reasonable fit. This AIMS Texture shift was discussed in detail in the Phase I report. A brief discussion is provided below to help explain the reason this adjustment was selected.

Dr. Eyad Masad developed the AIMS technology and is a recognized leader in pavement materials research. Therefore, his research team at Texas A&M was selected as the primary laboratory to validate the AIMS2 design. Dr. Masad provided expert advice regarding the AIMS technology throughout the Highways for LIFE project work.

In 2005, Manjula Bathina, working under the direction of Dr. Masad evaluated the repeatability and reproducibility of the AIMS1 system at the Texas Transportation Institute (TTI), which is the same system used by Dr. Masad at Texas A&M. Bathina reported in her thesis *Quality Analysis of the Aggregate Imaging System (AIMS) Measurements*, "AIMS has been found to have excellent repeatability and reproducibility for all measured parameters when compared with many other test methods."

Enad Mahmoud, also working under the direction of Dr. Masad, compared the outputs of two AIMS1 systems, one at TTI and one at the Texas Department of Transportation. He reported in his thesis work titled *Development of Experimental Methods for the Evaluation of Aggregate Resistance to Polishing, Abrasion, and Breakage* (December 2005), "Measurements using two AIMS units and two Micro-Deval machines were used to assess the variability. There was no statistical difference between the measurements of the two AIMS units or between the measurements of the two Micro-Deval units."

This same AIMS1 unit had also been reported to produce repeatable and reproducible results in "Simulation, Imaging, and Mechanics of Asphalt Pavements FHWA DTFH61-03-X-00026" by Eyad Masad. This AIMS1 system has been located in the same laboratory since it was acquired by TTI; therefore, the results from this system have not been influenced by variation in ambient light, as was confirmed by the high repeatability and reproducibility of this system by Bathina (2005). No other direct system comparisons, other than factory configuration data, were known to be available for consideration.

Based on this information, it was believed the system at TTI (located at Texas A&M) provided a reasonable representation of the AIMS1 system outputs. These reports provided support for selecting this AIMS1 system as the definitive baseline for comparison and calibration of the AIMS2 system in the Highways for LIFE project.

It was the understanding of Pine Instrument Company that the intent of the Highways for LIFE program was to leverage existing AIMS historical data, which had shown promising results. The AIMS1 system at this location had been used in the majority of the published research work utilizing AIMS technology. Matching the results of this AIMS1 system was believed to be appropriate and concurred with the advice from Dr. Masad.

- As we continue to attempt to develop pavement performance relationships with the AIMS2 values, would it be more valuable to shift the AIMS1 data to the AIMS2 data and "draw a line in the sand" to continue forward with AIMS2 unshifted or uncorrected values based on improved lighting and optics for performance relationships?

Response:

Dr. Masad recommended a shift of the AIMS2 data to fit the established AIMS1 system scale. The texture scale was also extended to be from 0 to 1000 instead of 0 to 800. This was simply an extension to a scale of 10 rather than 8 with no scaling of the actual values.

Each AIMS1 system was set up at the factory under controlled lighting conditions to achieve reproducible results. The repeatability work done at Texas A&M suggests that setup was successful. Therefore, based on the information available, it was believed this texture shift was appropriate to match the existing AIMS1 systems.

Top lighting problems had been reported by users of the AIMS1 systems, and the system at TTI was configured with additional lighting to account for this problem. The AIMS2 system's top-lighting arrangement was changed to address the cost and reliability issues associated with the ring light system used on the AIMS1. The camera technology was also updated from the outdated camera used on the AIMS1 system. These changes were believed to be the cause of the shift in AIMS2 texture from the AIMS1 data and a linear multiplier was determined to be the best fit.

The ruggedness testing performed in Phase I showed the texture output to be extremely sensitive to ambient lighting making the AIMS1 system output sensitive to laboratory conditions. This sensitivity is addressed in the AIMS2 system by creating an enclosed image acquisition chamber. The correlation of the results between the Texas Department of Transportation and TTI AIMS1 systems suggests that the ambient light conditions were similar, but no specific information on ambient lighting at the time the data were collected is available to corroborate this assumption.

Since the texture value output is sensitive to ambient light conditions, the only way to understand how a specific AIMS1 data set matches up with the TTI system, and therefore the AIMS2 systems, is to compare the results of a specific AIMS1 system directly to an AIMS2 system. A correlation between the specific AIMS1 system in question and the AIMS2 systems can then be established with reasonable certainty. The AIMS2 units have proven to be reproducible in multiple laboratory environments, so the goal would be to establish the texture relationship of any given AIMS1 system to the AIMS2 platform.

It is also important to consider the realized performance of any specific AIMS1 system. System field operation may have differed from these factory settings (aperture setting, ambient lighting, etc.), which may influence the results. Also, some AIMS1 users have reported poor focusing (blurry texture images) and partial particle images, which may impact the texture values. As a research platform, the AIMS1 system did not include controls on many of these variables.

2. The reference scale used in AIMS1 versus AIMS2 is not clear.

- Example (Angularity) Descriptions:

  AIMS1 (Angular, Sub-angular, Sub-rounded, and Rounded)
  AIMS2 (High, Medium, and Low)

- Why were the descriptions changed? Which descriptions are to be adopted and why?

<u>Response:</u>

The angularity scale was not changed. The AIMS2 system angularity output compared favorably with the AIMS1 system outputs over multiple aggregate sources.

The change to Low, Medium, and High for each of the AIMS characterizations was specifically requested by Dr. Masad. This change was intended to be an improvement to clarify and simplify the information. The Low, Medium, and High classifications are used consistently throughout the AIMS shape characterizations. In the specific case of angularity, the three categories of Low, Medium, and High are believed to be less ambiguous than sub-rounded and sub-angular categories. These changes were motivated by input from the aggregate industry in response to presentations that were made by Dr. Masad in various conferences, including especially, the annual meeting of the Transportation Research Board and the annual meeting of the International Center for Aggregate Research.

- In relating the AIMS shape properties to performance data, I think we would prefer to use the AIMS1 descriptions. The AIMS1 descriptions are also easier for people to relate visually to aggregate shape.

  Response:

  The AIMS Angularity values and scale have not changed. The Low, Medium, and High category descriptions were presented to the FHWA for review in September of 2008. The AASHTO provisional specifications were balloted and accepted using the Low, Medium, and High categories. Given the variety of AASHTO committee members' comments on the terminology used in the specification, changing the descriptions is expected to raise additional concerns, comments, and negative votes. The break point value for each category will likely require supporting documentation for the AASHTO ballot process.

3. **AIMS1 quantifies angularity using two methods (gradient and radius). The gradient method is only utilized in AIMS2 and the AASHTO specification.**

- Why is the radius method not included or used? The report should discuss why the radius method is not included or adopted.

  Response:

  The use of multiple angularity values was a cause of confusion. From a practical point of view, it is preferred to provide one method for measuring each of the physical characteristics (shape, angularity, and texture). The work that was conducted as part of NCHRP 4-30 showed that the gradient method is better than the radius method for differentiating between aggregates with different angularity characteristics. In several presentations to the industry, Dr. Masad received feedback that providing two methods to measure the same property is confusing and poses a challenge for developing one set of specifications for angularity. Therefore, the Radius Angularity is not provided in the output.

- How can we use the angularity values obtained using the radius method?

  Response:

  To obtain the Radius Angularity values, a separate analysis of the existing images must be performed.

4. **AIMS1 reports coarse aggregate 2D Form. It is not mentioned in the report why AIMS2 and the AASHTO specification are not using the 2D Form index for coarse aggregate particles.**

- What happened to the coarse aggregate 2D Form and why was it removed?

Response:

The 2D Form is a two-dimensional parameter. The system provides a three-dimensional measurement in millimeters for each coarse aggregate particle; short, intermediate, and long dimensions. The AIMS Sphericity, F&E and ForE ratios are calculated from these dimensions. This three-dimensional information is not available for fine aggregates; therefore, the two-dimensional form is provided as a means to characterize fine aggregate particle form.

The 2D Form for coarse aggregate particles is still available on the data sheet in each AIMS report workbook (raw values and cumulative distribution). These data can be evaluated if desired. These output data are presented in Excel workbooks specifically for the purpose of customization for specific user requirements. As discussed in the response to Question 3 above, only one method to measure each of the physical characteristic is desired. Therefore, the three-dimensional shape measurements over the two-dimensional (form index) measurements of coarse aggregates is provided. Current AIMS2 AASHTO specifications do not include 2D Form for coarse aggregate sizes.

- Does the coarse aggregate 3D Form also address the 2D Form? Descriptions should be given if the coarse aggregate Sphericity (3D Form) is thought to address the coarse aggregate 2D form.

Response:

AIMS2 Sphericity addresses the three dimensional form of coarse aggregate particles. There is correlation between coarse aggregate 3D and 2D Form. However, the 3D form is the preferred method since it considers the three dimensions of particles instead of the two dimensions. The industry has used three-dimensional measurements of shape for many years through the use of the flat and elongated percentage of particles. As such, the use of the 3D Form is more accurate and more consistent with the industry experience.

5. The aggregate texture shift factor (AIMS1/AIMS2) is reported to be 2.4563. This value was obtained using 32 aggregate samples.

- Certainly the aggregate texture index depends on the illumination and gray-scale intensity of aggregate surface image. In order to obtain reasonable texture shift factors (if we even want to use shift factors, see comment 1 above), wouldn't the study need a larger number of aggregate types and specimens with different type combinations including RAP aggregates to ensure a precise shift factor?

Response:

While this concern might apply if the AIMS1 system had wide scale usage, the AIMS1 platform has been utilized in a very limited manner, by limited users. The

32 aggregate samples are believed to provide a reasonable representation of a broad spectrum of materials tested in the AIMS1 system. The 2.4563 value provides a reasonable fit for the materials tested as shown in Figure 1.5 of Appendix A. Because the AIMS1 has only been used in limited research applications, this fit provides a reasonable link to the research data, while essentially drawing a "line in the sand" as the AIMS2 platform moves forward.

6. The report states that additional work is needed to improve the performance of the system for the sieve size 0.075 mm (#200) due to multiple particles (connected/touching) being analyzed as a single particle.

- When is this work going to occur on CHRP values and touching particle analysis in order to allow the imaging and analysis of the #200 material and improve the variability?

- The AASHTO specification still states the procedure is applicable to the #200 material when the statement above and not utilizing the #200 material in the precision statement means that it is not applicable to #200 material.

Response:

At the time the draft procedure was submitted to AASHTO, it was expected that the #200 work would be completed before the specification was accepted. However, time constraints delayed further investigation into the selection of the appropriate CHRP value for #200. In addition, the specifications were approved rather quickly.

It is appropriate to revise the precision statement in the AASHTO specification to include a separate line for the #200 retained material. This will allow AIMS2 data to be collected at that size while providing the user with the proper variability information. As the system performance is improved, this precision value can be adjusted accordingly.

- The method of edge detection followed by image segmentation may possibly be used to effectively delineate the overlapping or toughing aggregate particles of size 0.075 mm. We can discuss in more detail to see if this is worth pursuing.

Response:

There were many methods investigated for solving the issue of defining particle edges with several showing promise. It is certainly possible that there are more effective ways to address the touching particles in fine aggregate images. The CHRP was selected as it appeared to be reasonably effective at removing touching particles while not impacting the angularity values.

7. The precision statements are a result of the combination of all sieve sizes (except the #200 material).

- Why was the precision of all aggregates combined versus separate statements for individual sieve sizes? If some sizes are more variable than other sizes would it be valuable to differentiate the higher variability sizes from the others?

  Response:

  Early in the Interlaboratory Study, labs reported higher variability in the #200 results. This variability in the #200 ILS data was determined to be linked to touching particles in the images. This indicated the CHRP value used for #100 and larger is not the optimum value for the #200 retained. The need for a different CHRP variable is likely due to particle size and image resolution interactions. The number of touching particles in a specific image is also related to how well the operator distributed the material over the tray surface. The system is currently capable of collecting #200 shape characteristics but with slightly higher variability than the other sizes.

  The ILS data, shown in Appendix B and analyzed by Gates et. al. (Texas A&M University 2009) with results shown in Table 3.13 and Table 3.16, clearly shows similar variability in all sizes with statistically insignificant differences, except #200. Therefore, for simplicity and practicality, one precision statement value based on the geometric average variability is reasonable for all sizes excluding #200 retained. As noted in the response to question 6, the AASHTO specification precision statement should be revised. This revision will be introduced at the next AASHTO Sub-Committee on Materials ballot opportunity along with the appropriate information to correct the error.

8. The AASHTO M 323 (i.e., Standard Specification for Superpave Volumetric Mix Design) test protocol requires an aggregate particle to be flat or elongated if the longest particle dimension (i.e., length) divided by smallest particle dimension (i.e., thickness) exceeds five. In addition, the percentage of particles for this ratio is limited to a maximum of 10%.

- AIMS2 present this information using Figure 1. This graphic is busy and not clear for the average user who is looking to see if their material meets the M323 specifications. For the average user to determine pass or fail requirements the software should include an additional simplified figure (example Figure 2) for the stockpile blend and sieve sizes. This is how we present the MAMTL reported data.

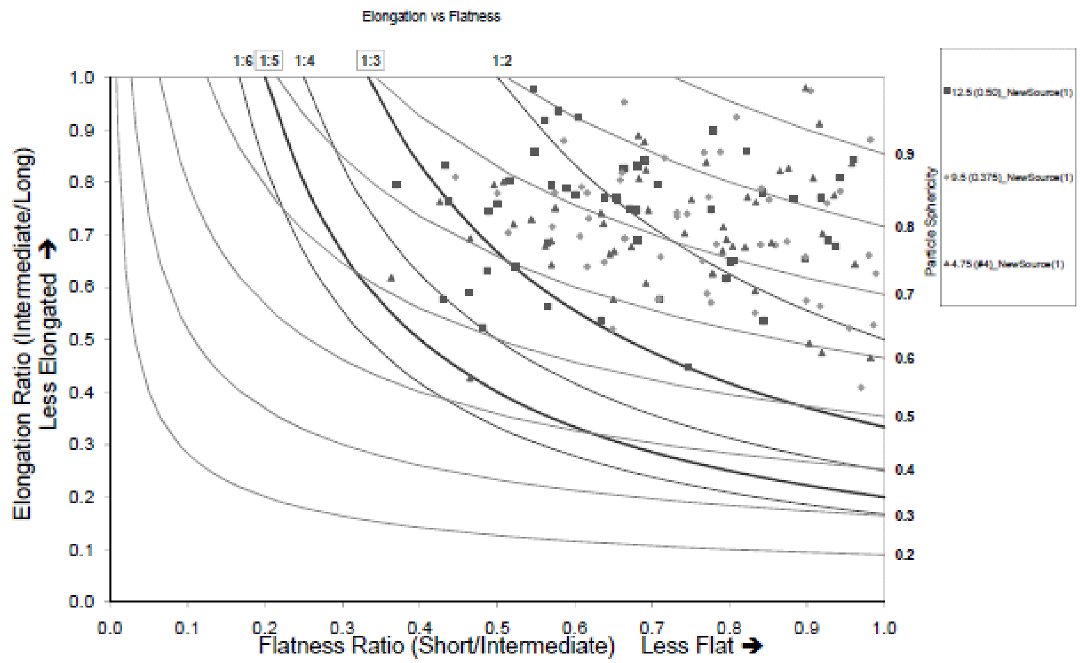

Figure 1. Comparison of Aggregate Sphericity and Superpave Flat and Elongated Limits; Aggregate Source CG-1 (After KS0882 project).

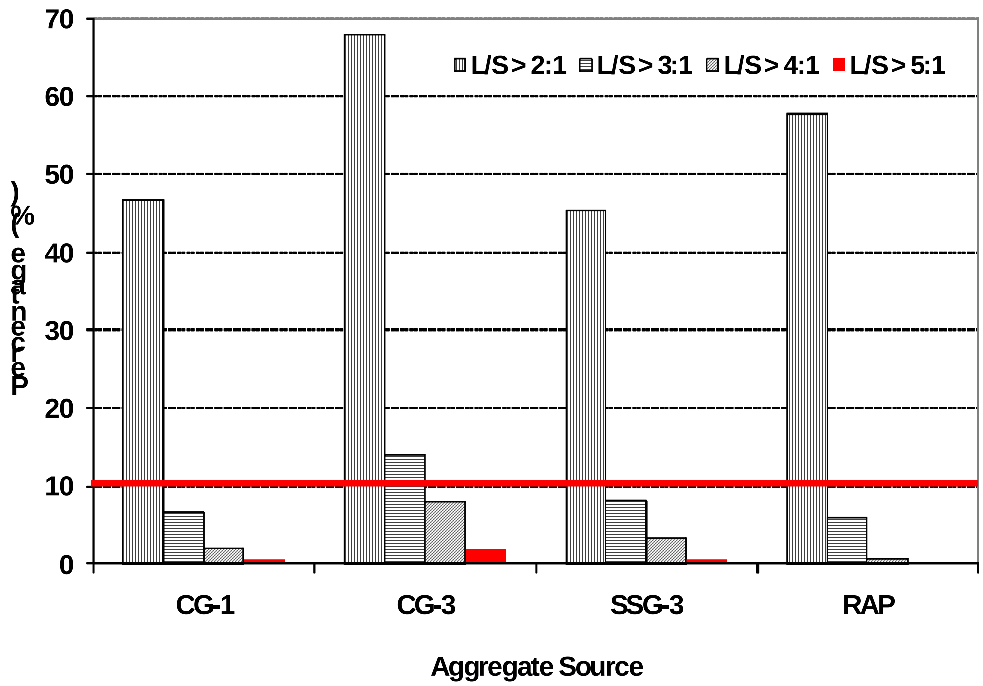

Figure 2. AIMS Aggregate Flat & Elongation Index (After KS0882 project).

Response:

Figure 1: Elongation vs. Flatness as provided by the AIMS2 output file is certainly a “busy” chart. The cumulative distribution graphs for the F&E and for the ForE ratios were added (see figure 1A below) specifically to address the need to understand how the material fits within the M323 specification. These cumulative distribution charts are consistent with the other AIMS2 characteristic charts and provide a clear means to determine if an aggregate material meets F&E requirements.

Changes to the current F&E and ForE specifications have been discussed within the research community, so it is believed this cumulative distribution graph, which provides the full spectrum of ratio data, not just integer break points, was the best configuration for this information. This distribution chart is not limited to providing integer F&E ratios. The scatter plot represented in figure 1 was retained in the output file so that users familiar with the F&E concept utilized in M323 could understand how it relates to the concept of AIMS2 Sphericity, introduced by Dr. Masad in the AIMS shape characterizations. Sphericity includes all three dimensional measurements of the coarse particle.

Figure 1A below shows the AIMS2 F&E cumulative distribution chart. The limit line in this figure was added to depict how specification limits might be shown for multiple ratio categories. In this case, arbitrary limits of Maximum 20%>3:1 and Maximum 10%>5:1 are shown. All materials meet the Max 10%>5:1 criteria, but two materials fail the Max 20%>3:1. These red-line limits are not currently included on the graphs. It is up to the user to understand the information and apply the appropriate specification limits.

The bar graph representation had been casually suggested by one AIMS1 user. It is respectfully suggested that the cumulative distribution graph (figure 1A) presents the data in a reasonable form and is consistent with the other AIMS2 data.

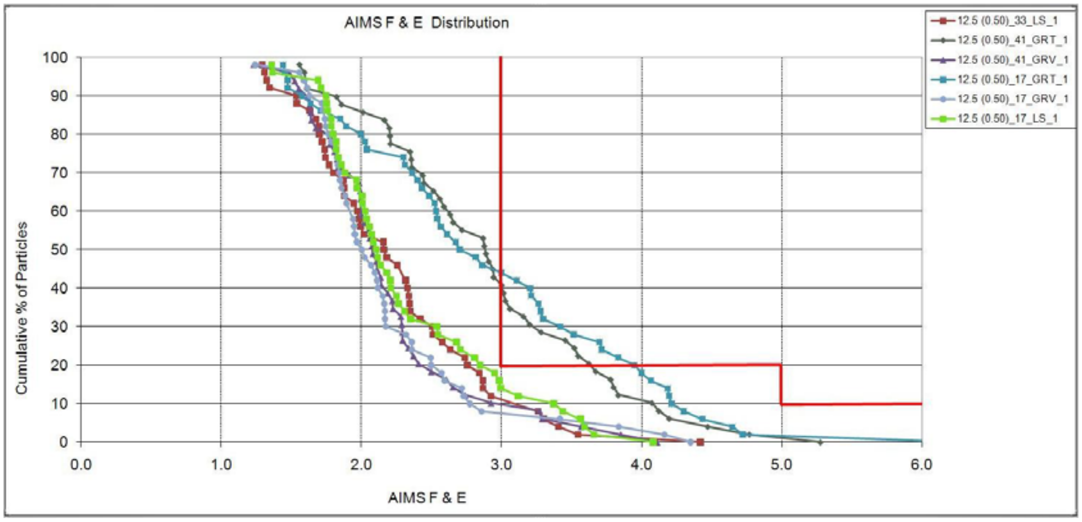

Figure 1A: Cumulative F&E Distribution with shaded specification limits added.

However, if a specific user wishes to present the information in a specific way, all the AIMS2 shape characterizations are provided in an Excel workbook. Each material's scan data are provided on a separate worksheet. These AIMS2 values are accessible to the user, permitting custom charts within the Excel format to be created. These custom formats can also be saved as the working template within the AIMS2 system allowing future scans to be loaded directly into the desired format. The Excel format was chosen specifically to permit customization of the report formats for specific reporting requirements.

The AASHTO TP81 specification was approved with the F&E cumulative distribution chart. Any changes to the reporting will need to be submitted to the AASHTO Sub-Committee on Materials for approval.

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2. Jagan Gudimettla, Leslie A. Myers, and Charles Paugh, n.d., *AIMS: The Future in Rapid, Automated Aggregate Shape and Texture Measurement,* Federal Highway Administration, Washington, DC (available online: http://www.pineinst.com/test/pdf/FHWA_Gudimettla-Myers-Paugh.pdf).

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