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The Development of a Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties

Final Report for Highway-IDEA Project 77

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February 2003

TRANSPORTATION RESEARCH BOARD • THE NATIONAL ACADEMIES

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ACKNOWLEDGMENTS

The principal investigator would like to acknowledge the funding provided by the Federal Highway Administration for the purchase of the components necessary to develop the aggregate imaging system (AIMS). The technical input of John D'Angelo, John Bukowski, and Thomas Harman from the Federal Highway Administration is highly appreciated. The funding provided by the International Center for Aggregate Research on a parallel study has helped in providing this IDEA project with laboratory performance data on a wide range of aggregates.

The principal investigator would also like to acknowledge those individuals who helped in different aspects of the projects. Dr. Krishna Sivakumar and Mr. Chandan from the School of Electrical Engineering and Computer Science at Washington State University contributed to the development of the image analysis software. Mr. Thomas Fletcher and Mr. Taleb Al-Rousan from the Department of Civil and Environmental Engineering at Washington State University contributed to the development of the AIMS motion and image acquisition program.

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1. EXECUTIVE SUMMARY

This report presents the design and development of a unified computer automated system for characterizing all aspects of shape of fine and coarse aggregates. The system is referred to as the **Aggregate Imaging System (AIMS).** AIMS consists of stand-alone software for the analysis of aggregate shape, and a computer-automated system for image acquisition.

The system provides rapid and accurate determination of aggregate shape properties with minimum interference from the operator. This report describes the unique and innovative features of the system and the experimental design considerations. These considerations are related to the required image resolution, field of view, and lighting scheme. The system is developed with the capability of analyzing fine and coarse aggregate, quantifying texture, angularity and the three-dimensions of form.

AIMS was used to measure aggregate shape properties for a wide range of fine and coarse aggregates, and the results were compared with hot mix asphalt (HMA) performance. The analysis showed that AIMS gives detailed information on shape properties of aggregates in a short time. The measurements had very good correlation with the resistance of asphalt mixes to permanent deformation measured in the laboratory using different wheel tracking devices.

AIMS is considered a major technological advancement over the current methods used in the practice for measuring aggregate shape. The benefits of AIMS will be realized in two main areas of pavement engineering. The first area is incorporating aggregate shape properties into the design procedure of hot mix asphalt. The aggregate properties control their interaction with the asphalt binder, and consequently influence the design of mix volumetrics. The second area is the quality control/assurance of aggregates. The system will offer an automated method of enforcing aggregate shape specifications and ensuring consistent properties. Consequently, it will contribute to the creation of higher-quality and longer-lasting pavements, with large savings due to reduced requirements for pavement maintenance and rehabilitation.

The development of AIMS has already drawn significant interest from both government and private industry. The Federal Highway Administration (FHWA) is in the process of acquiring AIMS in their mobile laboratory. AIMS will be used to measure the aggregate shape properties used in a wide range of asphalt mixes. The results will serve the purpose of verifying the mechanical properties of asphalt mixes measured using the performance tests of asphalt mixes. Also, the FHWA will evaluate the capabilities of AIMS as standard laboratory equipment for measuring aggregate shape properties.

The PI is interested in further development of AIMS capabilities and features. The FHWA's implementation of AIMS will yield comprehensive database of aggregate shape properties and asphalt pavement mechanical properties and performance. It is essential to continue working with the FHWA during the implementation stage to develop relationships between AIMS measurements and pavement mechanical properties and performance. In addition, there are a number of experimental improvements that would enhance AIMS capabilities. The first one is the improvement of light uniformity during image acquisition irrespective of the aggregate location on the table. The second one is the development of a mechanism to ensure continuous feed of aggregates to analyze the shape of sufficient amount of aggregates.

2. IDEA PRODUCT

The main product of this study is an automated system for measuring aggregate shape properties, hence referred to as the "**Aggregate Imaging System (AIMS)**". The system provides rapid and accurate determination of aggregate shape properties with minimum interference from the operator. The capabilities of this system are demonstrated by characterizing aggregates from mixes with known field and laboratory performance. It is anticipated that this system will be part of the future methodology for characterizing aggregates and will supercede currently used index type methods.

3. CONCEPT AND INNOVATION

AIMS is designed to be versatile enough to capture images at different resolutions, field of view, and using different lighting schemes in order to be able to analyze the form, angularity, and texture of fine and coarse aggregates. Figure 1 shows a conceptual 3-D graphical model of AIMS illustrating the various components of the system. Figure 2 gives a picture of the entire AIMS set-up.

AIMS utilizes three closed loop DC servo motor linear actuators with 250 mm of travel in the x and y-axes and 50 mm of travel in the z-axis. This allows for precision movement of all three axes simultaneously and independently from each other. The x-axis motion is running on a slider bar where the camera is attached. The y-axis motion of the aggregate tray and backlighting table is running on a bearing guide assembly, which creates smooth uniform motion. The z-axis controls the auto focusing of the camera. The auto focus utilizes high spatial frequency for a signal of a video microscope connected to the camera.

The video microscope has a 16:1 zoom ratio, which allows capturing a wide range of particle sizes without changing parts. A black and white video camera with an external control is used. The camera is connected to a magnification lens. The camera and video microscope are attached to dovetail slide with a motion range of 300 mm in the z-axis in order to allow capturing images of a wide range of aggregate sizes. All motions are connected to a multi-axis external controller that offers both manual and automatic control of motions, as well as enhanced black level and contrast controls. The auto focus microscope-camera assembly allows capturing high contrast gray images for texture analysis, and black and white images for angularity analysis. The measurements needed for the form analysis are conducted in two steps. The particle thickness is measured in the first step, while the other two dimensions are measured in the second step. The thickness is measured by focusing the microscope on the lighting table and registering its location on the z-axis as the zero or reference point. Then, the microscope is moved to capture a gray image of a particle. In order to do that, the microscope moves upward until a high frequency signal from the microscope is received indicating that a high-resolution gray image is detected. The difference between the new location of the microscope and the zero point gives a particle thickness. The other two dimensions of a particle are measured on black and white images of particle projections. The system operates based on two modules. The first module is for the analysis of fine aggregates (smaller than 4.75mm), while the second is devoted for the analysis of coarse aggregates.

The software for AIMS motion control and image acquisition was developed under LABVIEW and IMAQ Vision packages. The LABVIEW program automates the process of capturing images at specified resolution and field of view. The program is user-friendly and can be used by engineers and technicians with minimal training.

Once the images are captured, they are analyzed using the image analysis software developed in this study. This software was developed as a stand-alone application, which could run on any 32-bit Windows platform. The programs for form, angularity, and texture analysis were primarily written in C and incorporated within the user-interface application, which was programmed in Visual C++. The image analysis software is very user-friendly and can be used to analyze form, angularity, and texture for both fine and coarse aggregates.

4. PROJECT INVESTIGATION

4.1 PROBLEM STATEMENT AND OBJECTIVES

The current Superpave™ system describes aggregate shape using three tests. The first test is fine aggregate angularity, which is inferred from the volume of air voids in a loosely compacted aggregate sample (Method A of AASHTO Standard T304) (*1*). The second test is coarse aggregate angularity, which is inferred from the number of aggregate fractured faces (ASTM Standard D5821) (*2*). The third test deals with the relative dimensions of coarse aggregates to identify flat-elongated particles (ASTM D4791) (*3*). The Superpave tests for measuring coarse aggregate shape properties are laborious, and limited in their ability to test a representative sample of aggregates. Furthermore, the current flat-elongated procedure (ASTM D4791) yields a single index reflecting the proportion of aggregates that exceeds a predetermined average dimension ratio. This is far less descriptive than a probabilistic method for summarizing the results, such as the distribution of relative particle dimensions.

Recent experience with the current Superpave criterion for fine aggregate angularity shows that there are cases where the test does not discern poor quality from high quality aggregates (*4, 5*). Texture measurements are not emphasized in the current methods for characterizing aggregate shape (*6*). The limitations of the current aggregate shape tests have caused inconsistency in predicting the extent to which the measured properties influence pavement performance. Developing methods that are able to distinguish among the aggregate characteristics and not a combination of their interaction is crucial in order to link each of these characteristics to pavement performance.

Recently, there have been a number of developments in digital vision, along with the availability of software for motion control of system's components. Thus, providing the means for the development of automated methods for aggregate shape analysis based on measurements made directly from the individual aggregate.

There have been several investigations on the use of imaging technology to quantify the aggregate shape properties and relate them to mix performance. Some studies have been focused on developing procedures to describe the shape properties of aggregates with emphasis on form, angularity, and texture. A comprehensive review of these procedures can be found in reference (*7*). In addition, there are several systems available commercially and at research institutions for directly measuring aggregate characteristics. These systems use different concepts such as image analysis techniques, laser scanning, and physical measurements of aggregate dimensions (*8, 9, 10*). Most of these systems focus on the form of coarse aggregates, with little attention to the angularity and texture of aggregates and especially fine aggregates.

The objective of this study is to develop a working prototype of an automated system for measuring the aggregate shape properties, which is referred to as the "Automated Imaging System" (AIMS). The specific tasks are:

- **Task 1.** Develop a user-friendly stand-alone software for the analysis of aggregate shape properties.
- **Task 2.** Develop a computer-automated system to control the image acquisition and the analysis procedures.
- **Task 3.** Correlate the aggregate shape characteristics to the aggregate samples with known laboratory performance to demonstrate the systems capabilities.

4.2 DESCRIPTION OF THE AGGREGATE IMAGING SYSTEM (AIMS)

The system, referred to as AIMS, is designed to be versatile enough to capture images at different resolutions, field of view, and using different lighting schemes in order to be able to analyze the form, angularity, and texture of fine and coarse aggregates. Figure 1 shows a conceptual 3-D graphical model of AIMS illustrating the various components of the system. Figure 2 gives a picture of the entire AIMS set-up.

AIMS utilizes three closed loop DC servo motor linear actuators with 250 mm of travel in the x and y-axes and 50 mm of travel in the z-axis. This allows for precision movement of all three axes simultaneously and independently from each other. The x-axis motion is running on a slider bar where the camera is attached. The y-axis motion of the aggregate tray and backlighting table is running on a bearing guide assemble, which creates smooth uniform motion. The z-axis controls the auto focusing of the camera. The auto focus utilizes high spatial frequency for a signal of a video microscope connected to the camera.
The video microscope has a 16:1 zoom ratio, which allows capturing a wide range of particle sizes without changing parts. A black and white video camera with an external control is used. The camera is connected to a magnification lens. The camera and video microscope are attached to dovetail slide with a motion range of 300 mm in the z-axis in order to allow capturing images of a wide range of aggregate sizes. All motions are connected to a multi-axis external controller that offers both manual and automatic control of motions, as well as enhanced black level and contrast controls. The system operates based on two modules. The first module is for the analysis of fine aggregates (smaller than 4.75mm), while the second is devoted for the analysis of coarse aggregates.

4.2.1 Fine Aggregate Module

Recent studies have shown that although angularity and texture of fine aggregate are fundamentally different properties, there is reasonable correlation between these two properties that allow measuring only one of them. Also, it is easier to capture black and white images for angularity analysis rather than gray high-resolution images required for texture analysis (*11, 12*). Therefore, it was decided in this study to analyze the fine aggregate angularity only.
The images required for measuring fine aggregate angularity are captured at a resolution such that the pixel size is less than 1% of the average aggregate diameter, and the field of view covers 6-10 aggregate particles (*13*). Backlighting under the aggregate tray is used to capture images for angularity analysis. This type of lighting creates a sharp contrast between the particle and the tray, thus giving a distinct outline of the particle.

The shape analysis of fine aggregate starts by randomly placing an aggregate sample on the aggregate tray with the backlighting turned on. The camera and video microscope assembly moves incrementally in the x direction at a specified interval capturing images at every increment. Once the x-axis range is complete, the aggregate tray moves in the y-direction for a specified distance, and the x-axis motion is repeated. This process continues until the whole area is scanned. In each x-y scan, the z-location of the camera and the microscope magnification are specified in order to meet the resolution criteria mentioned earlier. Aggregates that are not within the size for which the scan is conducted are removed from the images. This is a very important step in order to analyze all aggregates according to the image resolution criterion specified earlier (a pixel size is less than 1% of average particle diameter).

4.2.2 Coarse Aggregate Module

The coarse aggregate module is developed to quantify form (three-dimensional), angularity, and texture. The analysis starts by placing aggregates on a transparent sheet with marked grid points. Two scans are conducted for the analysis of coarse aggregate. In the first scan, backlighting is used, and the image resolution is determined such that the pixel size is less than 1.0% of the aggregate average diameter. In this scan, black and white images are captured. These images are analyzed to determine angularity, and the major (longest axis) and minor (shortest axis) axes on two-dimensional images.

The second scan captures gray images of aggregate surface for texture analysis and measures the average thickness of aggregates. The second scan starts by focusing the video microscope on a marked point on the lighting table. The location of the camera on the z-axis at this point is taken to be zero. Then the camera moves to the location where an aggregate is placed. The video microscope automatically moves up on the z-axis in order to focus on aggregate surface. Since, the video microscope has a fixed focal length, the difference between the z-axis coordinate at this location and the zero point is the depth of the aggregate length. This thickness, along with the major and minor axes measurements captured in the first scan, is used to quantify the three dimensional properties of aggregate form. It is noted that this procedure allows capturing the three-dimensions of aggregates using only one camera, thus reducing the cost and complexity of the system. The gray image is used to analyze texture as discussed in the following section. A user-friendly software is developed to control image acquisition, resolution, and motion. Detailed information about this software is available in reference (*12*).

4.3 IMAGE ANALYSIS SOFTWARE OF AGGREGATE SHAPE

The captured images are analyzed using a user-friendly stand-alone software developed as part of this study. Aggregate texture is analyzed using the Wavelet method (Energy Signature), angularity is analyzed using the gradient method and radius method (Angularity Index), and three-dimensional form is analyzed using the Sphericity and Shape factors (*6, 11, 16*). This software reads all the images stored in a certain directory and provides a text file of the angularity, texture, and form measurements, which can then be imported into a spreadsheet.

4.3.1 Texture Analysis

Texture in an image is represented by the local variation in the pixel gray intensity values. Although there is no single scale that represents texture, most texture analysis schemes analyze texture only at a single scale (*17, 18*). In this study, a method is presented for multi-scale analysis of textural variation on aggregate images. This is advantageous to determine the texture scale or a combination of them that has the best correlation with HMA performance. Wavelet theory offers a mathematical framework for multi-scale image analysis of texture (*19*). The wavelet transform works by mapping an image onto a low-resolution image and a series of detail images. An illustration of the method is presented here with the aid of Figure 3. The original image is shown in Figure 3a. It is decomposed into a low-resolution image (Image 1 in Figure 3b) by iteratively blurring the original image. The remaining images contain information on the fine intensity variation (high frequency) that was lost in Image 1. Image 2 contains the information lost in the y-direction, Image 3 has the information lost in the x-direction, and Image 4 contains the information lost in both x and y-direction. Image 1 in Figure 3b can be further decomposed similarly to the first iteration, which gives a multi-resolution decomposition and facilitates quantification of texture at different scales. An image can be represented in the wavelet domain by these blurred and detailed images. The texture parameter used in this study is the average energy on images 2, 3, and 4 at each level. More details on this method can be found in other references (*19, 20*).

Owing to this multi-resolution nature of the decomposition, the energy signature, or equivalently, the texture content has a physical meaning at each level. Energy signatures at higher levels reflect the "coarser" texture content of the sample, while those at lower levels reflect the "finer" texture content.

4.3.2 Angularity Analysis

The black and white images are analyzed using the gradient method and radius method (Angularity Index) (*14*). The idea behind the gradient method is simple, yet intuitive. At sharp corners on the outline of an image, the direction of the gradient vector for adjacent points on the outline changes rapidly. Whereas the direction of the gradient vector for rounded particles changes slowly for adjacent points on the outline. Figure 4 illustrates the method of assigning angularity values to a corner point on the outline of the particle. Gradient values for all the corners are calculated and their sum accumulated around the outline, concluding to the angularity gradient for the aggregate particle.

Masad et al. (*11*) developed the radius method for the analysis of aggregate angularity on black and white images. This method measures the difference between the particle radius in a certain direction and that of an equivalent ellipse:

$$AI = \sum_{\theta=0}^{355} \frac{|R_\theta - R_{EE\theta}|}{R_{EE\theta}} \quad (1)$$

where AI stands for the angularity index, R_θ is the radius of the particle at an angle of θ, $R_{EE\theta}$ is the radius of the equivalent ellipse at an angle of θ (*11*). The equivalent ellipse has the same major and minor axes as the particle, but has no angularity.

4.3.3 Form Analysis

Information about the three dimensions of a particle; longest dimension (d_L), intermediate dimension (d_I), and shortest dimension (d_s) is essential for proper characterization of the aggregate form. As mentioned earlier, the thickness is measured using the auto focus microscope and gray images. The major and minor axes on black and white images of aggregate projections are determined using eigen vector analysis of aggregate boundary (*14*). There have been several indices proposed for measuring form based on these three dimensions such as Sphericity and Shape Factor:

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

$$\text{Shape Factor} = \frac{d_s}{\sqrt{d_L . d_I}} \tag{3}$$

The above two equations are used in this study to calculate aggregate form based on the three-dimensional analysis of aggregates.

The form index, proposed by Masad et al. *(11)*, was used here to quantify a particle form in two dimensions. This index uses incremental change in the particle radius. The length of line that connects the center of the particle to the boundary of the particle is the radius. The form index is expressed by the following equation:

$$\text{Form Index} = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{\left|R_{\theta+\Delta\theta} - R_\theta\right|}{R_\theta} \tag{4}$$

where θ is the directional angle, and R is the radius in different directions. By examining Eq. 4 we can see that if the particle were a perfect circle the form index would be zero.

4.4 ANALYSIS OF FINE AND COARSE AGGREGATE SHAPE

The fine aggregates analyzed in this study had a wide range of compositions and sizes. Most of these aggregates were used previously in laboratory experiments to determine the influence of aggregate shape on HMA performance. Table 1 shows these aggregates along with their main composition, and performance data.

The first group of aggregates consists of aggregate samples used in an experiment conducted by the Joint Transportation Research Program (JTRP) at Purdue University (*21*). Asphalt mixtures were designed using the same crushed gravel coarse aggregate. All gradations had a 9.5mm nominal maximum aggregate size. The Purdue University wheel-tracking device (PURWheel) was used to evaluate the rutting resistance. Failure was defined as the number of wheel passes to produce a rut depth of 6.45mm. It is noted that two fine aggregate samples that were examined in the JTRP study are not included here. One of these aggregates was used in an HMA that had distinctly different gradation from the other mixes, while the other one had very high void in mineral aggregate (VMA) compared with the rest of the mixes. These two factors have been shown by the JTRP study to overshadow the effect of aggregate shape on performance (*21*).

The second group consists of six fine aggregates that were used in an experiment conducted at Texas Transportation Institute (TTI) to relate fine aggregate properties to the rutting potential of asphalt mixes measured using the asphalt pavement analyzer (APA) (*22*). All mixes were designed to conform to the Superpave mix design criteria. Crushed limestone coarse aggregates of same gradations were used in all mixtures. The APA monitors the rut depth as a function of the load cycles. The final rut depth was taken after 8000 load cycles.

The angularity analysis of fine aggregate was done using the radius and gradient methods explained earlier. The analysis yields the angularity value for each particle in the sample. For example, Figure 5 shows the angularity distribution of natural rounded sand and crushed sand. The average and standard deviation values for fine aggregate angularity using the gradient and angularity methods are shown in Table 2. These statistics are calculated from about 50 particles from each sample.

The correlation between the results of the angularity analysis of fine aggregates FA-1 to FA-7 with HMA rutting resistance under wet conditions from the JTRP study is shown in Figure 6. There is a good correlation between gradient method and the performance data for these aggregates when FA-3 is excluded. Also, a good correlation exists between the radius method and the performance data.

The second study conducted by TTI used fine aggregates FA-8 through FA-13. The correlation of the performance data to the angularity results can be seen in Figure 7. The correlation between the gradient method and performance is marginal. On the other hand, the correlation between the radius method and the performance is reasonable.

It should be noted that the correlations were done with and without FA-9. According to the mix performance data, mixes with FA-9 behaved similar to those with natural sand, FA-13. However, by comparing the angularity values in Table 2, it can be seen that FA-9 has much high texture and angularity than FA-13. The distribution of angularity in these two aggregates adds more information on their differences. FA-9 had a small percentage of particles (about 25%) that had an extremely high angularity, while the rest of particles had low angularity. However, FA-13 exhibited a more uniform distribution of angularity values in comparison to FA-9. Further analysis is needed to investigate the influence of angularity distribution on performance.

Nine coarse aggregates were obtained from a study conducted at the National Center for Asphalt Technology (NCAT) (*23*). These aggregates were used in asphalt mixes with the same gradation, and natural rounded sand. The mix properties and the performance data for these aggregates can be found in Table 3. The gradation was below the Superpave restricted zone to maximize the amount and effect of the coarse aggregate. The Superpave volumetric mix design was used to determine the optimum asphalt content for all mixes. The resistance of these mixes to permanent deformation was measured using the Georgia Wheel Tracking Device (GWTD) (*23*).

As mentioned earlier, the Wavelet analysis yields different levels of energy signatures that correspond to different levels of gray scale variations. The energy signature analysis was done here using level six following the recommendations of Fletcher et al. (*6*) who found this level to capture the actual texture with minimal influence of the aggregate color variations. A comparison of the texture distribution for natural rounded gravel and blast furnace slag can be found in Figure 8. Table 4 shows the mean and standard deviation of the texture measurements using AIMS. Approximately twenty-five aggregate particles were used to determine these statistics for each sample. Figure 9 shows that there is a good correlation between the texture measurements and the permanent deformation performance. Figure 9 also shows that the correlation dropped with the inclusion of CA-6. As reported by Kandhal and Parker (*23*), the mix that included CA-6 had high VMA which shadowed the influence of the aggregate texture.

The angularity analysis was done on black and white images. The mean and standard deviations for the gradient and radius methods for these aggregates can be found in Table 4. There was poor correlation between the gradient and radius methods and performance as can be seen in Figure 10. There was a slight increase in the correlation when CA-6 was excluded.

A sample of coarse aggregates was selected and the dimensions of particles were measured using a digital caliper. Then, the Sphericity and Shape Factors were calculated based on the manual and AIMS measurements. Figure 11 shows good correlations between the manual and AIMS measurements of

Sphericity and Shape factor. AIMS tends to slightly underestimates the shape factor compared with the manual measurements.

5. PLANS FOR IMPLEMENTATION

Measuring the fundamental shape properties of aggregates using an automated system will yield significant and immediate benefits to the transportation practice. These benefits will be realized in two main areas of pavement engineering. The first area is incorporating aggregate shape properties into the design procedure of hot mix asphalt. The aggregate properties control their interaction with the asphalt binder, and consequently influence the design of mix volumetrics. The second area is the quality control/assurance of aggregates. The system will offer an automated method of enforcing aggregate shape specifications and ensuring consistent properties. Consequently, it will contribute to the creation of higher-quality and longer-lasting pavements, with large savings due to reduced requirements for maintenance and rehabilitation.

The development of AIMS has already drawn significant interest from both government and private industry. The following activities demonstrate the great interest in AIMS:

- The Federal Highway Administration (FHWA) is in the process of acquiring AIMS in their mobile laboratory. AIMS will be used to measure the aggregate shape properties used in a wide range of asphalt mixes. The results will be used in verifying the mechanical properties of asphalt mixes measured using the performance tests of asphalt mixes. Also, the FHWA will evaluate the capabilities of AIMS as standard laboratory equipment for measuring aggregate shape properties.
- AIMS has already been used in a number of studies sponsored by the International Center for Aggregate Research (ICAR) to relate the shape properties of aggregates to the mechanical properties of pavement layers.
- Research and technical papers on AIMS has been presented to a wide range of audience in the transportation community. These technical papers were published by the Transportation Research Board (TRB), the American Society of Testing and Materials (ASTM), and the American Society of Civil Engineers (ASCE). In addition, several presentations have been delivered about AIMS to ICAR, technical committees of the TRB, and the TRB Superpave Mix/Aggregate expert task group.

The technical publications and presentations related to AIMS are:

Chandan, C. *Geometry Analysis Of Aggregate Particles Using Imaging Techniques,* M.Sc Thesis, School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA., 2002.

Chandan, C., Sivakumar, K., Masad, E., and Fletcher, T. "Geometry Analysis Of Aggregate Particles Using Imaging Techniques," Journal of Computing in Civil Engineering, ASCE. 2002.

Fletcher, T. *Aggregate Imaging System for Characterizing Fine and Coarse Aggregate Shape*, M.Sc Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA., 2002.

Chandan, C., Sivakumar, K., Masad, E., and Fletcher, T. (2002). "Geometry Analysis of Aggregate Particles Using Imaging Techniques," Journal of Computing in Civil Engineering, A Special Issue on Applications of Imaging Technologies in Civil Engineering Materials.

Fletcher, T., Chandan, C., Masad, E., and Sivakumar, K. (2002). "Aggregate Imaging System (AIMS) for Characterizing the Shape of Fine and Coarse Aggregates," Transportation Research Record, Journal of the Transportation Research Board.

Fletcher, T., Chandan, C., Masad, E., Sivakumar, K. (2001). "Measurements of Aggregate Texture and its Influence on HMA Permanent Deformation," *Journal of Testing and Evaluation, American Society for Testing and Materials, ASTM,* Vol. 30, No. 6.

Masad, E., and Fletcher, T. "AIMS: Aggregate Imaging System for Characterizing the Shape of Coarse and Fine Aggregates," *Proceedings of the 10th Symposium of the International Center for Aggregate Research*, Baltimore, MD. (CD Publications).

Masad, E. (2002). "Aggregate Imaging System (AIMS)", *The Transportation Research Board, Superpave Mixture/Aggregate Expert Task Group,* August 28-29, Minneapolis, MN.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

Aggregate shape characteristics are important factors that affect the performance of the HMA. In asphalt pavements, the aggregate shape properties have been correlated with permanent deformation, fatigue resistance, shear resistance, and skid resistance of the pavement. The critical aggregate properties that affect the performance of the pavement are form, angularity, and surface texture. These properties all contribute to making a strong pavement.

The current Superpave system describes aggregate shape using three tests. These tests are the fine aggregate angularity (Method A of AASHTO Standard T304), coarse aggregate angularity (ASTM Standard D5821), and the relative dimensions of the coarse aggregate to identify the flat-elongation particles (ASTM Standard D4791). There is a debate over the ability of these tests and their ability to predict the desired aggregate shape property.

Recent experiences show that the fine aggregate angularity test cannot discern between poor quality and high quality aggregates. This is due to the fact that the packing properties of aggregate are not only a function of the angularity, but also a compilation of several aggregate properties including surface texture, form, and gradation. Furthermore, Superpave tests for measuring coarse aggregate properties are laborious, and limited to the ability to test a representative sample. The final limitation to the current Superpave aggregate shape tests prescribes of two distinct and unrelated tests to measure the angularity of coarse and fine aggregates. As a result, quantifying the overall effect of angularity on pavement performance is not feasible. In addition, the test for measuring coarse angularity is a subjective test based on visual inspection. Automated aggregate image analysis is becoming a popular way of measuring the aggregate shape properties fast and accurately, meanwhile eliminating the subjectivity.

This study presents the design and development of a unified computer automated system for characterizing the shape and gradation of aggregates. The system, referred to as AIMS, was developed to have the ability to capture images and analyze the shape of a wide range of aggregate sizes.

The report describes the experimental considerations that formed the basis for the system's design and its unique features. These considerations include the type of lenses, image resolution, field of view, and lighting scheme with respect to the aggregate size, and the shape characteristic under consideration (form, angularity, and texture).

The most important advantages of the system include the ability to analyze form, angularity, and texture of a wide range of aggregate sizes, conducting three-dimensional analysis of form through the use of a single camera, and measuring texture on gray scale images. A program was developed using LABVIEW to control the motion of the system in the x, y, and z directions, the auto focusing, and image acquisition.

The image analysis software developed is capable of determining the aggregate shape properties of each aggregate. This includes the minimum, intermediate, and maximum dimensions of the particles. These dimensions are used to calculate the shape factor and sphericity index, which are both indicators of form. The main advantages of the texture analysis is its ability to capture the different sizes of texture elements, separating the true texture from the color variations on aggregate surface, and applicability to characterize fine and coarse aggregates. The angularity is analyzed using two methods. The first method is based on the changes of the gradient on aggregate boundary. The second is based on the variation of aggregate radii with direction. The thrust of the development of the image analysis software was documented by Chandan (2002).

The capabilities of AIMS were demonstrated using twenty-one fine aggregate samples and nine coarse. Thirteen of the fine aggregate samples and all of the coarse aggregate samples had known laboratory performance data. The following section highlights the main conclusions from the analysis of the aggregate shape using AIMS.

6.2 CONCLUSIONS

This study presents the design and development of a unified computer automated system (AIMS) for characterizing aggregate shape. Several experimental considerations formed the unique features of the system including the selection of the lenses, image resolution, field of view, and lighting scheme depending on the aggregate size, and the shape characteristic under consideration (form, angularity, and texture).

AIMS has the ability to analyze the shape of fine and coarse aggregates. It measures the three-dimensions of form through the use of a single camera and autofocus microscope. Aggregate texture is quantified by analyzing gray scale images, and angularity is quantified by analyzing black and white images. A program was developed for controlling the motion of the system in the x, y, and z directions, auto focusing, and image acquisition. In addition, user-friendly software was developed to analyze aggregate images.

The capabilities of AIMS were demonstrated by measuring the shape of thirteen fine aggregate samples and nine coarse aggregate samples. All these aggregates were used in asphalt mixes with known laboratory performance. The angularity analysis of fine aggregates using the radius method had a reasonable correlation with the mix performance data. However, the results show clearly that using only an average angularity value might not be sufficient to capture performance. More statistical analysis is needed to determine the influence of angularity distribution on performance.
There was a strong correlation between the coarse aggregate texture and the performance of asphalt mixes. The coarse aggregate angularity, however, had poor correlation with the performance of asphalt mixes. The three-dimensional analysis of form using AIMS had excellent correlation with manual measurements using a digital caliper.

6.3 RECOMMENDATIONS

It is recommended that a number improvements to be done on AIMS to enhance its capabilities. The first one is to improve the top and bottom light uniformity throughout the experiment irrespective of the location of aggregates on the table. For the top lighting, it is recommended to use a ring light source that can be connected to the microscope. This would ensure uniform top lighting on each coarse particle. Also, a bottom lighting that would provide a uniform intensity should be used. Another improvement has to do with small size of aggregate sample that the system can analyze in each experiment. A mechanism should be installed in the system to provide a continuous feed of aggregates.

The findings of this research show that the correlation between the fine aggregate and performance is reasonable. However, all comparisons are based on average shape properties. More statistical analysis should be done to find the influence of the shape distribution within a sample on performance, and to determine if other statistical parameters besides the average value have better correlation with performance. In this study, there were only thirteen mixes with laboratory performance data. A more in depth study of the correlation of the AIMS results with asphalt mix laboratory and field performance is needed.

7. INVESTIGATOR PROFILE

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Dr. Masad is an assistant professor of civil engineering at Washington State University (WSU). His primary area of research is characterization and modeling of highway materials including unbound aggregates, asphalt mixes, and cement concrete. He has conducted several studies related to the development of methods for characterizing aggregate characteristics. He is currently conducting studies to evaluate the influence of aggregate characteristics on cement concrete and hot mix asphalt. He is conducting a study sponsored by the NCHRP (NCHRP4-30: "Test Methods For Characterizing Aggregate Shape, Texture, And Angularity"). Dr. Masad has also conducted several studies related to performance of asphalt mixes, permeability of pavement systems, and mechanical properties and durability of Portland cement concrete. Sponsors of his research include the National Science Foundation, National Cooperative Highway Research Program, Federal Highway Administration, International Center for Aggregate Research, the Asphalt Institute, Washington State Department of Transportation, Idaho Transportation Department, as well as private industrial firms.

Dr. Masad is an active member of the American Society of Civil Engineers (ASCE), Association of Asphalt Paving Technologists (AAPT), and American Society of Engineering Education (ASEE). He is a member of TRB committee A2J03, and a friend of TRB committees A2DO2, A2D03, and A2D04. He is also the vice chair of the pavement committee of the Geo-Institute, ASCE. He is a member of the technical advisory committee of the International Center for Aggregate Research (ICAR). He is the recipient of the Eisenhower Graduate Research Fellowship at Turner-Fairbank Highway Research Center for the year 1997, and the Faculty Eisenhower fellowship in Transportation Engineering for the year 1998. He is also the recipient of the W. J. Emmons award for the best paper published in the Journal of the Association of Asphalt Paving Technologists (AAPT) for the year 2001

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TABLE 1 Summary of Fine Aggregate Angularity (FAA), Mix Properties, and Performance Data of Fine Aggregates.

Label	Description		Mix Properties			Performance
		FAA	VMA	VTM	AC	Data
Source of Data: Reference 921)						
FA-1	Crushed Gravel Sand	49.00	15.0	4.0	5.4	131539[a] 12424[b]
FA-2	DolomiteSand	48.00	15.3	4.0	5.0	43709[a] 14191[b]
FA-3	Limestone Sand	45.00	15.1	4.0	5.3	53063[a] 18282[b]
FA-4	Natural Sand (NS)	39.00	12.4	4.0	4.4	8169[a] 2938[b]
FA-5	26% of (4) & 74% (1)	46.00	15.0	4.0	5.5	73366[a] 11910[b]
FA-6	36% of (4) & 64% of (1)	45.00	14.8	4.0	5.3	69115[a] 9213[b]
FA-7	56% of (4) & 44% (1)	43.00	14.4	4.0	5.0	51228[a] 7656[b]
Source of Data: Reference (22)						
FA-8	Crushed Limestone	43.50	14.8	3.73	4.8	4.4[c]
FA-9	Crushed River Gravel	44.30	14.7	4.03	5.6	9.1[c]
FA-10	Crushed Granite	48.00	14.8	3.73	5.2	4[c]
FA-11	85% Granite 15% NS	46.00	14.8	3.80	5.6	5.3[c]
FA-12	70% Limestone 30% NS	42.20	11.9	4.0	4.2	5.2[c]
FA-13	Natural Sand (NS)	39.00	11.4	4.37	3.8	9.2[c]

[a] Purdue Wheel Passes to 6.45 mm rut depth under dry conditions
[b] Purdue Wheel Passes to 6.45 mm rut depth under wet conditions
[c] Rut Depth in mm from the APA

TABLE 2 Mean and Standard Deviation of the Angularity Analysis of Fine Aggregate.

	Gradient Method		Radius Method	
	Average	Standard Deviation	Average	Standard Deviation
FA-1	4499	1448	9.442	3.183
FA-2	4671	1588	9.574	2.740
FA-3	3954	1363	9.792	5.392
FA-4	3863	1232	7.704	4.325
FA-5	4700	1894	9.552	5.045
FA-6	4313	4313	8.711	2.982
FA-7	4243	1371	8.888	4.597
FA-8	4321	1232	8.632	3.411
FA-9	4670	919	9.723	2.244
FA-10	5768	1170	8.758	1.654
FA-11	5628	5628	8.819	2.287
FA-12	4092	1350	8.401	4.147
FA-13	3527	1144	7.276	3.113

TABLE 3 Summary of Mix Properties, and Performance Data of Coarse Aggregates.

Source of Data: Reference (23)					
	Description	Mix Properties			Performance Data
Label		VMA	VTM	AC	Rut Depth[a] (mm)
CA-1	Round Natural Gravel	12.8	3.9	4.1	8.82
CA-2	Crushed Gravel	14.0	3.9	4.5	8.30
CA-3	Crushed Gravel	15.5	3.7	5.6	7.34
CA-4	Sandstone	13.8	3.3	5.7	6.48
CA-5	Limestone	15.2	4.0	4.75	6.87
CA-6	Dolomite	13.5	3.5	4.2	5.10
CA-7	Granite	16.2	4	5.25	6.35
CA-8	Siltstone	19.2	4	6.9	8.23
CA-9	Blast Furnace Slag	15.3	3.9	8.5	4.41

[a] Rut Depth in mm from GWTD

TABLE 4 Mean and Standard Deviation for Shape Analysis of Coarse Aggregates.

	Energy Signature		Gradient Method		Radius Method (Angularity Index)	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
CA-1	120.85	96.08	4034.20	770.91	6.873	1.816
CA-2	124.77	95.14	3987.78	744.10	7.339	1.548
CA-3	500.84	285.29	4153.32	819.54	7.512	2.532
CA-4	650.57	357.38	4202.79	748.53	7.080	1.554
CA-5	590.30	235.30	4167.38	803.66	8.264	1.677
CA-6	388.13	245.47	3537.78	579.72	7.900	1.452
CA-7	536.99	301.55	4848.35	919.23	9.264	2.300
CA-8	270.59	226.47	4671.14	792.37	8.859	2.804
CA-9	882.75	479.59	4689.75	728.65	8.350	1.784

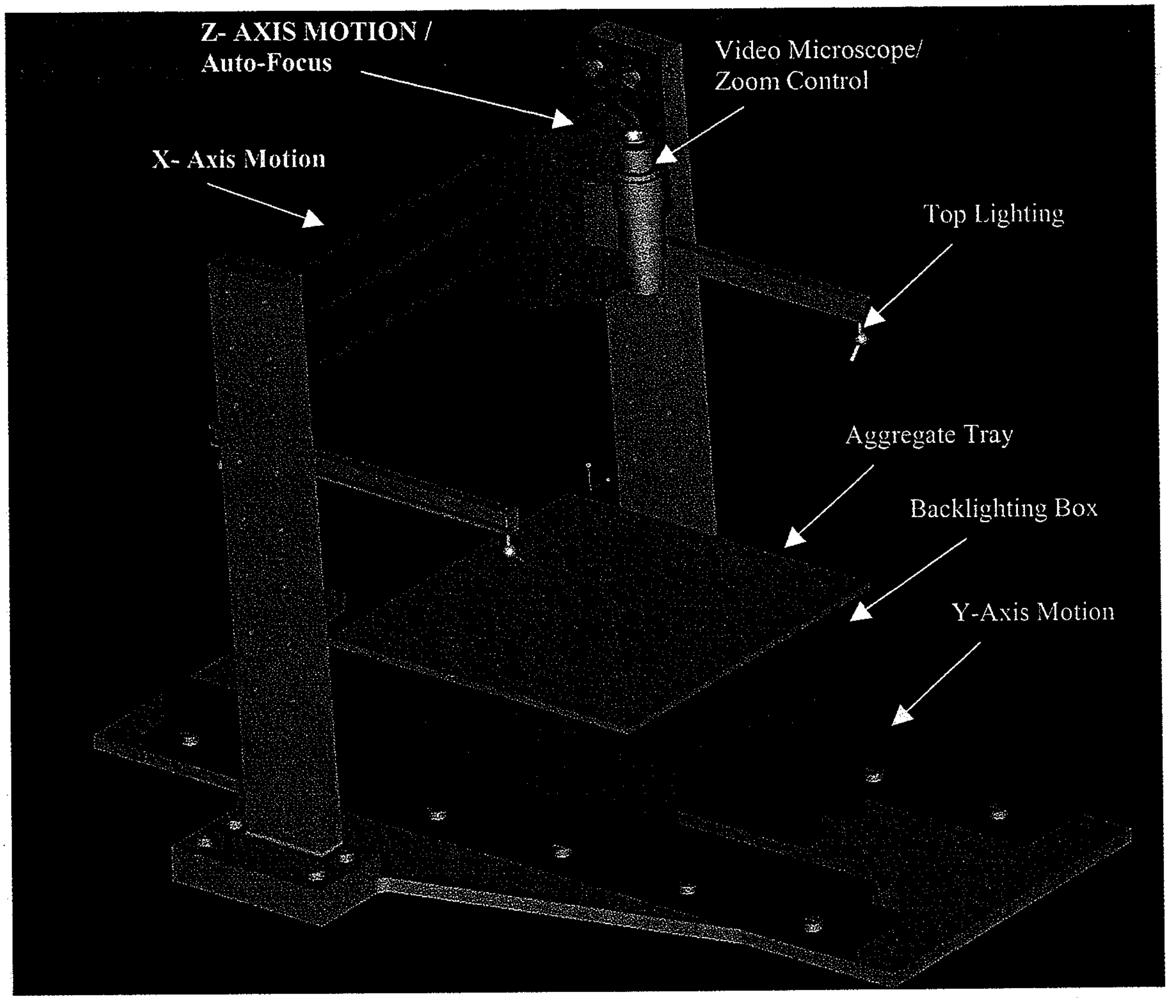


FIGURE 1 3-D Graphical Model of AIMS.

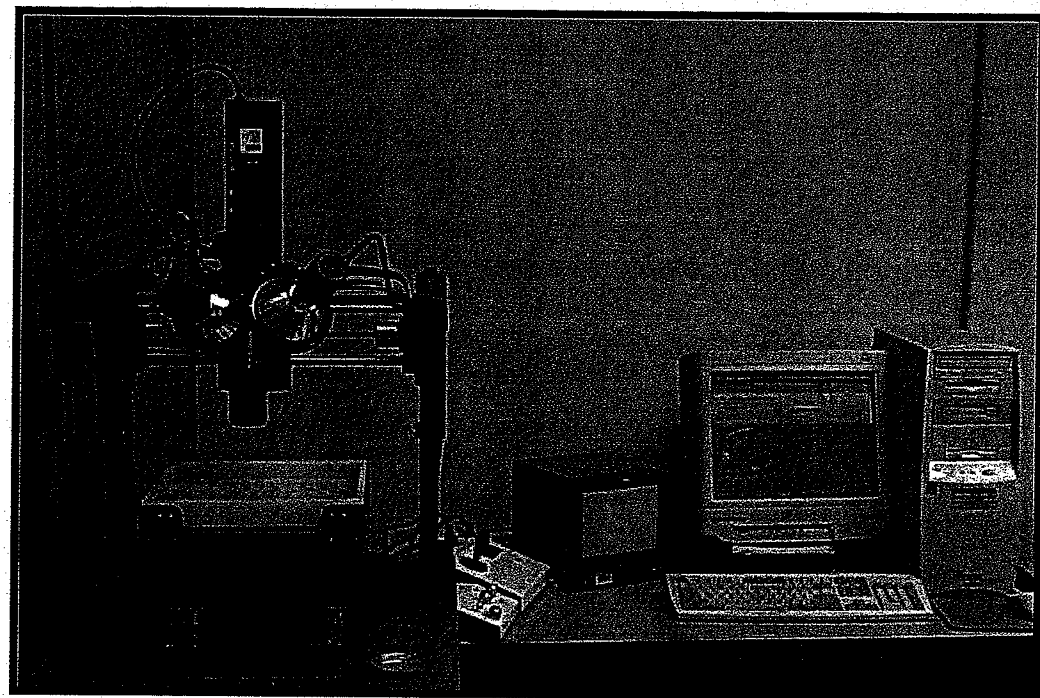
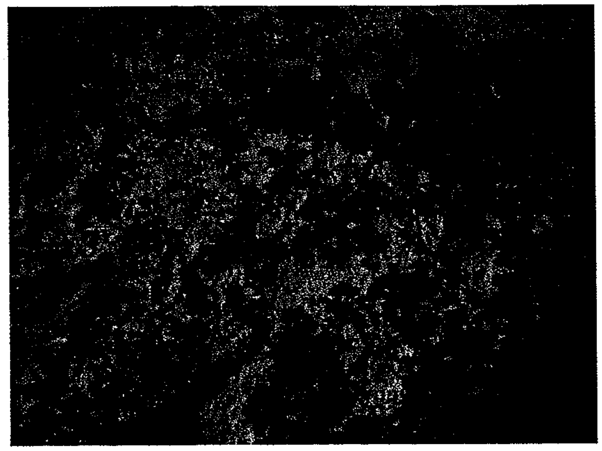
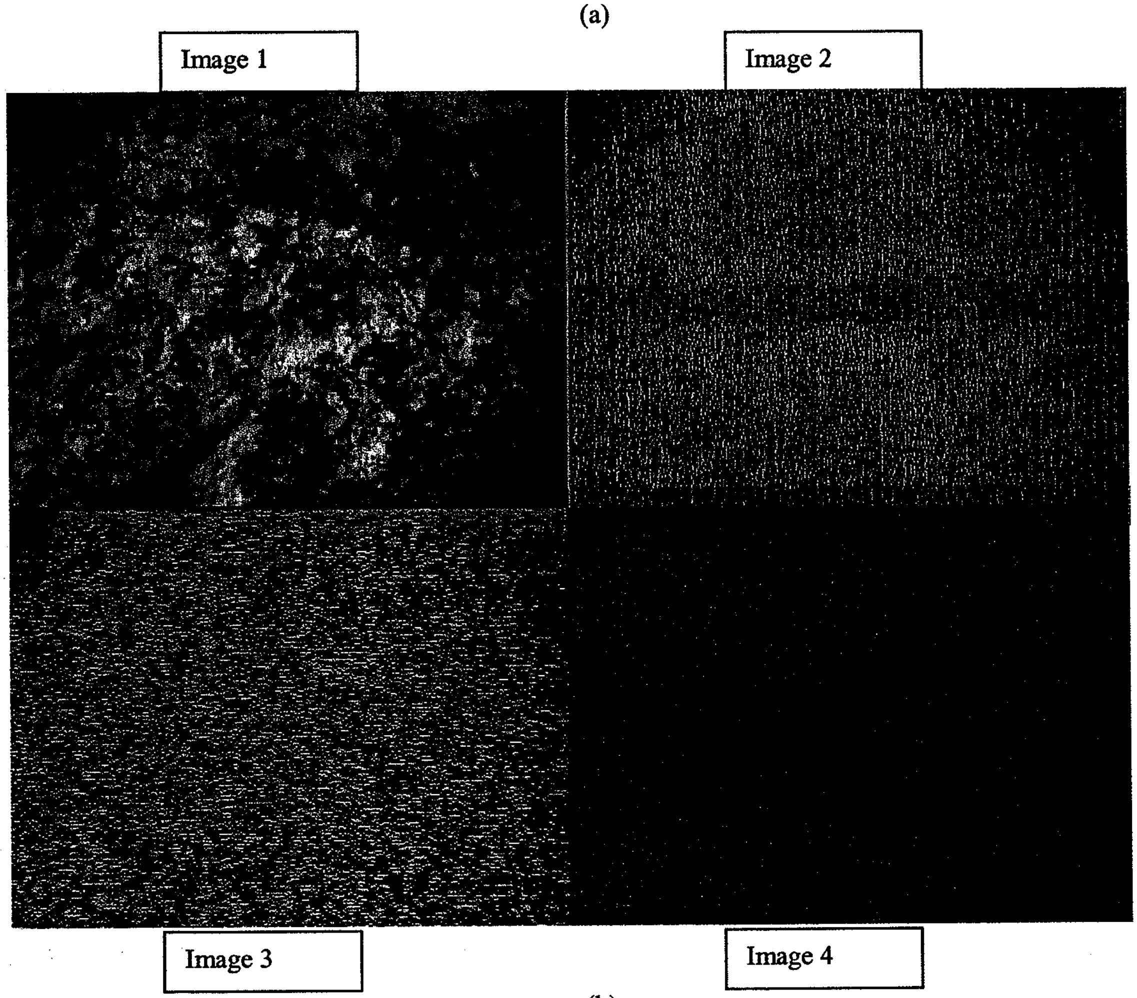


FIGURE 2 A Picture of the AIMS System.



(a)



(b)

FIGURE 3 Illustration of the Wavelet Decomposition.

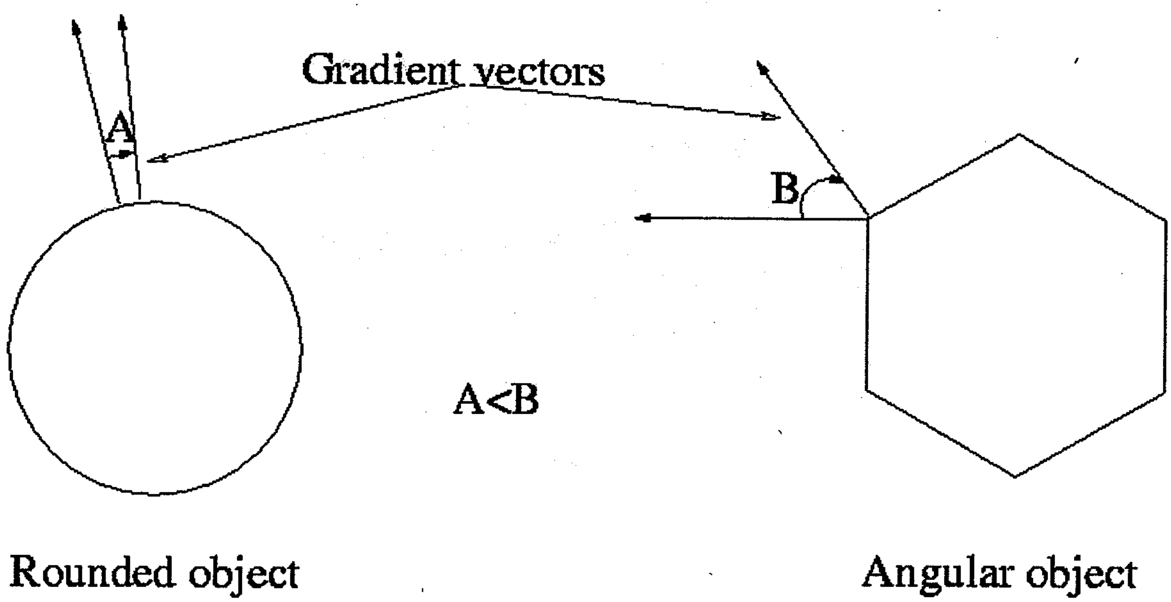


FIGURE 4 Illustration of the difference in gradient between particles.

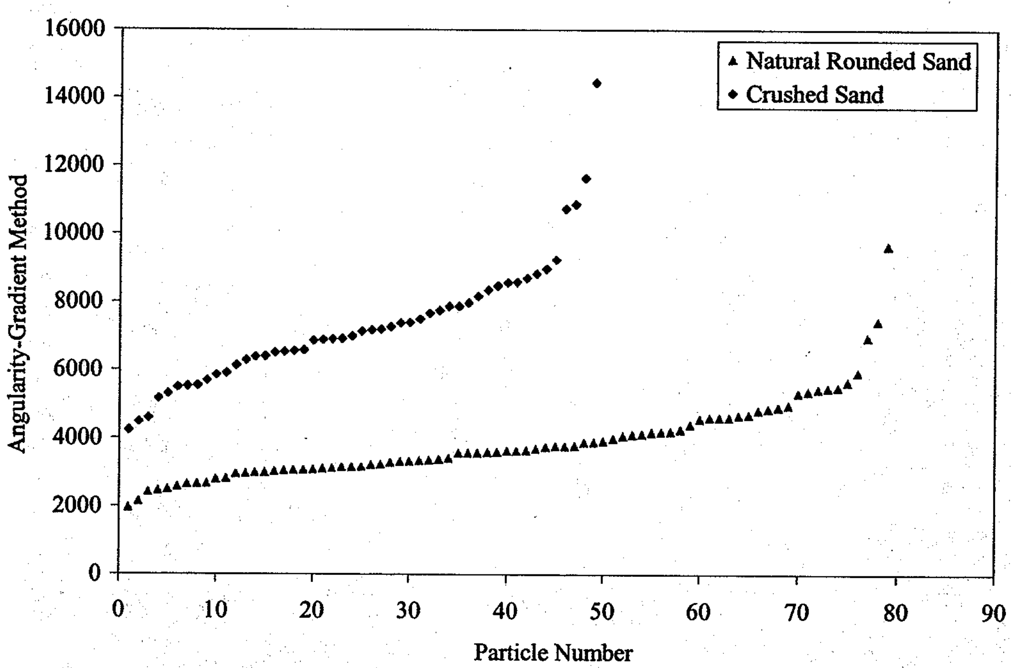
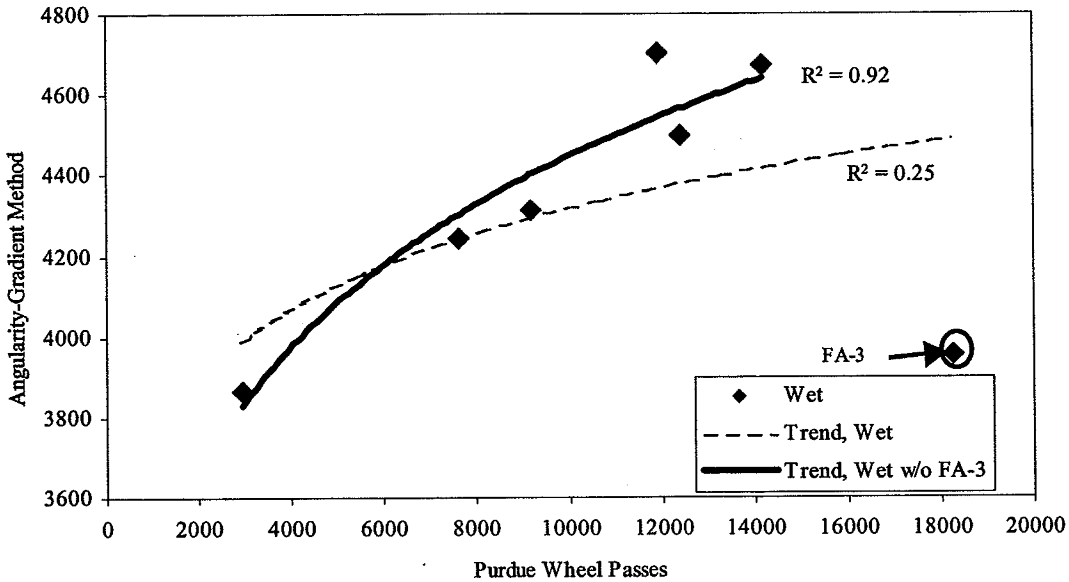
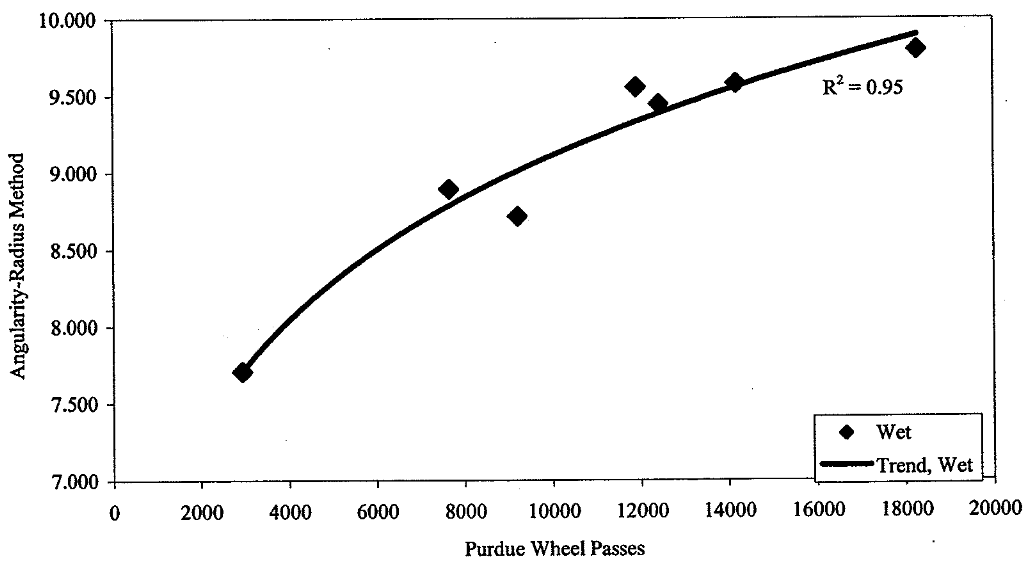


FIGURE 5 Comparison between the Angularity Distribution of Natural Sand and Crushed Sand.

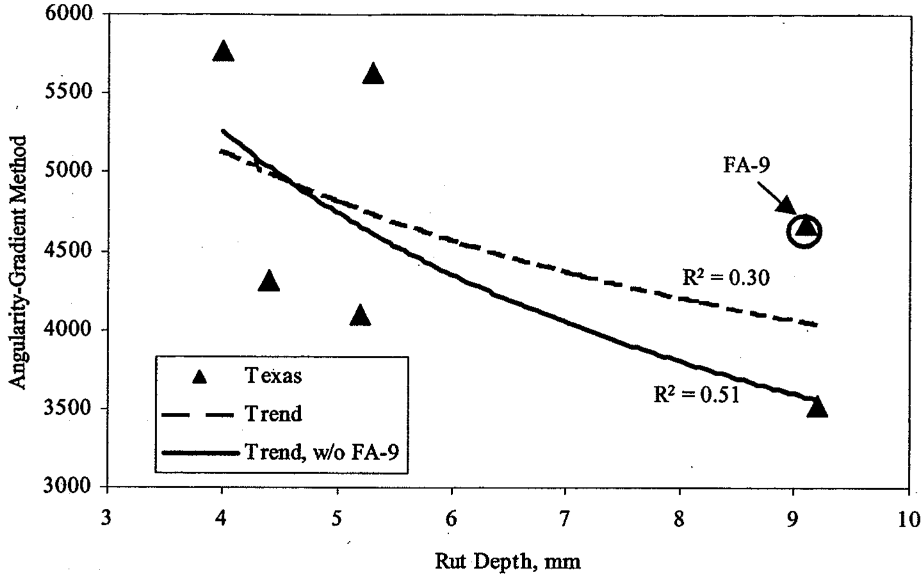


(a) Gradient Method.

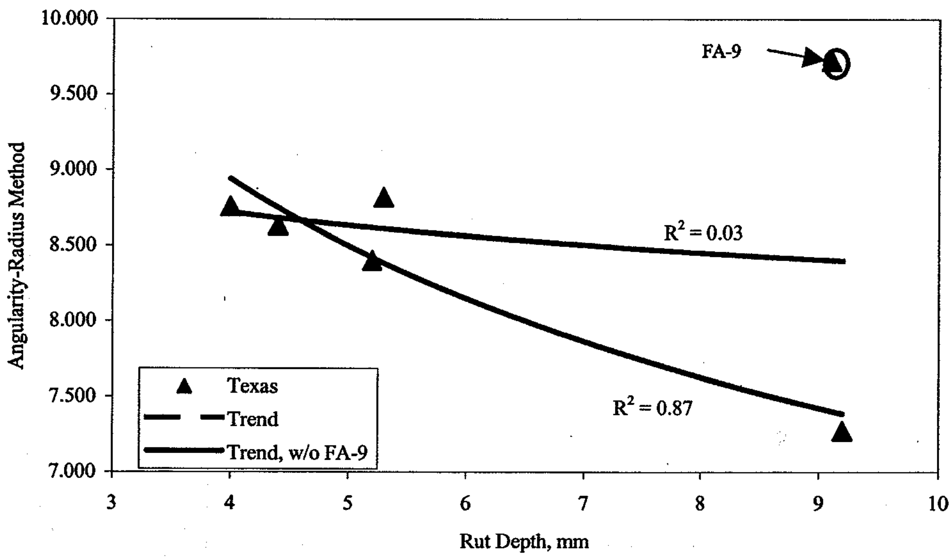


(b) Radius Method.

FIGURE 6 Correlations between Performance of JTRP Fine Aggregates and Angularity.



(a) Gradient Method



(b) Radius Method

FIGURE 7 Correlations between Performance of TTI Fine Aggregates and Angularity.

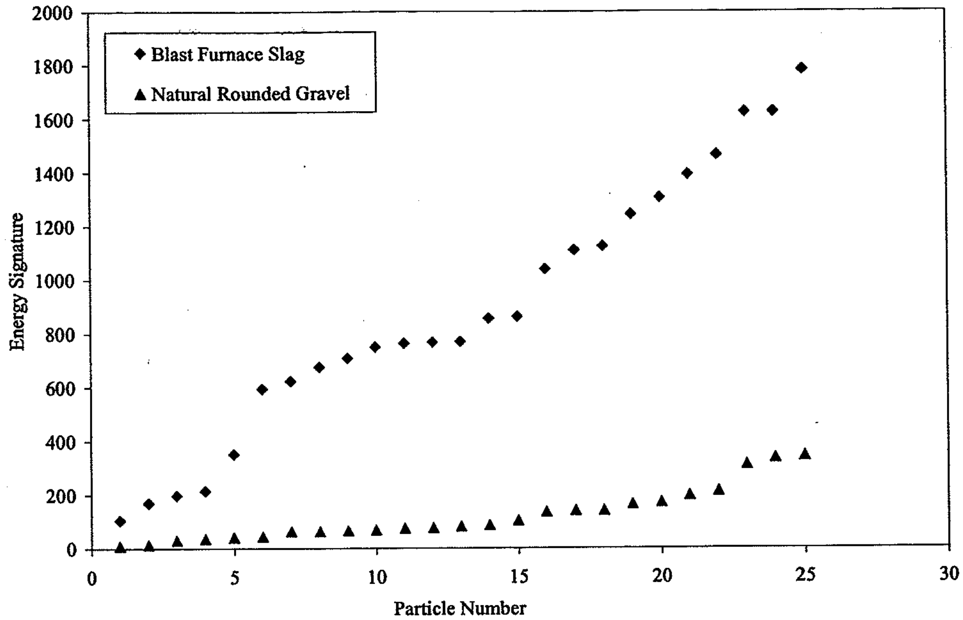


FIGURE 8 Comparison between the Texture Distribution of Blast Furnace Slag and Natural Rounded Gravel.

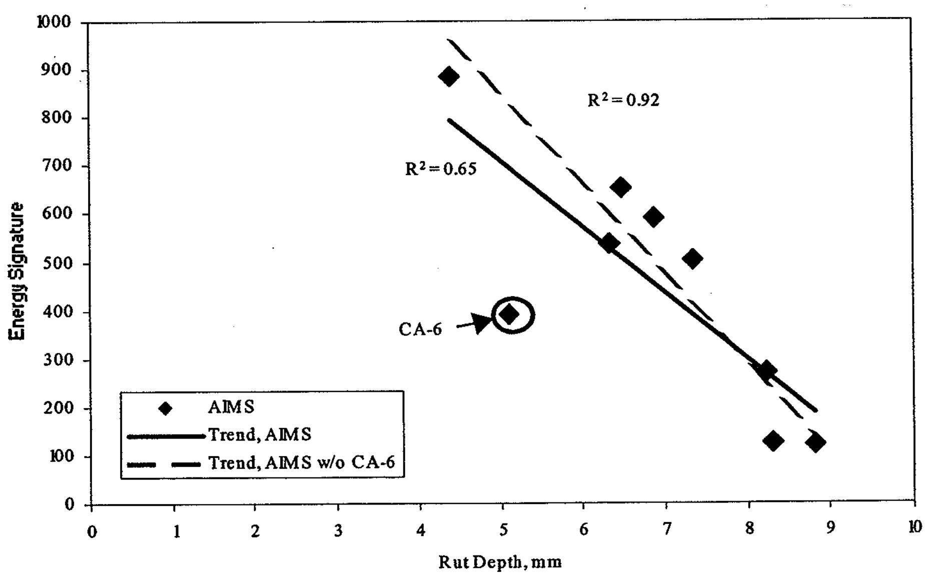
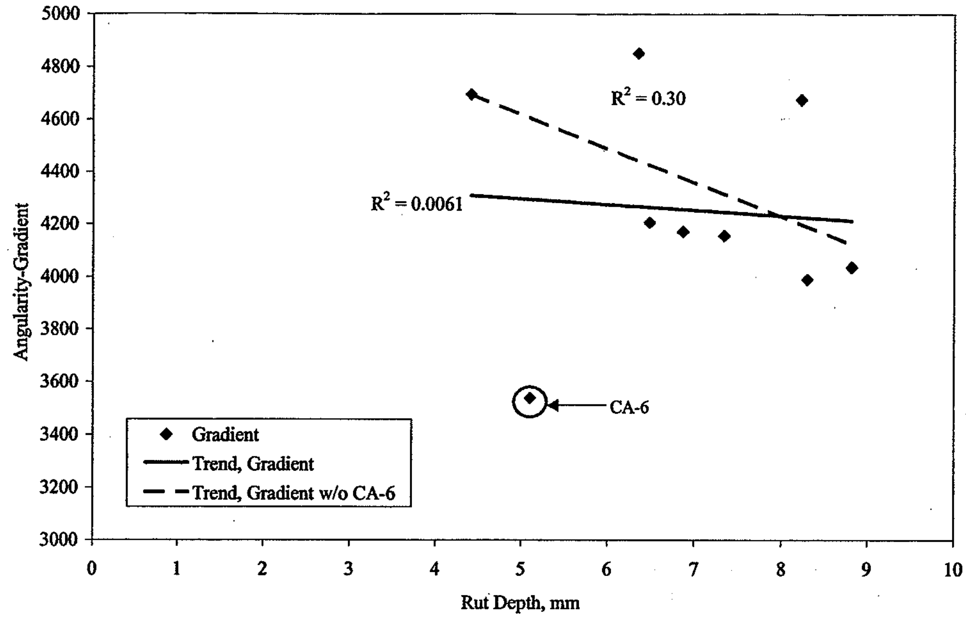
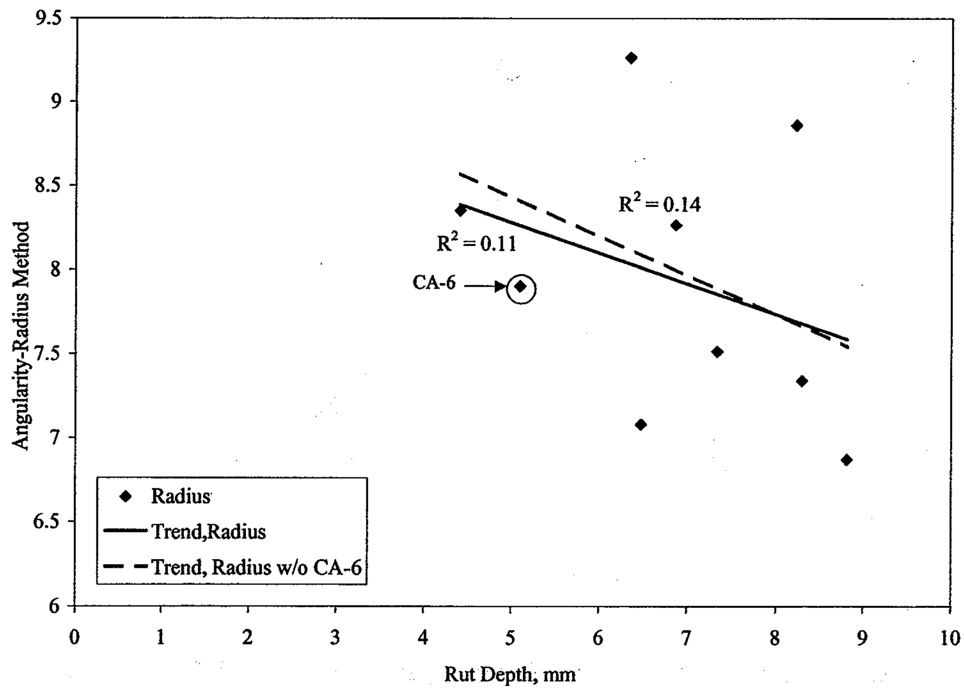


FIGURE 9 Correlation of Energy Signature of Coarse Aggregate with GLTW Rut Depth.

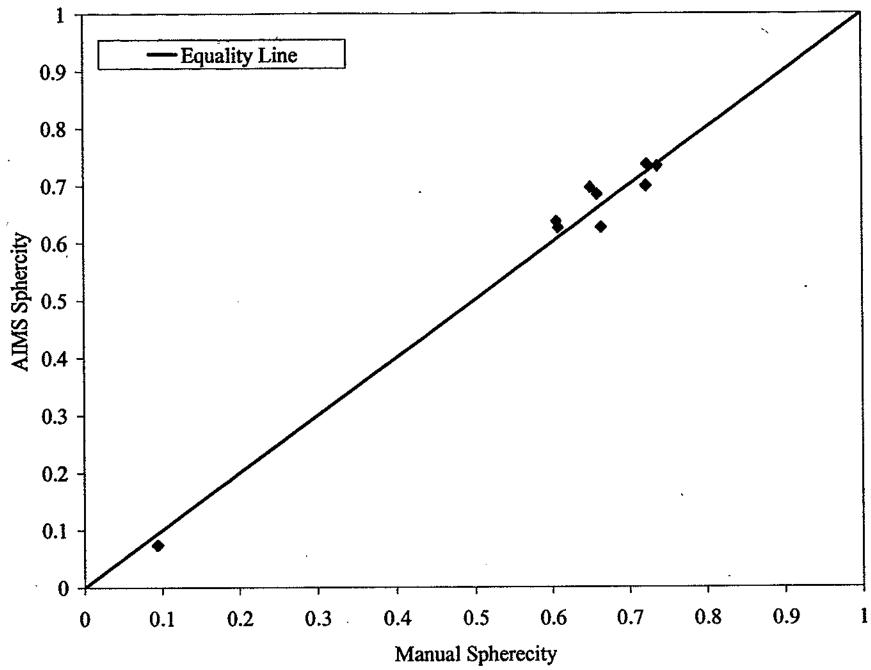


(a) Gradient Method

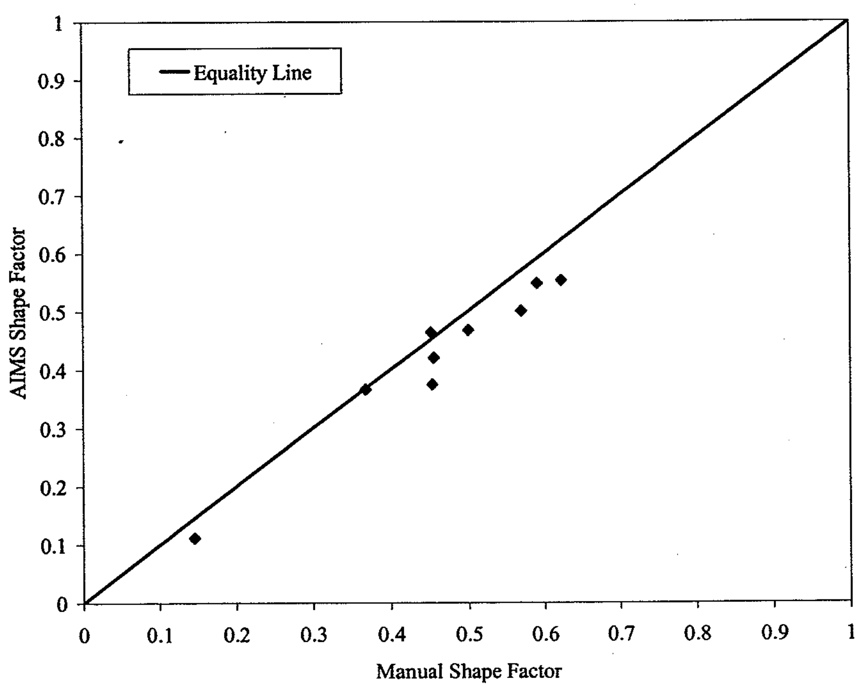


(b) Radius Method

FIGURE 10 Correlations between Performance of NCAT Coarse Aggregates and Angularity.



(a) Shape Factor.



(b) Sphericity

FIGURE 11 Correlation between Manual and AIMS Measurements of Form.