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Determination of Volume of Aggregates
New Image-Analysis Approach

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The importance of using quality aggregates with specific gradation and shape properties in asphalt concrete has been recognized by the Strategic Highway Research Program under a set of developed consensus aggregate properties. The flat and elongated ratio and angularity of the aggregate particles are those properties that directly influence the rutting potential of an asphalt pavement. Along with a need to develop rapid and automated methods for determining flat and elongated ratios of individual aggregate particles, there is also a need to develop an accurate and repeatable experimental technique. A new aggregate image analyzer has been recently developed at the University of Illinois that uses three video cameras for accurately determining the volume of each aggregate and for automating the determination of flat and elongated particles, angularity, and gradation. A new image-analysis approach determines the percentage by weight of the flat and elongated particles providing results comparable to the manual results from ASTM D4791 by presenting the results as ratios of weights. The significance of making such accurate volume computations of an individual aggregate using images is discussed. The computed aggregate volumes and the percentages by weight of flat and elongated ratios obtained for two bag samples were in very good agreement with the manual measurements, thus validating the correctness of the imaging technique and the effectiveness of the new aggregate image analyzer.

Aggregate particle shape, size, and gradation can impact the performance of asphalt-concrete (AC) pavements (*1–3*). In AC mixtures, the shape of aggregate particles has been related to permanent deformation, fatigue resistance, and skid resistance of the pavement. Additionally, it affects the workability and optimum binder content of the mixture. AC properties that are affected include stiffness, stability, durability, permeability, resistance to moisture damage, and air voids in the mix. To design asphalt mixtures with long service lives, the aggregates must have the proper gradation and shape. The gradation, shape, and hardness have by far the greatest influence on the mechanical behavior and the strength properties of aggregate particles in contact. In general, it is preferable to have somewhat equidimensional rather than flat, thin or elongated particles (*4*).

The Strategic Highway Research Program has developed a set of consensus properties to identify proper aggregates for Superpave mix designs (*1*). This set includes the following properties: coarse aggregate angularity; fine aggregate angularity; flat and elongated ratios of coarse aggregate particles; and clay content. Coarse aggregate angularity is determined manually by counting the number of fractured faces. Fine aggregate angularity is obtained from a simple test in which a sample of fine aggregate is poured into a small, calibrated cylinder through a standard funnel. Gradation is determined through sieve analysis, and clay content must be determined through hydrometer testing A proportional caliper is normally used to determine the shape of the aggregate particles: flatness and elongation (*5*). The manual processes used primarily for determining the flat and elongated ratios, as percent by weight, and the aggregate angularity are very tedious and time consuming to be used on a daily basis for quality control. A faster method is needed to determine the following coarse aggregate properties: flat and elongated ratio, angularity, and gradation.

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The use of video image-analysis techniques for determining aggregate properties has received much attention lately as a more viable and cost-effective alternative. Automated aggregate analysis using video imaging is not only a fast, dependable, and accurate method but also allows personnel more time for other duties. These computerized approaches have proven to be highly time efficient, although there is a fairly large initial cost involved in setting up a system. Nonetheless, the benefit derived from employing a digitized imaging system could recover the initial cost of the investment.

A new aggregate image analyzer has been developed recently at the University of Illinois (U of I) for automating the determination of high-priority aggregate properties (i.e., flat and elongated ratio, coarse aggregate angularity, and gradation). As an improvement over the existing systems, the new U of I Aggregate Image Analyzer uses three video cameras to collect aggregate images from three orthogonal directions. The use of three cameras provides the unique capability of accurately reconstructing the three-dimensional (3-D) shape and hence determining the volume of each aggregate using the three views (top, front, and side) of the particle needed for the flat and elongated ratio determination and gradation analysis.

Preliminary results obtained from processing a typical aggregate bag sample using the U of I Aggregate Image Analyzer are presented in this paper. The image-analysis approach employed for aggregate volume determination is described. The accuracy and repeatability of the imaging technique are evaluated for the computed aggregate volumes and the percent by weight flat and elongated ratios by comparing the results to the manual measurements done for the same bag sample by the Illinois Department of Transportation (IDOT). Additionally, the computed values are compared with U of I measurements and to the results obtained by other image-analysis techniques.

CURRENT SPECIFICATIONS

The Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate is the test procedure generally referenced for determination of the percentages of flat, elongated, or flat and elongated particles in coarse aggregate (ASTM D4791-95). This test method aims at limiting percentages calculated by number or by weight of flat, elongated, or both flat and elongated particles in a given sample. The particles can be classified as flat, elongated, or flat and elongated according to the undesirable ratios of width to thickness, length to width, or length to thickness, respectively. These dimensional ratios may be set at 2:1, 3:1, and 5:1 in the manual caliper by adjusting the fixed position of a swinging arm so that the openings between the arms and the two fixed posts on both ends of the arm maintain a constant ratio (ASTM D4791).

The Superpave specifications characterize an aggregate particle only as flat and elongated by comparing its length to its thickness or the maximum dimension to the minimum one (*1*). Superpave allows no more than 10 percent by weight of flat and elongated particles for the combined aggregate blend used in asphalt pavements having greater than 3 million equivalent single-axle loads in the design life. Different than ASTM D4791, the test is performed on the greater than 4.75-mm (+No. 4) aggregate, and the flat and elongated particles are reported only as percent by weight of particles having a ratio of over 5:1. This is also the case for the modified test procedure being used in Illinois as the percentages of flat and elongated particles are calculated based on weights. Moreover, sieve analysis results are also presented as a function of percentage weight passing on the 0.45-power gradation chart.

In using imaging systems, it is therefore essential to be able to calculate the weights of the particles besides being able to estimate their flat and elongated ratios or their nominal sizes. By first computing the volume of a particle, its weight can be determined knowing its specific gravity. In the next section, the most recent developments in the area of aggregate size and shape quantification using image-analysis techniques are summarized. This is an area that is still in need of significant technological advancement to properly address the important issues of the 3-D aggregate shape analyses, accurate volume determination, and the computation of specific surface area.

PREVIOUS WORK

In the last decade, there have been a growing number of applications incorporated by video imaging techniques (*5–9*). The use of a video-imaging system primarily involves acquiring the image of the particles to be evaluated and then processing it with the use of an image analyzer system. A computer algorithm analyzes the image to estimate the desired information: dimensions and size of aggregate, shape, texture, angularity, and gradation, depending upon the capabilities of the image-analysis algorithm used. Among the concepts that have been used for pattern recognition are the fractal dimension analysis (*5–7*) and the two-dimensional (2-D) to 3-D reconstruction models based on stereology, model shape of choice or geometric probability, and Hough transforms (*8, 9*).

Fractal dimension analysis is based on an algorithm that studies variation in gray scales of the image captured by a camera. Fractals are defined as a family of mathematical functions that describe natural phenomena and shapes. The fractal dimension is the characteristic that defines these fractals. The steps involved in the calculation of the fractal dimension number, a characteristic of the contour of the particle, are explained in detail elsewhere (*3*). The fractal dimension number was found to serve as a practical measure of the shape and texture of a particle. A direct correlation could be established between rutting, percent crushed stone, and asphalt-concrete quality to the shape and texture of the particles. However, this technique has the limitation of being applied to only 2-D measurements, and it assumes that the particle lies on its flattest surface.

Another technique used for recognition of collinearity in pixels that form the particle outline on an image is the mathematical tool Hough transforms. The x and y coordinates corresponding to the image outline of the particle are translated such that the centroid of the area falls on the origin of the new transformed axes. Each point stored on the perimeter of the particle is a 2-D array in its polar coordinates and H denotes the Hough space, containing the arrays for the radial and tangential coordinates, r and θ. The angularity of the particle can be easily determined by detecting and measuring the length of any straight lines in a 2-D image (*8, 9*). Recent research focused on the development of more refined and sophisticated systems that address all issues from building a controlled aggregate transport mechanism for imaging to correlating the features extracted with the asphalt-mix performance. Also included are software development considerations and the insight into pinpointing the exact feature that needs to be analyzed. The Hough transform was ultimately used to determine roundness and angularity of the particle (*9*).

Two commercially available systems, the VDG-40™ and WIPSHAPE™ (modified from the earlier model named WIPFRAG™), have also been evaluated. The VDG-40 uses a single camera to grab an image of the particles as they fall from a vibrating hopper (*10*). Gradation and flat and elongated coefficients obtained with a VDG-40 system are based on the assumption that the thickness of the particle is the same as the width of the particle (i.e., the intermediate and the shortest lengths are the same). The volume is calculated based on an ellipsoid of revolution, and the flatness is determined as the ratio of the assumed volume to the actual volume determined from the weight and the specific gravity of the sample. The shape factors determined are hence applicable to the entire sample but not to each individual particle. Although a good correlation can be found in the flat and elongated data by size class, there is a misconception in the approach because the currently used specifications are based on determining the ratios of individual particles but not of the bulk sample (*11*). On the other hand, WIPFRAG furnishes information only about the gradation but has the flexibility of collecting images from, say, stockpiles or trays or feed lines (*12*). In WIPFRAG, the method used for 2-D to 3-D reconstruction and the volume determination of a particle is based on principles of geometric probability and stereology.

A slower but yet a fairly reliable method used is a 3-D digital analysis, which combines images taken for a particle from two perpendicular directions (*13*). The aggregates are attached to a tray that has two perpendicular faces, one with an adhesive surface. After the initial projected image of the aggregates is captured and measured, the sample trays are rotated 90° such that the aggregates are now perpendicular to their original orientation, and then another projection of the aggregates is captured and measured. This way all three dimensions of the particle—the long, intermediate, and short dimensions—are obtained, and they provide direct measurement of flatness and elongation or other required shape indices.

The need to automate imaging and comply with the testing standards for flat and elongated ratios led to the development of the WIPSHAPE image analysis system (*14*). Two cameras positioned in perpendicular directions take pictures of aggregate particles moving on a conveyor, and the images are processed at an approximate rate of 1.6 seconds per particle. The WIPSHAPE system employs a state-of-the-art triggering mechanism and image-acquisition and processing software program. Determination of the 3-D shape (i.e., volume) of each particle is achieved from the two camera views by the use of weighting factors and statistical techniques to compute the flat and elongated ratios by percent weight.

NEED FOR THREE VIEWS FOR VOLUME DETERMINATION

In video imaging-based aggregate-gradation and shape analyses, accurately estimating the volume of an individual particle has a significant effect on the computed grain-size distribution and the percentage by weight of flat and elongated particles in a given sample. Once the volume is estimated, the ratio of the volume of the flat and elongated particles to the total volume of all the particles in the sample will be equivalent to their ratios by weight. This equivalency arises because the weight and the volume differ by a constant factor, the specific gravity (G_s), if all aggregates processed are from the same parent material.

Any technique that utilizes a single 2-D image of a particle to estimate the volume assumes the size of the third view. Although this assumption simplifies and reduces the image capturing and the analysis setup, it introduces serious errors in calculating the volume and, consequently, the weight. More information about the depth of the particle is essential for volume determination. Getting an additional view of the particle from the third orthogonal direction shows clearly its depth and hence aids in a more realistic estimate of its volume.

Figure 1 shows 3-D views of two regular-shaped solids, a rectangular box and a triangular prism. Clearly, both the top and side views of the two solids are identical rectangles. Using a 2-D video image-analysis setup consisting of only top and side cameras and capturing the two images of each solid, therefore, would not be effective in distinguishing the 3-D shapes of the solids. In reality, the rectangular box has twice as much volume as that of the triangular prism. Incorporating the front view obtained from an additional third camera would certainly be beneficial in getting a "real" 3-D view of the solids, which is needed for the proper shape analysis and the 3-D volume determination.

For the triangular prism shown in Figure 1, one may argue that correct positioning of only two cameras to capture the front and side views would be sufficient to determine the 3-D shape of this regular-shaped solid. However, it must be realized that aggregates are not regular-shaped particles. The outline of an aggregate image in any view never continues into the third dimension that is not visible.

U OF I AGGREGATE IMAGE ANALYZER

In an attempt to overcome the above-mentioned shortcomings in accurate volume determination, a new aggregate image analyzer has been developed at the U of I for automating the determination of the high-priority aggregate properties (i.e., flat and elongated ratios, coarse aggregate angularity, and gradation). This new image analyzer named herein the U of I Aggregate Image Analyzer has a unique three-camera setup to capture three orthogonal views and in essence get an "actual" 3-D view of each aggregate particle. The overall goal has been to automate the currently used procedures for properly characterizing the shapes and sizes of aggregates from captured images. The use of three cameras provides the unique capability of accurately determining the volume of each aggregate.

Figure 2 shows a schematic of the aggregate image analyzer, illustrating the operating principle of the conveyor-belt system. The belt is run by a variable-speed motor, which provides smooth and steady operation, even at fairly low traveling speeds of aggregates. As the individual particles travel on the conveyor, approximately 0.25 m (10 in.) apart and approach the end of the belt, each particle comes into the field of view of a sensor that recognizes the particle

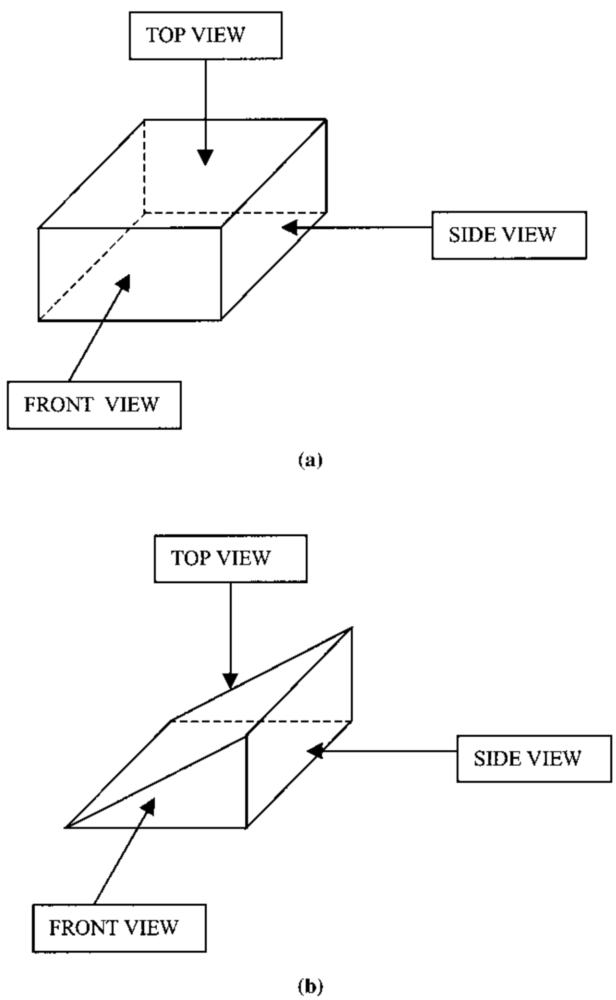

FIGURE 1 Three-dimensional views of two regular-shaped solids: (*a*) rectangular box and (*b*) triangular prism.

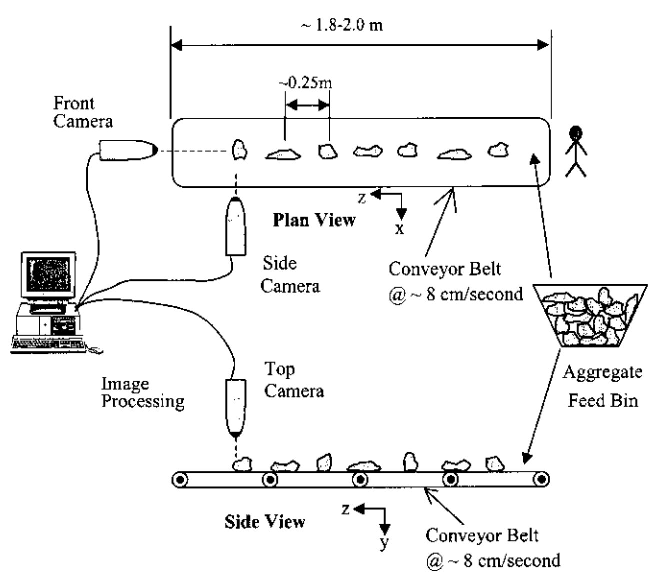

FIGURE 2 Schematic diagram of U of I Aggregate Image Analyzer.

and immediately triggers the cameras with a predetermined delay time. Two such sensors are used for the various aggregate sizes. The first is an infrared sensor that triggers when an infrared beam is cut by the passage of an aggregate. For thin, flat particles, a second, fiber-optic sensor placed on top of the belt is used instead to sense the moving aggregates. Once triggered, the three synchronized cameras capture the images within a span of 0.1 s in succession. A single-frame grabber board is used to capture images from all three cameras almost simultaneously in a predetermined sequence. Because the aggregates are moving on the conveyor, progressive scan-type video cameras are used. These cameras are especially needed in motion-control applications and can capture sharp, unblurred images of moving objects using high shutter speeds. A cloth curtain placed on the belt between the cameras and the sensors conveniently provides the black background needed for the front camera view. The U of I Aggregate Image Analyzer is shown in Figure 3.

The data-acquisition process, which includes image capturing and storing, is controlled by a program written using the virtual instrumentation software LabVIEW™, developed by National Instruments. The images are saved on the hard drive and processed after all the images of aggregates have been collected. Image processing, which includes first defining the outline of each aggregate image and then determining the volume, flat and elongated ratio, and angularity of each particle, is performed using another program that incorporates basic image-analysis tools in LabVIEW's IMAQ Vision module. LabVIEW provides a working platform to program the user-defined image-processing and analysis functions using its graphical programming language. Knowing the volume and dimensions of each particle and the specific gravity of the aggregate sample, gradation analysis of the sample can also be performed. Real-time processing of the images is also envisioned as the development of the U of I Aggregate Image Analyzer continues.

VOLUME COMPUTATION

All images captured for one aggregate particle from all three views should be combined for volume computation of that particle. Figure 4

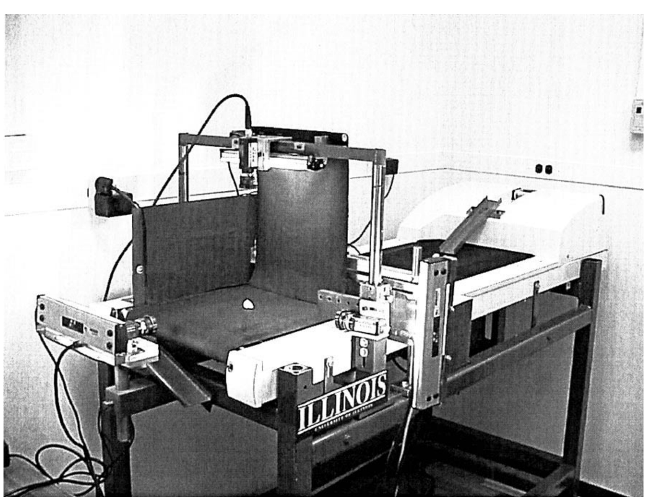

FIGURE 3 U of I Aggregate Image Analyzer.

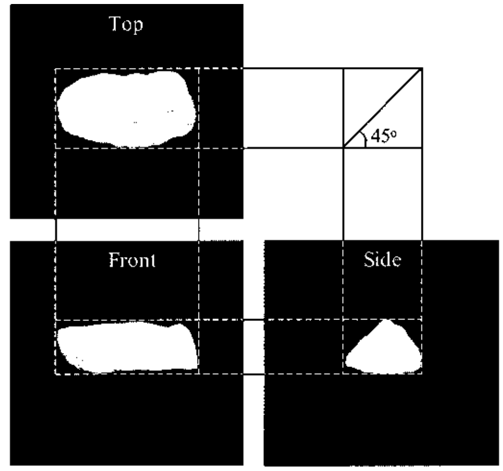

FIGURE 4 Orthogonal views of an aggregate particle as obtained by the U of I Aggregate Image Analyzer.

shows three orthogonal views of a particle obtained from the three cameras of the U of I Aggregate Image Analyzer. Each black and white image consists of several pixels that are assigned a certain value in the gray scale ranging from 0 to 255. A gray scale value of 0 corresponds to the darkest black, while the brightest white takes the maximum value of 255. The new image-analysis approach for volume computation is therefore based on identifying the gray-scale values that belong to the particle and those that belong to the background and using all three captured views of the particle simultaneously. The steps used in the volume-computation program are as follows:

1. Thresholding. Thresholding determines the outline of the aggregate particle in a captured image. Clearly, the particle should have a sharp contrast against the background to accurately delineate the actual boundaries. A threshold value of pixel gray level is typically specified, and the actual image is converted to a binary image. This binary image has only black or white (gray level 0 or 255) pixels to clearly identify the particle against its background.
2. Converting image to array. Each image is of 640×480 resolution (i.e., it has 640 pixels in the horizontal direction and 480 in the vertical). This is not the case for images shown in Figure 4 since these images had to be cropped for presentation purposes. The image is then converted to a 2-D array having 480 rows and 640 columns, identical to the dimensions of the image. Each element in the array has the value of the gray level of the corresponding pixel. In essence, all elements of the array associated with the particle take the value 255 while all the others of the background take the value 0.
3. Choosing particle array subset. Each particle occupies an area that is only a part of the image, as can be seen in Figure 4. This region containing the particle is of interest for image processing and hence is extracted from the array formed in the previous step. An array subset of the particle is chosen this way to essentially represent the smallest rectangle enclosing the particle. The process is applied to all three views, and the created subset arrays are combined to determine the smallest 3D rectangular box in which the particle can exactly fit. Figure 5 illustrates this mathematical operation pictorially.

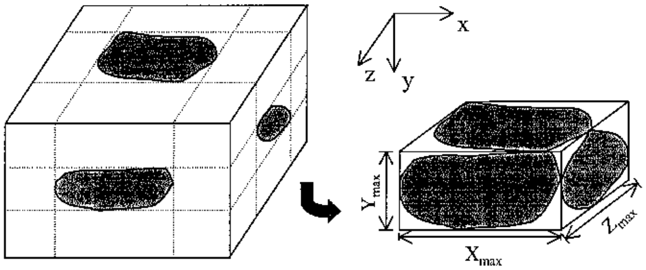

FIGURE 5 Three orthogonal images cropped down to aggregate views for volume computation.

4. Determining number of solid pixel cubes. In image analyses, the length measurement is commonly done by counting the pixels. The actual length is then obtained by multiplying the pixel count by a calibration factor. The objective is now to eliminate the portions of the rectangular box that do not contain the solid particle. The volume computation program iteratively scans the entire 3-D space and counts all the pixels that belong to the particle from all views. The number of pixels that satisfies this condition of occupying the mass of the particle from all three directions, therefore, gives the volume of the particle in units of pixel-length cube. Knowing the uniform calibration factor used in three cameras, the volume can then be easily converted to cubic centimeters or cubic inches.

Since all the processing and analyses are done on the captured images of aggregates, good-quality images are needed to obtain reliable results. Considerable attention should be given to the lighting provided for the cameras, the type and quality of the cameras, the use of correct calibration factors, and, most importantly, the thresholding, that is, the ability to recognize the particle and differentiate it from the background. The background color must be different from the color of the aggregates. Over- or underthresholding can cause erroneous results, especially in samples that have darker-colored aggregates and aggregates having spots of varying gray levels.

VALIDATION OF THE NEW IMAGE-ANALYSIS APPROACH

Several aggregates were used to validate the performance of the volume computation algorithm. To get a true judgment of the achieved accuracy, two bag samples, identified as Sample 62A and Sample 85, with a total of 1037 and 740 aggregates, respectively, were analyzed. These bag samples were selected from the available 10 bags provided by IDOT for displaying the adequacy of the newly designed digital image-analysis system. The samples were previously tested for their flat and elongated ratios content by different methods. Results from the standard ASTM D4791 tests performed both at IDOT's Bureau of Materials and Physical Research and at the U of I were available for comparison. Additionally, tests were also performed on these bags using the WIPSHAPE (*14*) and the VDG-40 (*10, 11*) systems. In addition, for Sample 62A, results using the digital image-analysis technique developed by Frost and Lai (*13*) were available. Owing to the availability of all these test results for comparison, these bag samples were chosen for validating the image-analysis approach adopted here for use with the U of I Aggregate Image Analyzer.

One image for each of the three views of each aggregate was captured at the designed operational speed, approximately 8 cm/s (3 in./s), of the conveyor belt. It took approximately 70 minutes to test the entire bag of Sample 62A (over 1000 particles) using a Pentium II computer with a 350-MHz processor speed. The summary results for the flat and elongated ratios obtained from both the image analyzer and the other image-analysis systems are shown in Table 1. The number of processed aggregate particles that fall under each flat and elongated category and its percentage by weight of the total particles are tabulated for manual and imaging techniques for the two bag samples. The results from the U of I Aggregate Image Analyzer are in very good agreement with the manual caliper test results obtained from IDOT and locally at the U of I. The flat and elongated percentages computed by the other imaging systems were not as close to the manual caliper results.

The total weights of the bag Sample 62A and Sample 85 were measured manually to be 1891.4 and 2596.9 grams, respectively, while the calculated value by the U of I image-analysis approach

TABLE 1 Percentage by Weight of Flat and Elongated Ratios of Bag Sample 62A with Different Techniques

	Flat and Elongated Ratio	Manual Calipers		WIPSHAPE Analysis (*14*)	Digital Imaging (*13*)	U of I Image Analyzer
		IDOT	U of I			
SAMPLE 62A	< 3:1	56.7 %	61.5 %	66.5 %	72.2 %	**62.04 %**
	≥ 3:1 and < 5:1	39.0 %	36.1 %	31.4 %	27.5 %	**35.36 %**
	≥ 5:1	4.3 %	2.5 %	2.1 %	0.3 %	**2.61%**
	Total Weight (grams)	-	1891.4	-	-	**2004.6**
SAMPLE 85	< 3:1	96.7 %	97.6 %	97.1 %		**97.39 %**
	≥ 3:1 and < 5:1	3.3 %	2.4 %	2.9 %	-	**2.61 %**
	≥ 5:1	0.0 %	0.0 %	0.0 %		**0.01 %**
	Total Weight (grams)	-	2596.9	-	-	**2768.1**

using a G_s of 2.66 and 2.67 grams were 2004.6 and 2768.1 grams, respectively. This difference in total weights of about 5.9 percent and 6.5 percent, respectively, is small. This rather consistent overprediction in calculating total weights of the samples can be attributed to an error in the calibration factor used to convert the volume in cubic pixel length to the volume in cubic centimeters. However, this error does not affect the flat and elongated ratio results as the percentage of flat and elongated particles by weight is determined as a ratio of weights, and any small error in the calibration gets cancelled out in the ratio. On investigation, it was found that the calibration is very sensitive not only to small variations in the distance of the specimen from the camera but also to the location of the particle on the image. Considering that the position of the particle on the image is random and that the size of the particle varies such that the distance between the particle and the camera varies for each particle, a small error might be induced in the calibration factor. The calibration used was experimentally determined to be 1 cm = 60 pixels. If the calibration was changed to 1 cm = 61 pixels, the error in total weights would be reduced from 5.9 percent to 0.86 percent and from 6.5 percent to 1.4 percent for Sample 62A and Sample 85, respectively. Another reason for overprediction could be the presence of small caverns and hollow areas in the particles that cannot be viewed by any of the three cameras.

To further verify volume computations, the weights of 50 individual aggregate particles were also compared against their actual weights. Figure 6 presents a plot of the actual and the computed weights for those 50 particles. The weights of the aggregates estimated from the U of I Aggregate Image Analyzer agree quite well with the physically measured values. The errors are clearly biased towards the positive side. This is expected, as the volumes are slightly overestimated because the cameras cannot capture information about surficial dents and hollow portions not seem by the cameras. An average absolute error of 0.46 g, corresponding to an 11.49 percent error, was given for an average particle weight of 3.89 g. The actual weights, the weights computed from the image analysis approach, and the errors in the measured weights are tabulated in Table 2.

The errors seen in individual weight measurements are primarily attributable to the G_s value used for converting the computed volumes to weights. A G_s value of 2.66, the G_s determined for the entire bag, was used as a standard value for each individual particle. In reality, the G_s of each particle might vary from the G_s value for the whole bag by a small amount. This can substantially alter the weights calculated by this procedure. The fact that the total weights for the whole sample and for the 50 particles matched their actual weights very closely indicates that the standard G_s value is more typical to the whole sample but not always to an individual particle.

Careful examination of the scanned images revealed that the higher errors could also be caused by the variability in the lighting conditions brought about by irregularly shaped particles. Improved lighting arrangements may help resolve these problems in the future. Further, it was also noted that the preset threshold limit of gray-scale level of 180 that was typically used for all particles might not work the best for all aggregates. Instead, an adaptive thresholding scheme that is well suited for conditions where the color of the particles varies will be adopted in the future to further reduce the errors. Given all these constraints, the observed errors seem reasonably low, and the presented results are believed to adequately validate correctness of the employed imaging technique for volume computation and the effectiveness of the new aggregate image analyzer.

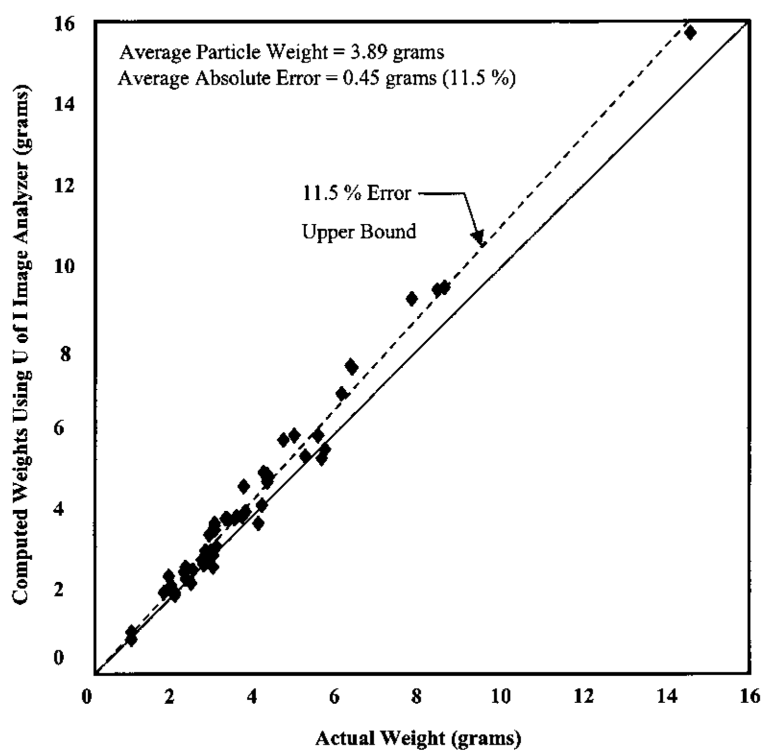

FIGURE 6 Actual and computed weights for 50 aggregate particles.

TABLE 2 Weights of 50 Aggregate Particles Computed with the U of I Image Analyzer

Particle Number	Weight = Volume*G_s (grams)			Particle Number	Weight = Volume*G_s (grams)		
	Actual	Imaging	Error		Actual	Imaging	Error
1	8.56	9.49	0.93	**26**	2.21	2.33	0.12
2	4.20	4.70	0.50	**27**	2.66	2.69	0.02
3	5.46	5.83	0.37	**28**	5.62	5.50	-0.12
4	4.89	5.84	0.95	**29**	2.23	2.62	0.39
5	6.31	7.50	1.19	**30**	2.60	2.77	0.17
6	6.25	7.52	1.27	**31**	3.67	4.06	0.39
7	7.80	9.17	1.38	**32**	2.04	2.36	0.32
8	6.04	6.84	0.80	**33**	2.35	2.20	-0.15
9	5.17	5.32	0.15	**34**	4.64	5.74	1.10
10	1.69	1.99	0.30	**35**	3.65	4.59	0.94
11	2.93	3.54	0.61	**36**	2.88	2.62	-0.26
12	2.94	3.65	0.71	**37**	1.88	2.13	0.25
13	5.56	5.29	-0.27	**38**	3.21	3.82	0.62
14	14.59	15.73	1.14	**39**	4.11	4.91	0.79
15	3.61	3.84	0.23	**40**	4.11	4.14	0.03
16	3.40	3.80	0.40	**41**	2.98	3.15	0.17
17	8.40	9.39	1.00	**42**	2.70	2.98	0.28
18	4.21	4.91	0.69	**43**	2.79	3.40	0.61
19	3.45	3.86	0.41	**44**	2.40	2.67	0.27
20	2.91	2.87	-0.04	**45**	2.17	2.34	0.17
21	2.71	2.71	0.00	**46**	1.94	1.94	0.01
22	0.90	1.03	0.13	**47**	2.87	3.01	0.14
23	0.88	0.83	-0.05	**48**	4.02	3.69	-0.33
24	2.92	3.68	0.77	**49**	1.95	1.96	0.01
25	3.26	3.77	0.51	**50**	3.63	3.93	0.30
				Average	3.89	4.29	

SUMMARY AND CONCLUSIONS

Among the critical aggregate properties that impact performance of asphalt pavements are the flat and elongated ratio, angularity of the particles, and the gradation properties. Along with a need to develop rapid and automated methods for determining flat and elongated ratios of individual aggregate particles, there is also a need to develop an accurate and repeatable experimental technique. The use of video image analysis techniques lately has become a more viable and cost-effective alternative for automation of aggregate analysis and determination of aggregate properties.

A new aggregate image analyzer has been developed at the U of I to provide a reliable means of obtaining flat and elongated ratio, angularity, and gradation of coarse aggregates in a fast and efficient way. The new image-analysis approach uses three camera images of an individual particle and is capable of providing reliable results for computing volumes of aggregates so that results can be expressed in percentages by weight. Using this system, the volumes were computed for two bag samples containing 1037 and 740 aggregate particles, and the weights of flat and elongated particles falling in each size category were determined. Results from this procedure were in very good agreement with the flat and elongated ratios obtained from the standard ASTM D4791 tests conducted in the laboratories of IDOT and the U of I. Good comparisons with the actual measured weights were also obtained for the computed weights of 50 individual aggregate particles and the entire bag samples. The image analyzer is considered to be a significant technological advancement towards automating analysis of coarse aggregates and for properly characterizing the three-dimensional shapes and sizes of aggregates from captured images.

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