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**Analysis of Volumetric Properties of Bituminous Mixtures Using
Cellular Phones and Image Processing Techniques**

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Abstract

This study aims to develop the micro-analysis of the bituminous mixtures using Cellular Phone Images (CPI) and Image Processing Techniques (IPT). A new methodology and scheme was developed for faster and accurate procedure to compute volumetric design parameters; Voids in Mineral Aggregate (VMA), Voids in Total Mix (VTM) and Voids Filled with Asphalt (VFA) using CPI and IPT instead of the conventional methods. Five types of cellular phones with different high resolutions were used to analyze the horizontal cross section (face) of HMA slices. A cellular phone digital mapping frame for Micro-structure of the bituminous mixture for data collection was designed and implemented. New models for computations of volumetric design parameters (VMA, VTM and VFA) were developed. Results showed that the best cellular phone for micro-analysis of the bituminous mixture is type D, even though it doesn't have the highest resolution, and the best height of capturing the images is 35 cm.

Key words: Cellular Phone Images (CPI), VMA, VTM, VFA, Volumetric Properties, ImageJ software

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69 **Introduction**

70 Asphalt concrete is prepared by mixing graded aggregate (coarse and fine aggregate) with
 71 asphalt cement content and then compact the mixture to get a specific percentage of air void
 72 level. The basic components of asphalt concrete are divided into a graded aggregate, binder,
 73 and air void. Fine aggregates of the graded aggregate are embedded in the matrix of asphalt
 74 binder. The physical and mechanical properties of asphalt concrete mixtures depend on the
 75 quantities and mechanical properties of the individual constituents. Aggregate shape,
 76 orientation, and gradation also play a very important role in the mixture performance (You et
 77 al. 2013).

78 The volumetric design of bituminous mixtures requires consideration of the percentage of air
 79 voids in the total mixture (VTM), voids in the mineral aggregate (VMA), and voids filled
 80 with asphalt (VFA). The percentage of air voids is used as the basis for selecting the
 81 percentage of asphalt binder content (AC%) that will be used in the mixture. Conventional
 82 procedures used to quantify the volumetric design parameters (VMA, VTM, and VFA)
 83 require a series of exhaustive analytical and laboratory steps which depend on different types
 84 of specific gravities of the bituminous mixes (Asphalt Institute 1988). However, most of the
 85 available models for HMA volumetric analysis were developed without experimental
 86 measurements of the microstructure distribution. This was due to the difficulties associated
 87 with the quantitative analysis of the microstructure, which has prevented continuum modeling
 88 from becoming a state-of-the-practice technique for HMA engineering applications (Wang et
 89 al. 2001).

90 One of the most effective methods is the digital image processing and analysis technique.
 91 Tashman and Wang (2011) summarized the recent advances in imaging technology and its
 92 applications to the characterization of HMA microstructure including aggregate distribution,

93 aggregate contact, aggregate shape properties, and air void distribution. The micro-structure
94 of HMA is linked to the macroscopic behavior of the material within the framework of
95 integrated modeling by microstructure tensors that are incorporated in the modeling
96 formulations.

97 Bessa et al. (2012) used digital image processing (DIP) techniques to characterize the
98 distribution of aggregates within the asphalt mixes. Results show that using DIP is easier,
99 faster, and more precise than the results from the laboratory tests.

100 Vadood et al. (2014) introduced a simple and quick approach to determine aggregate
101 gradation in the HMA. Image processing techniques and colour space system were used on
102 cylindrical HMA samples. Results showed that aggregate gradation can be detected with high
103 accuracy.

104 Obaidat et al. (1998) examined the effectiveness of using a semi-automated computer-vision
105 system to quantify the percentage of voids in mineral aggregates (VMA %) of bituminous
106 mixtures. The system that was used in this study was a hybrid system which utilized a
107 planimeter surveying instrument, and a digital image analysis scheme. Thirty-nine Marshall
108 Specimens were prepared using two types of aggregate; limestone and gravel. The values of
109 VMA% were obtained by the ASTM conventional procedure and the computer-vision
110 procedure. For computation of the VMA% by using the computer-vision procedure a normal
111 case photography with uniform scale images was used for mapping horizontal and vertical
112 cross sections of Marshall Specimens. Spatial filters and image processing operations were
113 used to detect the aggregate edges. The results showed slight differences between VMA%
114 computed using conventional and the computer-vision procedures. This study emphasized
115 that the low-resolution image was a major factor in reducing the accuracy of the computed
116 VMA%. Researchers started to use image analysis techniques to characterize the distribution
117 of air voids and assess the gyratory compaction efforts in AC mixtures based on X-ray CT

118 images (Tashman et al. 2001 and Tashman et al. 2002). You and Buttlar (2004) said that it
119 was challenging to get accurate data for asphalt mixtures from images of the cutting faces for
120 Superpave mixture specimens. The researchers got data for the morphology and positions of
121 aggregate, sand mastic, and air void phases of asphalt concrete. Images of the microstructure
122 can be obtained from a flat-bed scanner, X-ray computed tomography (CT), or X-ray Micro-
123 fluorescence. Image processing techniques are then worked to acquire the aggregate, binder
124 and air void shape and orientation. You et al. (2013) developed a microstructure
125 characterization technique to map the multi- phase nature of asphalt concrete using X-ray
126 micro-fluorescence. This study examined the morphology and positions of aggregates, sand
127 mastic, and air void phases of asphalt concrete. Three different samples of mixtures with air
128 void levels of 4%, 7%, and 10% were analyzed using an X-ray microscope. The cylindrical
129 asphalt samples were cut into slabs. These slabs were polished; then white zinc-oxide powder
130 was pressed into the voids. This powder helped to discern air voids from aggregate and
131 binder. The relative intensities of pixels in the elemental images were used to categorize
132 pixels in each image according to the binder, the air voids, and the aggregate using multi-
133 spectral analysis techniques. The images were analyzed and the aggregate gradation was
134 calculated and compared with the real gradation. It was concluded that the microstructure
135 characterization techniques via capturing the multi-phase nature of asphalt concrete using x-
136 ray micro-fluorescence were moderately successful.

137 Zelelew and Papagiannakis (2007) developed the Digital Image Processing (DIP) algorithm
138 called Volumetric-based Global Minima (VGM). It is a thresholding algorithm for processing
139 the asphalt concrete mixtures X-ray CT images. The image preprocessing and gray scale
140 thresholding were considered for characterizing of the asphalt concrete mixtures
141 microstructure X-ray CT images. There were briefed descriptions of different types of DIP
142 techniques applicable to characterize and simulate of asphalt concrete mixtures that include

three-dimensional representation, edge detection, and segmentation of mastic and aggregate objects. The method consists of Volumetric-driven thresholding based on a global minimum percent error approach that utilizes thresholding criterion the actual volumetric properties of the asphalt mixtures. It was applied to images of cross-sections of asphalt mixtures cores. Generally, the VGM processed images are significantly improved compared to the raw X-ray CT images.

The usage of image processing is growing fast in many aspects of science and engineering application, in parallel with the distribution of cellular phones and their contribution in most of the life issues. This is why this research can be considered as the first of its kind, since it uses cellular phone images for micro-analysis of bituminous mixture by extracting the volumetric design parameters (VMA, VTM, and VFA) from the cellular phone images. The micro-structure of the bituminous mixture will affect the macro-structure of the pavement and its performance. The conventional methods of the micro-analysis of bituminous mixture (computation of the volumetric design parameters for Superpave mixtures and determination of aggregate shape indices) require a series of exhaustive analytical and laboratory steps, special technicians and they are considered to be time-consuming. The main limitation of X-ray CT is that the equipment is expensive, and therefore difficult to be available for every researcher. In this study the easy and simple usage of cellular phones and image processing techniques will be used to develop the micro analysis of the bituminous mixture. The aim of this study is to perform the micro-analysis of the bituminous mixture for different bituminous mixtures with different aggregate gradations and different asphalt contents. This micro-analysis is developed by using five types of cellular phones and ImageJ Software. Furthermore, this study aims to investigate the image processing potential in accurate measurements of the bituminous mixture volumetric design parameters (VTM, VFA, and VMA).

Materials and Methodology

HMA specimens with different volumetric design parameters (VTM, VMA, and VFA) were prepared in the laboratory using the Superpave gyratory compactor. Different volumetric values were achieved by changing the gradation of the aggregates and the asphalt content (AC %) in the mixtures. As shown in Figure 1, two aggregate gradations were used; gradation ARZ (above restricted zone) and gradation BRZ (below restricted zone). Nine asphalt contents were used for each aggregate gradation.

The conventional calculation methods of computations for the volumetric design parameters (VMA, VTM and VFA) of bituminous mixtures need to find some massive ratios and volumetric variables of the mix. Also, the bulk specific gravity for the aggregates (G_{sb}), the bulk specific gravity of the compacted mixture (G_{mb}) and the theoretical maximum specific gravity for the loose mixture (G_{mm}) must be determined for each HMA specimens.

Eighteen Superpave specimens were prepared in the laboratory using the gyratory compactor (108 gyrations), with the same cylindrical shape (15 cm diameter, 11 cm height) but different volumetric properties (VMA, VTM and VFA). According to ASTM D3203, equations 1, 2 and 3 were used to compute VMA, VTM and VFA respectively. Table 1 shows the volumetric design parameters for the ARZ and the BRZ samples.

$$VMA = 100 \left[1 - \frac{G_{mb} \left(\frac{Ps}{100} \right)}{G_{sb}} \right] \quad (1)$$

Where:

VMA = Voids in mineral aggregates.

G_{mb} = Bulk specific gravity of compacted HMA.

G_{sb} = Bulk specific gravity of aggregate.

Ps = Aggregate, percent by total weight of HMA = 100 – AC%.

$$VTM = 100 \left[1 - \frac{G_{mb}}{G_{mm}} \right] \quad (2)$$

Where:

VTM = Voids in total mix.

G_{mb} = Bulk specific gravity of compacted HMA.

G_{mm} = maximum theoretical specific gravity for the loose mix.

$$VFA = 100 \left[\frac{VMA - VTM}{VMA} \right] \quad (3)$$

Where:

VFA = Voids filled with asphalt.

VTM = Voids in total mix.

Table 1 shows the volumetric properties for the HMA specimens. The bulk specific gravity of the aggregates (G_{sb}) in the above restricted zone gradation is 2.55 and in below restricted zone gradation is 2.532.

Superpave sample has cylindrical shape, 15 cm diameter and various heights depend on the number of gyration in the gyratory compactor. In this research, the number of gyration was 108 so the sample height was 11 cm. Each sample was cut off from the middle into two halves, upper half and lower half with 5.5 cm height each. For each half there are two faces the upper face is black due to the compactor plate and the lower face (cut face) which had to be flat and smooth. One slice was taken from each half. Each slice has two smooth and level faces, as shown in Figure 2.

In this study the micro-analysis of the bituminous mixtures was developed by using Cellular Phones Images (CPI) for the mixture slice faces and Image Processing Techniques (IPT), specifically the ImageJ software. The image processing composed off; Superpave mixtures slices, five types of cellular phones, Cellular Phone Digital Mapping Frame for Micro-

Structure of Bituminous Mixture and ImageJ software as shown in Figure 3 (a). The image processing procedure is shown in Figure 3 (b).

Five types of cellular phones were chosen to map the mixture slices faces. These types are the most common using types and they have high camera resolution. Each slice face was mapped by five high resolution cameras and from three heights (25 cm, 35 cm and 45 cm). Table 2 shows the resolution for each camera of selected cellular phones.

Data Acquisition system development

A special frame was designed and implemented to map the faces of the mixture slices. This frame was designed using AutoCAD software as shown in Figure 4. The idea of this frame is to standardize and facilitate the way of capturing the images of the faces of the mixture slices from certain height, vertically top view and center to center (the center of the camera with the center of the circular mixture slice face). As shown in Figure 4, the frame consists of top plate, bottom plate, thin plate and four gradient columns. All the components were made of reinforced plastic. The top plate has square shape (25 cm x 25 cm) and in the middle of this plate there is a circular opening for the cellular phone camera. The bottom plate also has square shape (30cm x 30cm) and in the middle there is a circular shape opening with 15 cm diameter and 3.5cm in depth for the mixture slice. Under this opening there is a thin plate that can be pulled, so the first slice can be replaced with second one. Between these two plates there are four gradient columns with rulers on them, the scale of these rulers begins with zero and ends with 45 cm so the height of capturing the image can be changed and fixed. The upper plate can be moved by hand and leveled by using water level and it can be fixed at certain height using stoppers under it, see Figure 5 (a). The cellular phone can be fixed above the upper plate as the camera should be on the center's opening, see Figure 5 (b). Three heights were chosen to map the mixture slices by the cellular phones 25 cm, 35 cm, and 45 cm.

In this frame, there are four gradient columns with rulers on them. The scale of these rulers begins with zero and ends with 45 cm so the height of capturing images can be changed and fixed by the stopper under the plate. Three heights were chosen to map the mixture slices by the cellular phones 25 cm, 35 cm, and 45 cm. Each cellular phone was fixed on three different heights (25 cm, 35 cm, and 45 cm) using cellular phone digital mapping frame for microstructure of the bituminous mixture for capturing images of the upper face and the lower face of the mixture slices as shown in Figure 5. The images were analyzed by ImageJ program.

Two slices were taken from each HMA specimen, and each slice has two faces. So, there are four images for each sample. Five cameras were used to map these faces and from three different heights, so for each sample there are 60 images ($2 \text{ slices} \times 2 \text{ faces} \times 3 \text{ heights} \times 5 \text{ camera types}$). The total number of the images was 1080 images ($18 \text{ sample} \times 60 \text{ images}$). The testing matrix was summarized in Table 3.

ImageJ Software

ImageJ is a public domain Java image processing program inspired by NIH Image for the Macintosh. This software runs, either as an online applet or as a downloadable application, on any computer with a Java 1.4 or later virtual machine. It can display, edit, analyze, process, save and print 8-bit, 16-bit and 32-bit images. It can measure distances and angles. It can create density histograms and line profile plots. It supports standard image processing functions such as contrast manipulation, sharpening, smoothing, edge detection and median filtering. It does scaling, rotation and flips. All analysis and processing functions are available at any magnification factor. The program supports any number of windows (images) simultaneously, limited only by available memory. Spatial calibration is available to provide real world dimensional measurements in units such as millimeters. Density or gray scale calibration is also available (Werner Bailer 2000).

In this study all the images were analyzed by ImageJ program which is an open source image processing program designed for scientific 2D images. This software is high usage for biological tasks such as cells detection, but it was used in this study for micro-analysis of the bituminous mixture and analysis for coarse aggregate shape.

The calibration for the ImageJ has been done by comparing the ImageJ results with the standard software AutoCAD which is used for edge detection and find shapes areas, perimeters and dimensions. Firstly, in the ImageJ software the suitable threshold value should be determined using trail threshold values through analyzing the images. In 8-bit grey scale images (as colored images converted into 8 bit images) there are 256 (2^8) intensity graduations which can be assigned to a pixel. A pixel with an intensity of 0 is black, a pixel with a value of 255 is white, everything in between is a shade of grey.

Thresholding works by separating pixels which fall within a desired range of intensity values from those which do not, (also known as 'segmentation'). Thresholding can be a very effective method of measuring complex or disjointed features in an image. Image analysis software has no intuitive moves up its sleeve; it will take all the information in an image and treat it literally. All the threshold values were tested for determining the suitable value which gives the highest accuracy percentage for the particles areas by comparing it with AutoCAD areas. In most of the images, if the threshold values were between 0 and 100, then the white color will be prominent and small particles will not be spotted. On the other hand, if the values were between 150 and 255, then the black color will prevail. So the suitable threshold value should be in the range of 100-150. The checked threshold values were 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150 and the average value 127.

ImageJ software was calibrated by computing the accuracy percentage and the error percentage of measurements of areas and perimeters for three kinds of shapes. The AutoCAD software was used to compute the actual areas and perimeters for these shapes. These kinds of

shapes are: regular shapes, irregular shapes, and selected 45 aggregate irregular shapes from a selected HMA slice, see Figure 6. The selected regular shapes were: circle, triangle, trapezoid and rectangle, see Figure 6 (a). The irregular shapes, in Figure 6 (b), were not from mixture cutting face, they were random irregular shapes similar to the aggregates shapes the mixture slice face. Fifteen random irregular shapes were classified into three groups based on their areas; 5 large particles, 5 medium particles and 5 small particles. For the regular and irregular shapes, the ImageJ accuracy percentage for the measured areas was almost 100% and the error percentage was almost zero. Figure 6 (c) shows the selected forty-five irregular aggregate particles. A comparison between the collected data from AutoCAD with the data from ImageJ analysis of the areas and perimeters for the regular shapes was shown Figure 7 (a) and Figure 7 (b), respectively. Figure 7 (c) and Figure 7 (d) show the comparison between collected data from AutoCAD with data from ImageJ analysis of the areas and perimeters for the irregular shapes.

Forty-Five of irregular shapes of aggregate were selected from mixture slice image. The image in Figure 8 was captured by cellular phone camera with high resolution. The selection of 45 particles was for calibration of ImageJ software and selecting the suitable thresholding value. In Typical HMA slice's image, the maximum number of detectable large aggregate particles was 15, similar particle numbers of medium and small particle sizes were selected with a total number of 45 particles. It shows the whole particles in the mixture clearly. These particles have irregular shapes with known areas and perimeters by using AutoCAD software. The irregular shapes were classified upon their areas into three classes. The large particles have area more the 80 mm^2 , the medium particles have areas between 20 mm^2 and 80 mm^2 and the small particles have areas less than 20 mm^2 . Figure 8 shows the selected fifteen large particles (Figure 8(a)), fifteen medium particles (Figure 8(b)) and fifteen small particles (Figure 8(c)) according to their areas and perimeters.

The threshold value has been changed from 100 to 150 in an increment of 5, and including the average value 127. This changing of the threshold value for detection the irregular areas of the aggregates in mixture slice face was effecting on the accuracy percentage, and the error percentage. The ImageJ analysis was done for this mixture image at each threshold value. Figure 9 shows how to analyze the mixture particles after selection the threshold value. Mixture slices face before and after Thresholding is shown in Figure 9(a) while the area detection by ImageJ is shown in Figure 9(b). This procedure was repeated for 12 times changing the threshold value. The results showed that the suitable threshold value for analyzing the images is 130. This value scored the highest accuracy percentage and the lowest error percentage for the measurements of areas and perimeters of the aggregate particles by ImageJ software. Figures 10 shows an example of accuracy (Figure 10(a)) and error percentages (Figure 10(b)) for the large particles.

ImageJ Analysis Variables

The 1080 cellular phone images, from the five types of cellular phones as mentioned before and on three heights of capturing, were analyzed by ImageJ software using threshold value 130. The ImageJ analysis results for the one mixture slice face were got out in table and a summary for the columns data will be shown at the end of each column. This summary includes mean, standard deviation (SD), minimum, and maximum values for the data in one column. From this summary, the mean of the particle areas and the mean of the particle perimeters were selected variables for the models.

Also, another summary will be got out from the analysis. It shows the count of the particles that were detected by ImageJ in the mixture slice face and the total area of these particles. These two variables also selected for the models. Also, the percentage of the total areas of detected particles from the whole circular area of the mixture slice was selected to be in the

models. These data collected from the five cellular phone types and on the three heights. The selected variables were the average values, from the four images for each mixture (i.e. each image at different depth of the HMA sample, with slightly different results for each variable).

Analysis and Results

The main objective of this study is to make image processing outcomes more reliable rather than being always dependent on laboratory test results only. New models for the volumetric design parameters were integrated from the results of ImageJ analysis for the mixtures images. SPSS software was used to analyze the ImageJ data for all cellular phones images from all types of cameras and from three heights (25 cm, 35 cm and 45 cm) asphalt concrete mixtures slices. Two specimens were ignored which have AC% = 7% because there was significant difference in the values of needed variables (count of particles, total area of particles, area percentage and average perimeters of particles) in the four images of same Superpave specimen and from the same height due to the bleeding that happened on the specimen with the time before cutting it into slices. So the data were collected from 16 Superpave specimens. The results show that the cellular phone type D gave the most accurate volumetric data about the mixtures even though it does not have the highest resolution. However, these images (using type D cellular phone) show more contrast between the white and black colors in ImageJ software, as shown in Figure 9 (a). The colored image should be converted to 8-bit image to be analyzed by ImageJ software. The data from ImageJ analysis for 16 mixtures slices imaged from cellular phone type D were analyzed statistically by SPSS software using Backward method and Multiple Non-linear regression to integrate the volumetric design parameters models (VTM, VMA and VFA). The integrated models were followed the formula below:

$$Y = f(x_1, x_2, x_3, x_4, x_5)$$

Where:

$Y = \text{VMA, VTM or VFA.}$

$\text{VMA} = \text{Void in Mineral Aggregates. (\%)}$

$\text{VTM} = \text{Void in Total Mix (\%)}$

$\text{VFA} = \text{Voids Filled with Asphalt (\%)}$

$x_1 = \text{log count} = \text{log count of detectable aggregate particles that have been detected by ImageJ (Number).}$

$x_2 = \text{log total area} = \text{log total area of the selected aggregate particles (mm}^2\text{).}$

$x_3 = \text{log area percentage} = \text{log area percentage of total area of aggregate particles to the total area of the cutting face (\%)}.$

$x_4 = \text{mean area} = \text{mean area of the aggregate particles (mm}^2\text{).}$

$x_5 = \text{mean perimeter} = \text{mean perimeter of the aggregate particles (mm).}$

The integrated models in this research were:

$$\text{VMA\%} = 198.428 + 19.482 \log \text{count} - 134.121 \log \% \text{ area} + 0.343 \text{ mean area} \quad (4)$$

$$\text{VTM\%} = 294.656 + 108.991 \log \text{count} - 55.194 \log \text{total area} - 226.702 \log \text{area\%} + 1.555 \text{ mean area} \quad (5)$$

$$\text{VFA\%} = -207.367 - 759.061 \log \text{count} + 654.656 \log \text{total area} - 10.318 \text{ mean area} \quad (6)$$

Equation 4 is the first integrated model for computation of VMA of the HMA mixtures. The coefficient of determination R^2 was 0.895, the adjusted R^2 was 0.868, and the standard error of the estimate (SE) was 0.47. The count of the detectable aggregate particles represents the volume of the aggregate in the mixture which affects the VMA value, if the count increase the VMA value will increase. On the other hand, the area percentage of total area of aggregate particles to the total area of the cut face affect negatively on the VMA value, which is logically true.

Equation 5 is for computation of VTM of the HMA mixtures and for this model R^2 was 0.895, the adjusted R^2 was 0.857, and SE was 1.283 %. The count of the aggregate particles represents the volume of the aggregate in the mixture which affect the VTM value, if the count increase the VTM value will increase. On the other hand, the total area of the aggregate particles and the area percentage of total area of aggregate particles to the total area of the cut face affect negatively on the VTM. Therefore, when the particles in the mixture have different sizes (large, medium and small) this will make the total area of the cut particles increase as well as their percentage area to the total cut face, and this will decrease the total voids in the mixture (VTM). In the equation 4 and 5, the most effective variable was the percentage of the particles' areas to the total cutting face area.

Equation 6 is the integrated model for computation of FVA of the HMA mixtures. With R^2 was 0.896, the adjusted R^2 was 0.845, and SE 7.689%. Here, the model shows that the count of the particles will effect on the VFA negatively, if the count increase the VFA will decrease. But, the total area and the mean area effect positively on the VFA. This means that the voids filled with asphalt will increase if the aggregate size increase. The effective variable in VFA model is the count of the detectable aggregate particles. Table 4 and Figure 11 show that there are slight differences between the predicted values (using the new models) and the actual values (using conventional methods) of VMA, VTM and VFA. Table 5 shows the minimum, maximum and the average differences between the actual and the predicted values of VMA, VTM and VFA and the error percentages.

The linearity assumption checks for the models are shown in Figures 12. It is clear that all the residuals are clustered around the line suggesting that the assumption of normality has been met. On other hand the predicted values are normally scattered around the center line which is another prove of the normality assumption.

Conclusions

The usage of image processing is growing fast in many aspects of science and engineering applications. The aim of this study is to use cellular phone cameras in one of the civil engineering applications. The micro-analysis of bituminous mixtures, namely is to determine volumetric design parameters of bituminous mixtures and identify some shape properties of coarse aggregate. This study reduces and eliminates the error associated with the assumptions traditionally made in the micro structure and improves the validity of integrated models that can fundamentally describe the behavior of HMA. Furthermore, the incorporation of the microstructure into computational simulation demonstrates its flexibility and power. The outcomes of this study were promising and there is a great potential for development and improvements for the micro-analysis of the bituminous mixtures. Therefore, this technique will not require the expensive x - ray computed tomography equipment. The study provided the simple and easy usage of cellular phones and ImageJ software. This system has a potential to bridge the gap between conventional or manual procedures and fully automated calculation methods. From the statistical analysis and comparisons made in this study, the following conclusions could be drawn:

- 1- It was found that the usage of the image analysis technique for VMA, VTM, and VFA of bituminous mixture computation is practical. The experiment emphasized the importance of the application of cellular phones and image-processing operations to enhance aggregate edge detection, count the number of the particles, and compute their areas and perimeters. The result did not depend on the resolution of the cellular phone camera, it depends on the camera contrast after converting the colored image to 8-bit image (black and white image). This conversion is to be able to use the ImageJ software to analyze the images.

2- New models for the volumetric design parameters were integrated using the ImageJ outcomes variables and backward linear regression method.

3- ImageJ software provides a powerful tool to accurately and nondestructively quantify the microstructure. This has an important implication as it bridges the link between the microstructure and the macroscopic response of HMA, which significantly improves our understanding of its behavior as well as the interpretation of experimental results.

The usage of cellular phones and Image processing techniques, a strongly emerging technology, have proven to be capable of objectively quantifying volumetric design parameters of the bituminous mixture and coarse aggregates shape characteristics.

Recommendations

The results of this research led to the conclusion that there is a highly potential of using cellular phone image and image processing technique for micro-analysis of bituminous mixture. The potential can most fully be exploited if further research is directed to the following recommendations:

1- Further research is recommended to use cellular phone images and image processing for micro-analysis of the bituminous mixtures that uses dark aggregates in the HMA such as basalt.

2- Further research is recommended to build a cellular phone application which calculates the volumetric design parameters automatically on the phone without using the computer software.

3- Vertical cross sections of the bituminous mixtures were not involved in this research. A further investigation could be done to highlight the significance of the vertical cross

section in the micro-analysis of the mixture and if they are affecting the values of volumetric design parameters.

4- Further research is recommended for determining the degree of compaction of the mixture based on the cellular phone images and image processing for determination the changes in the center to center distances between the aggregate particles before and after the compaction.

5- Further research is recommended for determining the aggregates gradation used in the mixtures by using cellular phone images and image processing to determine the percentage of the passing through or retained aggregates on each sieve according to the sieve size.

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Table 1: Volumetric Properties for the HMA specimens.

Aggregate Gradation	Sample No.	AC%	P _s %	G _{mm}	G _{mb}	VTM%	VFA%	VMA%
ARZ	1	4	96	2.463	2.284	7.27	48.14	14.01
	2	4.5	95.5	2.452	2.303	6.08	55.81	13.75
	3	4.75	95.25	2.443	2.311	5.4	60.518	13.677
	4	5	95	2.427	2.334	3.83	70.63	13.05
	5	5.25	94.75	2.417	2.337	3.31	74.856	13.164
	6	5.5	94.5	2.408	2.339	2.87	78.49	13.32
	7	6	94	2.398	2.348	2.09	84.49	13.45
	8	6.5	93.5	2.376	2.349	1.14	91.81	13.87
	9	7	93	2.364	2.346	0.76	94.73	14.44
BRZ	10	4	96	2.514	2.193	12.77	24.24	16.85
	11	4.5	95.5	2.48	2.213	10.77	34.88	16.53
	12	4.75	95.25	2.473	2.224	10.07	38.357	16.336
	13	5	95	2.465	2.244	8.97	43.28	15.81
	14	5.25	94.75	2.459	2.255	8.29	46.913	15.616
	15	5.5	94.5	2.455	2.278	7.21	51.87	14.98
	16	6	94	2.429	2.285	5.93	60.92	15.17
	17	6.5	93.5	2.402	2.334	2.83	79.50	13.81
	18	7	93	2.378	2.333	1.89	86.78	14.31

Table 2: The Selected Cellular phones.

Cellular phone type	Image Width (pixels)	Image Height (pixels)	Resolution	Resolution in Mega Pixels
Type A	3840	2160	3840×2160	8.29
Type B	3264	2448	3264×2448	7.99
Type C	3552	2000	3552×2000	7.10
Type D	2448	2448	2448×2448	5.99
Type E	2688	1520	2688×1520	4.08

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Table 3: Testing Matrix.

Camera Type	5	Type A, Type B, Type C, type D and Type E	Total Images $5 \times 1 \times 18 \times 2 \times 2 \times 3 = 1080$ images
Resolutions	1	One High resolution for each camera	
Superpave samples	18	(9) AC% x (2) Gradation	
Slices	2	(2) slices from each sample	
Faces	2	(2) smooth and flat faces for each slice	
Capturing height	3	25cm, 35cm and 45cm	

Table 4: Differences between the actual values of the mixtures' volumetric parameters (VMA, VTM and VFA) and the predicted ones.

Sample Number	VMA Actual	VMA Predicted	Difference	Error %	VTM Actual	VTM Predicted	Difference	Error %	VFA Actual	VFA Predicted	Difference	Error %
1	14.01	14.14	0.12	0.87	6.53	6.72	0.19	3.44	55.14	50.30	4.84	8.78
2	13.75	13.74	0.01	0.07	5.52	5.73	0.21	3.59	59.81	58.59	1.21	2.03
3	13.68	13.55	0.14	1.00	5.85	5.39	0.46	16.06	58.52	62.18	3.66	6.26
4	13.05	13.29	0.24	1.85	2.87	2.84	0.02	0.42	76.63	77.18	0.55	0.71
5	13.16	13.55	0.38	2.90	5.69	5.39	0.29	9.76	60.86	62.18	1.33	2.18
6	13.32	13.72	0.40	2.97	3.00	2.69	0.31	25.37	78.49	76.38	2.11	2.68
7	13.45	12.88	0.57	4.24	1.23	1.04	0.19	16.46	85.49	91.67	6.18	7.23
8	13.87	13.36	0.51	3.67	1.14	1.70	0.57	4.84	91.81	84.62	7.19	7.83
9	16.85	16.66	0.20	1.17	11.72	11.65	0.07	0.61	30.24	30.39	0.15	0.50
10	16.53	16.66	0.13	0.77	11.77	11.86	0.10	0.97	30.88	28.48	2.40	7.76
11	16.34	15.91	0.42	2.58	10.07	9.51	0.56	7.02	39.36	40.25	0.89	2.27
12	15.81	15.19	0.61	3.88	7.96	7.21	0.76	8.89	52.28	51.80	0.48	0.91
13	15.62	15.30	0.32	2.05	8.51	7.38	1.13	13.81	50.91	52.76	1.85	3.63
14	14.98	15.58	0.60	4.01	8.21	8.07	0.14	2.03	48.87	46.27	2.60	5.33
15	15.17	15.24	0.07	0.44	6.99	6.87	0.13	3.18	54.92	55.12	0.20	0.36
16	13.81	14.59	0.78	5.65	3.97	4.46	0.49	12.41	73.50	76.22	2.72	3.70

Table 5: Minimum, maximum and average values of the differences and error percentages between the actual and predicted values of VMA, VTM and VFA for 16 mixtures.

Difference	VMA	Error%	VTM	Error%	VFA	Error%
Minimum	0.01	0.07	0.02	0.42	7.19	7.83
Maximum	0.78	5.65	1.13	13.81	0.15	0.50
Average	0.34		0.35		2.40	

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(b) Fixing the cellular phone on the upper plate at certain height.

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(c) The Selected forty-five irregular aggregate particles.

Figure 6: Three kinds of shapes for ImageJ calibration.

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(c) Comparison between irregular shapes areas from AutoCAD and ImageJ.

(d) Comparison between irregular shapes perimeters from AutoCAD and ImageJ.

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(a) Fifteen large particles.

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(a) Predicted values from the proposed compared with actual values of VMA.

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Figure 11: Comparison between the predicted value of VMA, VTM and VFA using the new models, respectively, and the actual value from the conventional methods

(a) Normal P-P plot of Reg. standardized Residual.

(b) Regression Predicted Value vs Regression Residual.

(c) Normal P-P plot of Reg. standardized Residual.

(d) Regression Predicted Value vs Regression Residual.

(e) Normal P-P plot of Reg. standardized Residual.

(f) Reg. Predicted Value Vs Regression Residual.

Figure 12: The linearity assumption checks for proposed models.