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An innovative digital image analysis approach to quantify the percentage of voids in mineral aggregates of bituminous mixtures

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Abstract: The objective of this study was to examine the feasibility of using a semiautomated computer-vision system to quantify the percentage of voids in mineral aggregates (VMA%) of bituminous mixtures. The system used a hybrid procedure which utilized a digital image analysis scheme and a planimeter surveying instrument. Thirty-nine Marshall specimens were prepared using limestone and gravel aggregates. Values of VMA% were obtained using the ASTM conventional procedure and the computer-vision procedure. To compute VMA% using the computer-vision procedure, normal case photography with uniform scale images was used to map horizontal and vertical cross sections of Marshall specimens. Image domain measurements were corrected for distortion. Spatial filters and image processing operations were used to enhance the aggregate edges. Experimental results showed slight variations between VMA% computed using conventional and the computer-vision procedures. The average differences of VMA% between conventional and the computer-vision procedures were 0.81% and 0.006% for gravel and limestone specimens, respectively. Measurements of VMA% for limestone mixtures were more precise than those for gravel mixtures because of the angular edge shape of limestone particles. Variations in VMA% were due to the anisotropic properties of asphalt mixtures, aggregate distribution in the asphalt mixture, and different shapes of aggregates. Using the computer-vision-based technique, VMA% of horizontal and vertical cross sections were 50% consistent. The existence of fine aggregate in the asphalt mixture affected the accuracy potential of the developed system because a low-resolution camera was used. Increasing the camera resolution and automating the area computation of aggregate are expected to enhance the potential accuracy of the procedure. The proposed method for VMA quantification is anticipated to improve field quality control of hot-mix asphalt (HMA). The use of computer-vision technology with bituminous mixtures can open the doors to a wide variety of applications.

Key words: bituminous mixtures, voids in mineral aggregate, computer vision, automation, image processing.

Résumé : L'objectif de cette étude était d'examiner la faisabilité de l'utilisation un système de vision par ordinateur semi-automatisé pour quantifier le pourcentage de vides dans les granulats mineraux (%VGM) de mélanges bitumineux. Le système a utilisé une procédure hybride qui utilisait un plan d'analyse digitale d'images et un instrument de planimétrie. Trente-neuf spécimens Marchall ont été préparés en utilisant des granulats de calcaire et de gravier. Les pourcentages de VGM étaient calculés par la procédure ASTM conventionnelle et la procédure de vision par ordinateur. Des images à echelle uniforme obtenues par photographie de cas normaux, furent utilisée pour établir des coupes transversales horizontales et verticales de spécimens afin de calculer le %VGM par la procédure de vision par ordinateur. Les mesures du domaine d'image étaient rectifiées pour tenir compte de déformations. Des filtres spatiaux et des opérations de traitement d'images furent utilisés pour rehausser les bords des granulats. Les résultats expérimentaux ont montrés de légères variations entre les %VGM calculés par les procédures conventionelles et ceux calculés par vision par ordinateur. Les différences de %VGM moyennes entre les procédures conventionnelles et celles de vision par ordinateur étaient 0,81 et 0,006% pour les spécimens de gravier et de calcaire respectivement. Les mesures de %VGM pour les mélanges calcaires étaient plus précises que pour les mélanges de gravier, à cause de la forme du bord angulaire des particules de calcaire. Les variations de %VGM étaient dues aux propriétés non-isotropiques des mélanges d'asphalte, à la distribution du granulat dans le mélange d'asphalte et aux formes différentes des granulats. Les %VGM des coupes transversales horizontales et verticales obtenus par la technique de vision par ordinateur, étaient cohérents à 50%. La présence de fins granulats dans le mélange d'asphalte a affecté le potentiel de précision du système développé. Cela était dû à l'emploi d'une caméra à basse résolution. L'augmentation de la

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résolution de la caméra et l'automatisation du calcul de la superficie des granulats sont supposés accroître le potentiel de précision de la procédure utilisée. La méthode proposée pour quantifier le VGM est supposée améliorer le contrôle de qualité sur le chantier des mélanges d'asphalte chauds. L'utilisation de la technique de vision par ordinateur pour les mélanges bitumineux peut dorénavant ouvrir la porte à un large éventail d'applications.

Mots clés : mélanges bitumineux, vides dans les granulats mineraux, vision par ordinateur, automatisation, traitement d'image.

[Traduit par la Rédaction]

Introduction and background information

The percentage of voids in the compacted mineral aggregates (VMA%) of hot-mix asphalt (HMA) is defined as the percentage of void spaces between the granular particles, related to the total volume of the compacted mixture. VMA% includes the air voids and the volume occupied by the effective asphalt content. Figure 1 shows the VMA%, air voids, and effective asphalt content in compacted asphalt paving mixture. In addition to size gradation, VMA% is one of the most important HMA design criteria to obtain durable pavement. VMA% also affects permanent deformation and fatigue performance of a compacted mix (Harvey et al. 1994; Hinrichsen and Heggen 1996). VMA% and shape of aggregate particles influence workability, shear resistance, tensile strength, fatigue, stiffness, durability, and optimum binder content (Hargett 1970; Barksdale et al. 1991).

Conventional procedures used to quantify VMA% require a series of exhaustive analytical and laboratory steps which depend on different types of specific gravities of the bituminous mixes (Asphalt Institute 1988). For cored HMA samples, the size gradation of aggregates could be found using the quantitative extraction of bituminous paving mixtures where aggregates obtained by those methods were mainly used for sieve analysis. Although these conventional laboratory-based methods are accurate, they are time-consuming because they require extensive laboratory work. This is considered one of the major drawbacks of the conventional techniques, especially considering that asphalt concrete is a heterogeneous material consisting of asphalt cement, voids, and different aggregates gradation. Various innovative methods are available to facilitate the quantification of VMA% and size gradation of aggregate. One of the most effective methods is the digital image processing and analysis technique. This method provides the capability for rapid and high potential accuracy measurements of the characteristics of asphalt and aggregate particles. Further, numerous near real-time measurement activities for each particle can be quantified. For example, Yue et al. (1995) used a digital image processing technique to quantify the distribution, orientation, and shape of coarse aggregates having a diameter larger than 2 mm in asphalt concrete mixtures. Their quantitative results indicated that the microstructure characteristics of asphalt concrete mixtures can be accurately measured using a digital image processing technique, and that the measured cross sections of coarse aggregate particles have the tendency to lie horizontally in the mixture. Kuo et al. (1996) used three-dimensional image analysis techniques of aggregate particles to quantify the long, intermediate, and short particle dimensions. These measurements provided direct measures of the flatness and elongation of the particles. Different measurement parameters including shape, size, diameter, and surface area can also be defined. As one of the information-technology tools, the prices of devices associated with image analysis techniques have fallen, which encourages researchers to use such techniques (Wigan 1985).

Consequently, the spatial distribution of coarse aggregate microstructure can be measured and analyzed using digital image analysis. Yue et al. (1995) showed that the aggregate particles are randomly oriented in the asphalt concrete mixture and have larger areas on horizontal cross sections than on vertical cross sections. This indicates that any technique used to measure asphalt concrete mixtures should take into consideration horizontal and vertical cross sections because of the anisotropic properties of mixtures. Thus, the aggregate distribution is expected to affect the accuracy of the extracted measurements.

Image analysis technique has also been used to evaluate aggregate blends for the amount of fine aggregate of siliceous sand-size particles (Thomas et al. 1994). In fact, the automated image analysis technique was used with a higher degree of confidence and accuracy than manual techniques.

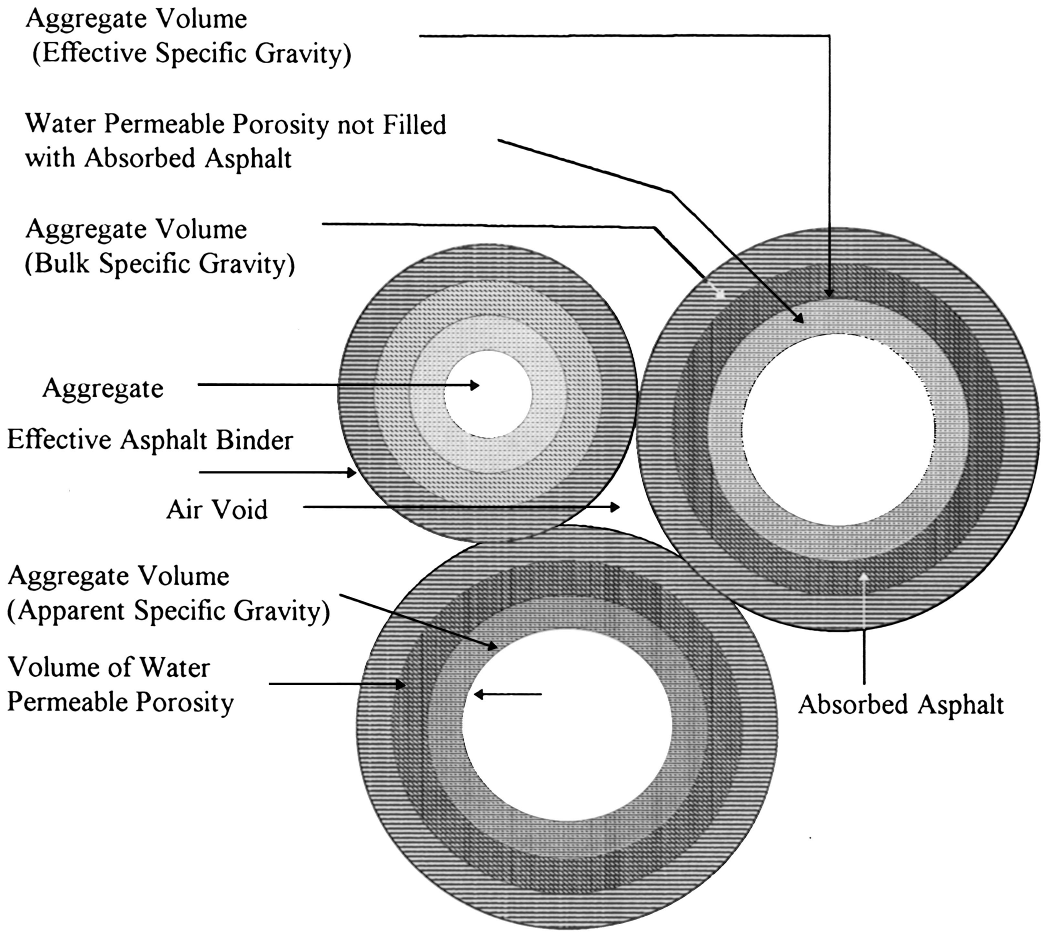
On the other hand, automated image analysis of pavement distresses is promising and indicates that the task of automating the analysis of pavement images is feasible (Koutsopoulos and Sanhouri 1991). Different approaches for automatic interpretation of pavement distresses, especially cracks and rutting, have been investigated and are used in practice (Obaidat et al. 1997).

Other methods, such as the fractionating water column methodology and national aggregate association flow test, are available to automate the size-gradation analysis of the finer portion of aggregate (<2.38 mm) (Aljassar and Haas 1994; Cross et al. 1994). These methods use a hybrid system to automate the analysis of aggregate blend. The modified national aggregate association flow test replaced the use of microscopic evaluation of fine aggregate to determine the percent crushed material in the mix.

Harvey et al. (1994) investigated the effects of laboratory compaction devices such as the rolling wheel, gyrator, and kneader on asphalt aggregate structure using an image analysis of plane sections cut from specimens. They also studied the effects of specimen surface condition on air-void structure. Their results indicated that the outer periphery of as-compacted specimens has a different air-void and aggregate structure than that found inside the specimen. Rolling-wheel specimens cut and cored from larger masses had little air-void content gradient.

The objective of this research was to develop a new approach to quantify VMA% of bituminous mixtures using an image-based technique. The technique uses a normal-based

Fig. 1. VMA%, air voids, and effective asphalt content in compacted asphalt paving mixture (Asphalt Institute 1988).



charged-coupled-device (CCD) camera configuration. Much progress has been made toward the automation of gradation analysis of the coarse portions of an aggregate blend, therefore gradation analysis was excluded from this study (Aljassar and Haas 1994).

Experiment setup

HMA samples

Two types of aggregates, i.e., limestone and gravel, and asphalt cement (AC) of type AC-10 (80–100 penetration) were used in this study. Table 1 shows the properties of AC used in the study, and Table 2 shows the aggregate gradation and the job mixing formula to prepare Marshall specimens used according to specifications of the Jordanian Ministry of Public Works and Housing (MPWH).

Twenty-one Marshall specimens using gravel aggregate and 18 crushed limestone specimens were used in the study. For the purpose of VMA% data analysis, every three specimens (having similar mixing conditions) for each type were represented by taking the average values of the computed VMA%. Marshall specimens were prepared according to American Society for Testing and Materials (ASTM) Standard D1559 (ASTM 1981*a*). The following equation was used to compute VMA% using the conventional procedure (Asphalt Institute 1988):

$$[1] \qquad \text{VMA\%} = 100 - \frac{G_{mb}P_s}{G_{sb}}$$

where VMA% is the percentage of voids in the mineral aggregate (percentage of bulk volume), G_{sb} is the bulk specific gravity of the aggregate, G_{mb} is the bulk specific gravity of the compacted mixture according to ASTM Standard D2726 (ASTM 1981*b*), and P_s is the percent aggregate by total weight of the mixture.

After quantifying VMA% using the conventional procedures according to ASTM (1981) and Asphalt Institute (1988), the samples were cut along longitudinal (vertical) and horizontal cross sections using an electric stone cutting machine.

Specimen mapping

Normal case photography of close-range photogrammetric mapping as described by Ghosh (1988) was used in this study. Normal case photography produces a constant scale for a flat two-dimensional surface. A single camera was sufficient to map the bituminous mixture specimens from one position. Scale uniformity was controlled by making the optical axis of the camera perpendicular to the object–space plane of the specimen. The camera was mounted on a tripod equipped with a manual leveling unit. To determine the scale of the mapped images, a 10 cm × 10 cm square (which should appear in every image) was outlined in black on a

Table 1. Properties of asphalt cement used in the study.

Test	Result	Methods
Ductility at 25°C (cm)	100 minimum	ASTM D113
Penetration at 25°C (0.1 mm), 100 g, and 5 s	80–100	ASTM D5
Softening point (°C)	45.8–52.0	ASTM D36
Specific gravity at 25°C	1.014	ASTM D70
Solubility in trichloroethylene (wt.%)	99.5 minimum	ASTM D2042
Flash point (Cleveland open cup) (°C)	320 minimum	ASTM D92

Note: All tests except solubility and flash point based on laboratory results.

Table 2. Aggregate gradation used in the study.

	Percent passing	
Sieve size	Specification[a]	Job mixing formula
1 in. (25 mm)	100	100
3/4 in. (19 mm)	90–100	95
1/2 in. (12.5 mm)	71–90	80.5
3/8 in. (9.5 mm)	56–80	68
No. 4 (4.75 mm)	35–65	50
No. 8 (2.35 mm)	23–49	36
No. 20 (850 μm)	14–43	28.5
No. 50 (300 μm)	5–19	12
No. 80 (180 μm)	4–15	9.5
No. 200 (75 μm)	2–8	5

[a]Jordanian Ministry of Public Works and Housing (MPWH) specification.

piece of white paper to provide different background intensities. Image scale was computed by knowing the object–space and image lengths of each side of the square.

A Samsung model SCX 800 8 mm CCD camera was used to capture images of the tested specimens. The camera has a low-resolution capability, but its geometric fidelity and low cost (less than US$500) encouraged its use in this study. A personal computer (PC) equipped with a digitizing board and a video monitor, forming the basic components of a vision system, were used to display digital images of the mapped specimens. Vision system usage was restricted to freezing image frames and converting from analogue to digital (A/D) image format. A camera focal setting of about 40 mm (1 mm is equivalent to about 94.5 pixels) was used in this study because it had the capability of visualizing the mapped specimens in the camera field of view with reasonable scale. The CCD camera was calibrated using a planar wall object to define its interior geometry, i.e., the effective focal length in pixels, radial and decentering lens distortion parameters, and the affine scaling parameter (Obaidat and Wong 1996). The camera was about 1 m from the tested specimens, and the specimens were approximately centered in the image in order to minimize the distortion affect and assure scale uniformity.

The digitizing board was used to capture digital images using a standard monochrome phase alteration line (PAL) system format of 752H × 480V pixels at 256 gray levels. Then the image was saved as a binary format file. Image coordinates for the square used for scale were measured directly from the computer screen to a subpixel accuracy. In order to overcome the problem of distortion of bundles of rays passing through the lens, measured image coordinates were refined to correct for decentering and radial distortions of the camera lens using the correction model shown in the following equations (Wiley and Wong 1990):

$$[2] \qquad \bar{x}_j = x_j + \Delta x_j$$

$$[3] \qquad \bar{y}_j = y_j + \Delta y_j$$

where $\bar{x}_j$ and $\bar{y}_j$ are the corrected image coordinates of image point j, x_j and y_j are the measured image point coordinates of point j, and Δx_j and Δy_j are the corresponding corrections for the distortion effect of the image.

Software development

Computer software was needed to capture images, identify and position targets in the image domain, refine image coordinates to correct for radial and decentering distortions, apply spatial filters to images, and perform edge enhancement. Image acquisition was performed using an existing function provided in silicon video image processing (SVIP) software with a PC vision system (EPIX Incorporated 1993); commercial software was not readily available for the rest of the required operations. Therefore, software was developed for the purpose of implementation of this work.

Image coordinates

A targeting program was developed to identify the position of image points in two dimensions on any displayed image using any image format. The origin of image coordinates was selected to be the upper left corner of the image. Equations [1] and [2] were then used to refine image coordinates, i.e., to find the corrected image coordinates. Corrections for both *x* or *y* coordinate should be unique for every image point.

Spatial filters

Development of image processing operations was needed to provide spatial and edge-enhancement filters. Spatial filters may provide low-pass, median, high-pass, or edge-enhancement filters. Low-pass, median, or high-pass filters replace each pixel with the results of a 3 × 3, i.e., 9 pixels, convolution with a different kernel on the full image or a selected image window defined by the user. The 9 pixels in the 3 × 3 neighborhood are examined, then the pixels with values within plus or minus a threshold (selected by the user) of the value of the center pixel are used to form an average which replaces the center pixel. Thus, edge smear will be minimized and noise will be reduced. For example, a high-pass filter enhances edges and makes image appear sharper by subtracting a blurred image from the original image.

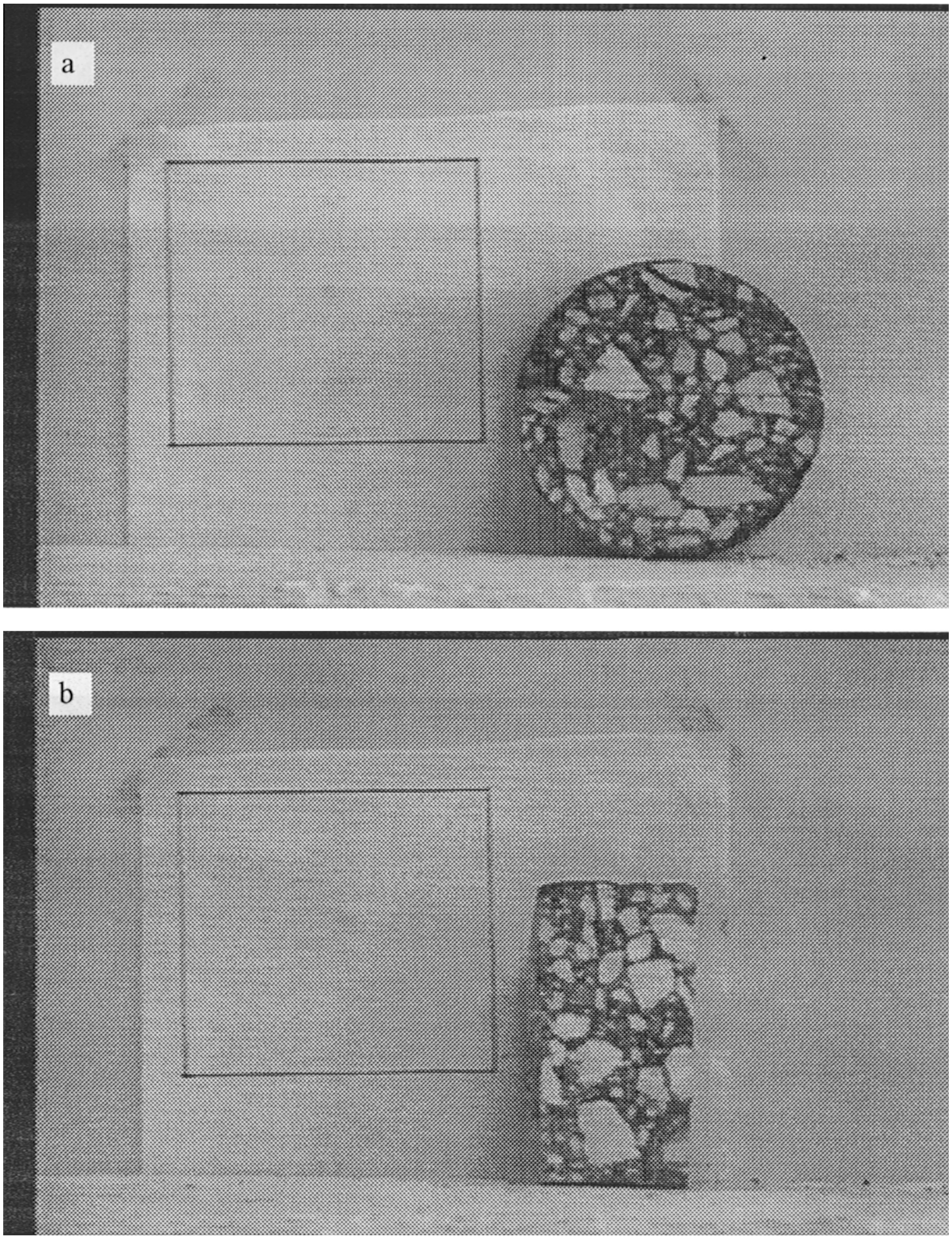


Fig. 2. Digital video images for limestone asphalt concrete mixture: (*a*) horizontal cross section and (*b*) vertical cross section.

The contrast of the edges was enhanced by applying the edge-enhancement operation. This simply subtracts the magnitude of the edge gradient from the image.

VMA% quantification procedure

The following hybrid steps were used to quantify VMA% for the studied samples:

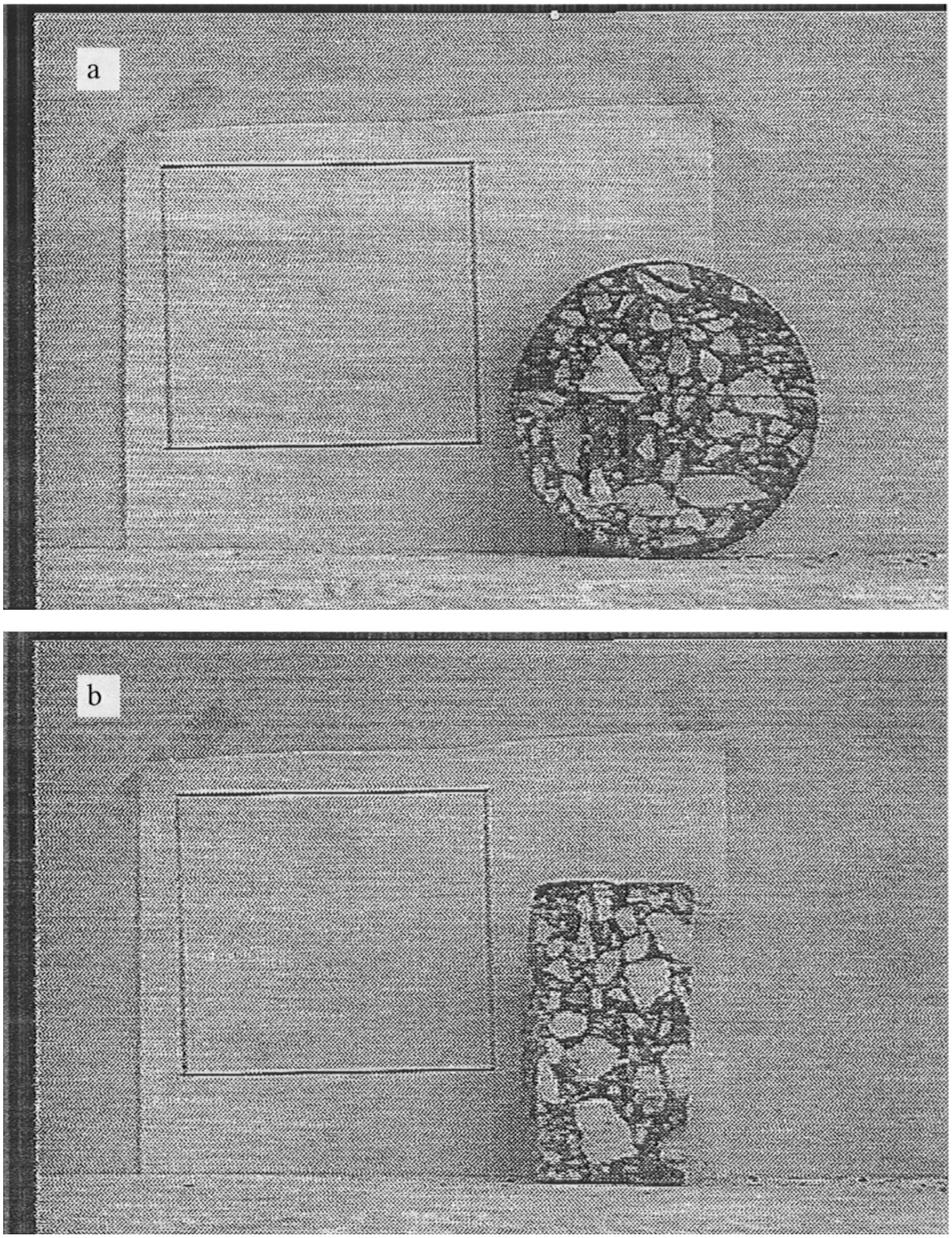
(1) Capturing video images for horizontal cross sections and vertical cross sections (longitudinal profiles) of Marshall samples.

(2) Digitizing the captured images into a digital format using the PC equipped with a digitizing board.

(3) Sharpening and enhancing the images using the image-processing software specifically developed for the purpose of facilitating the extraction of edges of aggregate boundaries. Figure 2 shows examples of horizontal and vertical cross section digital video images of limestone asphalt concrete mixture, and Fig. 3 shows their respective sharpened and enhanced images.

(4) Printing a high-resolution image of the specimens and the scale squares captured next to them using a laser printer.

Fig. 3. Sharpened and enhanced images of limestone asphalt concrete mixture: (*a*) horizontal cross section and (*b*) vertical cross section.



(5) Manually measuring the total area of each specimen and the area of aggregates using the planimeter for the horizontal cross sections and longitudinal profiles (vertical cross sections).

(6) Computing VMA% for each specimen by subtracting the area of aggregates from the specimen area using the following formula:

$$[4]\qquad \text{VMA\%} = \left[A_S - \sum_{i=1}^{n} A_i\right] \Big/ A_S$$

where A_S is the total area of the specimen, A_i is the area of aggregate particle i, and n is the number of aggregate particles in the specimen.

It is worthwhile mentioning here that the area (rather than specimen volume or density) was used for each cross section to compute VMA% because aggregate shape and mixture varied for each cross section, i.e., it is anisotropic. The aforementioned steps, except step 5, were operated with full automation capability using digital images of the HMA microstructure.

Table 3. VMA% for specimens using the conventional laboratory procedure.

Aggregate type	VMA%
Limestone	13.4
Gravel	15.7

Experimental results and analysis

Tables 3 and 4 show the computed VMA% of asphalt concrete mixtures of limestone and gravel using the conventional procedures and the proposed computer vision based procedure, respectively. The average VMA% using conventional procedures for mixes containing limestone and gravel aggregates were 13.4% and 15.7%, respectively. As shown in Table 4, there were variations in VMA% computed using the computer vision based technique between the horizontal and vertical cross sections for all specimens consisting of gravel and limestone. This was not due to accuracy problems associated with the computer vision technique, but to the anisotropic properties of asphalt mixtures. Thus, the aggregate distribution in the asphalt mixture was responsible for the differences in the VMA% between the computer vision based technique and the conventional procedure. This was also noted by Yue et al. (1995).

Differences between VMA% computed using the computer vision based technique and the conventional procedure are shown in Table 5. The average differences were 0.81% and 0.006% for gravel and limestone specimens, respectively. The absolute differences were 3.4% and 2.28%, respectively, for gravel and limestone specimens. VMA% measurements for limestone mixtures were more precise than those for gravel mixtures. Standard errors of computed VMA% were used as indicators of precision, with values of 4.2% and 2.7% for gravel and limestone, respectively. The computer vision based technique showed higher potential accuracy in VMA% quantification for limestone mixtures due to the angular edge shape of particles. In gravel aggregates the edges were less sharp, which increases the possibility of errors while measuring the area of aggregate using the planimeter.

The potential and limitations of the system

The system presented herein has the potential to bridge the gap between conventional procedures and fully automated quantification methods to quantify VMA%. The system does not require extensive computational and analytical efforts to compute VMA%, rather a direct measurement procedure is used. Thus, VMA% quantification will not require extraction of aggregates for Marshall specimens or highway cores, nor will it require computational procedure to quantify bulk specific gravity, maximum theoretical density, asphalt content, etc. The practicality, near real-time potential, and ease-of-use characteristics of the system will open the door for image-based and microstructure analysis of HMA for applications such as gradation (aggregate size and shape), stripping, and distress assessments. The system does not require the availability of experts nor extensive labor. This means that site and consultant engineers can control the quality of HMA without using conventional laboratory investigation.

This study was limited to the use of normal-based photography captured by CCD camera. Normal-based photography has the advantage of image scale uniformity. Stereovision technology and the electronic scanning microscope (ESM) may be other alternatives with better accuracy potential to quantify VMA%. Unfortunately, ESM is not available due to limited resources, and stereovision requires that the specimen be mapped from two different perspectives using single or dual cameras and it also requires longer to perform the camera calibration procedure. These two factors require extra time and thus do not encourage the use of stereovision technology for VMA% quantification, especially when seeking practical and easy to use procedures to overcome the problems associated with the available conventional laboratory procedure. Because of these reasons stereovision technology was not used in this study.

The potential of CCD cameras to capture clear images, i.e., higher scale images, for fine aggregate is another limitation of this study which affected the accuracy potential of the measured VMA%.

The method presented to assess VMA% is less time-consuming than the conventional method; however, this advantage is seriously compromised by the fact that the new method is semiautomated, since the total area of aggregates in cross sections is measured manually with a planimeter. The development of a fully automated system to measure the aggregate content is possible by using any image-processing software or technique. However, it was not used in this study because there was no image-processing software package readily available during the implementation of this research work. Therefore, despite the limitations of the method presented herein, it has the potential to bridge the gap between conventional procedures and fully automated quantification methods to find VMA%; however, it is not a substitute for the conventional procedure unless it is incorporated with a fully automated image-based analysis procedure to measure aggregate content.

Summary and conclusions

An attempt was made to quantify VMA% of bituminous mixtures using a semiautomated hybrid system which utilized a digital image analysis scheme and planimeter surveying instrument. From the described laboratory and normal-based image analysis scheme, it was found that the computer vision technique was sufficiently accurate to quantify VMA%. It was found that the use of the image analysis technique for VMA% computation is practical. The experiment emphasized the importance of the application of spatial filters and image-processing operations to enhance aggregate edge detection. Variations in VMA% between horizontal and vertical cross sections were most likely due to the anisotropic properties of asphalt mixtures. Other factors affecting the consistency of the results include aggregate distribution in the asphalt mixture and different shapes of aggregates. In fact, the low-resolution image, which pre-

Table 4. VMA% results using the vision procedure.

Sample No.	Average area of aggregate (cm²)[a] Vertical section	Horizontal section	Average area of full section (cm²) Vertical section	Horizontal section	VMA% from vertical section	VMA% from horizontal section	Average VMA% of vertical and horizontal sections
Gravel aggregate							
A-G	46.6	80.9	57.6	90.1	19.0	10.2	14.6
B-G	31.0	73.2	42.1	87.0	26.4	15.8	21.1
C-G	41.6	71.2	55.7	89.6	25.2	20.5	22.8
D-G	68.0	72.6	82.6	88.4	17.7	17.8	17.7
E-G	39.2	81.7	47.7	89.9	17.8	9.0	13.4
F-G	44.7	82.0	53.8	89.6	16.8	8.5	12.6
G-G	40.6	83.1	48.4	92.1	16.1	9.7	12.9
Average					19.9	13.1	16.5
Limestone							
A-L	67.6	80.9	80.9	93.3	16.4	13.2	14.8
B-L	36.3	89.4	45.0	103.7	19.3	13.7	16.5
C-L	88.4	86.7	97.9	96.9	9.3	10.5	10.0
D-L	47.0	88.1	55.7	98.1	15.6	10.1	12.9
F-L	40.9	76.1	49.6	88.2	17.5	13.7	15.6
G-L	45.5	78.0	49.9	88.7	8.7	12.0	10.3
Average					14.5	12.2	13.4

[a]Average of three specimens.

Table 5. VMA% differences between conventional and vision procedures.

Aggregate type	Average VMA difference (%)	Standard deviation (%)	Average VMA absolute difference (%)
Gravel	0.81	4.2	3.40
Limestone	0.006	2.7	2.28

vented visualization of fine particles, was a major factor in reducing the accuracy of the computed VMA%. The VMA% measurements for limestone mixtures were more precise than those for gravel mixtures because of the angular edges of the limestone particles. Therefore, the method could be successfully used to quantify VMA% for limestone HMA. Despite its limitations, the system presented herein has the potential to bridge the gap between conventional procedures and fully automated quantification methods to quantify VMA%. It is anticipated that increasing the image resolution and scale will enhance the consistency of the results.

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