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Digital image processing for aggregate orientation in asphalt concrete mixtures

Zhong Qi Yue and Isabelle Morin

Abstract: Asphalt concrete is a composite material which consists of asphalt cement, voids, fine particles, sand, and coarse aggregates. Previous investigations of asphalt concrete mixtures have mainly concentrated on the macroscopic properties of the composite materials based on the assumption that the mixtures are homogeneous and isotropic. This paper applies an innovative digital image processing technique to quantify the orientations of coarse aggregate particles (≥ 2 mm) in asphalt concrete mixtures such as hot mix asphalt, stone matrix asphalt, and large stone asphalt compacted in the laboratory or field. The results indicate quantitatively that asphalt concrete specimens compacted in the field or in the laboratory with gyratory compactor have an oriented structure of aggregate particle distribution where the major cross sections of aggregate particles have the tendency to lie horizontally, and that aggregate particles are more randomly oriented in the asphalt concrete specimens compacted in the laboratory with the Marshall compactor.

Key words: asphalt concrete mixtures, digital image processing, microstructure, aggregate orientation, anisotropy, compaction methods.

Résumé : Le béton bitumineux est un matériau composite constitué de ciment asphaltique, vides, particules fines, sable et particules grossières. Les études antérieures des mélanges de béton bitumineux se sont principalement attardées aux propriétés macroscopiques du matériau, le supposant homogène et isotrope. Cet article présente l'application d'une technique innovatrice, l'analyse digitale d'images, pour quantifier les orientations dominantes des particules grossières (≥ 2 mm) dans les mélanges comme l'asphalte mélangé à chaud, l'asphalte coulé gravillonné et l'asphalte à gros granulats compactés en laboratoire ou sur terrain. Les résultats démontrent de façon quantitative que pour les échantillons compactés sur terrain ou en laboratoire à l'aide du compacteur gyratoire, la structure formée par les agrégats présente une orientation dominante. Les agrégats ont en effet tendance à s'orienter de façon à ce que leur section principale soit dans le plan horizontal. Ce n'est pas le cas des échantillons préparés à l'aide du compacteur de labotaroire Marshall où les agrégats sont orientés de façon plus aléatoire.

Mots clés : mélanges de béton bitumineux, analyse digitale d'images, microstructure, orientation, anisotropie, méthodes de compactage.

1. Introduction

Asphalt concrete (AC) is a composite material which consists of asphalt cement, voids, fine particles, sand, and coarse aggregates. These individual materials and components have different physical and mechanical properties and behaviour which have a significant effect on the performance of AC mixtures. It is well recognized that AC performance is also influenced by compaction methods and the quality and effort of compaction. Realistic prediction of the performance of AC mixtures and pavements necessitates consideration of the heterogeneous nature of the composite materials (Sepehr et al. 1994; El Hussein and Yue 1994). However, mechanistic models and design of AC mixtures and pavements have concentrated mainly on the macroscopic properties of AC and have been constructed on the basis of general principles of continuum mechanics (Monismith 1992). The composite materials are always assumed to be homogeneous and isotropic and their heterogeneous and anisotropic properties are largely ignored (Selvadurai et al. 1990).

This paper presents a quantitative investigation on the three-dimensional (3-D) orientations of coarse aggregate particles (≥ 2 mm) in AC mixtures. An innovative digital image processing procedure, developed at the National Research Council of Canada (NRC), was utilized to carry out the investigation (Yue et al. 1995). Digital image processing is the term that pertains to converting video images into a digital form, and applying various mathematical procedures to extract significant information from the picture. A literature survey indicates that the application of digital image processing to the quantitative study of microstructure of AC mixtures is very limited (Frost and Wright 1993). A related study, funded by the U.S. Strategic Highway Research Program (SHRP) and carried out by the Danish Road Institute (Eriksen 1993), was on the microscopical analysis of voids in AC mixtures. In this paper, digital image processing has been applied to the quantitative investigation of coarse aggregate orientation in AC mixtures by examining statistically the differences between the aggregate particles on horizontal and vertical cross sections of AC mixtures. The outline of the paper is as follows:

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Written discussion of this paper is welcomed and will be received by the Editor until August 31, 1996 (address inside front cover).

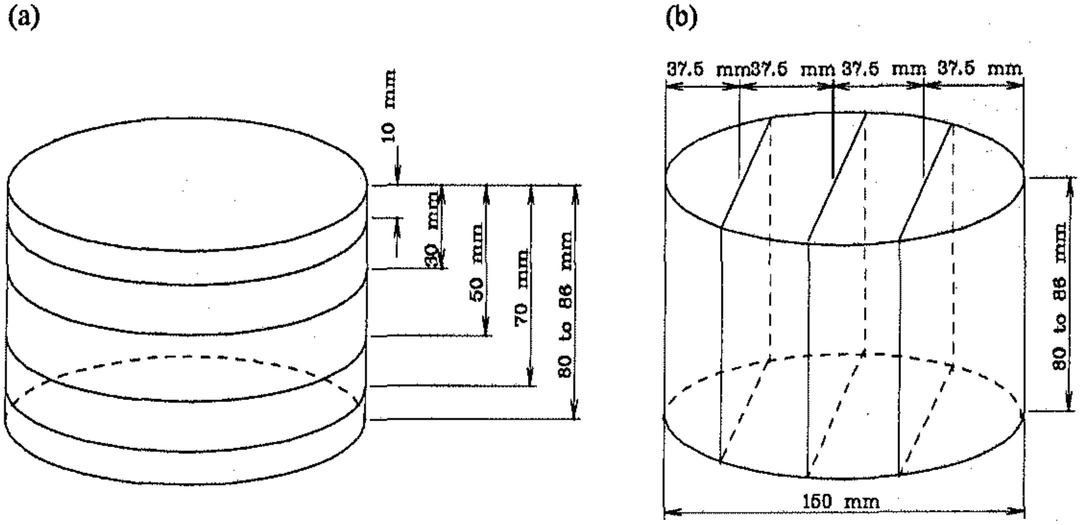


Fig. 1. Multiple cutting for plane cross sections of cylindrical AC specimens: (*a*) horizontal cutting; (*b*) vertical cutting.

(*i*) a brief description of the digital image analysis techniques used in this study;
(*ii*) definition of morphological measurements of aggregates on an AC cross section;
(*iii*) approach for analysis of 3-D aggregate orientation from two-dimensional (2-D) image data;
(*iv*) results and analysis of aggregate orientations in AC mixtures by taking into account different compaction methods; and
(*v*) summary of the main conclusions and recommendations.

2. Digital image processing procedure

Field cores or laboratory prepared AC specimens are cut using a circular masonry saw in multiple vertical or horizontal plane cross sections (Fig. 1). The AC cross sections are photographed with a ruler placed beneath the section for scaling and calibration in the digital image processing. A Microteck flatbed scanner is used to convert the photographs into digital files that can be processed by a computer. The image is stored in a file with .TIF format as series of pixels (or points). For a black and white print and a colour picture (4 in. by 6 in. (1 in. = 2.54 cm)), 300 dots per inch and 165 dots per inch were used, respectively. Each pixel has three digital values indicating the X and Y coordinates and grey level or colour intensity. It is noted that other systems are available for a direct input of a video image into a computer using a charge coupled device (CCD) camera (Eriksen 1993). However, such a system is quite expensive.

An image editing software, called Picture Publisher (v.4.0), was then used to manually outline the boundaries of aggregates on the digitalized image. A manual technique was used because the image analysis software cannot satisfactorily and automatically recognize if a pixel is part of an aggregate or the asphalt matrix. The automatic recognition of aggregates produced poor results owing to the following facts:

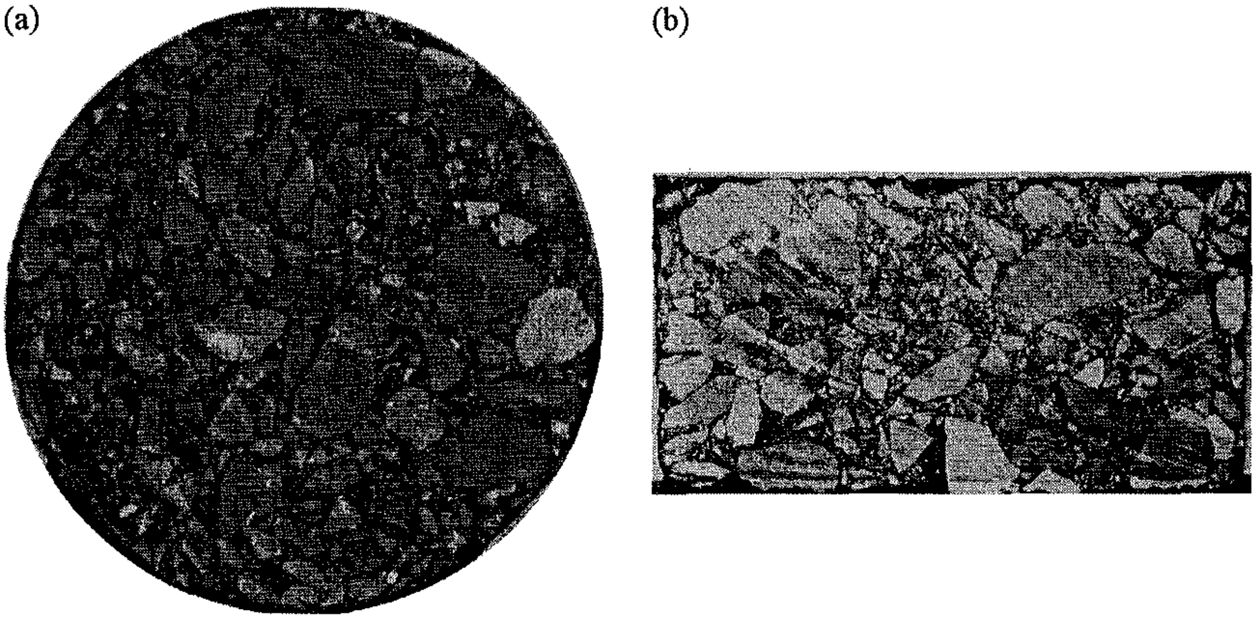
(*i*) There are aggregate to aggregate contacts. Two or more aggregates can be recognized as one larger aggregate by the computer.
(*ii*) The matrix surrounding the aggregate cross sections consists of bituminous material, fine particles (less than 2 mm), and voids. The bituminous material is black. However, the fine particles and voids have different colours. As a result, the matrix is not black and has different grey levels.
(*iii*) Some aggregate cross sections are very black which can easily be identified by human eyes, but could be identified as matrix by the computer.

Using the freehand mask tool in Picture Publisher, the area of every aggregate was marked and filled with a contrasting colour. Once all aggregates were contoured, the posterize-threshold tool was used to reduce the colour number to two. One colour represents the aggregates and the other the matrix. The grey scale of a modified image was transformed into black and white. A modified image file about 0.6 MB was then obtained. In this modified image file, pixels of aggregates are turned on while pixels of the matrix are turned off.

Image analysis statistics software, called MOCHA, is used to calculate the values of morphological parameters of aggregate cross sections from the modified image file. The ruler is utilized to set up the scale of the image for calculation. A plane Cartesian coordinate system (X, Y) is automatically set up. The calculated values of the morphological parameters of aggregate cross sections are saved in a file with ASCII format. The modified image file is saved in either .PCX or .TIF format. These morphological parameters are defined in the next section.

An example of digital image processing results is given in the following. Two digitalized images are illustrated in Fig. 2, which shows the horizontal and vertical cross sections of a 150 mm diameter sample of a gyratory compacted large stone mix (LSM). Figure 3 shows the modified images after using Picture Publisher and MOCHA. In this MOCHA image, each aggregate has an identifying number and the major and minor axes of each aggregate cross section are

Fig. 2. Digitalized images of a gyratory compacted large stone mix: (*a*) horizontal cross section (150 mm diameter); (*b*) vertical cross section (150 × 80 mm).



also illustrated. Table 1 presents an example of the digital results of the aggregate characteristics on the AC cross section in Fig. 2. The listed aggregates in Table 1 can easily be identified in Fig. 3 and the measurements can also be easily checked. It is noted that all the above digital image processing was performed on a 66-MHz 80486 personal computer.

3. Parameters of aggregate cross sections

Morphological parameters describing the geometry of an aggregate cross section can be measured using the above digital image processing procedure. Referring to Fig. 4, one can have the values of the following basic parameters of an aggregate cross section:

(*i*) perimeter;
(*ii*) area;
(*iii*) coordinate of the centroid;
(*iv*) coordinates of the major axis ends (Maj X_1, Maj Y_1, Maj X_2, Maj Y_2);
(*v*) coordinates of the minor axis ends (Min X_1, Min Y_1, Min X_2, Min Y_2);
(*vi*) major axis length;
(*vii*) minor axis length;
(*viii*) Feret diameter = $(4 \times \text{area}/\pi)^{1/2}$;
(*ix*) major axis orientation; and
(*x*) shape factor (= $4\pi \times \text{area/perimeter}^2$).

The major axis of an aggregate cross section is defined by the greatest distance between two points of the boundary contour. The minor axis of an aggregate cross section is defined as the longest line that can be drawn perpendicular to the major axis. Feret diameter is the diameter of a fictitious circular aggregate that has the same area as the aggregate being measured. Major axis orientation is the angle between the major axis and a horizontal line (i.e., the X-axis) on the scanned image. Shape factor is a measure of how nearly circular an aggregate cross section is. A perfect circle has a shape factor of 1 and a line has a shape factor of 0. In general, the less the shape factor, the more elongate the particle cross section (the less the ratio of the minor axis length to the major axis length). Figure 5 illustrates the shape factors of ellipses, rectangles, and right triangles versus the ratio of the width (height) to the length.

4. Approach for aggregate orientation in AC mixes

The above digital image processing procedure accurately measures the geometrical values of the characteristics of aggregate particles on the 2-D images of AC cross sections. The orientation of aggregate particles, however, is one of the 3-D and statistical characteristics of the aggregate distribution in AC mixtures. In order to estimate the 3-D orientation of coarse aggregate particles in AC mixtures from 2-D image data, this paper uses the quantitative measurements of coarse aggregates on horizontal and vertical cross sections of AC mixtures. In other words, the 3-D orientations of coarse aggregate particles are investigated by comparing the geometrical characteristics of coarse aggregate particles on horizontal and vertical cross sections of AC mixtures. This approach to investigate the dominant aggregate orientations using digital image processing is based on the assumption that the difference between the aggregate particles on horizontal and vertical cross sections is an index directly related to the dominant orientation of coarse aggregate particles in AC mixtures. The validation of this assumption is based on the following physical observations:

(*i*) Aggregate particles are not purely spherical and have major, intermediate, and minor planes.

(*ii*) Aggregate particles are randomly oriented during mixing before paving.

(*iii*) The major planes of aggregate particles are more likely to lie horizontally either during laying by the screed

Fig. 3. Digital images of Fig. 2 after MOCHA in a Cartesian coordinates system: (*a*) horizontal cross section (150 mm diameter); (*b*) vertical cross section (150 × 80 mm).

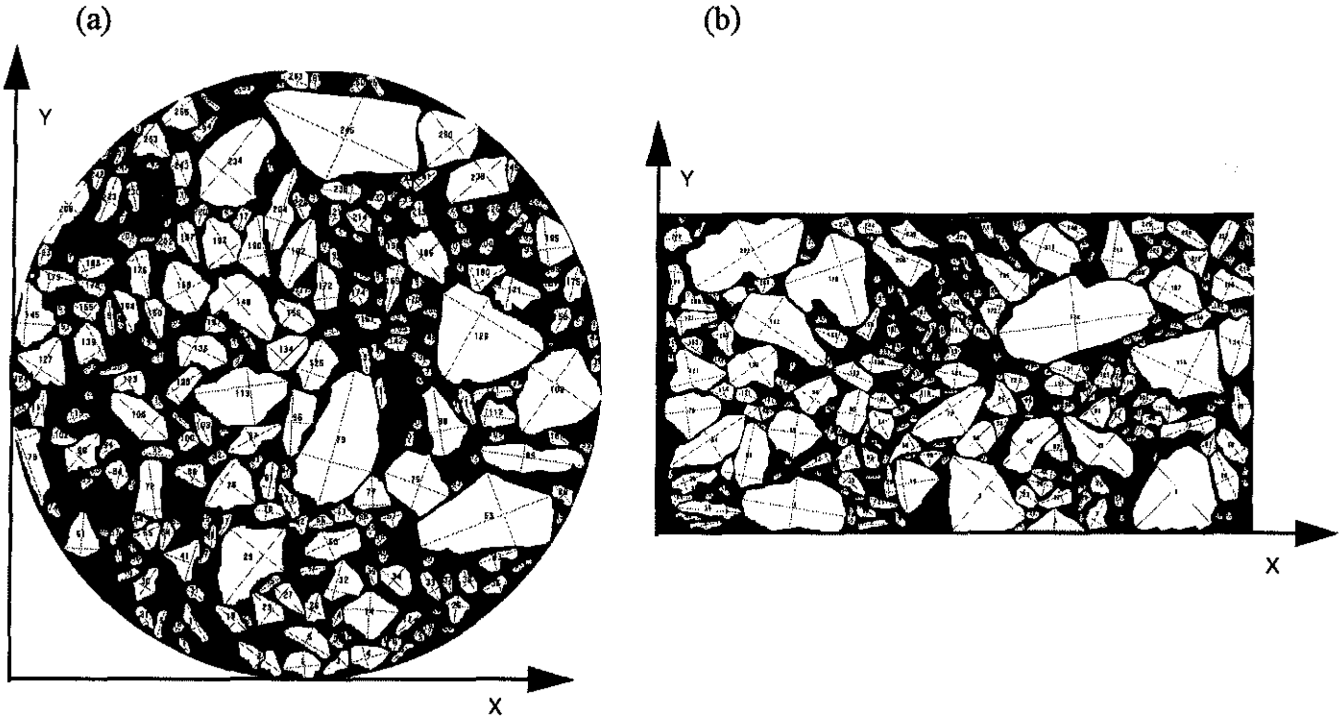


Table 1. Selected results for the basic measurements of aggregate cross sections of Fig. 3.

No.	Area (mm^2)	Perimeter (mm)	X_{ac} (mm)	Y_{ac} (mm)	Maj X_1 (mm)	Maj Y_1 (mm)	Maj X_2 (mm)	Maj Y_2 (mm)	Min X_1 (mm)	Min Y_1 (mm)	Min X_2 (mm)	Min Y_2 (mm)
						Horizontal cross section						
29	231.35	69.53	60.74	29.61	54.97	18.83	69.70	37.51	69.55	27.03	56.19	37.21
53	470.62	96.44	121.03	40.09	104.17	33.26	136.67	45.86	120.57	51.48	127.86	33.26
129	445.58	92.54	118.90	84.43	134.09	81.70	109.19	95.82	109.79	75.02	120.57	94.76
234	282.52	74.22	56.34	127.56	63.32	138.95	47.53	119.51	61.65	119.21	48.14	129.84
246	633.59	114.34	84.58	135.31	63.32	143.20	102.05	125.89	79.12	123.92	88.38	143.96
						Vertical cross section						
3	277.03	70.87	83.79	7.98	95.37	3.06	76.58	18.79	76.69	0.00	88.49	14.42
49	114.25	49.14	96.36	21.96	89.58	16.39	103.13	27.53	97.12	16.17	91.77	22.94
144	581.83	114.59	107.94	53.53	88.49	49.93	128.69	55.28	108.92	45.56	106.41	64.35
203	378.67	94.61	22.83	70.03	9.83	61.72	37.36	78.11	28.95	64.02	20.54	78.33
217	127.43	51.18	101.49	71.01	109.25	68.28	93.95	73.63	97.67	67.19	101.27	77.67

bar of a paving machine or during compaction.

If the structure of aggregate particles were oriented in an AC mixture, then the horizontal cross sections of AC specimens would cut more major and intermediate planes of the aggregate particles, and the vertical cross sections of AC specimens would cut more intermediate and minor planes of the aggregate particles. From statistical point of view, the sizes (or areas) of the aggregate particles on the horizontal cross sections would be greater than those of the aggregate particles on the vertical cross sections. In this paper, we use the following statistical parameters in the analysis:

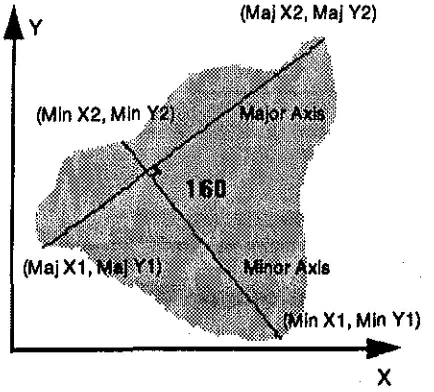
(*i*) *Number-per-unit-area*: total number of aggregate particles over the total area in square centimetres (cm^2) of the cross section.

(*ii*) *Area percentage*: percentage of the area occupied by aggregates over the total area.

(*iii*) *Area gradation by dimension*: summation of the areas of the aggregate cross sections whose minor axis lengths, major axis lengths or Feret diameter are respectively between 2 mm and a dimension *d* ($d \geq 2$ mm) over the total aggregate areas. It is expressed in percentage as a function of the dimension *d*.

(*iv*) *Area gradation by shape factor*: Summation of the areas of aggregate cross sections whose shape factors are

Fig. 4. Geometric definition of an aggregate cross section.



between 0 and a value s ($0 \leq s \leq 1$) over the total aggregate areas. It is expressed in percentage as a function of the value s.

In-house computer programs were developed to calculate the above statistical parameters of the characteristics of aggregate particles on AC cross sections from the morphological parameters of each aggregate cross section obtained using the digital image processing procedure. The three dimensions of an aggregate cross section (i.e., minor axis length, Feret diameter, and major axis length) can be applied to the definition of coarse aggregates ($d \geq 2$ mm) on an AC cross section.

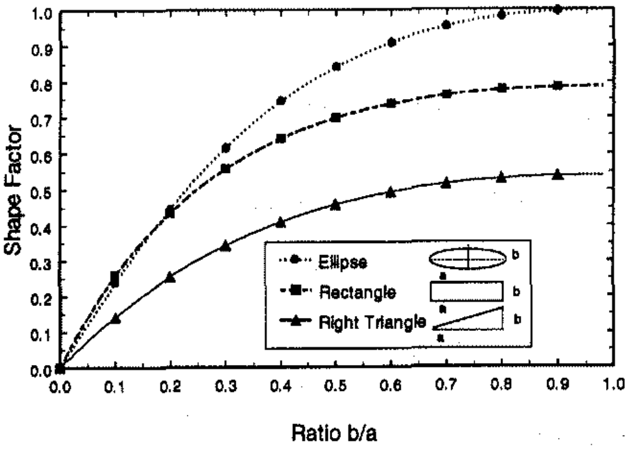
It is also noted that a sieve gradation is determined by the lengths of the intermediate and minor principal axes of the particle itself and a digital image gradation is based on planar particle cross sections whose dimensions, depending on the location and orientation of the cut surface, are usually governed by the minor, intermediate, and major principal axis lengths of the particle.

5. AC mixes used in the analysis

Four AC mixes are utilized in the following analysis of aggregate orientation in AC mixtures. Two of the four mixes are conventional, dense, hot asphalt mixes, referred to as HL4 and HL8 specified by the Ministry of Transportation of Ontario (MTO), Canada. The other two mixes are a large stone asphalt mix (LSM) and a stone matrix asphalt (SMA) developed at the Pavement Research Group of NRC (El Hussein et al. 1993). Details of the four mix formulae are presented in Table 2. In particular, SMA is a gap-graded hot asphalt mix that maximizes the binder and coarse aggregate contents. High resistance to rutting of LSM and SMA can be achieved through stone-to-stone contact in the AC mixtures. Four AC specimens of 150 mm in diameter and 85 mm in height of each of the four mixes were compacted in the laboratory using SHRP gyratory compactor. The number of gyrations was 250, the applied pressure was 0.6 MPa, and the gyratory angle was 1°.

Furthermore, AC specimens (HL4 mix) prepared with four different compaction methods are also used in order to investigate the effect of compaction methods on aggregate orientation in AC mixtures. Three specimens (100 mm in diameter and 65 m in height) were prepared using the gyratory compactor with the same compaction effort as described above. Five specimens (100 mm in diameter and 65 mm in height) were prepared with the Marshall compactor using 100 impact blows. The high compaction effort of Marshall compaction is selected deliberately in order to show the effect of the compaction method under an extreme condition. Four cores of 95 mm in diameter and 60 mm in height were recovered from each of two sections of an experimental pavement compacted respectively using a conventional vibratory steel roller followed by a rubber-tire roller and the Asphalt Multi-Integrated Roller (AMIR) (Svec and Halim 1991). The aggregates used in the mixes were limestone from McFarland Quarry, Ottawa, Ontario.

Fig. 5. Shape factors of ellipse, rectangle, and right triangle.



6. Results and analysis

Statistical results obtained from the digital image processing are summarized in Figs. 6 and 7 and Table 3. Figure 6 illustrates the average area gradations by the minor axis length, Feret diameter, and major axis length for aggregate particles on the two perpendicular cross sections of AC mixtures. The gradations of coarse aggregates obtained from a sieve analysis (Table 1) are also plotted in Fig. 6. Figure 7 illustrates the average area gradation by shape factor for aggregate particles on the AC cross sections, where the Feret diameters of the aggregate cross sections are equal to or greater than 2 mm.

From Fig. 6, one can observe that the curves of the image gradation by either the minor axis length or the major axis length on the horizontal AC cross sections are always on the right side of those on the vertical AC cross sections, respectively. From Figs. 6 and 7, one can observe that the curves of the image gradation by the Feret diameter on the horizontal AC cross sections are always on the right side of those on the vertical AC cross sections. These observations indicate that the sizes and shape factors of aggregate particles on the horizontal cross sections are greater than those on the vertical cross sections of the AC mixtures. The difference in shape factors represents that the aggregate particles on the vertical AC cross sections are more elongated than those on the horizontal AC cross sections.

From Fig. 6, one can also observe that the curves of the

Table 2. Mix design details of HL4, HL8, LSM, and SMA.

(*a*) Average bulk specific gravity and asphalt content by weight

Mix	Average bulk specific gravity*	Asphalt content (%)	
		MTO specification	Chosen
HL4	2.48	5.0–7.0	5.0
HL8	2.49	4.5–7.0	4.5
LSM	2.49	—	4.0
SMA	2.40	—	4.6

(*b*) Sieve analysis (percent passing by dry weight of aggregates)

	HL4		HL8				
Sieve (mm)	MTO specification	Chosen	MTO specification	Chosen	Sieve (mm)	LSM	SMA
25.0				100	37.5	100	
19.0	100	100	94–100	99.5	25.0	95	
16.0	98–100	99	77–95	85	16.0	61	100
13.2	83–95	90	65–90	75	11.0	49	95
9.5	62–82	72	48–78	60	8.0	40	65
4.75	50–60	55	30–50	40	4.75	31	40
2.36	27–60	45	21–50	35	2.00	24	25
1.18	16–60	30	12–49	30	0.85	19	
0.600	8–47	25	6–38	20	0.425	12	
0.300	4–27	15	3–22	15	0.250	6	
0.150	1–10	5	1–9	6	0.150	3	
0.075	0–6	2	0–6	2	0.075	1	10
<0.075	0	0	0	0	<0.075	0	0

*According to ASTM Standard D2726-90.

image gradation by the minor and the major axis lengths provide the lower and upper bounds of those curves from the sieve analysis, respectively, and that the curves of the image gradation by the Feret diameter are the closest ones to those curves from the sieve analysis for each of the four AC mixtures (HL4, HL8, SMA, and LSM).

Table 3 illustrates the exact values of the statistical differences of the characteristics of aggregate particles on the horizontal cross sections and the vertical cross sections of the AC mixtures. Table 3 shows the statistical data, including (*i*) the number of horizontal and vertical cross sections used in the analysis; (*ii*) the average number of aggregates per unit AC area (cm^2); (*iii*) average area percentage occupied by aggregate particles; and (*iv*) average area per aggregate cross section.

From Table 3, one can make the following observations:

(a) For the HL4, SMA, and LSM specimens of 150 mm in diameter compacted with the gyratory compactor and for the HL4 specimens compacted with Marshall and AMIR, the area percentages on the horizontal cross sections are almost the same as those on the vertical cross sections, respectively.

(b) For all the specimens except the HL4 specimens compacted with the Marshall compactor, the average areas per aggregate on the horizontal cross sections are much larger than those on the vertical cross sections.

(c) The number of aggregates per AC unit area (cm^2) on the AC vertical cross sections are much greater than those on the AC horizontal cross sections.

(d) For the HL4 gyratory compacted mixtures, the average area percentage on the vertical cross sections of the specimens of 100 mm in diameter is about 30% less than that of the specimens of 150 mm in diameter.

(e) The area percentages and the average areas per aggregate are almost the same for the aggregate particles on the horizontal and vertical cross sections of the HL4 specimens compacted with Marshall compactor. This result can also be observed in Fig. 6*f*.

The observations (a), (b), and (c), and those from Figs. 6 and 7 indicate that the aggregate particles on the vertical cross sections have less areas, and their shapes are more elongated than those on the horizontal cross sections in the AC specimens compacted in the field or in the laboratory with gyratory compactor. This result represents that the major planes of aggregate particles in the AC specimens compacted in the field or with gyratory compactor in the laboratory lie more horizontally in the mixtures. As a result, the aggregate particles in the AC specimens have an oriented structure which makes the AC mixtures have an anisotropy property.

The observations (a) and (d) may indicate that the specimen size (diameter) has an effect on the orientation of aggregate particles during the gyratory compaction.

Fig. 6. A comparison of area gradation by either the minor axis length (Minor), the Feret diameter (F. Dia), or the major axis length (Major) for aggregate particles on horizontal (H) and vertical (V) cross sections of AC mixtures.

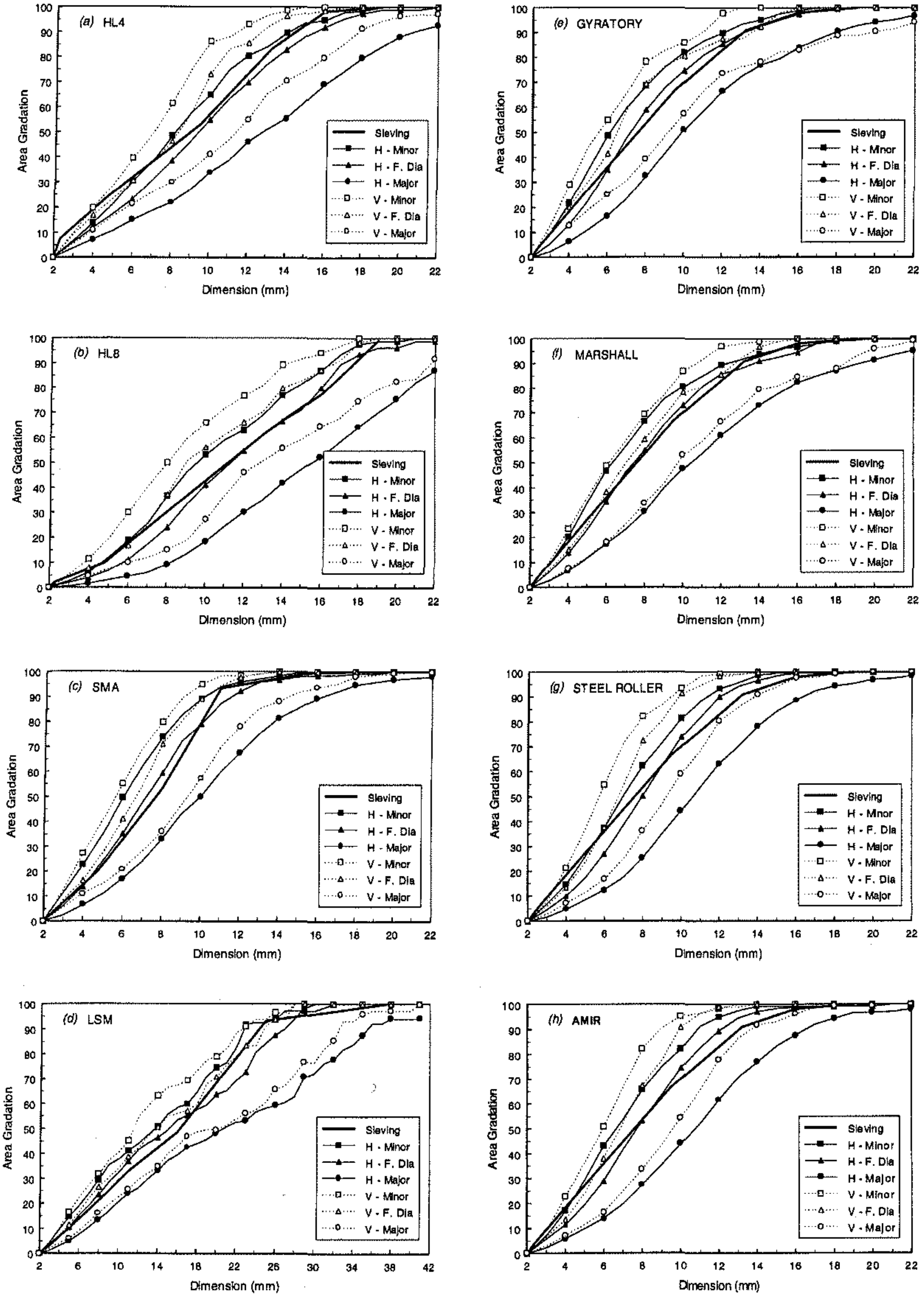
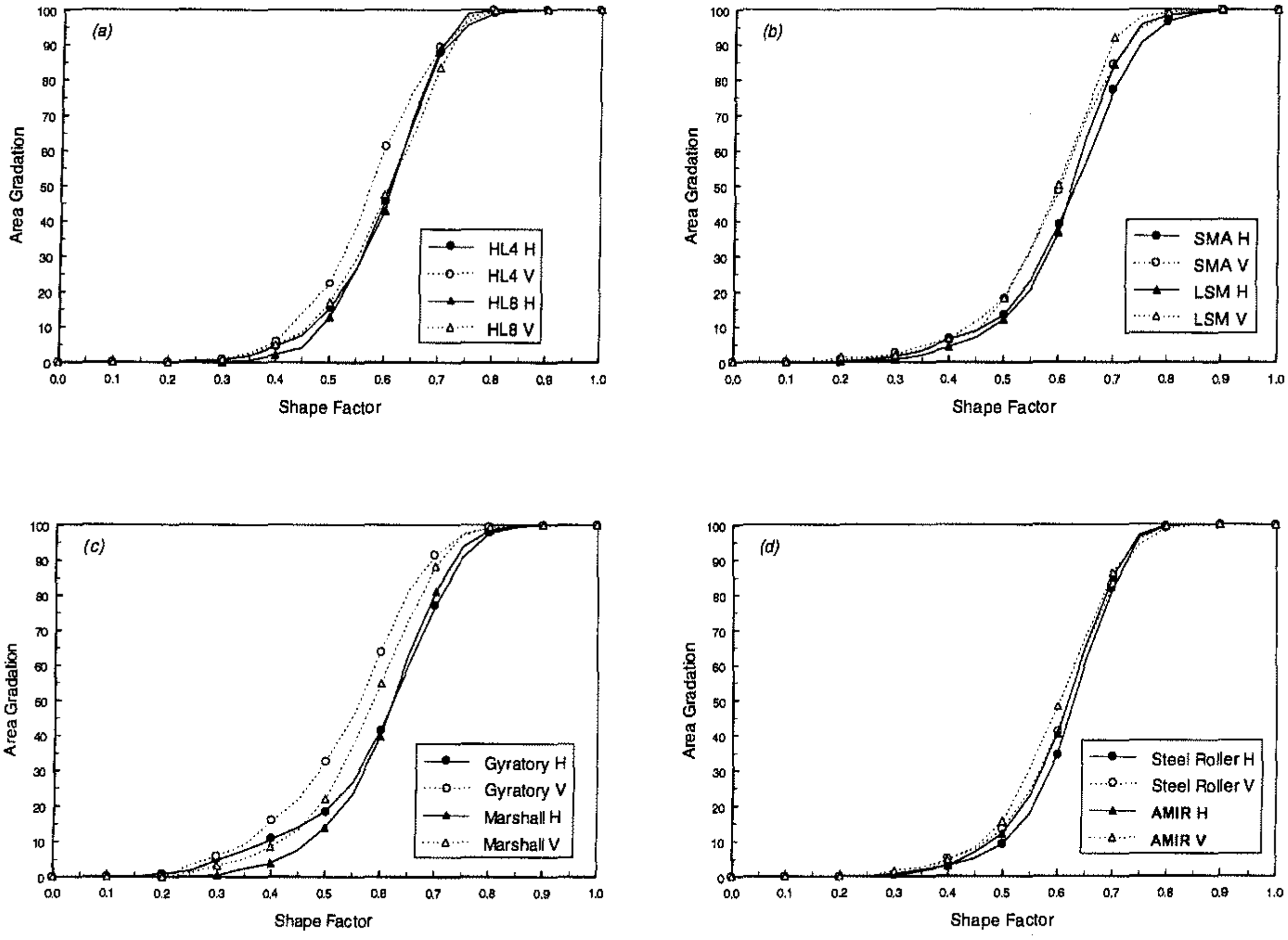


Fig. 7. A comparison of the area gradation by shape factor for aggregate particles of Feret diameter ≥2 mm on horizontal (H) and vertical (V) cross sections of AC mixtures.



The observations (a) and (e) and Figs. 6*f* and 7*c* indicate that the aggregate particles on the vertical cross sections almost have the same areas as those on the horizontal cross sections and are little more elongated than those on the horizontal cross sections of the AC specimens compacted with a Marshall hammer. Consequently, the AC specimens compacted with the Marshall compactor had a more randomly oriented distribution of aggregate particles.

The above analysis indicates that Marshall compaction results in a more randomly oriented structure of the coarse aggregate particles which is not found in the AC pavement. This finding has implications for voids in asphalt mix design using the Marshall method. When Marshall testing is done on an aggregate gradation with a significant number of elongated and flat particles, these particles will resist reorientation that would be achieved by the paving process. This incomplete compaction in the Marshall process will underestimate the compaction likely to be achieved in the field and hence overestimate the voids in the mix. In some cases, especially with skinny mixes, the overestimation of voids in the mixes can result in closing of the voids and flushing of asphalt cement to the pavement surface.

7. Conclusions and recommendations

The digital image processing procedure has been successfully applied to the quantitative investigation of the orientation of coarse aggregates in AC mixtures. The 3-D orientation of coarse aggregate particle structure was investigated by comparing the geometrical characteristics of aggregate particles on horizontal and vertical cross sections of AC mixtures. The differences of aggregate characteristics on the horizontal and vertical cross sections are affected by aggregate gradations and shapes and compaction methods. The differences indicate quantitatively that the major cross sections of aggregate particles have the tendency to lie horizontally in the AC specimens compacted using the gyratory compactor, steel roller, or AMIR, and that the aggregate particles may be more randomly oriented in the AC mixtures compacted with the Marshall compactor. These findings indicate that compaction similar to the paving process may not be achieved in the laboratory using the conventional Marshall compactor, but could be achieved in the laboratory using the gyratory compactor. The oriented structure of aggregate particles contributes to the anisotropic properties of AC mixtures, which

Table 3. A comparison of statistical parameters of aggregate particles on horizontal (H) and vertical (V) cross sections of AC mixtures.

Mix	Compaction method	Number of AC cross sections		Criterion ≥2 mm	Average number of aggregates per AC unit area (cm^2)		Average area percentage (%)		Average area per aggregate (mm^2)		Ratio*
		H	V		H	V	H	V	H	V	
				Specimens of 150 mm diameter							
HL4	Gyratory	4	3	Minor	1.165	1.516	44.17	45.08	37.93	29.80	1.273
				Feret diameter	1.619	2.194	46.25	48.20	58.58	21.93	1.303
				Major	2.032	3.214	47.28	50.56	23.27	15.70	1.482
HL8	Gyratory	4	3	Minor	0.955	1.118	56.16	48.16	58.81	43.20	1.361
				Feret diameter	1.116	1.437	56.98	49.68	51.08	34.57	1.478
				Major	1.174	1.858	57.13	50.60	48.65	27.28	1.783
SMA	Gyratory	4	3	Minor	1.840	1.997	50.64	49.56	27.53	24.78	1.111
				Feret diameter	2.277	2.675	52.88	52.75	23.22	19.62	1.183
				Major	2.427	3.548	53.27	54.85	21.95	15.44	1.421
LSM	Gyratory	4	3	Minor	0.959	1.033	59.47	57.59	62.00	55.60	1.115
				Feret diameter	1.204	1.345	60.72	59.04	50.43	43.70	1.154
				Major	1.282	1.690	60.93	59.88	47.53	35.22	1.350
				Specimens of 100 mm diameter							
HL4	Gyratory	17	3	Minor	1.479	1.506	42.72	34.29	28.89	22.74	1.270
				Feret diameter	1.830	2.080	44.50	36.84	24.31	17.71	1.373
				Major	2.022	2.701	44.98	38.28	22.25	14.16	1.571
HL4	Marshall	14	5	Minor	1.528	1.660	44.46	45.35	29.10	27.35	1.064
				Feret diameter	1.968	2.180	46.65	47.90	23.72	22.01	1.078
				Major	2.256	2.518	47.37	48.71	21.00	19.39	1.083
HL4	Steel roller	19	6	Minor	1.368	1.529	43.97	39.98	32.13	26.14	1.229
				Feret diameter	1.622	1.875	45.21	41.57	27.87	22.17	1.257
				Major	1.831	2.280	45.71	42.53	24.97	18.67	1.337
HL4	AMIR	13	6	Minor	1.444	1.597	44.56	42.72	30.85	26.76	1.153
				Feret diameter	1.813	2.037	46.34	44.86	25.55	22.02	1.160
				Major	2.103	2.455	47.04	45.84	22.37	18.69	1.197

*Ratio of average area per aggregate on horizontal cross sections to average area per aggregate on vertical cross sections.

should be taken into account in pavement stress analysis and performance modelling.

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