STUDY ON THE QUANTIFICATION AND CORRELATION OF GRADATIONAL SEGREGATION IN ASPHALT MIXTURES

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ABSTRACT

In order to evaluate the gradational segregation in asphalt mixtures, Superpave Gyratory Compaction specimens were compacted according to 21 common gradations. Sectional images of the specimens were acquired using the digital image processing technique. FeretDiameter was used to distinguish the coarse aggregates. The stereological determination technology that was used to evaluate the anisotropy of the structures was improved. The coarse aggregate structure factor, J_f, was used to evaluate the anisotropy of the asphalt mixtures. Linear regression was done between J_f and the subtotal triage of coarse aggregates, and the correlation coefficient achieved was 0.96. For the gradations with the same maximum nominal grain size, grey correlation was used to analyze the results. It was concluded that, except for the 9.5 mm maximum nominal grain size gradation, J_f was affected most by the subtotal triage of coarse aggregates in the third-largest sieve size.

1. INTRODUCTION

The uniformity of asphalt mixtures is one of the most important ways of assuring a long lifespan for an asphalt pavement. Segregation of asphalt mixtures has been found to be related to the premature damage of asphalt pavements. The segregation of asphalt mixtures can be divided into gradational segregation and temperature segregation. Gradational segregation refers to the non-uniform distribution of coarse and fine aggregates, which means that the actual gradation no longer accords with the designed gradation. The air voids will be much larger where the coarse aggregates congregate. At the same time, the air voids will be much smaller where the fine aggregates congregate. This is the reason for permanent deformation and bleeding (Sha Qing-Li, 2001).

At present, the study on the gradational segregation of asphalt mixtures still needs further work. Muhunthan (2000), Masad and co-workers (2002) and Li Xiao-jun (2004) have all undertaken research into the distribution of air voids in asphalt mixture specimens. In evaluating the anisotropy of asphalt mixtures, these researchers did not take into account the distribution of aggregates, which would have made the work much more complex. Li Zhi (2002) assessed the distribution characteristics of aggregates in annular and zonal manners but did not achieve a satisfying result. Peng Yong et al. (2004) evaluated the uniformity of asphalt mixtures directly according to the position of the aggregates. However, because he did not use the fabric sensor system, it is difficult to translate his results into structural measurements.

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2. RESEARCH METHOD BASED ON THE IMAGE PROCESSING TECHNIQUE

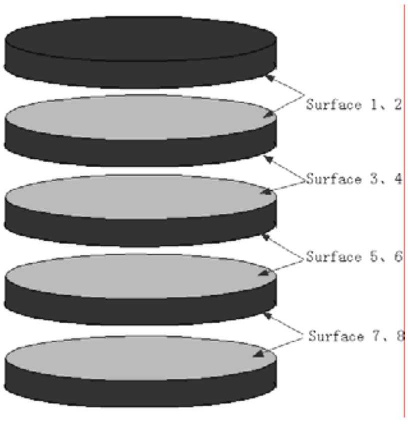
Six-inch (150 mm) asphalt mixture specimens were compacted using an SGC (Superpave Gyration Compacter). The gradations of the asphalt mixture are shown in Table 1. Three specimens were compacted according to one gradation.

Table 1. Gradations of SGC specimens.

Grada-tions	Mass proportion (%) through the following sieves (mm)												
	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-25I	100	98	83	71	63	53	42	34	25	19	13	9	5
AC-25II	100	95	75	61	52	42	30	22	16	11	8	6	4
AM-25	100	95	65	58	52	40	21	11	7	5	4	3	3
AC-20I	100	100	98	83	71	62	48	37	27	21	15	10	6
AC-20II	100	100	95	75	61	50	36	25	18	13	9	6	4
AM-20	100	100	95	73	63	53	28	14	9	7	5	4	3
AC-16I	100	100	100	98	83	68	53	41	30	22	16	11	6
AC-16II	100	100	100	95	75	60	40	27	19	13	9	6	4
AM-16	100	100	100	95	73	57	30	16	11	8	5	4	3
AK-16	100	100	100	95	71	58	35	25	18	13	10	7	5
SMA-16	100	100	100	95	75	55	26	20	18	15	13	12	10

Grada-tions	Mass proportion (%) through the following sieves (mm)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13I	100	98	79	58	45	33	24	17	12	6
AC-13II	100	95	70	43	30	21	14	10	7	4
AM-13	100	95	65	33	18	12	9	5	4	3
AK-13A	100	95	70	42	30	23	17	13	9	6
AK-13B	100	93	60	29	20	15	10	8	6	4
SMA-13	100	95	63	27	21	19	16	13	12	10
AC-10I	100	100	98	65	48	35	25	17	11	7
AC-10II	100	100	95	50	33	23	16	11	7	4
AM-10	100	100	93	50	23	14	9	6	5	3
SMA-10	100	100	95	29	23	20	17	14	13	10

The specimens were cut using a double-edged saw, and eight sectional images could be acquired from one specimen. The cutting method is shown in Figure 1.



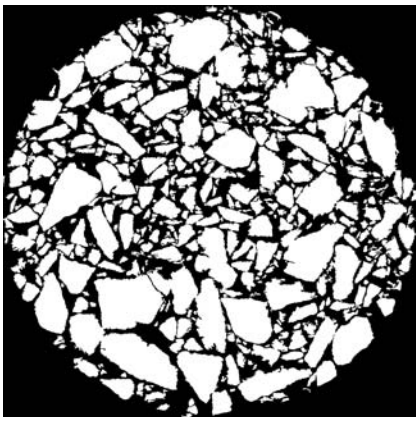



Fig. 1. Sketch map of specimen cutting.
Fig. 2. Sectional image of SMA-16 specimen.
Fig. 3. 2D image of SMA-16 specimen.

The sectional images of the asphalt mixture specimens were acquired using a CCD digital camera, and those images are shown in Figure 2. After enhancement and noise elimination, we used the double-peak method to segment the images in order to acquire the information on the aggregates. The original images were converted into two-dimensional images, as shown in Figure 3.

To be able to evaluate the distribution of the coarse aggregates, those belonging to the different sieve sizes needed to be distinguished. Masad et al. (1999) used the FeretDiameter to distinguish between the coarse aggregates. Li Zhi (2002) presented the equivalent minor axis as the shape parameter for separating the coarse and fine aggregates. Yang Yu-liang (2003) regarded the sectional area of aggregates as a suitable index.

Through comparison, it was found that the FeretDiameter is a much more suitable parameter for distinguishing between the coarse aggregates. The FeretDiameter can be calculated from equation 1:

$$FeretDiameter = 2\sqrt{Area/\pi} \tag{1}$$

where $FeretDiameter$ = equivalent diameter and $Area$ = sectional area of the aggregates.

The coarse aggregates are segregated according to the sieve size after the fine aggregates have been eliminated. The results of the SMA-16 specimen segregation are shown in Figures 2 and 3.

Referring to the images of the coarse aggregates, the structure factor, J_f, is used to evaluate the anisotropy of the internal structure of the asphalt mixture.

3. STEREOLOGICAL DETERMINATION TECHNOLOGY FOR EVALUATING THE STRUCTURE ANISOTROPY

The internal structure of an asphalt mixure can be evaluated through the distribution of the aggregates, the major axis orientation of the aggregates, and so on. Hillard (1968) presented stereological determination technology to measure the voids ratio. Muhunthan and Chameau (1997) developed this method further. This method has been improved since this study is trying to evaluate the gradational segregation of asphalt mixtures. Firstly, a sectional image is selected as a typical unit circle. A series of measuring lines are picked up to intersect the coarse aggregates (Figure 4). After the intersecting length between the measuring line and the coarse aggregates has been measured, the ratio of the coarse aggregates' length on the measuring line versus the whole measuring line can be calculated.

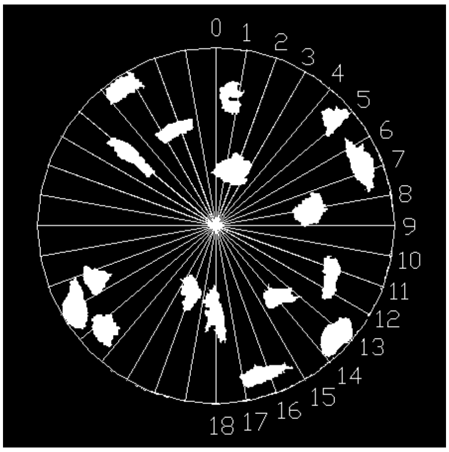


Figure 4. A typical unit circle.

According to this ratio, the function of the directional area ratio of the coarse aggregates can be calculated as follows:

$$n(l) = n_m(1 + F_{ij} l_i l_j) \tag{2}$$

where n_m = the average area ratio of the coarse aggregates, F_{ij} = the second-order fabric tensor of the coarse aggregates and l = the unit vector.

For the two-dimensional problem, the method of determining the directional area ratio of the coarse aggregates is as follows:

1) Represent the sectional images with typical unit circles. In the circle, draw a series of lines through the centre of circle. The angles between the lines are defined as $\theta_m = \frac{m\pi}{N}$, $m =$ 0,1,2,3, $N-1$. Measure the proportion of coarse aggregates, $L_l(\theta_m)$, in every line (as shown in Figure 5).

2) Calculate the average area ratio of the coarse aggregates, as shown in equation 3.

$$n_m = \sum_{m=0}^{N-1} \frac{L_l(\theta_m)}{N} \tag{3}$$

3) Calculate the fabric tensor of the coarse aggregates, as shown in equations 4 and 5.

$$F_{ij} = \begin{bmatrix} A_2 & B_2 \\ B_2 & -A_2 \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = 2\sum_{m=0}^{N-1} L_l(\theta_m) \begin{bmatrix} \cos(2m\pi / N) \\ \sin(2m\pi / N) \end{bmatrix} \Bigg/ \sum_{m=0}^{N-1} L_l(\theta_m) \tag{5}$$

4) Calculate the function of the directional area ratio of the coarse aggregates. With regard to the two-dimensional problem, it can be calculated from equation 6.

$$n(\theta_k) = n_m(1 + A_2\cos^2\theta_k + 2B_2\sin\theta_k\cos\theta_k - A_2\sin^2\theta_k) \quad (6)$$

Define $J_f = \frac{1}{2}(F_{ij}F_{ji})$ as the structure factor, J_f, which is the invariant of the fabric tensor, F_{ij}. For the two-dimensional problem, J_f can be calculated from equation 7.

$$J_f = F_{11}{}^2 + 2F_{12}{}^2 = A_2^2 + 2B_2^2 \quad (7)$$

As the anisotropy grows, J_f becomes larger. In this paper it is accepted that $A_2 = B_2 = 0$, $J_f = 0$. The structure factor, J_f, is used to evaluate the gradational segregation of the asphalt mixture specimens.

4. DATA ANALYSIS

The average structure factor, J_f, of every specimen was calculated. Using the subtotal triage of coarse aggregates as weighting parameters, the J_f of every gradation can be determined through average processing, as shown in Table 2.

Table 2. Structure factor (J_f) of every gradation.

26.5 mm maximum nominal grain size gradation	AC-25I	AC-25II	AM-25	—	—	—
Coarse aggregates structure factor J_f	0.7872	0.8799	0.7134	—	—	—
19.0 mm maximum nominal grain size gradation	AC-20I	AC-20II	AM-20	—	—	—
Coarse aggregates structure factor J_f	0.7735	0.8013	0.6875	—	—	—
16.0 mm maximum nominal grain size gradation	AC-16I	AC-16II	AM-16	SMA-16	AK-16	—
Coarse aggregates structure factor J_f	0.6260	0.6911	0.6025	0.6342	0.6985	—
13.2 mm maximum nominal grain size gradation	AC-13I	AC-13II	AM-13	SMA-13	AK-13A	AK-13B
Coarse aggregates structure factor J_f	0.5503	0.5027	0.3379	0.3090	0.3260	0.4527
9.5 mm maximum nominal grain size gradation	AC-10I	AC-10II	AM-10	SMA-10	—	—
Coarse aggregates structure factor J_f	0.2607	0.3742	0.2698	0.2013	—	—

After analysing the data the following is observed:

1. As the maximum grain size increases in the gradation, the gradational segregation of an asphalt mixture becomes a matter for greater concern, which accords with experience.

2. With the subtotal triage of coarse aggregates set as an independent variable, and the structure factor, J_f, set as a dependent variable, a linear regression analysis was carried out. The results of the significance test are shown in Table 3.

Table 3. Results of significance test.

Sieve size 'mm'	26.5	19	16	13.2	9.5	4.75
Structure factor J_f	H		H	H		H

Note：H means there is a highly significant relation between variables and results（$p < 0.01$), a blank means there is no significant relation between variables and results.

The linear correlation result is shown in equation 8, and the correlation coefficient, R, was 0.96:

$$y = 0.5449+0.03246P_{26.5}+0.01051P_{16}+0.009021P_{13.2}-0.006100P_{4.75} \quad (8)$$

where $P_{26.5}$, P_{16}, $P_{13.2}$, $P_{4.75}$ = subtotal triage of the coarse aggregates of the corresponding sieve size (%).

3. According to the usual experience, when the maximum nominal grain size is no larger than 13.2 mm, there is little gradational segregation. So we can extrapolate that, when the structure factor, J_f, is no larger than 0.5000, the asphalt mixture can be regarded as having little segregation.

For the same maximum nominal grain size gradation, grey correlation was used to analyse the data.

5. GREY CORRELATION ANALYSIS

"Grey system" theory was developed by Professor Deng Ju-long in 1982, when it was a new interdisciplinary subject. The research objective of grey system theory is the system of uncertainty. By analyzing the partly known information and extracting the valuable information, the theory helps to implement efficient control of the system. Since the system of uncertainty exists everywhere, grey system theory has a promising future (Liu Si-feng et al., 1999).

The basic concept of grey correlation is to judge the correlation relationship according to the similarity of curves. The more similarity there is between the two curves, the more correlative they are. The grey correlation analysis method makes up for the disadvantages of the statistical method, which is very convenient for calculation.

We shall take the 16.0 mm maximum grain size gradation as an example to show the calculation procedure of grey correlation analysis. The variant and correlation factors are shown in Table 4.

Table 4. Variant and correlation factors.

Gradation	AC-16I	AC-16II	AM-16	AK-16	SMA-16
Structure factor J_f	0.6260	0.6911	0.6025	0.6985	0.6342
Subtotal triage of 16.0 mm sieve (%)	2.5	5.0	5.0	5.0	5.0
Subtotal triage of 13.2 mm sieve (%)	15.0	20	22.5	24.0	20.0
Subtotal triage of 9.5 mm sieve (%)	14.5	15.0	16.0	13.5	20.0
Subtotal triage of 4.75 mm sieve (%)	15.5	20.0	26.5	22.5	29.0

1) Calculate the absolute degree of association.

$$\because\ X_i^0 = (x_i(1)-x_i(1), x_i(2)-x_i(1), x_i(3)-x_i(1), x_i(4)-x_i(1), x_i(5)-x_i(1))$$
$$= (x_i^0(1), x_i^0(2), x_i^0(3), x_i^0(4), x_i^0(5)); i = 0,1,2,3,4$$

$$\therefore X_i^0 = (x_0^0(1), x_0^0(2), x_0^0(3), x_0^0(4), x_0^0(5)) = (0,0.065,\text{-}0.024,0.073,0.008)$$
$$= (x_1^0(1), x_1^0(2), x_1^0(3), x_1^0(4), x_1^0(5)) = (0,2.5,2.5,2.5,2.5,)$$
$$= (x_2^0(1), x_2^0(2), x_2^0(3), x_2^0(4), x_2^0(5)) = (0,5.0,7.5,9.0,5.0)$$
$$= (x_3^0(1), x_3^0(2), x_3^0(3), x_3^0(4), x_3^0(5)) = (0,0.5,1.5,\text{-}1.0,5.5)$$
$$= (x_4^0(1), x_4^0(2), x_4^0(3), x_4^0(4), x_4^0(5)) = (0,4.5,11.0,7.0,13.5)$$

$$\because |s_i| = \left|\sum_{k=2}^{4} x_i^0(k) + \frac{1}{2}x_i^0(5)\right|; i = 0,1,2,3,4$$

$$\therefore |s_0| = 0.118; |s_1| = 8.750; |s_2| = 24.000; |s_3| = 3.750; |s_4| = 29.250$$

$$\because |s_i - s_0| = \left|\sum_{k=2}^{4} (x_i^0(k) - x_0^0(k)) + \frac{1}{2}(x_i^0(5) - x_0^0(0))\right|; i = 1,2,3,4$$

$$\therefore |s_1 - s_0| = 8.6319; |s_2 - s_0| = 23.8819; |s_3 - s_0| = 3.6319; |s_4 - s_0| = 29.1319$$

$$\because \varepsilon_{0i} = \frac{1+|s_0|+|s_i|}{1+|s_0|+|s_i|+|s_i - s_0|}; i = 1,2,3,4$$

$$\therefore \varepsilon_{01} = 0.5334; \varepsilon_{02} = 0.5856; \varepsilon_{03} = 0.8878; \varepsilon_{04} = 0.5386$$

2) Calculate the relative degree of association.

$$\because X_i^{'} = (x_i^{'}(1), x_i^{'}(2), x_i^{'}(3), x_i^{'}(4), x_i^{'}(5)) = (\frac{x_i(1)}{x_i(2)}, \frac{x_i(2)}{x_i(2)}, \frac{x_i(3)}{x_i(2)}, \frac{x_i(4)}{x_i(2)}, \frac{x_i(5)}{x_i(2)}); i = 1,2,3,4,5$$

$$\therefore X_i^{'} = (x_0^{'}(1), x_0^{'}(2), x_0^{'}(3), x_0^{'}(4), x_0^{'}(5)) = (1.00,1.1039,0.9624,1.1158,1.0131)$$
$$= (x_1^{'}(1), x_1^{'}(2), x_1^{'}(3), x_1^{'}(4), x_1^{'}(5)) = (1.00,2.00,2.00,2.00,2.00)$$
$$= (x_2^{'}(1), x_2^{'}(2), x_2^{'}(3), x_2^{'}(4), x_2^{'}(5)) = (1.00,1.3333,1.50,1.60,1.3333)$$
$$= (x_3^{'}(1), x_3^{'}(2), x_3^{'}(3), x_3^{'}(4), x_3^{'}(5)) = (1.00,1.0345,1.1034,0.9310,1.3793)$$
$$= (x_4^{'}(1), x_4^{'}(2), x_4^{'}(3), x_4^{'}(4), x_4^{'}(5)) = (1.00,1.2903,1.7097,1.4516,1.8710)$$

A similar procedure is just like calculating the absolute degree of association.

$$\gamma_{01} = 0.5861; \gamma_{02} = 0.8121; \gamma_{03} = 0.9761; \gamma_{04} = 0.6494$$

3) Calculate the comprehensive degree of association. $\because \theta$=0.5

$$\rho_{0i} = \theta\varepsilon_{0i} + (1-\theta)\gamma_{0i}; i = 1,2,3,4,$$
$$\therefore \rho_{01} = 0.5597, \rho_{02} = 0.6989, \rho_{03} = 0.9320, \rho_{04} = 0.5940$$

4) Results analysis: $\because \rho_{03} > \rho_{02} > \rho_{04} > \rho_{01}$

Therefore the subtotal triage of the 9.5 mm sieve size > the subtotal triage of the 13.2 mm sieve size > the subtotal triage of the 4.75 mm sieve size > the subtotal triage of the 16.0 mm sieve size.

For the same maximum nominal grain size gradation, the structure factor, J_f, is affected most by the subtotal triage of the 9.5 mm sieve size.

The grey correlation analysis results of the same maximum nominal grain size gradation are shown in Table 5.

Table 5. Grey correlation analysis results of the same maximum nominal grain size gradation.

Subtotal triage of coarse aggregates (%)	26.5 mm maximum-nominal grain size gradation			19.0 mm maximum nominal grain size gradation			16.0 mm maximum nominal grain size gradation			13.2 mm maximum nominal grain size gradation			9.5 mm maximum nominal grain size gradation		
	Ab	Rel	Co	Ab	Rel	Co	Ab	Rel	Co	Ab	Rel	Co	Ab	Rel	Com
26.5 mm sieve size	0.565	0.652	0.609	—	—	—	—	—	—	—	—	—	—	—	—
19.0 mm sieve size	0.581	0.516	0.549	0.559	0.659	0.609	—	—	—	—	—	—	—	—	—
16.0 mm sieve size	0.986	0.696	**0.841**	0.606	0.517	0.562	0.533	0.586	0.560	—	—	—	—	—	—
13.2 mm sieve size	0.885	0.715	0.800	0.867	0.699	**0.783**	0.585	0.812	0.699	0.517	0.534	0.526	—	—	—
9.5 mm sieve size	0.742	0.643	0.693	0.676	0.702	0.689	0.887	0.976	**0.932**	0.566	0.706	0.636	0.532	0.607	0.570
4.75 mm sieve size	0.577	0.660	0.619	0.612	0.621	0.617	0.538	0.649	0.594	0.674	0.625	**0.649**	0.556	0.870	**0.713**

6. CONCLUSION

In this paper, an index for evaluating the anisotropy of an asphalt mixture – the coarse aggregate structure factor J_f – was presented. It is based on an image-processing technique and stereological determination technology that focuses on the two-dimensional distribution of coarse aggregates. The gradational segregation in 21 common gradations was analysed with this index. However, cutting of the specimens with a two-edged saw leads to a destructive measurement. The authors have not been able to acquire enough sectional images of asphalt mixture specimens. With the development of CT (computerised tomography) techniques, the authors expect to be able to depict the internal structure of asphalt mixture specimens three-dimensionally in the near future.

7. REFERENCES

[1] Hilliard, JE. 1968. Measurement of Volume in Volume Quantitative Microscopy. McGraw-Hill Book Co. Inc., New York, USA.

[2] Li Xiao-juan. 2004. Simulation and discrimination of damage process of asphalt mixture. Post-PhD research report of the South China University of Technology.

[3] Li Zhi. 2002. Analysis of volume constituent characteristics for asphalt mixture based on digital image processing. Doctoral dissertation, Harbin Institute of Technology.

[4] Liu Si-feng, Guo Tian-bang and Dang Yao-guo. 1999. The theory and application of grey system. Second Edition, Science Press.

[5] Masad, E and Somadevan, N. 2002. Microstructural finite-element analysis of influence of localised strain distribution on asphalt mix properties. Journal of Engineering Mechanics, American Society of Civil Engineers, 128(10), October, pp. 1106-1115.

[6] Masad, E, Muhunthan, B, Shashidhar, N, et al. 1999. Internal structure characterization of asphalt concrete using image analysis. Journal of Computing in Civil Engineering, 13(2), April, pp. 88-96.

[7] Muhunthan, B and Chameau, JL. 1997. Void fabric tensor and ultimate state surface of soils. Journal of Geotechnical and Geo-environmental Engineering, 123(2), February, pp. 173-181.

[8] Muhunthan, B, Masad, E and Assaads, A. 2000. Measurement of uniformity and anisotropy in granular materials. Geotechnical Testing Journal, GTJODJ, 23(4), December, pp. 423–431.

[9] Peng Yong, Sun Li-jun and Dong Rui-kun. 2005. Discussion on new method for evaluating the homogeneity of asphalt mixture. Journal of Tongji University (Natural Science Edition), 33(2), pp. 166-170.

[10] Sha Qing-lin, 2001. Premature Damage and Precaution in Asphalt Pavement of Expressway. China Communication Press.

[11] Yang Yu-liang. 2003. Study of sub-microstructure analysis system for asphalt concrete. Doctoral dissertation, Tongji University.