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Research on Relationship between Gradation Type and Segregation Degree of Asphalt Mixture

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Abstract: In order to investigate the relationship between the type of gradation and the degree of segregation of asphalt mixture, five kinds of gradations were employed based on the design gradation of the asphalt pavement in an expressway. By detecting the spot gradations, texture depths, and densities of the mixture in different positions on the asphalt pavement, the degree of segregation in the process of construction could be determined. It was found that the mixtures with S type gradation or micro-arch type above the maximum density curve can assure stability in the production and transportation. Mixtures with maximum density curve changed in production and transportation, but not in the construction. For gap-graded gradation, the mixture's gradation curve scatters a lot in the construction. For mixtures with Reserve-S type, the pavement's uniformity changes obviously in the construction. For mixtures with micro-arch type below the maximum density curve, the gradation provides better stability and the pavement uniformity is good.

Key words: *Asphalt mixture; Fractal dimension; Gradation; Highway engineering; Segregation.*

Introduction

Segregation is a common phenomenon for asphalt mixtures in practical construction of asphalt pavement because of the influence of different factors. It makes the pavement performance simulation from laboratory results inconsistent within practice. Tashman et al. [1] proposed that to study the segregation condition, the particles size should be bigger than 2.36*mm* in asphalt mixture. Based on the digital image processing technology, Hunter et al. [2] evaluated the segregation degree by comparing the aggregates' accumulation area in the equal region of the section. Current research on the segregation of asphalt mixture is mostly focused on the construction process. Whereas, the segregation of asphalt mixtures is not only related to the disturbance in the construction process but also has something to do with the characteristic of the aggregate gradation [3, 4]. Asphalt mixture has great variability and uncertainty in mechanical performance because of the influence of many factors, such as material properties and construction quality. Such uncertainty, fuzziness, and non-linearity adequately reflect the complexity of the material, and these properties have been found to relate to the fractal theory significantly [5]. Therefore, this article plans to use the fractal geometry theory and study the relationship between the types of gradation of asphalt mixtures and the segregation in construction. More specifically, the object of this study is in hope of deriving the indices which can reflect the degree of segregation of the asphalt mixtures.

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Study of Relationship between Gradation Types with Segregation Degree

Gradation Adjustment

The degree of segregation for different gradation types were investigated in the production and construction process. Based on the original designed gradation in known-performance projects, five kinds of gradation types were applied through adjusting the scale of hot bunker of an asphalt mixing plant. Different types of gradations were designed as #0, #1, #2, #3, and #4. The quality passage rate of each sieve pore in the five different types of gradations are as follows and shown in Table 1.

Gradation #1 is adjusted according to the principle of the maximum density curve; #2 gradation is adjusted according to the principle of gap-graded asphalt mixture; #3 gradation is adjusted according to the principle of micro bow type, which is below the maximum density curve. This is based on Brock's finding [6]; he thought in his study that the micro arched gradations have better containing ability. Gradation #4 is a gap-graded gradation, where particles are discontinuous. In other words, this gradation has the characteristics that coarse materials and fine materials are very little and the middle particles are major.

Testing Results and Analysis

Several related parameters were recorded in appropriate sites in the construction. This aims to analyze the segregation degree of the five aforementioned different gradations. Hot storage, service vehicle, central of pavers, quarter of spiral distributor, and the edge of pavers were chosen to be the site positions where samples were taken (the number sequence was 1, 2, 3, 4, and 5). Samples were carried after paving and before rolling for the latter three sites. During spot test, a cross-section was chosen per 10*m*, and the texture depth and density were recorded in the latter three sites to decide the segregation degree of the different gradation types.

Table 1. Quality Passage Rate of Each Sieve Pores of Different Gradations.

Size of Sieve Pore (*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
Passage Rate (%)	#0	100	98.68	79.62	72.11	64.53	53.78	36.08	20.74	16.42	10.75	7.00	4.63	3.73
	#1	100	98.62	78.75	70.31	61.35	49.95	44.37	27.12	21.2	13.38	8.17	4.92	3.84
	#2	100	99.21	87.68	82.13	74.90	64.21	43.82	29.70	23.19	14.50	8.67	5.04	3.89
	#3	100	99.36	89.96	83.47	72.56	56.40	29.38	19.63	15.66	10.38	6.83	4.59	3.71
	#4	100	99.36	89.96	83.47	72.56	56.40	29.38	19.63	15.66	10.38	6.83	4.59	3.71

Table 2. The Spot Test Results of #0 Gradation.

Test Content	Texture Depth (Lay Sand's Diameter: *cm*)			Density (g/cm^3)		
Pole Number/Site	3rd Site	4th Site	5th Site	3rd Site	4th Site	5th Site
827	20.5	20.25	16.25	2.307	2.369	2.290
837	20.25	19	16.25	2.332	2.242	2.189
847	23	21.25	17.75	2.401	2.319	2.045
857	22	19.25	17.25	2.337	2.231	2.203

Table 3. #1 Gradation Analyses in Each Site.

Sieve Pore (*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
Design Gradation		100.0	98.68	79.62	72.11	64.53	53.78	36.08	20.74	16.42	10.75	7	4.63	3.73
1	Passing Rate (%)	100.0	100.0	83.5	78.0	72.9	62.1	35.8	21.6	16.3	10.4	7.1	4.6	3.6
2		100.0	98.4	85.1	77.1	69.5	53.8	30.2	22.1	17.1	11.2	7.7	5.2	3.8
3		100.0	100.0	89.6	80.9	71.2	55.9	31.9	21.5	16.7	10.6	7.3	4.7	3.3
4		100.0	100.0	86.8	72.5	65.6	53.4	31.2	20.9	16.6	11.0	7.6	5.3	3.9
5		100.0	92.9	79.9	74.2	69.1	53.4	31.8	20.8	16.1	10.4	7.3	4.9	3.5

Table 4. The Spot Test Results of #1 Gradation.

Test Content	Texture Depth（Lay Sand's Diameter: *cm*）			Density (Core-Drilling Method: g/cm^3)		
Pole Number/Site	Center	Quarter	Edge	Center	Quarter	Edge
580	22.65	22.45	18.65	2.465	2.484	2.425
590	21.25	21.5	17	-	-	-
600	20.35	22.5	16.6	-	-	-
610	12.75	19.65	14.4	2.472	2.463	2.427

#0 Gradation

The typical results of spot texture depth and density in different positions are shown in Table 2. As seen from Table 2, the segregation mostly occurred on the edge of the paver, and the segregation degree is large for #0 gradation. And the gradation analysis indicated that it is stable.

#1 Gradation

The #1 gradation had the properties of the maximum density curve. In different sites, the gradation changed to some extent (in Tables 3 and 4). The coarse aggregates whose size was above 2.36*mm* changed more, while the others changed less, and the average change was 0.5 percent lower.

It can be seen from the test results that the edge's texture depth was bigger, the density was smaller, and the values decreased compared with that of #0 gradation. This result indicates that the gradation changed in paving, and the segregation was due to the composition of particles. Also its degree was lower than that of #0 gradation. As a result, the nature stability of #1 gradation was poor but was barely affected in the construction.

#2 Gradation

The #2 gradation was designed to decrease the mixture of 4.75*mm* intentionally. The results, as shown in Table 5, indicate significant difference.It can be seen that even in the hot storage, the passing rate change of 4.75*mm* was more than 10 percent, and the gradation curve was as smooth as the target one. In other words, the compositions of particles were distributed proportionally.

Table 6 shows that this gradation didn't have the same uniform change as those of #0 and #1, and its curve fluctuated more significantly. The change in gradation #2 tended to be continuous but fluctuated significantly under internal and external effect.

#3 Gradation

The #3 gradation curve was down-bow under the maximum density curve and was coarser. Table 7 shows that the #3 gradation changed a little, and the fine aggregates were increased. The segregation occurred due to the construction, and it tended to make the middle aggregates increase.

As seen from the test results, shown in Table 8, the lay sand diameters of the latter three sites were little different, and the

Table 5. #2 Gradation Analyses in Each Site.

Sieve Pore (*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
Design Gradation		100	98.62	78.75	70.31	61.35	49.95	44.37	27.12	21.2	13.38	8.17	4.92	3.84
1	Passing Rate (%)	100.0	98.0	85.7	77.5	64.8	50.6	31.7	22.2	17.0	11.0	7.7	5.3	3.8
2		100.0	94.9	74.2	63.8	52.1	41.0	26.2	19.1	14.5	9.1	5.8	3.7	2.6
3		100.0	100.0	90.4	82.8	73.7	62.0	41.5	26.4	19.8	12.8	9.0	6.2	4.5
4		100.0	93.5	80.1	68.7	62.7	50.6	33.7	23.4	18.5	12.3	8.4	5.5	3.6
5		100.0	97.9	85.4	72.4	59.7	55.9	37.9	25.2	19.4	12.3	7.9	4.8	2.6

Table 6. The Spot Test Results of #2 Gradation.

Test Content	Texture Depth (Lay Sand's Diameter: *cm*)			Density (Core-Drilling Method: g/cm^3)		
Pole Number/Site	Center	Quarter	Pole Number/Site	Center	Quarter	Pole Number/Site
780	27	29.6	22.45	2.475	2.493	2.484
750	26.1	24.6	15.9	2.482	2.507	2.491
720	21.65	24.05	17.1	2.498	2.460	2.506

Table 7. #3 Gradation Analyses in Each Site.

Sieve Pore (*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
Design Gradation		100.0	98.52	77.17	68.83	60.54	48.99	33.54	22.39	17.72	11.5	7.33	4.71	3.76
1	Passing Rate (%)	100.0	100.0	82.4	74.4	60.8	47.2	32.0	24.2	20.6	14.1	9.5	5.8	3.8
2		100.0	97.3	81.9	69.5	59.1	48.0	32.6	23.9	20.2	13.8	9.3	5.7	3.6
3		100.0	100.0	83.6	75.1	65.8	52.3	35.6	24.0	19.2	13.4	9.6	6.5	4.5
4		100.0	97.7	81.3	70.9	58.8	43.8	27.7	20.0	16.1	10.9	7.6	5.1	3.3
5		100.0	96.1	80.3	71.7	60.2	45.6	29.8	20.9	17.2	11.9	8.2	5.7	3.8

Table 8. The Spot Test Results of #3 Gradation.

Test Content	Texture Depth (Lay Sand's Diameter: *cm*)			Density (Core-Drilling Method: g/cm^3)		
Pole Number/Site	Center	Quarter	Pole Number/Site	Center	Quarter	Pole Number/Site
57	20.5	18.75	19.75	2.434	2.445	2.474
103	19.4	16.9	17.25	2.438	2.446	2.392
110	16.5	16.95	16.25	2.493	2.394	2.497

Table 9. #4 Gradation Analyses in Each Site.

Sieve Pore (*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
Design Gradation		100.0	99.36	89.96	83.47	72.56	56.4	29.38	19.63	15.66	10.38	6.83	4.59	3.71
1	Passing Rate (%)	100.0	98.6	91.8	83.7	76.8	60.1	28.5	18.1	14.0	8.8	6.2	4.1	3.1
2		100.0	98.5	91.8	84.1	77.1	60.1	28.8	18.2	14.2	8.9	6.3	4.2	3.1
3		100.0	100.0	95.9	88.6	76.2	55.6	27.4	17.1	13.4	8.8	6.3	4.4	3.3
4		100.0	100.0	85.1	77.5	68.0	51.4	25.2	16.8	13.4	8.9	6.5	4.7	3.6
5		100.0	100.0	91.2	80.6	71.3	53.5	25.2	16.5	13.1	8.5	6.1	4.3	3.2

average densities have the same tendency. In other words, the #3 gradation had a better stability and changed unobvious in the condition of construction.

#4 Gradation

Compared with the other curves, the coarse and fine aggregates in the #4 gradation decreased, and the middle size aggregates increased before paving, as shown in Table 9.

Table 10 shows the spot test results for #4 gradation. As seen from Table 10, the fifth site's lay sand diameter was smaller than the others. Density results were also substantially uniform with the texture depth results.

Correlation Analysis of Gradation Type and Segregation Degree

With testing data in texture depth test, characterization of segregation degree was established as well as the relationship between gradation type and segregation.

Characterization Index of Segregation Degree

Based on the theory of a dimension deviation analysis, the sum of squares (SSA) for factor A was defined as the square sum of mean in each level and total mean deviation, which reflects different influence of factors. The equation used is as follows [7]:

$$SSA = \sum_{i=1}^{k} n_i (\bar{x}_i - \bar{x})^2 \tag{1}$$

where $\bar{x}$ = mean of all samples, $\bar{x}_i$ = mean of samples in the same level, n_i = number of samples in the same level, and k = number of

Table 10. The Spot Test Results of #4 Gradation.

Test Content	Texture Depth（Lay Sand's Diameter: *cm*）			Density (Core-Drilling Method: g/cm^3)		
Pole Number/Site	Center	Quarter	Pole Number/Site	Center	Quarter	Pole Number/Site
385	17.5	19.75	16.00	2.292	2.321	2.232
390	18.5	20.5	16.25	2.128	2.355	2.209
395	18.75	18.25	16.25	2.317	2.361	2.326
405	17.75	17.75	16.75	2.317	2.295	2.194
415	18.25	16.75	14.75	2.278	2.298	2.264

Table 11. Transverse Distributing Variance Analyses.

Gradation	Vertical Mean of Lay Sand's Diameter (*cm*)			Difference Value (*cm*) (3-5)	Vertical MSA	
					Groups	Interclass
0#	20.90	20.48	17.25	3.65	47.55	2.49
1#	19.75	20.49	17.41	2.34	25.79	5.27
2#	23.70	24.40	18.50	5.2	103.34	8.23
3#	17.82	17.29	16.92	0.9	2.64	3.88
4#	17.23	17.91	15.56	1.67	17.59	1.29

Table 12. Gradation Characteristic Parameters.

Content	D	DC	DF
0#	2.424	2.4311	2.4465
1#	2.4292	2.4423	2.4693
2#	2.4559	2.5236	2.3928
3#	2.4439	2.3948	2.4469
4#	2.4129	2.3432	2.4848

Table 13. The Correlation Analyses of MSA and Fractal Dimension.

	MSA	D	DC	DF
MSA Poisson Correlation	1	0.729	0.677	-0.859*
Significance (Dual Mantissa)		0.063	0.095	0.013
N (Number of Samples)	7	7	7	7
DF Poisson Correlation	-0.859*	-0.805*	-0.841*	1
Significance (Dual Mantissa)	0.013	0.029	0.018	
N (Number of Samples)	7	7	7	7

*In the significance level, α = 0.05, the correlation is significant (dual mantissa detection).

different levels.

Calculations based on the data from third through fifth spots indicate that the SSA reflects the mixture's transverse distance along the spiral distributor and affected the lay sand's diameter. In different gradation curves, with bigger SSA, the corresponding gradation's stability was worse, and segregation occurred easier. Mean Square Deviation (MSA) [7] was used as the characteristic of segregation in order to eliminate the level division's influence. Eq. (2) is the equation to calculate MSA:

$$MSA=\frac{SSA}{k-1} \qquad (2)$$

The variance results of lay sand test are shown in Table 11.

From Table 11, the ranking of every gradation's MSA is: #2 > #0 > #1 > #4 > #3. It can be seen that the texture depth with #2 gradation changes more obviously; following by the #0 gradation with S character; #1 closes to the maximum density, and #4 has more middle aggregates. The #3 gradation, which is under the maximum density curve, has the smallest MSA and can be counted for better stability.

Characterization Index of Graduation

Fractal dimension is used as the characterization index of gradation [5, 8, 9]. First of all, the following three parameters were calculated: D (fractal dimension of the whole particles size), DF (fractal dimension of particles), and DC (fractal dimension of particles). The D is among the whole range from 0.075 to 31.5*mm*, DF is a partial fractal dimension from 0.075 to 2.36*mm*, and DC is between 4.75 and 31.5*mm*. Secondly, correlation between these indices and segregations were analyzed respectively. The results are shown in Table 12.

Correlation Analysis between MSA and Gradation Fractural Dimension

The correlation coefficient r reflects the degree of correlation within two variables. When the absolute value of r (correlation coefficient) is bigger than 0.8, it means that the relativity is strong, and when the value is smaller than 0.3, the relativity is weak [10]. The results are listed in Table 13.

It can be seen that correlation between MSA and DF is strong. In the common significance level of α = 0.05, it is reputed that they are linear correlative.

It can be seen that the segregation degree in construction can be evaluated if the linear model can be found.

Conclusions

This article researched the relationship between the gradation type and segregation degree occurred in construction as well as researched the correlation analysis of the segregation degree index and gradation fractal dimension. The main conclusions are as follows:

1. The mixture of the S type gradation or micro-arch type above the maximum density curve can assure stability in production and transportation, and the segregation mainly occurred on

the edge of a paver. Maximum density curve mixture changed in production and transportation but not in construction. Its gradation curve distorted. For gap gradation, the mixture's gradation curve continuously changed relatively and deviated from design gradation in production and transportation, whereas in the construction, the gradation fluctuated stronger. For mixture with Reserve-S type, the pavement's uniformity changed obviously in the construction. For mixture of micro-arch type below the maximum density curve, the gradation kept better stability and the pavement uniformity was good.

2. MSA reflects the change degree of lay sand's diameter along with the change of mixture's transverse distributing distance and can be used as the characterization of segregation. The descending permutation of every gradation's segregation degree is: Reverse-S gradation, gap gradation, micro-arch type above the maximum density curve, S gradation, the maximum density curve gradation, and micro-arch type below the maximum density curve (#2 > #0 > #1 > #4 > #3).
3. Segregation degree in construction can be evaluated by a linear model. That is good for pavement construction.

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