第 47 卷 第 3 期 中山大学学报（自然科学版） Vol. 47 No. 3
2008 年 5 月 ACTA SCIENTIARUM NATURALIUM UNIVERSITATIS SUNYATSENI May 2008

Effect on Fatigue Properties of Inner Structure and Composition of Asphalt Mixtures*

WU Kuang-huai[1], ZHANG Xiao-ning[2]

(1. Institute of Civil Engineering, Guangzhou University, Guangzhou 510006, China;
2. Institute of Road Engineering, South China University of Technology, Guangzhou 510640, China)

Abstract: A big sample of beam specimens of asphalt mixtures was used to carry out strain-control fatigue tests under the same conditions. IMAQ digital image processing was used to process and analyze the inner structure and composition of the flexural section at the centre of the beam specimens through fatigue tests. In this way, the indices of the inner structure and composition of asphalt mixtures wre indentified. Furthermore, SPSS was used to establish a model on relationship between results of fatigue tests and indices of its inner structure and composition. The analysis result shows that fatigue properties of asphalt mixtures are directly correlated with the indices of its inner structure and composition, and the difference in the inner structure and composition of asphalt mixtures causes the significant difference in fatigue properties under the same conditions, which unveils the laws of effect of the inner structure and composition of asphalt mixtures on fatigue properties.

Key words: asphalt mixture; inner structure and composition; digital image processing; fatigue properties

CLC number: U416.217; U414 **Document code**: A **Article ID**: 0529-6579 (2008) 03-0051-06

The fatigue properties of asphalt and asphalt mixtures had been the focus of research on road engineering. The foreign research on the fatigue properties of asphalt mixtures has a history of nearly 50 years[1~4] and a lot of researches has been carried out in China in recent years[5~8]. However, due to the various reasons, most of the fatigue tests of asphalt mixtures use small samples, and the data of fatigue tests tends to have high discreteness, particularly the data of strain-control fatigue tests. A big sample of beam specimens was used to carry out strain-control fatigue tests under the same conditions using the fatigue tester produced by COOPER, UK, and digital image processing technology was used to process and analyze the inner structure and composition of the flexural section at the centre of the beam specimens of asphalt mixtures after the test. Further analysis had established models on relationship between results of fatigue tests and indices of its inner structure and composition which unveils the laws of effect of the inner structure and composition of asphalt mixtures on fatigue properties.

1 Test Design

In order to get the inner structure and composition of particles in asphalt mixtures, the asphalt mixtures need to be cut. When the asphalt mixtures are being cut, the angles of coarse particles will often be cut. In common asphalt mixtures, since the color and grey level of such angels are the same as those of other fine aggregates, the angles of such coarse particles will often be filtered out in digital image processing for they are regarded as fine particles mistakenly. Thus, the information on coarse aggregates has big errors in digital image processing. To reduce such wrong judgment, coarse and fine aggregates must be distinguished. Therefore, this research used the color indication method to distinguish the various parts of section image of asphalt mixtures with different colors, so that the information on inner voids of specimens and particles can be extracted accurately. In order to minimize the errors in digital image processing and reduce wrong judgment of colors, the colors of the aforesaid parts must be bright and the difference between colors must be obvious. Therefore, scrushed red screes with bright color from the Pearl River was used for coarse aggregates, and diabase powders with the color of dark grey from Pinghu, Shenzhen was used for fine aggregates, Shell decolorized asphalt was used for asphalt binder, and also green marinace inorganic pigments with the volume of 2% was used. Voids on plane of section are filled with land plaster with yellow pigments. The medium particle-size gradation of asphalt mixtures was used for extraction

* 收稿日期：2007 - 11 - 02
基金项目：国家西部交通建设科技资助项目（200431800004）
作者简介：吴旷怀（1969 年生），男，工学博士，副教授；E-mail：wukuanghuai@163.com

and analysis of the digital image information on coarse aggregates. Thus, the coarse particles are red, the plastic paste is green, and the voids are yellow. After preparing and trial-producing, the above components can be distinguished obviously for extracting the digital image information of the various parts.

1.1 Raw Materials

1.1.1 Aggregates

Red screes from the Pearl River were crushed to pieces using a small jaw crusher in the laboratory, and the grain size of above 2.36 mm was used for Coarse aggregates. See Table 1 for the performance parameters of coarse aggregates. Diabase grains from Pinghu, Shenzhen, were used for fine aggregates, and limestone mineral filler from Lvtian, Conghua was used. See Table 2 for the performance parameters of fine aggregates and mineral filler.

Tab. 1 Test results of coarse aggregate

Items	Crushed stone value/%	Weared stone value/%	Aggregate impact value/%	Apparent specific gravity	Bulk specific gravity	Water absorption/%
Requirements[9]	≯25	≯28	/	≮2.5	/	≯2.0
Test Result	20.5	18.9	8.7	2.550	2.499	0.81

Tab. 2 Test results of physical parameters of fine aggregates

Items Mineral Name	Apparent Specific Gravity	Sand Equivalent/%	Aggregate Gradation Percentage of passing the following sieves(%)							
			9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
0-5mm Diabase Grains	2.555	72.3	100	100	74.5	47.7	39.1	29.0	20.6	13.5
mineral filler	2.674								100	95.8

1.1.2 Asphalt

Shell decolorized asphalt was used for asphalt binder. See Table 3 for its performance indices.

1.1.3 Mineral Gradation

Mineral of mixture was gradated according to targets in Table 4.

Tab. 3 Test results of performance indices of Shell decolorized asphalt binder

Item	Penetration 25℃, 0.1mm	Ductility, 10℃, 5cm/min, cm	Softening point/ ℃	Wax content/ %	Specific gravity of bitumen
Test result	65	16.8	45	1.7	1.016

Tab. 4 Gradation of Mineral mixture

Item	Weight percentage (%) of aggregate passing the following sieves (mm)											
	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Target Gradation	100	93	81	66	54	45	39	31	24	16	10	5

1.2 Method and Condition of Fatigue Test

The testing instrument is a Cooper fatigue tester. The 300 mm × 70 mm × 400 mm test sample was firstly made in laboratory which was molded with fixed height by pressure using the vibration edge-running molding equipment produced in Finland to guarantee the uniformity of specimens and the designed void ratio. The molded test sample was stripped after 2 days and nights of natural curing, and was cut into 65 mm × 50 mm × 380 mm beams using the double-cut saw imported from USA. Each test sample was made into 4 beams. The size of each beam was measured precisely, the bulk specific gravity of each beam was measured using the standard method, and then the void ratio of each beam was calculated. This test used the four-point bend strain-control fatigue testing method. Total 100 beams were made and then tested with the test temperature of 15℃, the load frequency of 10Hz, and the control strain of 200$\mu\varepsilon$. The fatigue life of each beam was determined as the cycle number when loss modulus was 50% of the initial modulus.

2 Results of Fatigue Test

The elementary statistics of the fatigue life, initial modulus and cumulative dissipated energy of asphalt mixtures obtained from the test was conducted. See Table 5 for the results. From the results of the fatigue test, we can see that, under the same conditions, the discreteness of the strain-control fatigue life and cumulative dissipated energy of asphalt mixtures are large, While the discreteness of initial modulus of asphalt mixtures is small.

Tab. 5　Statistical results of fatigue test

Statistical Parameter		Average	Standard deviation	Median	Max.	Min.	Range	Variation coefficient/ %
Fatigue life	N_f	147402.5	156216.7	113012.5	800732.5	19432.5	41.2	106.0
	$\ln N_f$	11.525	0.855	11.635	13.593	9.875	1.4	7.4
Initial modulus	E_0, MPa	7717.4	1257.8	7741.3	11812.5	4492.6	2.6	16.3
	$\ln E_0$	8.938	0.164	8.954	9.377	8.410	1.1	1.8
Cumulative dissipated energy	W_f, kJ/m^3	110453.7	104024.3	90727.8	506168.7	10687.8	47.4	94.2
	$\ln W_f$	11.275	0.833	11.414	13.135	9.277	1.4	7.4

3 Digital Image Processing and Analysis[10]

3.1 Specimen Processing and Digital Image Capture

When the fatigue test is finished, the specimen is still in tact, without dehiscence, etc. Therefore, the specimen after the fatigue test can be cut again. The specific method is to cut the beam specimen after the fatigue test using the double-cut saw along front elevation into three sections of approximately equal thickness to obtain six faces parallel to front elevation.

In order to better extract the information on voids in asphalt mixtures through the digital image, the colors of voids need to be differentiated. It has the best result to fill with plaster, for the time for hardening is short, the edge of voids is fully filled, and it is easy to polish. Therefore, the macroscopic voids on the specimen surface are filled with plaster containing yellow pigments, and the digital image is obtained through scanning after polishing.

The plane of section of the specimen is applied with vegetable oil appropriately to make the color of the plane of section brighter and more distinct. The plane of section processed is put on the scanner and the face of the three small specimens cut from one specimen can be scanned at a time. A black-out cloth is used to wrap the scanner, and the scanned image of the face of the three small specimens is obtained. The three small specimens are turned over and scanned following the above steps. Thus, the colorful scanned images of six faces of the three small specimens from one specimen are obtained.

3.2 Definitions

(1) Coarse aggregate area ratio G.

Coarse aggregate total area ratio G_{total} refers to the ratio of the sum of the areas of all coarse aggregate in an image to the area of the whole image:

Coarse aggregate total ratio

$$G_{\text{total}} = \frac{\sum \text{Area of single particle } A_i}{\text{Total area of image } A} \quad (1)$$

(2) Thickness of mastic film F.

Thickness of mastic film refers to the ratio of total area of fine aggregates and plastic paste and voids to the total perimeter of coarse particles in the image of asphalt mixtures.

$$F = \frac{S_f + S_a + S_v}{\sum P_i} \quad (2)$$

In which, F is the thickness of mastic film; S_f is the area of fine aggregates; S_a is the area of asphalt binder; S_v is the area of voids; $\sum P_i$ is the total perimeter of coarse particles.

(3) Principal axis and direction angle of particles.

The aggregate particles of asphalt mixtures are not regularly cubic, but a long and flat shape as shown in Figure 1. The principal axis of aggregate particles is defined as the line between two points with the maximum distance on the protruding boundary of particles, and the direction angle of particle α ($0° \leqslant \alpha \leqslant 90°$) is defined as the inclination between the principal axis of particles and the neutral axis in the fatigue test of the beam.

(4) Compliance factor.

Compliance factor ψ defines the ratio of the sum of the products of the length L_i of the long axis of particles

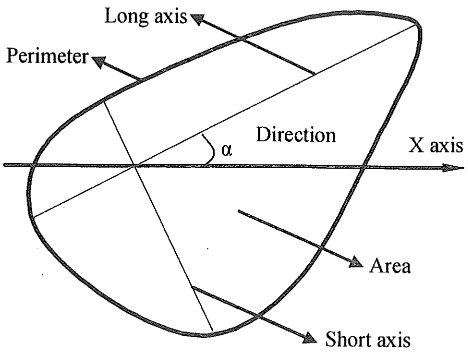

Fig. 1 Orientation of aggregates in asphalt mixture

and sin α_i to the sum of the lengths L_i of the long axis of particles. When the direction angle of all the particles in the mixture are zero, the compliance factor is zero; when the direction angle of all the particles in the mixture are 90°, the compliance factor is 1. The compliance factor ψ is between 0 ~ 1 and indicates the orientation of aggregates in asphalt mixture.

$$\psi = \frac{\sum L_i \cdot \sin(\alpha_i)}{\sum L_i} \quad (3)$$

(5) Definition of void indices.

Void area ratio is the primary void index. Void area ratio J_i defines the ratio of the area of a single void to the area of the whole image. Void total area ratio j_{total} defines the ratio of the sum of areas of all the voids in the image to the area of the whole image:

$$\text{Void area ration } J_i = \frac{\text{Area of single void } A_i}{\text{Total area of image } A} \quad (4)$$

$$\text{Void area ration } J_{total} = \frac{\sum \text{Area of single void } A_i}{\text{Total area of image } A} \quad (5)$$

3.3 Digital Image Processing

The flexural section at the centre (10cm length) in the image was extracted for digital image processing and analysis using IMAQ Version Builder software. IMAQ Version Builder is the product of National Instruments, USA and is an all-purpose digital image processing software. The whole course of digital image processing can be finished just after selecting the proper parameters. In this paper, the software was mainly used to extract the information on the inner structure and composition of asphalt mixtures to analyze the relativity between the inner structure and composition of asphalt mixtures and the fatigue properties, as well as the laws.

Through the above processing and analysis, the Excel spreadsheet containing the voids of each image and the features of red coarse particles was obtained. After analysis and calculation using the Matlab program programmed independently, the indices of the voids of each image and the red coarse particles were obtained. The statistical results were collected in Table 6.

Tab. 6 Statistical result of coarse aggregates indices of sectional image

Index Name	Total Area of Image /mm^2		Image Height /mm		Total Area of Particles /mm^2		Coarse Aggregate Area Ratio G_{total}/%	
	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimenv	6 Images of Specimen C_v%
Sample Average	5032.6	0.97	48.3	0.79	2414.0	8.63	48.0	8.6
Sample Max.	5275.5	3.32	49.4	3.06	2725.1	16.05	53.8	16.6
Sample Min.	4589.1	0.01	46.0	0.25	1604.4	3.43	32.7	3.3
C_v%	2.84		1.62		9.33		8.48	
Index Name	Thickness of Mastic Film F/mm		Compliance Factor ψ		Total Area of Voids /mm^2		Void Area Ratio JTotal /%	
	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimen	6 Images of Specimen C_v%	Average of 6 Images of Specimen	6 Images of Specimen C_v%
Sample Average	1.15	9.00	0.401	8.10	61.1	8.622	1.212	4.36
Sample Max.	1.58	17.65	0.453	17.82	143.6	25.909	2.738	11.06
Sample Min.	1.02	2.59	0.355	2.89	1.6	0.52	0.030	1.39
C_v%	9.54		5.649		121.71		55.03	

From Table 6, for the coarse aggregate total area ratio G_{total}, the maximum variation coefficient of the six sectional images in the specimen is 16.6%, the minimum is 3.3%, the average is 8.6%, and the variation coefficient in the sample is 8.48%, which indicates that the variation of G_{total} is high both in the same specimen and sample. Likewise, for the Thickness of Mastic Film F, coarse particle Compliance Factor and image Void Area Ratio J_{total}, the variation in the same specimens and sample is high. This means that the so-called "identical specimens" made by us under the same conditions are in fact quite different, and also means that the identical specimens visible with unaided eye actually have big difference in respects of microcosmic composition, orientation and microcosmic structure. It is such difference that may cause the big difference in macroscopic mechanical properties of the "identical specimens".

4 Regression Analysis

In this paper, SPSS software is mainly used to conduct regression analysis on the fatigue life and the corresponding influential factors of specimens of asphalt mixtures to establish the regression model of fatigue life. According to the results of analysis on relativity and prominence, the regression analysis was conducted by selecting the factors of high relativity and prominence, including Thickness of Mastic Film F, Compliance Factor and Void Area Ratio J_{total}, and the fatigue life of asphalt mixtures . See Table 7. Indices without prominent regression, such as void ratio, coarse aggregate total area ratio G_{total}, etc. are not included in the fatigue life model.

Likewise, the regression model of initial modulus can be established:

$$\ln E_0 = -3.272F - 0.017\psi + 10.714 \quad (6)$$

Indices without prominent regression, such as void area ratio J_{total}, void ratio V_0, coarse aggregate total area ratio G_{total}, etc. are not included in the initial modulus model.

Tab. 7 Logarithmic fatigue life regression model

Model: $\ln N_f = 0.158F + 9.291\Psi - 0.509J_{total} + 4.106$								R = 0.757	
Results of Factor Analysis		Nonstandard Coefficient		Standard Coefficient	t	Prominence	95% Confidence Interval of B	
		B	Standard Deviation	Beta			Lower Limit	Upper Limit
	(Constant)	4.106	1.689		2.431	0.019	0.714	7.497
	Thickness of Mastic Film F	0.158	0.039	0.413	4.039	0.000	0.080	0.237
	Compliance Factor ψ	9.291	4.087	0.232	2.274	0.027	1.083	17.499
	Void Area Ratio J_{total}	-0.509	0.132	-0.376	-3.840	0.000	-0.775	-0.243
Results of Covariance Analysis		Sum of Square	df	Mean Square	F	Prominence		
	Regression	22.176	3	7.392	22.332	0.000(a)		
	Residual Difference	16.550	50	0.331				
	Total	38.726	53					

Regression model of cumulative dissipated energy:

$$\ln W_f = 0.149F + 7.606\psi - 0.539J_{total} + 4.826 \quad (7)$$

Indices without prominent regression, such as void ratio V_v, coarse aggregate total area ratio G_{total}, etc. are not included in the cumulative dissipated energy model.

From the above regression and covariance analysis, the results of fatigue test of asphalt mixtures do have close relationship with the indices of inner structure and composition of asphalt mixtures, which indicates that the fatigue properties of asphalt mixtures directly relate to the inner structure and composition factors such as thickness of mastic film, particle orientation and void ratio, etc. It is the difference of inner structure and composition of asphalt mixtures that causes the big difference of fatigue life of asphalt mixtures under the same conditions. The thickness of mastic film has the most obvious influence on the fatigue properties of asphalt mixtures, and the void ratio also has quite big influence on fatigue properties of asphalt mixtures, which completely complies with the conclusion of the past researches. But the obvious influence of the orientation of particles in asphalt mixtures on the fatigue properties has not been reported in the literature in the past.

5 Conclusion

A big sample of small beam specimens of asphalt mixtures was used to carry out strain-control fatigue tests under the same conditions, and digital image processing technology was used to process and analyze the inner structure and composition of the flexural section at the centre of the small beam specimens of asphalt mixtures to define the indices of the inner structure and composition of asphalt mixtures. Further analysis using the statistical software had established a model on relationship between results of fatigue tests and indices of its inner structure and composition. The analysis shows that the variation of these indices in the same specimens and sample is high. This means that the so-called "identical specimens" made by us under the same conditions are in fact quite different, and also means that the identical specimens visible with unaided eye actually have big difference in respects of microcosmic composition, orientation and microcosmic structure. The analysis shows that the fatigue life of asphalt mixtures has logarithm-linear relationship with the thickness of mastic film, coarse particle compliance factor and void area ratio, and the initial modulus and cumulative dissipated energy also have close relationship with the indices of coarse particles and voids in the image. The influence of inner structure and composition of asphalt mixtures on the fatigue properties of asphalt mixtures is obvious. Fatigue properties of asphalt mixtures are obviously influenced by the inner structure and composition factors such as the thickness of mastic film, void ratio, etc., as well as by the particle orientation of asphalt mixtures.

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沥青混合料内部结构和组成对疲劳性能的影响研究

吴旷怀[1]，张肖宁[2]

（1. 广州大学土木工程学院，广东 广州 510006；2. 华南理工大学交通学院，广东 广州 510640）

摘　要： 采用一个沥青混合料小梁试件大样本，在相同条件下进行了应变控制疲劳试验，利用IMAQ数字图像处理软件对疲劳试验后的小梁试件中部纯弯段的内部结构和组成进行了处理和分析，定义了沥青混合料内部结构和组成的指标，进一步利用SPSS软件分析建立了疲劳试验结果参数与内部结构和组成指标的关系模型。分析表明，沥青混合料的疲劳寿命与沥青混合料内部结构和组成指标密切相关，沥青混合料疲劳寿命内部结构和组成的差异直接造成了相同条件下沥青混合料疲劳寿命的巨大差异，揭示了沥青混合料内部结构和组成对沥青混合料疲劳性能的影响规律。

关键词： 沥青混合料；内部结构和组成；数字图像处理；疲劳性能

中图分类号： U416.217；U414