Journal of Southeast University (English Edition) Vol. 21, No. 4, pp. 486 – 489 Dec. 2005 ISSN 1003—7985

Evaluation of environmental factors to fatigue performance of asphalt mixes

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Abstract: This paper studies the effect of different environmental factors, including the axle load weight, environmental temperature, vehicle speed, and the aging level of asphalt, on the fatigue performance of asphalt mixes based on four-point bending beam fatigue tests. A fractional factorial design method named "uniform design" was applied in experimental design. The relations of the environmental factors to initial stiffness, fatigue life, phase angle and cumulative dissipated energy were established with the general linear modeling method. It is found that there exists very good correlativity between the environmental factors and the fatigue performance indices of asphalt mixes. The coefficients of total correlation are mainly beyond 0. 95. The results indicate that the consideration of the effect of environmental factors is necessary in the fatigue performance evaluation on real asphalt pavement.

Key words: asphalt mixes; fatigue performance; environmental factor; uniform design; phase angle; cumulative dissipated energy

The fatigue performance of asphalt pavement has a strong relationship with the environmental conditions (such as the axle load weight, environmental temperature, vehicle speed, and the aging level of asphalt). The same asphalt mixture may have quite different fatigue properties under different environmental conditions. Therefore, the influence of the environmental factors should be considered to realize a more accurate prediction of the fatigue performance of asphalt pavement.

In this paper, the main environmental factors were simulated in laboratory. The influence of different environmental factors was evaluated by the four-point bending fatigue tests of asphalt mixes which refer to the AASHTO TP8 test specification. The analysis results provide a good foundation on which to establish the relationship between the different environmental factors and the fatigue performance of asphalt pavement.

1 Arrangement of Experimental Parameters

The environmental factors considered in this evaluation were: axle load weight, environmental temperature, vehicle speed, and the aging level of asphalt. Corresponding to the laboratory simulation, the following parameters were used: strain level, test temperature, test frequency, and the laboratory aging simulation of the asphalt mixes. The values of experimental parameters used in the tests are presented in Tab. 1; all the values selected were to span the range typically considered to be essential for the asphalt pavement fatigue performance. A certain asphalt volumetric property of asphalt mixes (traditional Chinese AC-16I gradation with target asphalt content 5. 0%, target air content 4. 0%) was designed for the fatigue test. Only one asphalt with penetration of 65 (0. 1 mm) was used. All the tests referred to the AASHTO TP8 test specification, and the strain controlled test mode was used.

Tab. 1 Experimental parameters for the evaluation of environmental factors

Environmental factors	Simulating parameters	Value range
Axle load weight	Strain level/10^{-6}	200, 400, 600
Environmental temperature	Test temperature/℃	5, 15, 25
Vehicle speed	Test frequency/Hz	5, 10, 15
Aging level of asphalt	Laboratory aging level for asphalt mixes	Un-aged, short-term aged and long-term aged

The laboratory aging-level grading method for asphalt mixes was developed at Oregon State University under the SHRP A-003A test development program[1]. The detailed grading standards[2,3] are presented in Tab. 2.

Received 2005-03-09.

Foundation item: The Code Program of the Highway Department of Ministry of Communications of China (No. 200107).

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Tab. 2 Grading standards of asphalt mixes aging level

Aging level	Laboratory aging simulating methods	Detailed methods	Simulated site aging conditions
Un-aged	None	The asphalt mixes were compacted after being mixed with no laboratory aging.	The aging level of asphalt mixes has already finished mixing in mix plant.
Short-term aged	Short-term oven aging (STOA)	Heat loose asphalt mixes for 4 h at 135 ℃ in a forced-drafted oven prior to compact the specimens.	The aging level of new asphalt pavement has already finished paving.
Long-term aged	Long-term oven aging (LTOA)	Heat the specimens (mixes being short-term aged) for 5 d at 85 ℃ in a forced-drafted oven.	The aging level of old asphalt pavement has been about 6 to 15 years after being paved.

2 Experimental Design

The experimental design of the main experiment was a fractional factorial design named "uniform design"[4] which was developed by two famous Chinese mathematicians Fang Kaitai and Wang Yuan. Three strain levels, three test temperatures, three test frequencies, three aging levels, and five replicates are considered in this experimental design, resulting in a nominal total of 60 tests by the Uniform Design Software (version 4.0). The aging level was considered as the qualitative factor in this experimental design[5,6]. The detailed uniform design results are summarized in Tab. 3.

Tab. 3 Uniform experimental design for the evaluation of environmental factors

Number of test group	Strain level/10^{-6}	Test temperature/℃	Test frequency/Hz	Aging level	Number of replicates
1	200	5	15	Short term	5
2	200	5	10	None	5
3	400	5	5	Short term	5
4	600	5	10	Long term	5
5	200	15	5	Long term	5
6	400	15	15	Long term	5
7	600	15	15	None	5
8	600	15	5	None	5
9	200	25	10	Short term	5
10	400	25	5	None	5
11	400	25	15	Long term	5
12	600	25	10	Short term	5

3 Analysis and Evaluation of Laboratory Results

A total of 60 four-point bending fatigue tests were performed with five replicates in each test group. In order to eliminate the abnormal values, the replicated results were preprocessed by the following criteria: if the difference between one test result and the average of the corresponding experimental level is k times larger than the modified standard deviation of the corresponded experimental level, this test result will be considered as abnormal (should be eliminated), and the remaining test results will be used in the statistical analysis. Moreover, the number of effective test results n should not be less than 3. Corresponding to different n values, there are different k values. The k value should be 1.15, 1.46, 1.67, respectively, when $n = 3, 4, 5$.

The following four test indices were preprocessed before analysis: initial stiffness, fatigue life, phase angle, and cumulative dissipated energy. Each effective test result must pass all the four-index preprocessing indices. Otherwise, the test result should be eliminated. Six test results were eliminated in the total 60 tests resulting in a total of 54 effective tests. The average values of test results are summarized in Tab. 4.

Tab. 4 Test results of the evaluation of environmental factors

Number of test group	Average initial stiffness/GPa	Average fatigue life/10^3 cycle	Average phase angle/(°)	Average cumulative dissipated energy/MPa	Number of effective tests
1	17.435	1 341.155	3.96	199.13	4
2	17.266	498.366	6.09	94.83	5
3	15.423	33.272	7.21	22.16	5
4	19.736	2.295	6.98	4.97	4
5	12.218	727.952	10.29	136.60	3
6	12.387	22.082	10.61	17.25	5
7	9.137	5.260	14.06	9.58	5
8	6.297	10.770	15.55	16.12	5
9	5.454	1 634.688	17.43	204.77	3
10	3.275	225.904	23.43	83.58	5
11	7.305	28.962	17.50	19.29	5
12	4.845	10.514	19.02	12.34	5

3.1 Analysis of variance

Routine statistical procedures were employed to quantify the correlations and relationship among the variables of interest and determine their statistical significance. Analysis of variance (ANOVA) was employed to establish the significance of environmental factors, the logarithm of fatigue life $\ln N_f$, the logarithm of initial flexural stiffness $\ln S_o$, phase angle φ, and the logarithm of cumulative dissipated energy $\ln W_N$. The ANOVA results are summarized in Tab. 5.

Tab. 5 ANOVA summary of test results

Factors	$\ln S_o$	$\ln N_f$	φ	$\ln W_N$
Strain level($\ln\varepsilon_t$)		H	S	H
Test temperature (T)	H	S	H	B
Test frequency (f)	S		S	
Aging level	H	S	H	B

Notes: H means highly significant (less than 0.01); S means significant (0.01 to 0.05); B means barely significant (0.05 to 0.10); blank means not significant (greater than 0.10).

3.2 Analysis of initial flexural stiffness

If we only consider the main effects of the four simulated environmental factors, the relationship between initial stiffness and the simulated environmental factors can be modeled as Eq. (1) by the general linear modeling method.

$$\ln S_o = 9.6685 - 0.0622T + 0.0222f + 0.1675A_1 + 0.4199A_2 \quad (1)$$

where ln is the natural logarithm; S_o is the initial flexural stiffness; T is the test temperature; f is the test frequency; A_1, A_2 are the aging coefficients, $A_1 = 0$ and $A_2 = 0$ means un-aged, $A_1 = 1$ and $A_2 = 0$ means short-term aged, $A_1 = 0$ and $A_2 = 1$ means long-term aged.

The modeling Eq. (1) achieved a very good correlation between the initial flexural stiffness and the simulated environmental factors; the whole correlation coefficient R^2 is 0.9687. The following conclusions can be drawn from the regression results: an asphalt mixture will suffer about 6% reduction in initial stiffness if the temperature increases 1 ℃; while if the test frequency increases 1 Hz, it will lead to a 2.2% increase in initial stiffness; the mixture after short-term aging will lead to an 18% increase in initial stiffness; and the mixture after long-term aging will lead to a 52% increase in initial stiffness. However, changes in strain level do not have a significant effect on initial stiffness.

3.3 Analysis of fatigue life

If we only consider the main effects of the four simulated environmental factors, the relationship between fatigue life and the simulated environmental factors can be modeled as Eq. (2) by the general linear modeling method.

$$\ln N_f = 37.7259 - 4.6128\ln\varepsilon + 0.0511T - 0.8625A_2 \quad (2)$$

where N_f is the fatigue life (cycle), and ε is the strain level (10^{-6}).

The modeling Eq. (2) achieved a very good correlation between fatigue life and the simulated environmental factors; the whole correlation coefficient R^2 is 0.9742. The following conclusions can be drawn from the regression results: an asphalt mixture will suffer about 5.5% reduction in fatigue life if the temperature decreases 1 ℃; the mixture after long-term aging will lead to a 56% reduction in fatigue life; the relationship between the fatigue lives of un-aged specimens and short-term aged specimens is statistically insignificant (significance level $\alpha = 0.10$). However, changes in frequency within 5 to 15 Hz do not have significant effect to fatigue life.

If we use the model recommended by Carl L. Monismith at University of California at Berkeley, the relationship between fatigue life, strain level, and initial flexural stiffness can be established as

$$N_f = 3.481 \times 10^{21}\left(\frac{1}{\varepsilon}\right)^{4.852}\left(\frac{1}{S_o}\right)^{1.091} \quad (3)$$

Eq. (3) achieved a very good correlation between fatigue life, strain level, and initial flexural stiffness, and the whole correlation coefficient R^2 is 0.9711. The regression results indicate similar conclusion as drawn by the SHRP A-003A researchers.

3.4 Analysis of phase angle

Phase angle is an index indicating the viscoelasticity of asphalt mixtures. It greatly affects the dissipated energy per cycle. If we only consider the main effects of the four simulated environmental factors, the relationship between phase angle and the simulated environmental factors can be modeled as Eq. (4) by the general linear modeling method.

$$\varphi = -6.7547 + 2.2525\ln\varepsilon + 0.6430T - 0.1888f - 2.0452A_1 - 2.7495A_2 \quad (4)$$

The modeling Eq. (4) achieved a very good correlation between phase angle and the simulated environmental factors; the whole correlation coefficient R^2 is 0.9862. The following conclusions can be drawn from the regression results: an increase in strain level will also lead to the increase in phase angle; both the short-term aging and long-term aging will lead to the reduction of phase angle; the asphalt mixture will have a 0.6° increase in phase angle if the test temperature increases 1 ℃; and the asphalt mixture will have a 0.2° reduction in phase angle if the test frequency increases 1 Hz.

3.5 Analysis of cumulative dissipated energy

If we only consider the main effects of the four simulated environmental factors, the relationship between cumulative dissipated energy and the simulated environmental factors can be modeled as Eq. (5) by the general linear modeling method.

$$\ln W_N = 18.0225 - 2.5094 \ln\varepsilon + 0.0309 T - 0.6079 A_2 \quad (5)$$

where W_N is cumulative dissipated energy (MPa).

The modeling Eq. (5) achieved a very good correlation between cumulative dissipated energy and the simulated environmental factors; the whole correlation coefficient R^2 is 0.9434. According to the significance test results, the statistically significant simulated environmental factors are (by significant degree): strain level ε > test temperature T > long-term aging A_2. However, the effects of test frequency f and short-term aging A_1 are not statistically significant (significance level $\alpha = 0.10$).

The relationship between cumulative dissipated energy and fatigue life can be established as

$$\ln W_N = -2.6454 + 0.5571 \ln N_f \quad (6)$$

The regression results indicate that there is a very strong correlation between fatigue life and cumulative dissipated energy, and the whole correlation coefficient R^2 is even as high as 0.9904. On the other hand, it is proved that fatigue life and cumulative dissipated energy have some similarity in predicting the fatigue performance of asphalt pavement.

4 Conclusions

1) The simulated environmental factors evaluated in this program significantly affect the fatigue performance of asphalt mixes in different aspects. It is proved that the environmental factors have a good relationship as regards fatigue life, stiffness, phase angle, and cumulative dissipated energy.

2) Uniform design is proved to be a good experimental design method, it can achieve the same effectiveness with fewer tests.

3) The general linear modeling method is a relatively rational method for establishing the correlations between environmental factors and fatigue properties.

4) Properly increasing the replicate tests and preprocessing the test results are good ways to improve the reliability and accuracy of analysis.

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沥青混合料疲劳性能环境影响因素评价

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摘要:通过4点弯曲小梁疲劳试验,研究了不同的外界环境因素(包括轴载大小、环境温度、车流速度以及沥青老化程度等)对沥青混合料疲劳性能的影响作用. 应用均匀试验设计理论设计了具体的试验方案,并采用广义多元线性回归方法建立了各环境因素与沥青混合料初始劲度模量、疲劳寿命、滞后角和累积耗散能指标之间的关系. 发现沥青混合料的各疲劳特性指标与环境影响因素之间存在很好的相关性,全相关系数基本在0.95以上. 结果表明在实际沥青路面疲劳性能评价中考虑外界环境因素的影响作用是必要的.

关键词:沥青混合料;疲劳性能;环境因素;均匀试验设计;滞后角;累积耗散能

中图分类号:U414