A STUDY OF THE FATIGUE PERFORMANCE OF ASPHALT MIXES BASED ON THE UNIFORM DESIGN METHOD

YU JIANG-MIAO, LI ZHI, WANG SHAO-HUAI and ZHANG XIAO-NING

Road Engineering Research Institute, South China University of Technology,
Guangzhou 510640, China.

ABSTRACT

In this paper, a fractional factorial design method named “Uniform Design” was applied in the study of the relationship of environmental factors to the fatigue performance of asphalt mixes. The environmental factors considered in the experimental design included strain level, temperature, loading frequency and asphalt aging level. The relations of the environmental factors to initial stiffness, fatigue life, phase angle and cumulative dissipated energy were established using the general linear modelling method. It was found that there is very good correlation between the environmental factors and the fatigue performance indices of asphalt mixes. The results indicate that the Uniform Design method is a effective experimental design method, with which the same effectiveness can be obtained with fewer tests.

1. INTRODUCTION

The fatigue performance of asphalt pavements bears a strong relationship to the environmental conditions (such as the axle load weight, environmental temperature, vehicle speed, and the level of aging of the 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 obtain a more accurate prediction of the fatigue performance of an asphalt pavement.

In this paper, the main environmental factors were first simulated in the laboratory, after which the influence of the different environmental factors was evaluated using the four-point bending fatigue tests for asphalt mixes, as specified in the SHRP four-point bending fatigue test (SHRP M-009, 1994). The results of the analysis provide a good foundation for establishing a relationship between the different environmental factors and the fatigue performance of asphalt pavements.

2. ARRANGEMENT OF EXPERIMENTAL PARAMETERS

The environmental factors considered in this evaluation were: axle load weight, environmental temperature, vehicle speed, and the level of aging of the asphalt. Corresponding to the laboratory simulation, the following factors were used: strain level, test temperature, test frequency, and the laboratory aging simulation of the asphalt mixes. The values of the experimental parameters used in the tests are presented in Table 1; all the values were selected to span the range typically considered to be essential for asphalt pavement fatigue performance. A certain asphalt volumetric property of asphalt mixes (traditional Chinese AC-16I grading with a target asphalt content of 5.0% and a target air content of 4.0%) was designed for the fatigue test. Only one original asphalt with a penetration of 65 (0.1 mm) was used. All the tests refer to the SHRP M-009 test specification. The strain-controlled test mode was used.

Table 1. Experimental parameters for evaluating the influence of environmental factors.

Environmental factors	Simulating parameters	Range of values
Axle load weight	Strain bevel	200, 400 and 600 (micro strain)
Environmental temperature	Test temperature	5, 15 and 25 (^{o}C)
Vehicle speed	Test frequency	5, 10 and 15 (Hz)
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 programme (Bell and Sosnovske, 1994). The detailed grading standard is presented in Table 2.

Table 2. Grading standards of asphalt mixes' aging levels.

Aging level	Laboratory aging simulation methods	Detailed methods	Simulated site-aged condition
Un-aged	None	The asphalt mixes were compacted after being mixed, with no laboratory aging.	The age level of asphalt mixes that have already finished being mixed in a mixing plant.
Short-term aged	Short-term oven aging (STOA)	Heat loose asphalt mixes for 4 hours at 135 ^{o}C in a forced-draft oven prior to compacting the specimens.	The age level of new asphalt pavements that have already been used in the construction of a pavement.
Long-term aged	Long-term oven aging (LTOA)	Heat the specimens (mixes being short-term aged) for 5 days at 85 ^{o}C in a forced-draft oven.	The age level of old asphalt pavements about 6 –15 years after construction.

3. EXPERIMENTAL DESIGN

A fractional factorial design, named the “Uniform Design” (Fang and Hickernell,1995; Fang *et al.,* 2001), which was developed by two Chinese mathematicians, Fang Kaitai and Wang Yuan (Wang and Fang, 1999 and 2000), was used in the experiment. Three strain levels, three test temperatures, three test frequencies, three aging levels and five replicates are considered in this experimental design, which results in a nominal total of 60 tests with the Uniform Design software (version 4.0). The detailed Uniform Design results are summarised in Table 3.

Table 3. Uniform experiment design for environmental factors evaluating.

Test group No.	Strain level (micro strain)	Test temperature (^oC)	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

4. ANALYSIS AND EVALUATION OF LABORATORY RESULTS

A total of 60 four-point bending fatigue tests were performed with five replicates of each test group. In order to eliminate the abnormal values, the replicated results were preprocessed using the following criterion: if the difference between one test result and the average of the corresponding experiment level is *k* times larger than the modified standard deviation of the corresponding experiment level, this test result will be considered as abnormal (and should be eliminated), and the remaining test results will be used in the statistical analysis. Moreover, *n* (the number of effective test results) should not be less than 3. Corresponding to different *n*'s, there are different *k* values. The *k* values are, respectively: 1.15, 1.46 and 1.67, where n = 3, 4 and 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 the four-index preprocessing at the same time; otherwise, the test result should be eliminated. Six test results were eliminated out of the total of 60 tests, resulting in a total of 54 effective tests. The average values of the test results are summarised in Table 4.

4.1 Analysis of Variance (ANOVA)

Routine statistical procedures were employed to quantify the correlations and relationship among the variables of interest and to determine their statistical significance. Analysis of variance (ANOVA) was employed to establish the significance of the environmental factors, the logarithm of fatigue life ($\ln N_f$), the logarithm of initial flexural stiffness ($\ln S_0$), the phase angle (φ) and the logarithm of cumulative dissipated energy ($\ln W_N$). The ANOVA results are summarised in Table 5.

Table 4. Summary and evaluation of test results on environmental influencing factors.

Test group No.	Average initial stiffness (MPa)	Average fatigue life	Average phase angle (degree)	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

Table 5. Summary of anova for test results.

Factor	$\ln S_0$	$\ln N_f$	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:	Description	Probability
	H = highly significant	less than 0.01
	S = significant	0.01 to 0.05
	B = barely significant	0.05 to 0.10
	Blank = not significant	greater than 0.10.

4.2 Analysis of Initial Flexural Stiffness

If only the main effects of the four simulated environmental factors are considered, the relationship between *initial stiffness* and the simulated environmental factors can be modelled as Equation (1), using the general linear modelling method:

$$\ln S_0 = 9.6685 - 0.0622T + 0.0222f + 0.1675A_1 + 0.4199A_2 \qquad (1)$$

Where

ln is the natural logarithm
S_0 is the initial flexural stiffness (MPa)
T is the test temperature (^{o}C)
f is the test frequency (Hz)
A_1, A_2 are 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 modelling Equation (1) achieved a very good relationship between the initial flexural stiffness and the simulated environmental factors; the whole correlation coefficient (R^2) was 0.9687. The following conclusions can be drawn from the regression results: an asphalt mixture will suffer a reduction of about 6% in its initial stiffness if the temperature increases by 1 ^{o}C; an increase in the test frequency of 1 Hz will lead to an increase of 2.2% in the initial stiffness; after short-term aging, the stiffness of the mixture will increase by 18% over the initial stiffness; and after long-term aging, the stiffness will increase by 52% over the initial stiffness. However, changes in the strain level do not have a significant effect on the initial stiffness.

4.3 Analysis of Fatigue Life

If only the main effects of the four simulated environmental factors are considered, the relationship between *fatigue life* and the simulated environmental factors can be modelled as Equation (2), using the general linear modelling method:

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

Where

ln is the natural logarithm
N_f is the fatigue life (cycle)
ε is the strain level (micro strain)
T is the test temperature (^{o}C)

A_1, A_2 are 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 modelling Equation (2) achieved a very good relationship between the fatigue life and the simulated environmental factors; the whole correlation coefficient (R^2) was 0.9742. The following conclusions can be drawn from the regression results: an asphalt mixture will suffer about a 5.5% reduction in its fatigue life if the temperature decreases by 1 ^{o}C; after long-term aging, there will be a 56% reduction in the fatigue life of the mixture; there is no statistically significant difference (significance level $\alpha = 0.10$) between the fatigue lives of un-aged specimens and short-term aged specimens. Changes in frequency within the range of 5 to 15 Hz do not have a significant effect on the fatigue life.

Using the model recommended by Prof. Carl L Monismith of the University of California at Berkeley, the relationship between fatigue life, strain level and initial flexural stiffness can be established as following equation (3):

$$N_f = 3.481 \times 10^{21} (1/\varepsilon)^{4.852} (1/S_0)^{1.091} \qquad (3)$$

Where

ln is the natural logarithm
N_f is the fatigue life (cycle)
ε is the strain level (micro strain)
S_0 is the initial flexural stiffness (MPa).

Equation (3) achieved very a good relationship between fatigue life, strain level and initial flexural stiffness; the whole correlation coefficient (R^2) was 0.9711. The regression results lead to similar conclusions to those drawn by the SHRP A-003A researchers (Deacon *et al.*, 1994).

4.4 Analysis of Phase Angle

Phase angle is an index indicating the viscoelasticity of asphalt mixtures. It greatly affects the dissipated energy per cycle. If only the main effects of the four simulated environmental factors are considered, the relationship between phase angle and the simulated environmental factors can be modelled as Equation (4), using the general linear modelling method:

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

Where

ln is the natural logarithm
ε is the strain level (micro strain)
T is the test temperature (^{o}C)
f is the test frequency (Hz)

A_1, A_2 are 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 modelling Equation (4) achieved a very good relationship between the phase angle and the simulated environmental factors; the whole correlation coefficient (R^2) was 0.9862. The following conclusions can be drawn from the regression results: an increase in the strain level will also lead to an increase in the phase angle; both short-term aging and long-term aging will lead to a reduction in the phase angle; and there will be a 0.2 degree reduction in the phase angle of the asphalt mixture if the test frequency increases by 1 Hz.

4.5 Analysis of Cumulative Dissipated Energy

If only the main effects of the four simulated environmental factors are considered, the relationship between cumulative dissipated energy and the simulated environmental factors can be modelled as Equation (5), using the general linear modelling method.

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

Where

ln is the natural logarithm
W_N is the cumulative dissipated energy (MPa)
ε is the strain level (micro strain)
T is test temperature (^{o}C)

A_1, A_2 are 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 modelling Equation (5) achieved a very good relationship between the cumulative dissipated energy and the simulated environmental factors; the whole correlation coefficient (R^2) was 0.9434. According to the significance test results, the statistically significant simulated environmental factors are (by degree of significance): 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 Equation (6):

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

Where

ln is the natural logarithm
W_N is the cumulative dissipated energy (MPa)
N_f is the fatigue life (cycle).

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

5. CONCLUSIONS

The following conclusions can be drawn from this study on the relationship of environmental factors to the fatigue performance of asphalt mixes:

- “Uniform Design” has been proved to be a good experimental design method – it produces the same effectiveness with fewer tests.
- The simulated environmental factors evaluated in this study significantly affect the fatigue performance of asphalt mixes in various ways. It was proved that there is a good relationship between these environmental factors and fatigue life, initial stiffness, phase angle, and cumulative dissipated energy.
- The general linear modelling method is a relatively rational method for establishing the relationships between environmental factors and fatigue properties.
- Properly considered increases in the number of replicate tests and preprocessing of the test results are good ways to improve the reliability and accuracy of the analysis.

6. REFERENCES

[1] Bell, Chris A and Sosnovske, Dan, 1994. Aging: Binder Validation. SHRP-A-384.

[2] Deacon, JA, Tayebali, A., Coplantz, J, Finn, F and Monismith, CL, 1994. Fatigue response of asphalt-aggregate mixes, Strategic Highway Research Program Report No. SHRP-A-404, National Research Council.

[3] Fang, KT and Hickernell, FJ, 1995. The uniform design and its applications. Bulletin of the International Statistical Institute, 50th Session, Book 1, p 333.

[4] Fang, KT, Lin, DKJ Winker, P and Zhang, Y, 2000. Uniform design: theory and applications. Technometrics, 42, p 237.

[5] SHRP, 1994. Standard method of test for determining the fatigue life of compacted bituminous mixtures subjected to repeated flexural bending.

[6] Wang, Zhu and Fang, KT, 1999. The uniform design with qualitative factors. 18, p 11.

[7] Wang, Zhu and Fang, KT, 2000. Measures of uniformity for uniform designs with qualitative factors. Mathematical Statistics and Management, 19, p 28.