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Normalization of fatigue characteristics for asphalt mixtures under different stress states

Songtao Lv [a,b], Chaochao Liu [a,*], Dong Chen [a], Jianlong Zheng [a], Zhanping You [b], Lingyun You [b]

[a] National Engineering Laboratory of Highway Maintenance Technology, Changsha University of Science & Technology, 410004 Hunan, PR China
[b] Department of Civil and Environmental Engineering, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931-1295, USA

HIGHLIGHTS

- The patterns of variation between the strength and loading rate was revealed in different stress state for asphalt mixtures.
- The yield surface of strength in 3-dimensional stress states for asphalt mixtures was established.
- The normalization of fatigue characteristics for asphalt mixtures under different stress states was realized.

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ABSTRACT

The fatigue test methods under different test conditions have strong impact on the test results, which obstructs a precise evaluation of fatigue characteristic for asphalt mixtures. Different test conditions means different stress states. Fatigue characteristic of a material is an objective attribute, and it should not vary with test methods and conditions. In order to accurately and objectively evaluate the fatigue properties of asphalt mixtures, a normalization model of fatigue characteristics for asphalt mixtures under different stress states was established based on the yield criterion in 3 dimensional stress states and the patterns of variation between the strength and the loading rate. The compressive, tensile and indirect tensile strength and fatigue tests were carried out respectively in different loading rates. The yield surface of strength for asphalt mixture was put forward based on the strength tests results and the yield criterion. Then, the normalization model of fatigue characteristics for asphalt mixtures under different stress states was established based on the yield criterion in 3 dimensional stress states. The results show that the differences of the fatigue tests results of asphalt mixtures under different test condition are large. It is difficult to evaluate the fatigue performance in different stress states of asphalt mixtures by using the conventional S-N fatigue equation. However, these differences can be reduced or even eliminated by using the normalization model, which considered the influence of the stress state and the strength corresponding to the fatigue loading frequency and stress level. The unified expression of fatigue characteristics under different test conditions for asphalt mixtures was realized. The fatigue behavior of asphalt mixture under different stress conditions can be objectively evaluated by using the normalized model.
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1. Introduction

Fatigue cracking is the most dominant form of asphalt pavement damage. In order to ensure the durability and usability of asphalt pavement, the anti-fatigue properties of pavement materials were taken as the basis for determining the design life of asphalt pavement in most asphalt pavement the design methods of all over the world [1,2]. Therefore, a variety of low-cost and short-cycle indoor fatigue tests were carried out by many researchers of different countries to study the anti-fatigue properties of asphalt pavement [3,4]. In Europe and America, two point bending, three point bending and four points bending fatigue test were normally conducted to study the anti-fatigue properties of asphalt mixtures, of which the specimens are trapezoidal or beam with semi-sine wave load loaded on them [5,6]. The researchers of Japan always conducted indirect tensile fatigue test to study the anti-fatigue properties of asphalt mixtures [7]. The scholars of Chinese revealed the fatigue properties mostly by carrying out tensile or indirect tensile fatigue tests [8] and analyzing the decay rules of modulus during the fatigue tests [9]. The previous researches show that the fatigue test results of asphalt mixture obtained by different methods were different, and the fatigue test results have higher sensitivity to the specimen shape, sizes and fatigue loading mode.

* Corresponding author.
E-mail address: lcccs@stu.csust.edu.cn (C. Liu).

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What's more, the existing fatigue models were failed to remove these difference to evaluate the anti-fatigue performance of asphalt mixture certainly. So, it is essential to develop a normalization model to gain a unified expression of asphalt mixtures fatigue characteristics under different test conditions.

As to fatigue model of asphalt mixtures, thousands of researches have been conducted by researchers of all over the world. Sabouri [10] developed failure criterion for the viscoelastic continuum damage (VECD) model and used it to evaluate the fatigue properties of asphalt mixtures in different modes of fatigue loading. The applicability of the simplified viscoelastic continuum damage (S-VECD) model to evaluate the fatigue behavior of aging asphalt mixtures was verified in Babadopulos' researches [11]. Kim [12] and Lundstrom [13] evaluated the fatigue characteristics by analyzing the Cyclic Tests results with viscoelastic continuum damage mechanics model, and found that the fatigue characteristics of fixed asphalt mixture with different testing methods were different in this model. Benedetto [14] studied 11 different test methods to evaluate the fatigue properties of asphalt mixtures, including uniaxial tension, uniaxial compression, bending and indirect tensile tests, and established individual fatigue equation for each test method. The former studies have made significant contribution to fatigue characteristics of asphalt mixtures, but failed to draw a certain conclusion. What's more, the current most widely used fatigue model, the S-N fatigue equation, cannot explain the fatigue characteristics of different stress states. In order to tackle this problem, Lv et al. [15] modified the S-N fatigue equation based on the actual stress ratio and the direct tensile fatigue test, which connect the stress states to fatigue equation.

Moreover, in order to eliminate the influence of stress state, specimen shape and size on the analysis and evaluation of fatigue characteristics, Li et al. [16,17] developed a series of test methods to study the fatigue performance of asphalt mixtures and reveal the effect of specimens' sizes on fatigue life. The results showed that the specimens' sizes have a trivial impact on tensile and compressive fatigue properties but effect the four point bending fatigue test results, especially the bending stiffness and fatigue life. He also used the Desai strength yield surface model to normalize the fatigue properties of asphalt mixture under different stress states [18], of which the fatigue tests were conducted under stress control and strain control modes, but every test results were obtained based on the hypothesis of that the tensile strength of specimen were constant, which was not consistent with the actual situation and would cause a considerable inaccuracy to the evaluation of asphalt mixtures fatigue characteristics.

Therefore, in this paper, the strength and fatigue tests under uniaxial compressive, direct tensile and indirect tensile stress states were carried out in different loading rates, respectively. The yield surface of strength for asphalt mixture was put forward based on the strength tests results and the yield criterion. Then, the normalization model of fatigue characteristics for asphalt mixtures under different stress states was established based on the yield criterion in 3 dimensional stress states. The normalization model reduced or even eliminated the uncertainty of evaluation of asphalt mixtures fatigue characteristics caused by the different test conditions. It provides a theoretical method and technical basis for the scientific transformation from material fatigue to structural fatigue.

2. Sample preparations

2.1. Material and mix design

In this paper, the strength and fatigue tests of indirect tensile, direct tension and unconfined compression were carried out respectively to establish a normalization model of asphalt mixture fatigue characteristics under different stress states. In order to reduce the interference of other test conditions, the dense gradation of asphalt mixtures (AC-13) were taken as research object, which were composed of SBS modified asphalt binders, limestone aggregates, and limestone powders. The performance indexes of SBS modified asphalt were shown in Table 1, and the physical and chemical properties of aggregates were shown in Table 2. The gradation of dense graded asphalt mixture were chosen according to the "Specifications for Design of Highway Asphalt Pavement" [19], which was presented in Fig. 1.

The dense gradation of aggregate was shown as Fig. 1.

The optimum asphalt-aggregate ratio was5.2%, which obtained by the Marshall Tests, and the test results are shown in Table 3.

2.2. Specimen preparation

According to the Chinese Standard Test Methods of Bituminous and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [20], block samples 400 mm × 300 mm × 80 mm were fabricated through the equipment of vibrating compaction. Then, the beam specimens were cut from block samples into the size of 250 mm × 50 mm × 50 mm for directly tensile test; and the cylindrical specimens for the unconfined compressive fatigue test were made by Superpave Gyratory Compactor (SGC), with the size of Φ100 mm × 100 mm, and the indirect tensile specimens were prepared by cut the top and bottom surface of the specimens of unconfined compressive test to the size of Φ100 mm × 60 mm. All the specimens can be seen in Fig. 2. All the specimens were put in an environment chamber at 15 °C for 24 h before the strength and fatigue tests. There were five parallel tests for each test.

3. Strength and fatigue tests

The strength and fatigue tests of asphalt mixtures were carried out according to the Chinese Standard Test Methods of Bituminous and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [20]. The temperature of the test was fixed at 15 °C which controlled by an environmental chamber, as shown in Fig. 2.

One of the strength tests' purpose was to gain the real stress ratio for fatigue tests. The strength tests were conducted under different loading rates which determined by the loading frequency f (The cycle time is T) and stress level σ of fatigue test, and the corresponding loading rate can be calculated, as shown in Eq. (1):

$$v = \frac{\sigma}{T/2} = 2f\sigma \tag{1}$$

where v is the loading rate; T is the cycle time; f is the loading frequency of fatigue test; σ is the stress level of fatigue test.

Generally, the speeds of vehicles are about 60–80 km/s, at which the pavements receive the loading frequency nearly equivalent to 10 Hz. Thus 10 Hz was taken as the loading frequency of the fatigue tests. In this paper, the aim of the fatigue test was to establish the relationship between the stress level and the fatigue life. If the values of stress level were improper, the test would be hampered. For instance, it would cost a long time before the specimen achieve its fatigue life if the stress level was too low. In turn, if the stress level was too high, the discreteness of experimental results would increase. After several trials, the values of stress level for direct tensile and indirect tensile fatigue tests were chosen as0.25 MPa, 0.5 MPa, 1 MPa, and 1.5 MPa respectively, while those of compressive fatigue tests were chosen as 2 MPa, 2.5 MPa, 3 MPa, and 3.5 MPa respectively. All of these fatigue tests were conducted in stress control model. Taking the values of loading frequency f and stress levels σ into Eq. (1), the loading rates for strength tests of asphalt mixtures were obtained: 5 MPa/s, 10 MPa/s, 20 MPa/s, 30 MPa/s, 40 MPa/s, 50 MPa/s, 60 MPa/s and 70 MPa/s, respectively.

Table 1
Performance Index of SBS (I-D) modified asphalt.

Technical indexes	Result	Specification
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	55.19	30–60
Ductility (5cm/min, 5 °C) (cm)	34.51	≥20
Softening point TR&B (°C)	78.91	≥60

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