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Research on the fatigue equation of asphalt mixtures based on actual stress ratio using semi-circular bending test

Jiwang Jiang [a], Fujian Ni [a,*], Qiao Dong [a], Fan Wu [a], Yiqing Dai [b]

[a] *School of Transportation, Southeast University, Nanjing, Jiangsu Province 210096, China*
[b] *Department of Civil Engineering, Monash University, Victoria 3800, Australia*

HIGHLIGHTS

- SCB strength models of asphalt mixtures based on loading rates and temperatures were established.
- The fatigue properties of asphalt mixtures were evaluated in aspect of energy consumption and vertical deformation.
- Fatigue equations based on real actual stress ratio and nominal stress ratio were developed.

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ABSTRACT

The semi-circular bending (SCB) strength test and fatigue test were used in this paper to evaluate the strength property and fatigue performance of asphalt mixtures. The SCB strength test was carried out at 8 loading rates and 3 temperatures, followed by the SCB fatigue test at 5 load levels on one common stone matrix asphalt (SMA) mixture. The time–temperature characteristics of strength from SCB test were studied. The fatigue performance was evaluated based on displacement development and energy consumption during the cyclic loading process. And according to the established strength-loading rate model, the fatigue equation based on actual stress ratio was obtained as well. The results showed that asphalt mixture strength was affected by loading rate and temperature significantly, the relation between strength and loading rate could be approximately expressed as a power function; the relation between fatigue life and stress level (or nominal stress ratio) could also be expressed as a power function. The lower the stress level, the longer the fatigue life was, and the fatigue life and the cumulative energy consumption showed a good linear relationship in the double logarithmic coordinates; the fatigue equation based on actual stress ratio revealed the connection between fatigue failure and strength failure.

1. Introduction

Influenced by two factors of traffic load and water temperature environment, the damage appeared gradually inside the pavement structure during the service life [1]. With the increase of the number of repeated loads, the pavement structural strength gradually reduced as a result of the continuous development of damage, which will lead to pavement crack and fatigue failure finally. For a long time, how to improve the durability of asphalt pavement is the key point of the work for road engineers [2], and the durability and service life of pavement will be greatly affected by pavement fatigue performance. At present, there are many kinds of laboratory fatigue tests for asphalt mixture, including direct tensile test, indirect tensile test (i.e. splitting fatigue test), beam bending test and semi-circular bending test [3–6]. The specimens for direct tensile test can be a variety of shapes and the operation is simple, but the stress mode of direct tension is different from the actual stress condition of pavement; indirect tensile test is relatively easy to operate, however the stress state of the specimen is complicated during the loading process, and the indirect tensile stress mode is different from the actual pavement structures; similar stress pattern to actual pavement can be obtained in bending test of small beam, yet it cannot evaluate pavement performance effectively since the beam specimens is not easy fabricated and it is not accessible from the cored specimen. Recently, a push-pull test provides a more reliable insight in the fatigue mechanism of asphalt mixtures by using the visco-elastic continuum damage model [7,8], but the operation of the test is very complicate and it can hardly be conducted on the cored samples from the field. In contrast, for

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* Corresponding author at: 2 Sipailou Rd., Nanjing 210096, China.
E-mail address: 101004746@seu.edu.cn (F. Ni).

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semi-circular bending test (SCB test), specimen preparation and testing process are simpler, and the stress state of specimen is similar to that of actual pavement, the specimen is pressed and pulled at the same time therefore this test has a certain superiority [9]. In recent years, semi-circular bending test are widely used in asphalt mixtures. SCB test was originally used to characterize the fracture resistance in rock mechanics [10]. It has been used to characterize the tensile strength properties by van and Smith in asphalt mixtures [11]. Considering the advantages and disadvantages of the above tests, this paper used semi-circular bending test to evaluate the time-temperature characteristics and the fatigue performance of asphalt mixture. Asphalt mixture is a typical viscoelastic material, its mechanical response is closely related to loading mode and temperature [12]. Few research has done the work of tensile strength at multiple temperature and loading rate under semi-circular configuration and no tensile strength model has been established before. At present, the reference strength in fatigue tests of asphalt mixture is determined as the strength value under one certain loading rate or temperature, then the stress levels are selected according to the value. However, the strength of asphalt mixture is affected by load rate, load waveform and temperature during the test [13], as a result, the dynamic strengths vary according to the load rates under different stress levels in the fatigue test. But the fatigue equation obtained from the conventional fatigue test by stress-control mode does not take into account the influence of the loading condition [14], which will affect the viscoelasticity of the asphalt mixture to a certain extent. Therefore, it is necessary to study the time-temperature characteristics of asphalt mixture strength before the fatigue test. Studying the time-temperature characteristics and fatigue equation of asphalt mixture have great significance for improving the durability of asphalt pavement.

2. Objectives and scope

The main objective of this study is to evaluate the fatigue behavior of SMA mixtures based on the results of SCB strength test and SCB fatigue test. The specific objectives are listed as follows:

(1) Explore the effects of temperature and loading rate on the strength of SMA mixture.
(2) Compare and analyze the fatigue curves of SMA mixture in SCB fatigue tests under several stress levels based on the displacement and energy consumption.
(3) Verify the fatigue equation of SMA mixtures in SCB fatigue test by the actual stress ratio.

3. Mix design and specimens preparation

In order to characterize the fatigue characteristic of asphalt mixtures based on SCB test, a stone matrix asphalt mixture with nominal maximum aggregate size of 13 mm (SMA-13) was selected for this study. The asphalt used in this paper was a SBS modified asphalt meeting the PG grading of 70–22. The aggregate and the mineral powder were basalt and limestone powder respectively. All materials were clean and dry during the compaction. In addition, cellulose fiber was selected as the fiber stabilizer for the mixtures and its content was determined to be 0.3% of the weight of the mixture. The base mixture was first designed by the standard Marshall procedure and optimal asphalt content was determined to be 6.2% by the weight of mix. The aggregate gradation of SMA-13 mixture are shown in Table 1.

In order to control the air voids of asphalt mixture more accurately, cylinder specimens with 180 mm in height and 150 mm in diameter were fabricated by the superpave gyratory compactor (SGC). Then both ends of the specimens with larger air voids [15] were cut off and the middle parts with similar air voids and aggregates evenly distributed were reserved to be cut into semi-circular specimens. Previous studies [16,17] indicated that the stress concentration would be severe when the thickness of specimens is less than 50 mm, and when the thickness was more than 50 mm, the tensile stress at the bottom of the specimens tended to be a constant value. Therefore, every SGC specimens were cut into six semi-circular specimens with the target size of 50 mm in height and 150 mm in diameter to reduce the error caused by the thickness of the specimens. The air voids of SCB specimens were mainly in the range of 3–5% and most specimens could meet the target requirement (4 ± 0.5%) and unqualified specimens were abandoned (see Fig. 1).

4. Setup of SCB test

A UTM-25 universal testing machine equipped with a temperature control chamber was utilized for the SCB test. As we can see in Fig. 2, the setup for SCB test consists of two supporting rollers at the bottom edge and a loading roller at the middle point of the top edge. The span over the two supporters was set to be 0.8 times of the diameter of the specimen. A contact load with maximum load of 0.2 kN is applied for 10 s before the actual loading to ensure uniform contact between the loading roller and the specimen. The testing is stopped when the load drops to 0.3 kN in the post peak region. During the actual loading process, a constant displacement with a pre-defined rate was applied on the specimen until cracking failure. In this paper, the SCB strength test was carried out at three different temperatures (−10 °C, 0 °C, 15 °C) and eight different loading rates (0.1 mm/min, 0.75 mm/min, 3 mm/min, 7.5 mm/min, 15 mm/min, 30 mm/min, 50 mm/min, 80 mm/min). Then the influences of loading rate and temperature on the strength of asphalt mixture were analyzed comprehensively. And the results could also provide basis of loading setup of the following semi-circular bending fatigue test. Three parallel specimens were prepared for each test conditions. As for the SCB fatigue test, the temperature was determined to be 15 °C based on the temperature gradient change in one year in Jiangsu province. The loading frequency was determined to be 10 Hz, and haversine wave was selected as the form of load. The stress levels were set at 5 different load levels (2 kN, 3 kN, 4 kN, 5 kN, 6 kN). In order to ensure the reliability of the fatigue test, 4 parallel tests were carried out at the same load level.

The tensile stress at the bottom of SCB specimens could be calculated according to Eq. (1) [18], the results of the SCB strength test are shown in Table 2:

$$\sigma_t = \frac{4.976F}{BD} \tag{1}$$

where σ_t = the tensile stress at the bottom of the specimen (MPa); F = the value of the vertical load (N); B = the height of the specimen (mm); D = the diameter of the specimen (mm).

Table 1
Gradation of SMA-13.

Sieve size/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing percent/%	100	91.1	62.6	27.3	20.3	16.8	14.4	12.8	11.4	9.4