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Fatigue performance evaluation of asphalt mixtures based on energy-controlled loading mode

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HIGHLIGHTS

- A simplified pavement analysis model was designed to analyze the loading conditions of pavement structures.
- The traditional loading modes can only reflect two kinds of critical loading conditions.
- The energy-controlled mode is more suitable to evaluate the fatigue performance of asphalt mixtures.

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ABSTRACT

Loading mode plays a key role in the fatigue performance evaluation of asphalt mixtures. However, the stress-controlled mode and strain-controlled mode cannot reflect the pavement structure loading conditions. In this paper, a simplified pavement analysis model was designed to analyze the loading conditions of pavement structure, and the energy-controlled mode was put forward. The improved 4PB beam fatigue test procedures were proposed to achieve the energy-controlled mode. And the traditional 4PB beam fatigue tests were also conducted under stress-controlled mode and strain-controlled mode for comparative analysis, respectively. Results show that stress-controlled mode and strain-controlled mode can only reflect two kinds of critical loading conditions in the pavement structures, and do not have universal applicability. An intermediate loading condition that the stored energy approximately remains constant is found. The energy-controlled mode can be achieved well by improved test procedures. And the fatigue life N_f of asphalt mixtures measured under energy-controlled mode falls in between fatigue life N_f that is measured based on the stress-controlled mode and strain-controlled mode. The test results coincide with the theoretical analysis of simplified pavement analysis model. Therefore, the energy-controlled mode is more suitable to evaluate the fatigue performance of asphalt mixtures.

1. Introduction

Fatigue cracking due to repeated traffic loadings is a critical distress in asphalt pavements and is also an important consideration in the design of asphalt mixtures and structural design of flexible pavements [1]. Depending on the dominant mechanism, the development and propagation of fatigue cracks inside an asphalt mixture can be categorised into two major phases: the initiation and propagation of micro-cracks, and formation and propagation of macro-cracks [2]. Therefore, the fatigue behavior of asphalt mixtures is extraordinarily complicated and there is an urgent need of a more rational method to accurately evaluate fatigue performance of asphalt mixtures.

In order to accurately evaluate the fatigue performance of asphalt materials, numerous studies have been conducted to characterize fatigue cracking of asphalt binders, asphalt mastics, and asphalt mixtures from different perspectives [3–6]. The phenomenological approach that relates the stress or strain at the bottom of asphalt layer to the number of loading repetitions that causes failure has been widely used in conventional asphalt pavement design and performance analysis because of its simplicity. However, the resulting fatigue relationship is dependent on material types and loading modes [7]. The fracture mechanics is often used for analyzing fatigue cracking in asphalt mixtures. But the results show that stress intensity factor *K* or generalized *J* integral can only describe the crack propagation in asphalt mixtures [8–9]. Kim et al. [10] introduced a viscoelastic constitutive model to account for the fatigue damage evolution of asphalt mixtures under cyclic loading conditions. The results indicate that this

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approach can separately evaluate viscoelasticity and time-dependent damage growth in asphalt mixture, and satisfactorily predicts the constitutive behavior of asphalt mixture all the way up to failure under various loading conditions. However, this approach only considers micro-cracking in asphalt mixtures. In addition, the creep compliance test is necessary to obtain model parameters, which increases the experimental and data analysis work. Unlikely the above approaches, others [11–13] evaluate the fatigue cracking of asphalt materials from dissipated energy which is defined as the area inside of stress-strain hysteresis loop for a loading-unloading process. These results demonstrate that the dissipated energy is a promising tool to evaluate fatigue cracking of asphalt mixtures. On the other hand, Huang et al. [14] analyzed the effects of test conditions and material characteristics on fatigue performance of asphalt mixtures. And the results indicate that stress-controlled mode and strain-controlled mode have significant effects on fatigue performance evaluation. And asphalt mixtures will show different fatigue behaviors under different loading modes respectively. Therefore, the stress-controlled mode and strain-controlled mode have certain limitations for fatigue performance evaluation of asphalt mixtures.

The above studies show that the current loading modes cannot accurately evaluate fatigue behavior of asphalt mixtures. This could be one of the major reasons that fatigue performance evaluation is not widely conducted in the asphalt mixture design process. And the dissipated energy is a promising tool to evaluate fatigue cracking of asphalt mixtures. Therefore, the main objective of this study is to propose a new loading mode based on energy that can reflect the real pavement loading conditions for enhancing the evaluation accuracy and reliability of fatigue performance of asphalt mixtures.

2. Objective and scope

The main purpose of this study is to propose a new loading mode that can reflect the field pavement loading conditions based on energy. Detailed objectives of this research work are as follows:

(1) A simplified pavement analysis model is designed to analyze the loading conditions of pavement structure, and the energy-controlled mode is put forward.
(2) The improved 4PB beam fatigue test procedures are proposed to achieve energy-controlled mode.
(3) The traditional 4PB beam fatigue tests are also conducted under stress-controlled mode and strain-controlled mode to compare with the energy-controlled mode, respectively.

3. Simplified pavement analysis model and energy-controlled mode

3.1. Simplified pavement analysis model

In order to further understand the nature of loading modes, a simplified pavement analysis model is proposed to analyze the traditional loading modes. However, the actual stress states of pavement are three-dimensional structures. Therefore, it is difficult to quantitatively calculate the loading transfer process in the pavement structure [15]. According to the theory of mechanics of materials, the deformation of the beam is different along the direction of Z axis. However, the Y direction is subjected to tensile stress in the XOY plane. The deformation of the beam is the same along the direction of Y axis because of the lateral constraint, as shown in Fig. 1. Therefore, in order to simplify analysis the loading conditions of pavement structure, the stress redistribution of pavement structure is simulated by one-dimensional tensile model of parallel springs. And the simplified pavement analysis model is shown in Fig. 2. The simplified pavement analysis model should obey the following hypotheses.

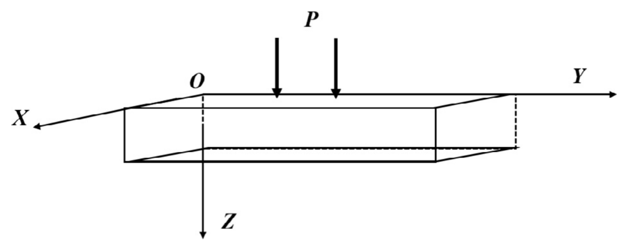

Fig. 1. Simplified beam model.

(1) The pavement structure is regarded as a force system that the eleven parallel springs are assembled on two steel pipes for considering the measuring calculated amount and analysis accuracy, and every spring represents the specific force area of pavement structure.
(2) The middle springs represent the stress concentration that obviously produces the fatigue damage under repeated traffic loadings. But the other springs show the homogeneous stress distribution that does not result in fatigue damage.

Where k_1 represents the stiffness of undamaged springs, k_2 represents the stiffness of damaged springs, F represents the tensile stress of total system. The simplified pavement analysis model needs to satisfy the following equations.

$$nf_2 + (11 - n)f_1 = F \tag{1}$$

$$\Delta L = \frac{f_1}{k_1} = \frac{f_2}{k_2} \tag{2}$$

$$f_1 = \frac{1}{(11 - n) + n(k_2/k_1)} \cdot F \tag{3}$$

$$f_2 = \frac{k_2/k_1}{(11 - n) + n(k_2/k_1)} \cdot F \tag{4}$$

$$\Delta L = \frac{1}{(11 - n) + n(k_2/k_1)} \cdot \frac{F}{k_1} \tag{5}$$

$$E_1 = \frac{1}{2} \cdot f_1 \cdot \Delta L = \left[\frac{1}{(11 - n) + n(k_2/k_1)}\right]^2 \cdot \frac{F^2}{2k_1} \tag{6}$$

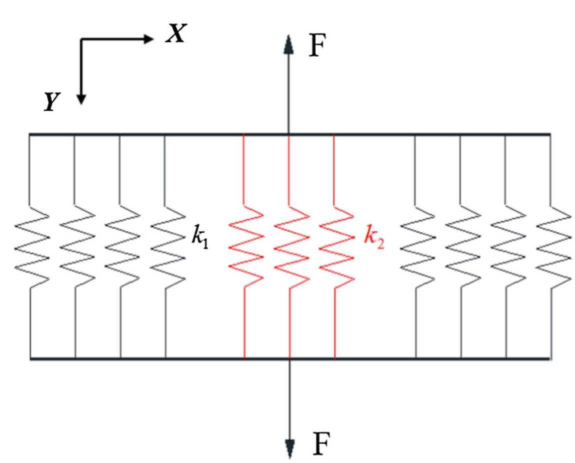

Fig. 2. Simplified pavement analysis model.