Fuel 189 (2017) 293–300

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Internal crack growth of asphalt binders during shear fatigue process

Liyan Shan [a,b,*], Shuang Tian [a], Hongsen He [a], Nanqi Ren [b]

[a] School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, Heilongjiang, China
[b] School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, Heilongjiang, China

HIGHLIGHTS

- The crack evolution in asphalt binders during fatigue process analyzed.
- Fatigue process of asphalt binder contains four stages.
- Fatigue performance under different control modes using equivalent levels compared.
- A new fatigue evaluation index for asphalt binders proposed.

ARTICLE INFO

Article history:
Received 17 June 2016
Received in revised form 10 September 2016
Accepted 19 October 2016
Available online 2 November 2016

Keywords:
Asphalt binder
Fatigue
Crack evolution
Evaluation index

ABSTRACT

Fatigue cracking is one of the main failure modes of asphalt pavement. However, the internal growth of cracks in asphalt binder during the fatigue process is still not well understood, which means that the fatigue mechanism itself remains unclear. In this study, the crack lengths and cracking morphology of three types of asphalt binders were analyzed using image analysis methods. The crack growth rule in the asphalt binder was investigated by combining the use of viscoelastic curves and cross-section images. The mechanisms of the asphalt binders were analyzed and a fatigue failure criterion was then developed. The results demonstrate that fatigue crack propagation can be divided into four stages: an incubation period (Stage I), transition period (Stage II), slow growth period (Stage III), and unstable growth period (Stage IV). In Stage I and Stage II, the binder exhibits unstable flow. In Stage III, damage manifests as Type I hairline cracks. In Stage IV, Type II hairline cracks appear and propagate. The fatigue performance of asphalt binders in Stage I and Stage II under controlled-strain mode and controlled-stress mode is the same when equivalent load levels are employed. Eventually, the demarcation point between Stage III and Stage IV is defined as the fatigue evaluation index. This index is independent of load control mode under the same equivalent load levels.

1. Introduction

Fatigue cracking is a primary concern for asphalt pavement engineers. The appearance of this distress can lead to poor load transfer or the penetration of moisture or chemical agents, which can deteriorate the pavement and end its service life [1]. Therefore, analysis of the fatigue cracking behavior of asphalt materials is critical to improve asphalt mixture design and lead to better pavement performance.

In the laboratory, the fatigue performance of asphalt binder usually is tested using a dynamic shear rheometer (DSR). The dynamic modulus, phase angle, dissipated energy, and pseudo dissipated energy values obtained by DSR testing or calculated based on test results have been used to analyze the fatigue performance of asphalt binders [2–4]. The indices that have been developed based on these parameters have been used to evaluate the fatigue life of asphalt binders [5–7].

However, these previous research efforts were based on macroscopic test results, which can reflect the fatigue characteristics and fatigue mechanisms of asphalt binder only to a certain extent. The actual fatigue process and fatigue mechanisms of asphalt binder are still unknown due to the difficulties associated with monitoring the internal crack growth of the asphalt binder. Although microscopic techniques, such as scanning electron microscopy (SEM) can be employed to investigate the microstructure of asphalt binder, the binder is in a static state during such investigations. In more recent studies, atomic force microscopy (AFM) has been proven to be a popular method in analyzing the microstructure of

* Corresponding author at: School of Transportation Science and Engineering, Harbin Institute of Technology, No. 73 Huanghe Road, Nangang District, Harbin, Heilongjiang 150090, China.

E-mail address: myshanliyan@126.com (L. Shan).

http://dx.doi.org/10.1016/j.fuel.2016.10.094
0016-2361/

asphalt binder [8–11]. The surface topography of an asphalt binder sample can be obtained using AFM. Also, AFM can apply force on the sample to obtain the modulus and adhesion stress values of the binder. Furthermore, some researchers have combined microscale tensile testing with AFM to determine the microstructure evolution that is due to tensile loading [11]. The failure process of asphalt film during tensile loading can be monitored and analyzed using tensile testing and a camera [12]. Nonetheless, monitoring the failure process of asphalt binder at the microscale is possible only when the sample is under tensile loading, not cyclic shear loading.

Although the crack growth process cannot be monitored directly under shear fatigue loading, another way to visualize cracking at different loading periods is to analyze the fractured surface of a specimen using photographic techniques. This method originates from the study of steel fatigue [13] and apply to polymer materials afterwards [14–17]. In these studies, a pre-crack was introduced in the sample prior to testing, and the sample was twisted and then photographed after the test. The resulting cracks were Model III fatigue cracks. The fractured surface was divided into three zones: the pre-crack zone, fatigue zone, and twisted zone from the outside of the specimen inward. The crack morphology and length could be obtained by analyzing the fractured surface. Keentok and Xue used the image analysis to observe the edge fracture of the viscoelastic fluid [18].

Using the aforementioned methods as references, Tan et al. monitored the cross-section morphology of asphalt binder samples during DSR fatigue testing under controlled-stress mode [19]. Their results showed that circumferential hairline cracks were generated at the periphery of the sample and propagated inward, which consequently reduced the effective sample radius. Also, no cracking was evident on the cross-section if the loading was stopped early enough. Hintz and Bahia revised this method by painting the DSR sample before breaking it apart and then determined the radii of fractured and intact cylindrical samples using different termination times [20]. They hold the view that fracture leads to the fatigue damage of asphalt binder during the DSR time sweep test. Hintz and Bahia's method is efficient for calculating the radius of the sample, but the crack morphology cannot be observed after the sample is painted.

Notwithstanding these earlier useful studies, few studies have been conducted on the crack growth of asphalt binders at the microscale during the shear fatigue process. In this study, cross-section image monitoring and DSR testing were combined to investigate fatigue crack lengths and crack growth morphology of asphalt binder samples during the shear fatigue process. In conjunction with this work, the fatigue mechanism of asphalt binder under shear loading was studied. Lastly, a fatigue evaluation index for asphalt binders was developed.

2. Materials and methods

2.1. Materials

Three neat asphalt binders were selected for this study. For the remainder of this paper, these materials are referred to as generic binders A, B, and C. Specifically, A is 80–100 penetration grade asphalt, B is 60–80 penetration grade asphalt, and C is 40–60 penetration grade asphalt, in accordance with the Chinese penetration grade system. In order to investigate the effect of aging on the performance of these asphalt binders, binder A and binder B were tested before and after aging. Before aging, the binders are referred to as A_v, B_v, and C_v, and after aging (aged in a rolling thin-film oven) are referred to as A_a and B_a, respectively. The basic properties of the studied asphalt binders are listed in Table 1.

2.2. Methods

Laboratory testing was conducted using a TA Instruments Discovery Hybrid Rheometer (DHR) and a Dino-Lite digital microscope. Three types of tests were conducted: the stress/strain sweep test, fatigue test, and crack growth monitoring test. All tests were conducted using an 8-mm diameter parallel plate geometry and a 2-mm gap setting. Two replicates were performed for each test condition; if the deviation was greater than 10 percent, a third replicate was required.

2.2.1. Stress/strain sweep tests

Prior to conducting the fatigue tests, stress sweep tests and strain sweep tests were conducted to determine the stress and strain levels of the samples. A sinusoidal load with a frequency of 10 Hz was employed in both types of sweep tests. The amplitude started at a low level and was increased linearly until the specimen nearly failed. Fig. 1 presents the results as stress amplitude versus strain amplitude curves. The data series labeled A_v-stress in Fig. 1 indicates the test results of unaged binder A under controlled-stress mode; the other data series labels have similar definitions. As shown in Fig. 1, the curves under the two different control modes are initially linear. In addition, the linear part of the stress sweep curve coincides approximately with that of the strain sweep curve for the same asphalt binder and at the same test temperature. The stress and strain levels for the fatigue tests were chosen to be in the linear range.

2.2.2. Fatigue tests

The fatigue tests were conducted under both controlled-stress and controlled-strain modes with 10 Hz continuous sinusoidal loading until the dynamic modulus value decreased to a target value. Each specimen was checked after the test to avoid the occurrence of an edge flow problem. Furthermore, the morphology of the cross-section surfaces indicated fracture rather than edge flow, which accounts for the changes in geometry that occur during the shear fatigue process. Fatigue is generally a concern at intermediate temperatures (10 °C and 30 °C). Considering the test time, 25 °C was chosen as the test temperature.

In order to investigate the crack growth and the fatigue damage mechanism of the studied asphalt binders under the two control modes, a specific method was introduced to select the stress and strain values used in cyclic shear fatigue tests. As shown in Fig. 1, a strain value to be used in the shear fatigue test was chosen first, and then a vertical line was drawn through that strain point on the x-axis, which intersected with the stress or strain curves of the different asphalt binders. Finally, a horizontal line was drawn through the intersection point, and the intersection point between the horizontal line and y-axis was the stress level used for the controlled-stress test [21]. The selected stress and strain values are referred to as the equivalent level. The equivalent level indicates that the load levels are the same during the fatigue tests. Using this method, the loads for the different shear fatigue tests were chosen. The loads of A_v, B_v and C_v is (5%, 0.12 MPa), (5%, 0.16 MPa) and (5%, 0.17 MPa). The loads of A_a and B_a is (5%, 0.19 MPa) and (5%, 0.26 MPa).

2.2.3. Crack growth monitoring tests

The crack growth in a sample is the key to understanding the fatigue damage mechanism of the asphalt binder during the shear fatigue process. However, it is difficult to monitor the crack growth of a sample during this test because the sample is small and the temperature-controlled chamber is opaque and closed during the test. Therefore, the image analysis method described in the literature review part of this paper was used in this research. After the loading was stopped at different dynamic modulus ($|G^*|$) levels,