International Journal of Fatigue 114 (2018) 198–205

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Investigating different fatigue failure criteria of asphalt binder with the consideration of healing

Umme Amina Mannan*, Rafiqul A. Tarefder

Civil Engineering Department, University of New Mexico, MSC01 1070, Albuquerque, NM 87131, USA

ARTICLE INFO

Keywords:
Fatigue
Healing
Dissipated Energy Ratio (DER)
Ratio of Dissipated Energy Change (RDEC)
Asphalt binder

ABSTRACT

Fatigue damage is the deterioration of material strength due to repeated traffic loading and healing is the restoration of the material strength, which essentially delays the fatigue cracking in the asphalt pavement. Several criteria have been developed to determine the fatigue life from laboratory fatigue tests, however, none of these criteria consider healing. The primary objective of this study is to explore the effect of healing on fatigue life using different fatigue failure criteria. Healing is introduced in the fatigue tests by incorporating a rest period between loading. Three different performance grade (PG) binders are tested using fatigue (loading without rest period) and healing (loading with rest period) test methods to assess the effect of healing on the fatigue damage. The fatigue life is determined using three different criteria: Stiffness reduction (Nf50), Dissipated Energy Ratio (DER) and Ratio of Dissipated Energy Change (RDEC). Statistical analysis showed that there is no significant difference between these three approaches for both the fatigue and healing tests. In addition, the fatigue curve is constructed for both the fatigue and healing tests. The comparison of these fatigue curves show that fatigue life increases due to the incorporation of healing in the fatigue tests. An empirical equation is proposed to incorporate healing in the fatigue life equation.

1. Introduction

Fatigue damage is one of the most crucial distresses in asphalt pavement. It is defined as the phenomenon where material properties degrade due to repeated loading. Healing on the contrary is the ability to repair damage or the restoration of the original material property. Therefore, healing only occurs when the material is damaged. Also, healing occurs during the rest period in between loading after damage. Asphalt binder in the asphalt pavement has healing capability. In the asphalt pavement industry, it is considered that due to the repetitive traffic loading fatigue damage occurs in the pavement and accumulation of this damage results in fatigue cracking. When any point of the pavement section goes under repetitive traffic loading, it experiences a rest period between loads. This rest period is controlled by the vehicle speed, loading, axle distribution and the gap between one traffic to the next. During these rest periods, healing occurs which causes recovery of damage [1]. Therefore, the incorporation of healing in the fatigue damage will delay or slow down the accumulation of fatigue damage.

It is important to define some failure criteria for laboratory testing to understand the effect of healing on the fatigue life of the asphalt material. Defining fatigue failure is very difficult for laboratory fatigue testing, specifically for the strain-controlled testing where no catastrophic failure is noticed. Traditionally in the asphalt industry fatigue failure is defined as the number of cycles required to reduce the modulus or stiffness of asphalt to 50% of its initial value (N_{f50}) [2–4]. However, the arbitrary assumption of this criterion has been under scrutiny. Over the last decades many different fatigue failure criteria have been developed to understand the fatigue damage of asphalt, among which the dissipated energy ratio is a notable one. Hopman et al. [5] developed the energy ratio parameter for strain-controlled test based on the assumption that the dissipated energy changes due to the fatigue damage. Later, Pronk and Hopman [6] introduced the Dissipated Energy Ratio (DER) concept using the accumulative dissipated energy to determine the fatigue life of asphalt mixtures and binders. Also, Carpenter and his research team [1,7,8] developed another DER concept based on the change of dissipated energy. They later modified this approach and renamed it as the Ratio of Dissipated Energy Change (RDEC) approach [1,7]. The RDEC approach is mostly used for the macroscopic failure in the asphalt mixture as it can identify the starting of macro-crack propagation. In addition to the energy criteria, there are some other approaches to define the fatigue damage failure in asphalt such as the maximum phase angle criterion by Reese [9] and the 50% loss in pseudo stiffness suggested by Lee et al. [10].

Healing is widely quantified as the recovery of the stiffness in the

* Corresponding author at: Applied Research Associates, Inc., 5007 NE 39th Ave., Gainesville, FL 32609, USA.
E-mail addresses: uam@unm.edu, uamannan@ara.com (U.A. Mannan), tarefder@unm.edu (R.A. Tarefder).

https://doi.org/10.1016/j.ijfatigue.2018.05.028
Received 5 February 2018; Received in revised form 10 May 2018; Accepted 27 May 2018
Available online 29 May 2018

asphalt materials during rest period. This increase in stiffness is considered equivalent to the increase in fatigue life. As viscoelastic material asphalt binder shows both viscoelastic recovery and damage healing during the rest period [11,12]. However, healing only occurs after the materials are scientifically damages. A multi-step healing model developed by Wool and O'connor [13] has been used to describe the healing mechanism of asphalt binder in previous studies [14,15]. This model describes random walk of the molecular chains on the surface of a micro-crack by surface rearrangement, surface approach, wetting, diffusion and randomization stages. The strength recovery due to healing starts with the micro-crack closing due to the wetting and is followed by diffusion at the micro-crack surface. Thus, at the rest period the recovery of strength occurs due to the random molecular walk and micro-crack closing. Some previous studies studied healing mechanism of asphalt binder, however the effect of healing on the fatigue criteria and calculation of fatigue life has not been studied yet. The fatigue criteria discussed so far were exclusively developed for continuous fatigue loading. However, when healing is to be considered in the fatigue testing, the loading is not continuous anymore since healing is incorporated by introducing rest periods between the loading cycles. Therefore, all these fatigue failure criteria need to be re-evaluated for fatigue testing with and without healing.

This study provides a comprehensive review of various failure criteria for both fatigue and healing tests. Here, the time sweep test without rest period is denoted as the 'fatigue test' and time sweep test with rest period is denoted as the 'healing test'. Also, fatigue curves are constructed for both fatigue and healing tests to understand the effect of healing in fatigue damage. The primary objective of this study is to explore the effect of different fatigue failure criteria to determine the fatigue life with and without considering healing.

2. Existing fatigue failure criteria

In this study, two approaches were used for defining fatigue failure of asphalt binders from the test data: the traditional stiffness reduction and dissipated energy approach. Within the dissipated energy approach, many different criteria exist, however in this study only two of them are discussed.

2.1. Stiffness reduction approach

The most commonly used fatigue failure criteria is 50% reduction of the initial stiffness or modulus. Sample stiffness at the 50th cycle is defined as the initial stiffness. Fig. 1(a) shows a typical plot of stiffness ratio (S) per loading cycle and the determination of fatigue life (N_f) based on 50% stiffness reduction. The stiffness ratio (S) is calculated as follows:

$$S = \frac{S_i}{S_{initial}} \tag{1}$$

where S_i is the stiffness at cycle i and $S_{initial}$ is the initial stiffness.

2.2. Dissipated Energy Ratio (DER) approach

The formula to calculate the dissipated energy ratio is shown in Eq. (2).

$$W_i = \pi\sigma_i\varepsilon_i\sin\delta_i \tag{2}$$

where W_i is the dissipated energy at cycle i, $\sum_{i=1}^{n} W_i$ is the cumulative dissipated energy up to a loading cycle n. For strain control test Eq. (2) can be rewritten as Eq. (3).

$$W_i = \pi(\varepsilon_i)^2 S_i\sin\delta_i \tag{3}$$

where S_i is the stiffness at cycle i and ε_i is the applied strain. The DER is defined as the ratio between the cumulative dissipated energy up to cycle n and the dissipated energy at cycle n as shown in Eq. (4).

$$DER = \frac{\sum_{i=1}^{n} W_i}{W_n} \tag{4}$$

Fig. 1(b) shows a typical plot of the dissipated energy and DER with the number of loading cycles. It is shown that initially DER increases linearly, but then deviates as damage accumulates due to the increase in the loading cycle. The fatigue failure indicator N_{p20}, is defined based on the DER deviation from the initial straight line. N_{p20} is the number of cycles at which the DER deviates 20% from no damage straight line [16].

2.3. Ratio of Dissipated Energy Change (RDEC) approach

As mentioned earlier, the $RDEC$ method is mostly used to define the macro-crack. Several researchers have shown that as the damage starts to accumulate the dissipated energy changes gradually with the number of cycles [1,5,7,8,16,17]. Therefore, change in the dissipated energy is considered as the failure criterion rather than the dissipated energy itself. $RDEC$ is calculated as following equation:

$$RDEC_a = \frac{DE_a - DE_b}{DE_a(b-a)} \tag{5}$$

where a and b are two consecutive loading cycles; $RDEC_a$ is the average ratio of dissipated energy change at cycle a with respect to the next cycle b; DE_a, DE_b are the dissipated energy at cycle a and b respectively.

For strain control testing, the typical plot for the $RDEC$ vs the number of loading cycles for the asphalt binder is shown in Fig. 1(c). It shows three distinctive regions: initially the RDEC decreases and then it becomes constant and then it starts to increase dramatically. The point where the RDEC starts to increase is known as the initiation of macro cracking. The constant value of RDEC is called the plateau value, where the micro-cracks start to develop. Once these micro-cracks start to propagate, then the third region begins, and eventually the samples fail. The number of cycles where the shift from the plateau value occurs is assumed to be the number of cycles to failure (N_{fl}).

3. Experimental plan

3.1. Materials

Three different performance grade (PG) binders were collected from a local plant in Albuquerque, NM. They are: PG 58-22, PG 64-22 and PG 70-22 binders.

3.2. Testing conditions

All the binders were tested in dynamic shear rheometer (DSR) under pure shear deformation. Fatigue and healing tests were performed by subjecting the asphalt binder to a sinusoidal deformation and measuring the resulting mechanical response (torque) as a function of time. Shear loading was considered because the force interaction between the wheel and the pavement generates shear stresses, which cause the fatigue damage in the pavement. Both fatigue and healing tests were conducted in strain control mode. This is because fatigue cracking is a problem in thin pavement and it is mainly strain controlled. Also, in the stress control test, the increase in temperature due to the change in dissipation energy is more prominent than the strain control test under cyclic loading. Therefore, it is difficult to conduct a constant temperature fatigue test under the stress control mode. Hence, strain controlled tests were performed.

Binders were tested at 10 Hz frequency. To determine the linear viscoelastic (LVE) strain limit, a strain sweep test was conducted using DSR. In this test, at 10 Hz frequency the applied strain was increased from 0.01% strain to 100% strain and the resulting stresses were recorded. Then the dynamic shear modulus (G^*) was calculated. Fig. 2 shows the stress vs. strain and G^* vs. strain curves. From Fig. 2(a) it