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A new comprehensive analysis framework for fatigue characterization of asphalt binder using the Linear Amplitude Sweep test

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HIGHLIGHTS

- The existing analysis framework for LAS test was critically reviewed.
- The revised formulation was rigorously derived based on the VECD theory.
- The proposed failure definition provided results consistent with experiments.
- The proposed failure criterion unified LAS and TS tests under various test conditions.

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ABSTRACT

The Linear Amplitude Sweep (LAS) test has become an efficient tool to characterize fatigue resistance of asphalt binders. The existing analysis scheme for this test based on the linear viscoelastic continuum damage (VECD) theory was critically reviewed. Based on the rigorous VECD formulation and experimental evidences, a new comprehensive analysis framework was developed which includes damage characteristic relationship, failure definition, and failure criterion. Compared to the existing approach, the proposed framework provided a more reasonable agreement with experimental observations on fatigue life and a more reliable mathematical description of fatigue failure, and was also capable of unifying both LAS and Time Sweep fatigue tests.

1. Introduction

Fatigue failure has been one of the primary distress types plaguing asphalt pavement. It generally occurs at intermediate temperatures under repeated traffic loading. In addition to traffic and environmental factors, performance of asphalt pavement critically depends on fatigue resistance of asphalt mixture. As a composite of aggregate, asphalt cement, and air void, asphalt mixture's fatigue characteristics is dominated by the fatigue properties of asphalt binder. As such, a standard test method and analysis framework are necessitated for evaluating fatigue resistance of asphalt binders.

In the 1990s, the Strategic Highway Research Program (SHRP) developed the Superpave fatigue parameter, denoted as $|G^*|\sin\delta$, which can be obtained using a dynamic shear rheometer (DSR). However, this parameter has been found to be an inadequate indicator of fatigue resistance of asphalt binders, which is partly explained by the fact that the measurement is taken in the linear viscoelastic range without interference of damage [1]. In order to simulate the process of damage accumulation in asphalt under repeated loading, the Time Sweep (TS) test was proposed in which the strain input is oscillated with a prescribed constant amplitude [1,2]. This test has proved a reasonable fatigue evaluation tool for asphalt binders with various compositions [3] using the concept of dissipated energy ratio in analysis [4]. However, the TS test has been considered time-consuming and thus is not practically favored as a routine specification test [5].

The Linear Amplitude Sweep (LAS) test was then developed as a substitute for the TS test [5,6]. In this test, the damage process is accelerated via a systematically increasing strain amplitude in a stepwise manner, which reduces the testing time from several hours down to minutes. Subsequently, a machine compliance issue was identified that certain DSR equipment was not capable of making abrupt changes in strain amplitude between loading steps.

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Given this, a variation of the LAS loading profile was proposed which implemented the linear ramping [7]. This modification avoided the compliance issue and also facilitated analytical modeling [8].

Analysis on the LAS data has been performed using the linear viscoelastic continuum damage (VECD) theory. This theory has seen a great success in fatigue characterization of asphalt mixtures and performance prediction of asphalt pavements [9,10]. Promising correlations were observed between fatigue prediction results of binders and cracking performance of field pavements [5,8]. On the other hand, the VECD theory is certainly also applicable to TS test for which the loading profile resembles that of fatigue test on asphalt mixtures performed in the uniaxial tension mode [11]. The G^R failure criterion [12] originally developed for asphalt mixtures has also found its success in asphalt binders, and moreover this failure criterion has demonstrated its capability in unifying both LAS and TS tests [8,13]. Based on the VECD theory, alternative analysis methods have also been proposed to characterize fatigue failure in TS and LAS tests using the concepts of dissipated strain energy and stored pseudo-strain energy, respectively [14].

It has been recognized that other mechanisms may be present and interacting with fatigue damage during continuous fatigue loading of binders, such as thixotropy, nonlinear viscoelasticity, and steric hardening [15–18]. Such mechanisms have not been fully understood and are highly challenging to be experimentally/mechanistically characterized. On the other hand, the application of the linear viscoelastic continuum damage theory to fatigue characterization and performance prediction of asphalt binders and mixtures has proved its effectiveness and versatility in the literature. This paper presents a critical review of the existing fatigue characterization scheme for asphalt binders using the LAS test and the VECD theory, followed by the development and validation of a new analysis framework that is theoretically more rigorous and practically more reliable. It should be noted that the work undertaken is confined to the linear viscoelastic continuum damage theory while the extra complicating effects such as thixotropy, nonlinearity, and steric hardening are excluded from consideration.

2. Objectives and scope

The objectives of this research were threefold:

- To reveal and demonstrate flaws in the existing analysis scheme for the LAS test;
- To propose a rigorous formulation for the LAS test within the framework of linear viscoelastic continuum damage theory;
- To propose a reasonable failure definition and a robust failure criterion which unify both LAS and TS tests.

Note that even though the focus of this research is on LAS, it appears unavoidable to involve TS test given their common nature in the VECD analysis and also given the unifying nature of the proposed failure definition and failure criterion, as will be demonstrated.

To achieve the above objectives, a critical review of the existing VECD formulation, failure definition, and failure criterion for LAS was first conducted. The revised formulation was obtained following rigorous derivation, and was verified using LAS data from various test conditions. The irrationality of the existing failure definition was illustrated using the LAS data on asphalt binders with three different aging conditions. A new failure definition was proposed which was aimed to provide more reasonable conformance with general engineering experience and experimental observations. A series of LAS and TS tests with various test conditions were designed and performed on additional asphalt binders to verify the validity and unifying nature of the proposed failure definition and failure criterion.

3. Theoretical background

Application of the VECD theory to fatigue characterization of asphalt materials yields the so-called damage characteristic relationship, which is a function relating material integrity (represented by C) and damage intensity (S). This function prescribes the path following which material loses its structural integrity as a result of damage accumulation under repeated loading. The damage characteristic relation $C(S)$ obtained for a given material is unique in that it is independent of test conditions (e.g., temperature, load level, frequency, and control mode). The VECD theory and thus the $C(S)$ relation are applicable to damaged material states prior to the occurrence of damage localization or macrocracking. Hence, the analysis framework should be completed experimentally with a proper failure definition and mathematically with a failure criterion function.

This section presents a brief review of the existing formulation of the damage characteristic relationship, failure definition, and failure criterion as the background for further exploration. To facilitate subsequent discussion, it is considered important to first clarify the two above-mentioned concepts necessary in fatigue analysis: failure definition and failure criterion. Failure definition prescribes when material failure occurs, and therefore determines fatigue life in testing. In general, selection of failure definition should be carefully determined with comprehensive and balanced considerations on experimental, theoretical, and analytical factors, as will be discussed subsequently. Failure criterion is typically represented by a function correlating two variables: one is associated with the material responses while the other is related to the load input. Identification of failure criterion needs a proper failure definition as the prerequisite.

3.1. Existing formulation

As previously mentioned, the LAS test was proposed as a surrogate of the TS test as an accelerated fatigue characterization method [6]. The analysis approach adopted then was already developed for evaluating fatigue behaviors of asphalt matrix under oscillatory distortion [19]. However, a close investigation of the derivation in [19] and comparison with the original VECD formulation [9,20] for asphalt mixtures expose a fundamental flaw, which lies in the use of dissipated strain energy in the damage evolution law:

$$\frac{dS}{d\xi} = \left(-\frac{\partial W}{\partial S}\right)^{\alpha} \tag{1}$$

where S represents damage intensity, ξ is reduced time, α is damage evolution rate, and W denotes the dissipated strain energy which is given by

$$W = \pi\gamma^2|G^*|\sin\delta \tag{2}$$

where γ, $|G^*|$, and δ denote shear strain amplitude, dynamic shear modulus (damaged), and phase angle of a cycle in interest. It then followed that the damage increment ΔS was given by

$$\Delta S_i = \left[\pi\gamma_i^2(|G^*|_{i-1}\cdot\sin\delta_{i-1} - |G^*|_i\cdot\sin\delta_i)\right]^{\frac{\alpha}{1+\alpha}}\cdot(\xi_i-\xi_{i-1})^{\frac{1}{1+\alpha}} \tag{3}$$

where i denotes cycle number. Additionally, it is worth mentioning that the use of dissipated strain energy led to the material integrity being represented by $|G^*|\sin\delta$, i.e., the loss modulus (damaged), or alternatively by its normalized form.