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A framework to characterize the healing potential of asphalt binder using the linear amplitude sweep test

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HIGHLIGHTS

- A LAS-based healing test procedure is established to quantify the binder healing potential.
- The effects of damage level and rest period on binder healing behaviour are characterized.
- The rest-damage superposition principle is investigated to construct a healing mastercurve.

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ABSTRACT

The healing characteristics of asphalt binders affect the fatigue performance of asphalt mixtures and field pavements. The objective of this paper is to quantify the healing potential of asphalt binders using the linear amplitude sweep (LAS) test under various damage level and rest period durations. A healing protocol based on the LAS test is successfully established to measure the healing behaviour of asphalt binder by applying the rest periods before and after cohesive failure. Based on the simplified-viscoelastic continuum damage (S-VECD) model, the percent healing ($\%H_S$) is quantified from the healing recovery of the accumulated damage growths. The neat asphalt binder exhibits better $\%H_S$ results than the SBS modified binder in the pre-failure conditions. However, the SBS modified binder exhibits a higher healing potential in the post-failure case. The rest-damage superposition principle (RDSP) is further investigated in the pre-failure cases to remove and unify the effects of damage level and rest period by constructing a $\%H_S$ mastercurve at a given reference damage level. The developed healing mastercurve and related damage shift factor can be used to represent the intrinsic healing potential of a given asphalt binder. A series of healing indices are proposed and discussed based on the healing mastercurve to numerically compare the healing performance of asphalt binders.

1. Introduction

Fatigue cracking, caused by repeated traffic loading, is one of the main distresses in asphalt pavements. In general, significant differences exist between the prediction of fatigue life using laboratory fatigue studies and the field performance observations, necessitating the use of so-called “transfer functions” to relate laboratory to field performance [1]. There are many factors that can lead to discrepancies between laboratory-based fatigue life predictions and measured field performance, including the mode of loading, moisture damage, loading history, and structural design. In addition, the self-healing characteristics of asphalt materials is known to be a primary source of the under prediction of fatigue life using laboratory studies. Most laboratory fatigue testing is conducted by means of continuous, repeated loading to identify the fatigue life (i.e., number of cycles to failure). However, pavements are actually subjected to intermittent loading, which depends on the vehicle speed and traffic volume. During the rest periods between vehicles, asphalt concrete has the ability to self-heal, which leads to the closure of cracks and consequently causes a gain of strength and stiffness and prolongs the fatigue life of pavements. In 1967, Bazin et al. firstly observed that asphalt concrete has healing capabilities [2]. They found that the tension strength of damaged asphalt concrete could be recovered to 90% of its initial level after 3 days rest. Raithb et al. [3] and Bonnaure et al. [4] both subsequently investigated the healing effects on the stiffness recovery and fatigue life improvements of asphalt concrete by introducing rest periods into cyclic fatigue tests. Kim et al.

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demonstrated the occurrence of healing in pavements from the spectral analysis of surface waves testing [5,6]. It has also been demonstrated that the self-healing characteristics of asphalt concrete significantly affect its fatigue endurance limit, which is a fundamental requirement for the design of perpetual pavements [7]. Therefore, the ability to understand and characterize the healing potential of asphalt materials would improve our ability to evaluate and predict the long-term fatigue performance of asphalt pavements.

Several efforts have been conducted to understand the mechanism by which asphalt concrete and comparable polymeric materials self-heal. De Gennes proposed the *Reptation model* to explain polymer molecule interaction at crack interfaces [8]. Wool et al. then presented a theory of crack healing in polymers that involves surface rearrangement, surface approach, wetting, diffusion and randomization [9]. Based on these theories developed for polymeric materials, Kim et al. investigated the relationship between the chemical composition and observed healing mechanisms in asphalt concrete [10,11]. Bhasin et al. proposed a healing model in asphalt materials, which describes healing as a combination of wetting and intrinsic healing processes that occur across a crack interface. *Wetting* is the process of the cracked surfaces coming into contact with each other. *Intrinsic healing* is the strength gained by a wetted crack interface over time [12]. Additionally, Schapery [13] and Little et al. [14] utilized the fracture mechanics principle and surface energy theory to develop correlations between the damage healing rate and surface energy parameters of asphalt concrete from intermittent fatigue tests. Garcia et al. examined the self-healing of macro-cracks in asphalt mastic and hypothesized that the primary cause of self-healing is the capillary flow of asphalt binder across the crack faces [15].

In addition to developing a fundamental understanding of the self-healing mechanism in asphalt materials, a laboratory test method is needed to quantify self-healing coupled with a healing model to predict the fatigue performance under variable loading histories. Kim et al. proposed a method to determine the healing rate of asphalt concrete in terms of recovered dissipated creep strain energy per unit time in a rest period based using the indirect tension test [16]. Carpenter et al. investigated the fatigue damage and self-healing properties of asphalt materials using the dissipated energy principles and proposed that two kinds of healing occur within asphalt concrete: asphalt-aggregate adhesion and cohesive healing within asphalt binder [17–22]. Bhasin and Bommavaram et al. developed a DSR based two-piece specimen healing test for asphalt binder and evaluated the self-healing of different binders under multiple temperature and aging conditions based on the recovery of the dynamic modulus with time [23–25]. Shan et al. studied the thixotropy effects on fatigue and healing process and proposed a series of healing indices that all provided consistent rankings of the self-healing capabilities of the materials evaluated [26–28]. Several other efforts have quantified healing by subjecting asphalt materials to intermittent fatigue loading and measuring the modulus recovery during rest periods [29–31].

Parameters termed "*stiffness recovery*" have been widely applied to quantify the healing capability of asphalt materials. The increase in fatigue life due to healing can be converted to equivalent increase in stiffness based on the original material behavior. However, it is also acknowledged that during the rest periods, two materials behavior: *viscoelastic recovery (relaxation)* and *healing* occur simultaneously and contribute to the stiffness recovery [21,22,32]. Therefore, the effects of viscoelasticity during the rest periods must be removed to accurately characterize and predict self-healing behavior. In the 1980s, Schapery developed the elastic-viscoelastic correspondence principle to reduce the form of viscoelastic constitutive equations to the form of an elastic solution to isolate the effects of viscoelasticity from damage and healing [33]. Kim and Lee et al. successfully separated the time-dependent relaxation from self-healing of asphalt concrete through the use of the correspondence principle and then extended the viscoelastic continuum damage (VECD) model to include healing [32,34–37]. Recent efforts from Palvadi [38] and Karki et al. [39] verified that healing effects can be integrated into the VECD model using the testing of fine aggregate matrix (FAM). They showed that maximum healing benefits are obtained when the rest periods are provided before extensive damage occurs, consistent with the findings reported by other researchers [40,41]. This finding suggests that micro-cracks tend to heal more efficiently than macro-cracks. Therefore, the occurrence of fatigue failure that corresponds to the onset of macro-cracking is likely a crucial threshold when quantifying the healing behavior of asphalt materials.

The self-healing in asphalt concrete is derived from the healing potential of the asphalt binder. Therefore, understanding and predicting the self-healing potential of asphalt binders is critical for understanding the self-healing of pavements. The linear amplitudes sweep (LAS) test (AASHTO TP101) has been proposed as a specification test to estimate the fatigue damage tolerance of asphalt binder [42–45]. This paper presents a framework to extend the use of the LAS test to quantify the healing potential of asphalt binders.

2. Objectives

The specific objectives of this study are to:

- Establish a healing model of asphalt binder that can be derived using a LAS-based healing test protocol and data interpretation;
- Propose the candidate healing indices that can be used to rank the relatively healing capabilities of neat and modified asphalt binders.

3. Materials and testing

3.1. Materials

Two types of asphalt binders commonly used by the paving industry in Beijing P. R. China were evaluated in this study: a PG 58-22 neat asphalt and a PG 70-22 SBS polymer modified asphalt binder. The original binders were tested without aging for simplicity because the work focused on the healing test procedure and method development rather than relating findings to mixture or pavement performance behavior. However, the effects of aging will be considered in the future work.

3.2. Continuous LAS test

The LAS tests were conducted using an Anton Paar MCR 302 dynamic shear rheometer (DSR) with the 8-mm parallel plate geometry and 2-mm gap setting. Typically, the fatigue tests temperatures are selected to be consistent across materials or to reflect an iso-stiffness condition. A single testing temperature is often selected to represent a typical intermediate temperature whereas the use of iso-stiffness temperatures allows for comparing different binders' fatigue resistance at an equal stiffness condition. In this study, both the continuous LAS tests and LAS tests with rest periods were conducted at a typical intermediate temperature of 20 °C to reflect a representative intermediate temperature in the Beijing area. After each test, it was checked that no occurrence of either the adhesive failure between binder and parallel plates or material flow phenomenon [46].

Before investigating the healing behavior of asphalt binder, the standard LAS procedure was conducted to measure the fatigue