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Energy-based crack initiation model for load-related top-down cracking in asphalt pavement

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HIGHLIGHTS

- Mechanisms of load-related top-down cracking initiation are investigated.
- An energy-based top-down cracking initiation model is developed.
- The model is used to predict top-down cracking of six sections at NCAT Test Track.
- The model prediction results are in good agreement with the field observations.

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ABSTRACT

This paper aims at investigating the mechanisms of load-related top-down cracking (TDC) and developing a framework to predict the TDC initiation life for asphalt pavements. Firstly, a three-dimensional model is constructed to simulate the pavement responses to traffic loading. The critical pavement responses (e.g., shear and tensile stresses) are identified and related to TDC initiation at different locations (i.e., longitudinal wheel path, longitudinal non-wheel path, and transverse direction). Secondly, an energy-based TDC initiation model is developed, which involves seven sub-models and one cracking initiation criterion. The cracking initiation model takes into account the effects of aging and healing on the cracking performance of asphalt mixtures. If the load-induced damage to the asphalt pavement exceeds the limited strain energy of the asphalt mixture, the crack will initiate at the pavement surface. Accordingly, this study develops the sub-models to calculate the tensile and shear stress induced damage to the asphalt pavement, and the limited strain energy of the asphalt mixture in tension and shear modes of fracture. Finally, the TDC initiation model is used to predict TDC development for six pavement sections at National Center for Asphalt Technology (NCAT) Test Track. The prediction results indicate that the load-related TDC always initiates in the longitudinal wheel path. Increased compaction density slightly prolongs the TDC initiation life of the asphalt pavement, while decreased compaction density significantly diminishes the TDC performance. The use of soft binder with more reclaimed asphalt pavement (RAP) and the use of highly polymer modified asphalt are both beneficial for the improvement of TDC performance, but the addition of reclaimed asphalt shingles (RAS) is detrimental to the resistance of asphalt pavement to TDC. The model prediction results are in good agreement with the field observations to date.

1. Introduction

Fatigue cracking induced by repeated traffic loads is one of the major issues in flexible pavement design and analysis [1,2]. Adjacent fatigue cracks are prone to connect and form alligator cracks. They can further deteriorate into potholes, which significantly reduce the pavement serviceability [3,4]. To avoid such serious problems, fatigue cracking may be prevented or significantly reduced using quality pavement design practices [5]. Most of the existing pavement design methods assume that the tensile strain at the bottom of asphalt layer is the critical pavement response that causes fatigue cracking [6–8]. If this tensile strain is beyond a threshold level, the crack will initiate at the bottom of asphalt layer. As the load application continues, this crack will propagate upwards to the asphalt surface. This type of cracking is so-called bottom-up fatigue cracking. Hence, a long-lasting pavement is

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designed to reduce the tensile strain at the bottom of asphalt layer by increasing the asphalt layer thickness [9]. Using this concept, the designed asphalt pavement has a high resistance to bottom-up fatigue cracking. However, recent studies have found that load-related fatigue cracks have also appeared in thick asphalt layers [10–15]. These cracks are defined as top-down fatigue cracks, which initiate at the pavement surface and then propagate downward through the asphalt layer.

Top-down cracking (TDC) is usually categorized into two groups: 1) construction-related TDC, which is attributed to the segregation of the asphalt mixture or loss of bond between asphalt lifts; and 2) load-related TDC, which is due to the tire-pavement contact stresses and asphalt aging effects [16]. The flexible pavement design mainly focuses on the prediction of the load-related cracking rather than construction-related cracking. This is because load-related cracking is significantly affected by the pavement design parameters such as the material properties (e.g., composition, modulus, and fracture properties), pavement structure, traffic, and climate [17].

The current Pavement ME Design utilizes the surface tensile strain and the asphalt stiffness to predict the TDC fatigue life, as shown in Eq. (1) [8].

$$N_f = Ck_1\left(\frac{1}{\varepsilon_t}\right)^{k_2}\left(\frac{1}{E}\right)^{k_3} \tag{1}$$

where N_f is the fatigue life of asphalt pavement or the number of load repetitions to fatigue cracking, C is the laboratory to field adjustment factor, ε_t is the surface tensile strain, E is the asphalt stiffness, and k_1, k_2, k_3 are the model coefficients. In this model, the surface tensile strain is the critical pavement response to TDC. One recognized shortcoming of this model is that the crack initiation and crack propagation portions of the model are not distinguishable from each other. To solve this problem, researchers from the University of Florida [18–21] developed a Fracture Mechanics (FM) based model that relies on an energy-based criterion to estimate the initiation and propagation states at the crack tips. This model considers the surface tensile stress as the critical response to TDC. In general, both the Pavement ME Design model and FM-Based model attribute the TDC to the surface tension. However, Soon et al. [22] found that the location of surface tensile stress or strain is at least 0.5 meter away from the tire edge. This indicated that the surface tensile stress or strain can only be related to the longitudinal non-wheel path cracking. Many other studies have also tried to investigate the mechanisms of TDC initiation. For example, Zhao et al. [23] suggested that the surface tensile strain is the major cause of TDC. Mohammad et al. [24], Al-Qadi et al. [25] attributed TDC to the load induced shear strain at the tire edge. Wang et al. [26] and Wang et al. [27] found that both tensile strain and shear strain contributed to TDC. Myers et al. [28] applied the measured tire-pavement contact stresses to a finite element model of the pavement structure and found that the computed surface tensile stress also occurs near the tire edge. They suggested that the near-tire tensile stress induced by the tire-pavement contact should be the primary cause of longitudinal wheel path cracking. The authors noted that using the measured tire-pavement contact stresses to compute pavement responses is still in a state of development, which is not feasible to implement into any pavement design program due to its complex load pattern and high variation of tire and pavement surface characteristics [29–31]. According to the literature review, there is no consensus explanation for the mechanism of TDC initiation. The existing studies showed that the TDC mainly occurred at the longitudinal wheel path, and sometimes appeared at the longitudinal non-wheel path or transverse direction [11–13]. The different cracking locations may be due to different critical pavement responses. Thus, it is necessary to first identify the critical responses corresponding to the different locations of TDC.

After identifying the critical pavement responses, there is still a need to establish the relationship between pavement responses and fatigue cracking initiation life. Roque et al. [18] proposed an energy-based crack initiation criterion based on the principle that asphalt mixtures have a limited available dissipated creep strain energy, and if load induced damage exceeds this limit a non-healable crack will initiate at the critical location. This criterion only considers the damaged induced by the surface tensile stress as the load induced damage, but whether this type of damage primarily contributes to the TDC is still not clear. In addition, Roque et al. [18] also introduced an energy ratio parameter to evaluate the TDC resistance of asphalt mixture. Therein, the energy ratio is defined as the ratio of limited dissipated creep strain energy of asphalt mixture to the minimum required dissipated creep strain energy of asphalt mixture. The energy ratio concept was validated by comparing the laboratory energy ratio results and field performance data for 22 different types of hot mix asphalt. However, whether this concept is applicable to hot mix asphalt containing reclaimed materials (such as reclaimed asphalt pavement and reclaimed asphalt shingle) needs further investigation.

To address the aforementioned research needs, this study aims to investigate load-related TDC initiation mechanisms and develop an energy-based initiation model to predict the TDC initiation life. Specifically, the critical pavement responses will be identified and related to TDC initiation at different pavement locations (i.e., longitudinal wheel path, longitudinal non-wheel path, and transverse direction). The identified critical pavement responses will be used to compute the corresponding load induced damage, which will then be compared to the limited strain energy of asphalt mixtures to estimate the crack initiation life. Both the effects of aging and healing are considered in the model.

This paper is organized as follows. The next section investigates the mechanisms of TDC initiation. The subsequent section presents the development of the TDC initiation model. After that, the model is applied to predict the TDC initiation life for the six selected pavement sections from the National Center for Asphalt Technology (NCAT) Test Track.

2. Mechanisms of top-down cracking initiation

A three-dimensional finite element model was constructed to simulate the responses of a conventional flexible pavement to traffic loads. Fig. 1 shows the pavement structure that consists of a 15-cm thick asphalt layer, a 15-cm thick base course and semi-infinite subgrade. Typical tire-pavement contact stresses were applied to the asphalt surface, which include (1) vertical stresses in a trapezoidal distribution with the magnitude of 650 kPa, (2) a triangularly distributed transverse stress with the maximum value of 247 kPa, and (3) longitudinal stresses in a trapezoidal distribution with the maximum value of 193.7 kPa. The shape of the tire-pavement contact zone is assumed to be rectangular with a tire width of 0.315 m and a tire length of 0.19 m. The details of tire-pavement contact stress pattern are found in De Beer et al. [32] and Ling et al. [33]. In this study, all pavement materials (i.e., asphalt, unbound aggregates, and subgrade soil) are assumed linear elastic. The model-inputted elastic moduli of these materials are also presented in Fig. 1.

Fig. 2 shows the computed pavement responses and the sensitivity of these responses to the asphalt modulus. For the transversal and longitudinal stresses, the positive value represents that the pavement is in tension, and the negative value indicates the pave-