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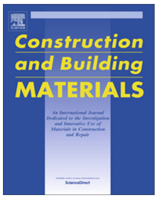

Crack initiation in asphalt mixtures under external compressive loads

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HIGHLIGHTS

- A crack initiation criterion is derived for asphalt mixtures in compression.
- Bond energy increases with aging and loading rate and decreases with temperature.
- Percentages of cohesive and adhesive cracking are determined for asphalt mixture.
- Compressive strength is predicted by simplified crack initiation criterion.

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ABSTRACT

Crack initiation was studied for asphalt mixtures under external compressive loads. High tensile localized stresses e direction of the external loads. A quantitative crack initiation criterion the edges of compressed air voids lead to the growth of wing cracks in thon was derived using pseudostrain energy balance principle. Bond energy is determined and it increases with aging and loading rate while decreases with temperature. Cohesive and adhesive cracking occur simultaneously and a method was proposed to determine the individual percentage. The crack initiation criterion is simplified and validated through comparing the predicted and measured compressive strength of the asphalt mixtures.

1. Introduction

Constitutive modeling of an asphalt mixture under an external compressive load requires different theories at different stages of the material. Viscoelastic theories are normally used to characterize nondestructive material behaviors and predict recoverable deformation. A yield criterion defines when the asphalt mixture begins yielding and from which irrecoverable viscoplastic deformation is initially accumulated. A hardening rule specifies the successive yielding after the initial yielding. For asphalt mixtures, it follows a strain/work hardening flow rule. The viscoplastic deformation will approach an asymptote and become saturated if no damage is introduced into the material. With the occurrence of damage the constitutive relation of the asphalt mixture exhibits strain-softening, a phenomenon that stress declines as strain increases. The peak stress is compressive strength. To characterize this overstress behavior of asphalt mixtures, a damage parameter is normally utilized in the stress–strain relationship and an evolution equation needs to be provided for this damage parameter. Three questions are raised by the authors that include (1) what the damage is physically; (2) when the damage initially occurs; and (3) what fundamental mechanisms the damage follows during its evolution. The authors focus on clarifying the first two questions in this study and will address the third question in a future study.

Two theories are currently used by the pavement research community to model the damaged behavior of asphalt mixtures: viscoelastic continuum damage (VECD) theory and continuum damage mechanics (CDM) model. The VECD theory was originally developed by Schapery [1–3], in which an internal state variable (i.e., S) was used as a representative of the damage in viscoelastic materials. An extended elastic–viscoelastic correspondence

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principle was proposed and the stress was linearly related to pseudostrain (i.e., ε^R) by a normalized pseudo-stiffness (i.e., $C(S)$) for the viscoelastic materials with damage. The evolution of the damage parameter was formulated as a power function of the pseudostrain energy (PSE) density. Schapery's viscoelastic damage theory was applied extensively in modeling the constitutive behavior of asphalt mixtures at low and moderate temperatures and in tension [4–9]. The time-dependent damage was interpreted as the growth of microcracks in tension. Gibson [10] and Schwartz et al. [11] extended these theories to characterize the viscoelasticity and damage of the asphalt concrete under compressive loadings, in which Schapery's viscoplastic models [3,12] were introduced to account for the viscoplastic deformation of the asphalt mixtures in compression. Then the total deformation was the sum of the damaged viscoelastic deformation and the viscoplastic deformation. The extended VECD theory that includes viscoplasticity is called viscoelastic plastic continuum damage (VEPCD) method, summary of which can be found in a project report [13]. In general, the VECD (or VEPCD) method characterizes the damage as a degradation of the normalized pseudo-stiffness and does well at low and moderate temperatures and in tension. However, more efforts are needed to explicitly specify the fundamental damage mechanisms of the asphalt mixtures. It is not clear that, especially in compression and at relatively high temperatures, how the damages are initiated and how the damage departs from the viscoplastic deformation.

The CDM model interprets the damage as a reduction of the intact material area due to cracks, voids and flaws existing in the material [14,15]. The characteristic parameter is damage density that is the ratio of the lost area to the total apparent area of the material, as below [16]:

$$\xi = \frac{A_L}{A_0} = 1 - \frac{\sigma^A}{\sigma^T} \tag{1}$$

where ξ is the damage density, A_L is the lost area and A_0 is the total (apparent) area of a cross section. σ^A is the apparent stress acting on the total material area and σ^T is the effective (or true) stress acting on the intact material area ($A_0 - A_L$). Effective stress is used in the constitutive relations to account for the influences of the damage. For example, the damage density and the effective stresses were embedded in Perzyna's rate-dependent viscoplastic theories [17] and used to characterize the viscoplasticity and viscodamage of asphalt mixtures [18–21]. These studies provided a comprehensive damage characterization for asphalt mixtures and indicated that the damage was due to the loss of the intact material area. The viscodamage thermodynamic driving force was developed to have a similar formulation to the extended Druker–Prager yield surface model. The evolution models for the viscoplasticity and the viscodamage were both formulated as power functions of the corresponding driving forces [22,23]. However, it is not clear how the viscodamage differs from the viscoplasticity. Furthermore, considerable laboratory efforts are needed to determine the parameters for the viscoplastic and viscodamage models. More studies are also needed to explain fundamentally what the damage exactly is, when the damage is initiated and how the damage evolves and differs from the viscoplasticity, especially in compressive loading conditions.

The two theories above both indicate that the damages in asphalt mixtures are microcracks in addition to viscoplastic deformation. Some studies in the literature have also directly demonstrated that, when subject to external compressive loads, cracks are initiated and propagated in the asphalt mixtures and lead to the cracking damage when the viscoplastic deformation approaches the saturation. Cracks were experimentally observed in compressive tests [24] and micro-cracking was modeled as one of the components of rutting [25]. Lytton [26] emphasized that the tertiary creep of rutting is not a plastic flow but a growth of microcracks. Both Wang et al. [27] and Freitas et al. [28] reported that cracks were observed within the compressive stress zone in the wheel-tracking rutting tests on asphalt mixtures at relatively high temperatures and they interpreted this phenomenon as one of the reasons for top-down cracking. Underwood et al. [29] explained that, in compression, the damages were the microcracks that developed in a direction parallel to the loading direction and found that this microcrack-induced damage may be significant for conditions when rutting is a primary concern. The authors' studies [30,31] demonstrated that the tertiary flow of rutting was caused principally by the growth of microcracks, which is parallel to the direction of the external loads and signaled by the increase of the phase angle in the tertiary stage. The tertiary flow under repeated compressive loading was characterized by an anisotropic viscofracture theory based on the damage density and Pseudo J-integral Paris' law [32].

The objective of this paper is to develop a microcrack (i.e. damage) initiation criterion for asphalt mixtures in compression based on fracture mechanics. At the peak stress (i.e., compressive strength) of a monotonic compressive load test or at the flow number of a repeated compressive load test, the asphalt mixtures are sufficiently hardened by viscoplastic work that no more energy due to external loads can be dissipated for viscoplastic deformation which has become saturated. The extra energy must be consumed for the initiation of the microcracks. Thus the microcracks are believed to be initiated at the compressive strength under monotonic load or at the flow number under repeated load. This initiation is demonstrated by the increased phase angle in the tertiary stage [30,32]. The next section shows the materials and laboratory tests used in this study, which is followed by viscoelastic characterization based on the pseudostrain concept. Then, a quantitative criterion for crack initiation is proposed for asphalt mixtures under external compressive loads based on fracture mechanics. Subsequently, the crack initiation criterion is employed to analyze the test results and determine the bond energy of the asphalt mixtures, which are decomposed into cohesive bond energy and adhesive bond energy. The crack initiation criterion is also simplified based on test results and validated through the compressive strength test data obtained in the literature for different types of asphalt mixtures at different conditions.

2. Materials and laboratory tests

Table 1 summarizes the test materials, test protocols and loading parameters of the laboratory tests used in this study. Twenty types of asphalt mixtures were tested with four binders, two air void contents (e.g., 4% and 7%) and three aging periods (i.e., unaged, 3-month and 6 month continuously aged at 60 °C in a conditioning room). The AAD-1 and AAM-1 binders were from Strategic Highway Research Program (SHRP) materials reference library [33] and the NuStar and Valero binders were from Asphalt Research Consortium (ARC) project. Uniaxial compressive creep (UCC) tests were performed to determine the viscoelastic properties of the mixtures such as creep compliance and relaxation modulus. The UCC test temperature was 40 °C and a constant stress of 40 kPa was used. Uniaxial compressive strength (UCS) tests were conducted on each type of the mixtures with at least two replicates and a third replicate was tested if a high variation was found in the results. The UCS test temperature was 40 °C and the strain rate was 311 με/s. To evaluate the effects of temperature and strain rate, one type of asphalt mixture samples (NuStar binder, 4%, 6-month aged) were tested at five different temperatures using the UCC and UCS tests, as shown in Table 1. Another type of asphalt mixture samples (NuStar binder, 7%, 6-month aged) were tested at five different strain rate levels using the UCS tests, as shown in Table 1.

For all asphalt mixtures, a common Texas limestone was used and the aggregate gradation was determined from a Type C dense gradation, specified by Texas Department of Transportation (TxDOT) [34]. The optimum asphalt content was calculated based on the TxDOT test procedure at the target air void content [35]. All of the tests were conducted on cylindrical asphalt mixture specimens with a diameter of 100 mm and a height of 150 mm. The Universal Testing Machine (UTM) was utilized to perform the tests. The stress was controlled at a constant in the UCC tests