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Energy-based damage and fracture framework for viscoelastic asphalt concrete

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ABSTRACT

A framework based on the continuum damage mechanics and thermodynamics of irreversible processes using internal state variables is used to characterize the distributed damage in viscoelastic asphalt materials in the form of micro-crack initiation and accumulation. At low temperatures and high deformation rates, micro-cracking is considered as the source of nonlinearity and thus the cause of deviation from linear viscoelastic response. Using a non-associated damage evolution law, the proposed model shows the ability to describe the temperature-dependent processes of micro-crack initiation, evolution and macro-crack formation with good comparison to the material response in the Superpave indirect tensile (IDT) strength test.

1. Introduction

Asphalt concrete is a viscoelastic composite construction material which consists of stones, sand and filler, blended with, and held together by a binder, typically bitumen or polymer modified bitumen. Damage in asphalt concrete is a result of changes in the microstructure of the material due to the application of external load and the effect of varying environmental conditions – temperature and moisture. These changes in microstructure result in different observable failure modes depending on the temperature range and can be mainly characterized as cracking or plastic deformation.

At low temperatures, cracking is the predominant damage mechanism characterized by micro-crack initiation and macro-crack formation. The fracture mechanism in asphalt concrete mixtures prior to and after macro-crack formation can be quite distinct. e.g., [54,4]. Cracking in asphalt concrete samples can be generally categorized into micro-crack initiation, micro-crack coalescence, macro-crack formation and the macro-crack propagation stages. Characterizing the macro-crack initiation is usually of major concern as the macro-crack propagation stage follows rapidly once a macro-crack is formed. The Displacement Discontinuity Boundary Element (DDBE) method, the Finite Element Method (FEM) and the Discrete Element Methods (DEM) have been used to satisfactorily model crack propagation in asphalt mixtures, e.g., [3,5,14,46,53,52].

Asphalt concrete contains a certain amount of air-voids (about 3–20% depending on the mixture type) which in terms of fracture mechanics analysis may be considered as pre-existing defects in the material acting as stress raisers. Provided that the geometry of the pre-existing flaw is known as well as the viscoelastic stress distribution in the material, the principles of viscoelastic fracture mechanics can be used to fully describe the process of fracture initiation and propagation in a

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Nomenclature

a_T	creep compliance shift factor
A	material parameter
C_{ex}, C_{sx}	Superpave IDT test correction factors
d	specimen diameter
D	isotropic scalar damage variable
$\mathbf{E}$	fourth order elasticity tensor
$\mathbf{E}(\mathbf{t})$	characteristic relaxation function
f^d, F_D	micro-crack initiation and micro-crack propagation criteria
k_1, k_2	damage model parameters
K	stress correction function
n	material parameter
P	applied load
R	isotropic damage hardening function
S_o	damage model parameter
t	specimen thickness
Y	energy density release rate
$\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^{\mathbf{e}}, \boldsymbol{\varepsilon}^{\mathbf{v}}$	strain tensor – total, elastic and viscous strain
ε_{xx}	horizontal tensile strain
η	dashpot viscosity
$\theta_1, \theta_2, \theta_3$	temperature coupling parameters
λ	Lagrange multiplier
μ	Young's modulus
$\boldsymbol{\sigma}, \bar{\boldsymbol{\sigma}}$	stress tensor – nominal and effective stress
$\boldsymbol{\sigma}_\infty, \boldsymbol{\sigma}_{\mathbf{neq}}$	long term equilibrium and non-equilibrium stress tensors
σ_{xx}	horizontal tensile stress
τ	relaxation time
ϕ, ϕ_{dam}	total dissipation and damage dissipation
Φ	viscous potential function
$\psi, \psi_\infty, \psi_{neq}$	free energy potential function – total, long term, non-equilibrium parts
$\wp_1^*$	micro-crack initiation potential function
$\wp_{1,c}^*$	critical micro-crack damage threshold
$\wp_2^*$	micro-crack propagation potential

viscoelastic medium [44,45]. However, as has been shown in several micromechanical studies, the mechanical properties of the asphalt mixture's constituents, the variation in the shape and size of voids as well as the spatial distribution of the voids inside the asphalt mixture limits the use of the principles of fracture mechanics for the description of fracture initiation in asphalt concrete mixtures (e.g., [30,34,48]).

Due to these limitations imposed by the non-uniform fracture geometries and inhomogeneous material properties, various researchers have used the continuum damage approach to generalize the damage characterization in asphalt concrete. The viscoelastic continuum damage based on the principle of work potential [43] have been used to characterize damage in asphalt mixtures e.g., [12,18,24,25,36,47,50,51]. The elastic–viscoelastic correspondence principle [44] can be used to reduce a viscoelastic problem to an elastic problem relying on pseudo variables, used to remove the time effects. Darabi et al. [9] proposed a three dimensional thermo-viscoelastic–viscoplastic–viscodamage constitutive model for nonlinear response of asphaltic materials. The thermo-viscodamage model is formulated to be a function of temperature, total effective strain, and the damage driving force. Kim and Little [19] developed a one-dimensional constitutive model of asphalt concrete under repetitive load conditions. Two mechanisms were identified as important in the stress–strain relationship of asphalt materials: viscoelastic relaxation and damage accumulation. The damage growth in the model is generalized and represented with a damage variable. Micromechanical models e.g., [8,13,17,28,33,42,49] have also been proposed by various researcher to model the response of asphalt materials when subjected to different loading conditions.

However, most of these existing models have been developed with focus around predicting the material response at intermediate temperatures despite the fact that the material is exposed to a wide range of temperature during its service life. It should be noted that in the range of service temperatures, the matrix binder stiffness varies significantly by some orders of magnitude from low to high temperatures. Due to this stiffness variation between the aggregate inclusions and the matrix binder, different damage mechanisms i.e. cracking and plastic deformation are dominant at low and high temperatures respectively at a moderate strain rates. The work presented in this paper suggests the possibility of developing two different potential-based models to accurately characterize the material behavior at low and high temperatures respectively. One of the models will focus on the characterization of cracking at low temperatures, while the other model will be used to characterize the plastic deformation at high temperatures. Both models can then be coupled to characterize the material at