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Characterization of viscoplastic yielding of asphalt concrete

Yuqing Zhang [a,*,1], Rong Luo [a,1], Robert L. Lytton [b,2]

[a] Texas A&M Transportation Institute, College Station, TX, USA
[b] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, USA

HIGHLIGHTS

- A temperature and rate dependent viscoplastic yield surface is developed for asphalt concrete.
- A strain decomposition method is proposed to obtain viscoplastic strain and initial yield strength.
- Cohesion and strain hardening amplitude of asphalt concrete decrease when temperature increases or strain rate decreases.
- Temperature and strain rate coefficients can be accurately determined solely by the ultimate yield strength.

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ABSTRACT

A temperature and strain rate dependent yield surface model was proposed to characterize the viscoplastic yielding of asphalt concrete. Laboratory tests were conducted on specimens that have two binders, two air void contents, and three aging periods. Strain decomposition was performed to obtain viscoplastic strain and stress-pseudostrain curves were constructed to determine the model parameters accurately and efficiently. Results indicate that a stiffer asphalt concrete has greater cohesion and strain hardening amplitude, both of which decline as temperature increases or strain rate decreases. The temperature and strain rate factors of the yield surface can be accurately determined solely by the peak stress of the strength tests.

1. Introduction

Rutting is one of the major distresses in asphalt pavements and it normally appears as longitudinal depressions along the wheel paths. Rutting accumulates gradually with repeated traffic loadings and it not only increases the road roughness but traps water and leads to wet-weather accidents due to hydroplaning and the loss of tire-pavement friction. One of the main resources of rutting is the permanent deformation developed in asphalt concrete layers, which are primarily attributed to the irrecoverable shear deformation under heavy truck loads at a high environmental temperature [1]. To accurately model and predict the permanent deformation which occurs in the asphalt concrete layers, a variety of mechanistic models based on viscoplastic theories have been proposed and widely employed as constitutive relations in the continuum mechanistic modeling [2–6]. As the kernel of the viscoplastic theories, the yield surface determines under what conditions the asphalt concrete begins to yield and how the yielding of the material evolves as the permanent deformation accumulates. Therefore, the yielding properties of the asphalt concrete should be characterized accurately and comprehensively using an appropriate yield surface model.

The existing yield surface models of asphalt concrete include the Mohr–Coulomb model, Drucker–Prager model, Extended Drucker–Prager model, Hierarchical Single-Surface model, etc. Five typical yield surface functions are presented as follows:

(1) Mohr–Coulomb (M–C) model [7,8]:

$$\tau - \sigma \tan\phi - C = 0 \quad (1)$$

(2) Drucker–Prager (D–P) model [9,10]:

$$\sqrt{J_2} - \alpha I_1 - \kappa_0 = 0 \quad (2)$$

(3) Extended Drucker–Prager (ED–P) model [11,12]:

$$\sqrt{J_2}\left[\frac{1}{2}\left(1+\frac{1}{d}\right)+\frac{1}{2}\left(1-\frac{1}{d}\right)\cos(3\theta)\right] - \alpha I_1 - \kappa = 0 \quad (3)$$

* Corresponding author. Tel.: +1 979 739 5366; fax: +1 979 845 0278.
E-mail addresses: zyqtamu@tamu.edu (Y. Zhang), rongluo@tamu.edu (R. Luo), r-lytton@civil.tamu.edu (R.L. Lytton).
[1] Address: CE/TTI Bldg 503C, 3135 TAMU, College Station, TX 77843-3135, USA.
[2] Address: CE/TTI Bldg 503A, 3136 TAMU, College Station, TX 77843-3136, USA.

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(4) Di Benedetto (DBN) model [13]:

$$\sqrt{J_2}\cos\left(\frac{\pi}{3}-\theta\right)-R\frac{I_1+3S_0}{\sqrt{3}}=0 \tag{4}$$

(5) Desai's Hierarchical Single-Surface (HISS) model [14,15]:

$$J_2[1-B\cos(3\theta)]^m-\left[\gamma(I_1+S)^2-\eta(I_1+S)^n\right]=0 \tag{5}$$

where τ is the yield shear stress; σ is normal stress; C and ϕ are cohesion and internal friction angle of the asphalt concrete, respectively; J_2 $(=\frac{1}{2}S_{ij}S_{ji})$ is the second invariant of the deviatoric stress tensor (i.e., $S_{ij}=\sigma_{ij}-\frac{1}{3}\delta_{ij}I_1$); δ_{ij} is Kronecker delta; I_1 (=σ_{kk}) is the first invariant of the stress tensor (i.e., σ_{ij}); α and κ_0 are material properties which are related to C and ϕ. In the ED-P model, κ is a strain hardening function and d is extension ratio that is a ratio of the yield strength in extension to that in compression. In the DBN model, R and S_0 are hardening variables; and θ is lode angle which is defined as:

$$\theta=\frac{1}{3}\arccos\left[\frac{3\sqrt{3}}{2}\frac{J_3}{(J_2)^{3/2}}\right]\quad\in\left[0,\ \frac{\pi}{3}\right] \tag{6}$$

where J_3 (=det (S_{ij})) is the third invariant of the deviatoric stress tensor; θ equals to zero in compression and $\pi/3$ in extension. In the HISS model, γ is a softening parameter; η is a hardening parameter; S is a cohesion related parameter; n is a parameter determining the yield surface shape on the meridian plane ($\sqrt{J_2}\sim I_1$); B and m are parameters determining the yield surface shape on the octahedral plane (I_1 = constant).

To evaluate these yield surface models, Table 1 lists five fundamental yielding properties of the asphalt concrete and one can conclude that none of the existing yield surface models can completely characterize all of the viscoplastic yielding properties of the asphalt concrete.

The ED-P model and the HISS model are two of the best candidate yield surface models for asphalt concrete. However, the HISS model exhibits a spindle shape in the principal stress space and nonlinear curves on the meridian plane. In fact, the HISS yield surface becomes nonlinear at relatively high confining pressures, which are normally used to characterize the nonlinear softening of soils or granular base [16]. In contrast, the yield surface of the asphalt concrete is a truncated cone in the principal stress space and remains linear on the meridian plane according to the measurements in the literature [9,17]. In addition, too many fitting parameters in the HISS model require complicated laboratory experiments for the determination of the model parameters. Thus the ED-P model was chosen as the basic yield surface model for the characterization of the viscoplastic yielding of the asphalt concrete. Furthermore, testing results in the literature [18,19] indicated that material cohesion of the asphalt concrete increased as the temperature decreased or loading rate increased. The authors found that the temperature and loading rate had the same impacts on the amplitude of strain hardening. Therefore the ED-P model still needs modifications to account for the effects of temperature and strain rate on the material cohesion and strain hardening.

One of the objectives in this study is to develop a temperature and strain rate dependent yield surface model based on the ED-P model, which is presented in the next section, which is followed by the laboratory testing. Then a pseudostrain based method is proposed to accurately determine the initial yield strength. A strain decomposition method is developed thereafter to calculate the viscoplastic strains so that the model parameters of the yield surface can be accurately determined, which achieves another objective of this study. Subsequently, the yield surface model parameters are determined and the yielding material properties are analyzed based on the testing results. The last section summarizes the major findings of this study.

2. Viscoplastic yield surface model for asphalt concrete

Based on the discussion in last section, the ED-P model is selected as the basic yield surface model. To consider the temperature and strain rate dependence, the ED-P model is modified as:

$$f=\sqrt{J_2}g(d,\theta)-\alpha I_1-\kappa a_T a_{\dot{\varepsilon}}=0 \tag{7}$$

where f is yield surface function; $g(d,\theta)=\frac{1}{2}[(1+\frac{1}{d})+(1-\frac{1}{d})\cos(3\theta)]$ is a function defining the yield surface shape on the octahedral plane. The term $\kappa a_T a_{\dot{\varepsilon}}$ is used to include the effects of temperature and strain rate on cohesion and strain hardening of the asphalt concrete, where a_T is a temperature factor; $a_{\dot{\varepsilon}}$ is a strain rate factor; κ is the strain hardening function at a reference temperature and a reference strain rate, and κ is modeled by an exponential function [20,21]:

$$\kappa=\kappa_0+\kappa_1\left[1-\exp\left(-\kappa_2\varepsilon_e^{vp}\right)\right] \tag{8}$$

in which κ_0, κ_1 and κ_2 are material parameters determined at the reference temperature (T_0) and at the reference strain rate ($\dot{\varepsilon}_0$); κ_0 is defined by material cohesion; κ_1 determines the amplitude of the strain hardening; κ_2 defines the strain hardening rate; ε_e^{vp} is the effective viscoplastic strain, which may have different expressions when different yield surface and flow rule models are used. For instance, when an elastoplastic material employs the von Mises yield surface and associated flow rule, the effective plastic strain is given in an incremental form as: $d\varepsilon_e^p=\sqrt{2/3d\varepsilon_{ij}^p d\varepsilon_{ij}^p}$ where $d\varepsilon_{ij}^p$ is the incremental plastic strain tensor [22]. The derivations of the general expression of ε_e^{vp} will be discussed in another study. In this paper, only ε_e^{vp} in a uniaxial condition is used, and in such a condition $\varepsilon_e^{vp}=\varepsilon_1^{vp}$ where ε_1^{vp} is the axial viscoplastic strain in a uniaxial test.

The measured data between cohesion and temperature reported in the literature were found to follow an Arrhenius function for the asphalt concrete [18,23]. Thus, to account for the effect of temperature on cohesion and strain hardening, the Arrhenius temperature function is proposed to formulate the temperature factor:

$$a_T=\exp\left[\frac{\Delta E_T}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{9}$$

where ΔE_T is the activation energy, J/mol; R is the universal gas constant, 8.314 J/mol K; T is the temperature of interest, K; and T_0 is the reference temperature, K. The activation energy ΔE_T is used as a regression parameter that can be determined by performing uniaxial strength tests at different temperatures. It is noteworthy that a_T totally differs from the time–temperature shift factor that is used for the master curve of viscoelastic materials. The Arrhenius temperature function a_T quantifies the effect of temperature on the yield strength during the strain hardening process while the time–temperature shift factor evaluates the equivalent effects of time and temperature on the responses of the viscoelastic materials. Eq. (9) indicates that the cohesion and strain hardening amplitude will decrease as temperature increases, which will be verified by experimental results.

The strain rate effect is quantified by the strain rate factor ($a_{\dot{\varepsilon}}$) which is modeled by a power function as follows:

$$a_{\dot{\varepsilon}}=\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\kappa_3} \tag{10}$$

where $\dot{\varepsilon}$ is the rate of total strain of interest, 1/s; $\dot{\varepsilon}_0$ is the reference total strain rate, 1/s; and κ_3 is a material property that can be determined by performing uniaxial strength tests at different loading (strain) rates. Eq. (10) shows that the cohesion and strain hardening