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Rheological viscoplastic models of asphalt concrete and rate-dependent numerical implement

Jianlian Cheng [a,*], Xudong Qian [b], Tieshuan Zhao [a]

[a] *Highway Maintenance Equipment National Engineering Laboratory, Key Laboratory of Road Construction Technology and Equipment Ministry of Education, School of Construction Machinery, Chang'an University, 322 mailbox, Xi'an, Shaanxi 710064, China*
[b] *Department of Civil and Environmental Engineering, National University of Singapore, Singapore 117576, Singapore*

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ABSTRACT

Based on the generalized plastic theory, a viscoplastic constitutive model is derived from Perzyna's theory of viscoplasticity and is used to model the ratcheting behavior exhibited by the mix. The evolution of the permanent strain with number of loading cycles is also captured. The loading surface is considered for the viscoplastic model of asphalt concrete (AC) according to Vermeer loading surface. A non-associate flow rule for the plasticity model as well as an evolution equation for hardening parameters is given. The viscoplastic component captures the rate-dependent behavior. The developed viscoplastic model takes into account the anisotropy in AC. Inherent anisotropy is introduced through the fabric tensor and considered by the preferred orientation of non-spherical particles. The developed damage model is incorporated in the viscoplastic model to capture the permanent deformation of AC. Numerical implementation and algorithm aspects of the multi-dimensional elastic-viscoplastic-damage model are presented. A robust integration algorithm for the nonlinear differential equations is carried out, which equations are solved by prediction-corrector method. Model results are compared to experimental observation. For the permanent deformation, results of the RSST-CH and Triaxial experimental are used to calibrate the model and test its prediction of different stress levels. RSST-CH is also modeled as a boundary value problem to assess the capability of the model to predict rutting in the pavement.

1. Introduction

The performance of asphalt concrete (AC) pavements is closely related to the performance of AC. Performance of AC can be categorized into two major distresses: permanent deformation and fatigue cracking (Sides et al., 1985; Collop et al., 2003; Masad et al., 2008). Under high temperature and slow loading rates, the binder becomes too soft to support the load, and thus permanent deformation is formed due to volume change and rearrangement of aggregate particles caused by shear flow (Eisenmann and Hilmer, 1987; Witczak et al., 2002). Aggregate interlocking and anisotropy in AC become important factors in the prediction of the permanent deformation behavior of AC. Understanding permanent deformation would benefit to design of roads and to enhance the service life of the pavement. Cracking of AC usually be caused by repetitive traffic mechanical loading and or thermal loading from changes in temperature. Under repeated loading, whether it is mechanical or thermal,

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* Corresponding author.
E-mail addresses: cheng19690912@163.com (J. Cheng), qianxudong@nus.edu.sg (X. Qian), zhao_tieshuan@trans-power.cn (T. Zhao).

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microstructural damage of AC occurs primarily in form of microcracks. The thickness of the pavement under the wheel path reduces considerably and the pavement gets susceptible to fatigue cracking.

In recent years, some novelty researches on constitutive model of various materials, which are related to AC, such as granular materials (Shao et al., 2006; Nicot and Darve, 2005; Nicot et al., 2012; Sibille et al., 2015; Zhu et al., 2008a; Collard et al., 2010; Kamrin, 2010; Henann and Kamrin, 2014), subgrade and frozen soil (Muraleetharan et al., 2009; Lai et al., 2009, 2010, 2012, 2014), unsaturated and saturated porous geomaterials (Ho and Fatahi, 2015; Xie and Shao, 2012; Le et al., 2015; Shen et al., 2015), clayey stone (Nguyen et al., 2014; Zhu et al., 2010, Bikong et al., 2015; Darabi et al., 2012b), concrete and rock (Shen et al., 2012; Abu Al-Rub, 2008; Abu Al-Rub and Darabi, 2012), the gradient plasticity of materials (Abu Al-Rub and Voyiadjis, 2004, 2006; Volokh and Trapper, 2007), provide the powerful support for the modeling of AC deformation. The cyclic viscoplastic strain response of AC is modeled in compression at high temperatures in order to improve the prediction of the permanent deformation under cyclic loading conditions. The results show that the current classical hardening viscoplasticity model fails to predict the permanent deformation in AC under repeated or cyclic loading conditions at high temperatures. This study reveals that the micro-stress term has an important effect on the development of the boundary layers and hardening of the material at both hard and soft interface boundary conditions in thin films. Their efforts are beneficial to enhance the development of plastic theory on AC as well as other materials.

For porous materials, the most important geometrical determinant is the matrix volume fraction, which is closely related to the porosity, in relation to the inherent deformation mechanisms (Gibson and Ashby, 1997), the order of magnitude of the mechanical properties. It cannot describe the mechanical or structural anisotropy. About anisotropic plasticity of rock-like materials, the structural anisotropy can be partially quantified by a fabric tensor (Pietruszczak et al., 2002, 2004; Lydzba et al., 2003). The fabric tensor is a symmetric, positive definite, second order tensorial measure of the structural arrangement of a porous medium. The fabric tensor is commonly computed from directional data. Directional data can be obtained by using stereographic or image analysis methods (Odgaard, 1997) such as Star Length Distribution (SLD) (Smit et al., 1998) or Intercept Segment Deviation (ISD) (Chiang et al., 2006).

The fatigue cracking of flexible pavements is based on the horizontal tensile strain at the bottom of hot mix asphalt (HMA). Cracks vent moisture movement into the pavement and result in damage of pavements. The moisture trapped in the cracks expand due to ice formation during cold temperatures and this results in further damage to the pavements. Uzan (2007) modeled the fatigue cracking as a two-stage process consisting of crack initiation and crack propagation. The crack initiation stage is characterized by conventional laboratory fatigue tests; while the crack-propagation stage is described using the Paris-Erdogan law. Owusu-Antwi et al. (1998) used the principles of fracture mechanics and developed a mechanistic-based performance model for predicting the amount of reflective cracks in composite AC/PCC pavements. This failure criterion relates the allowable number of load repetitions to the tensile strain of HMA. This type of distress includes both low-temperature cracking and thermal fatigue cracking. Low-temperature cracking is usually associated with flexible pavements in colder regions. Thermal fatigue cracking occurs in much milder regions if excessively hard asphalt is used or the asphalt becomes hardened due to aging. Little et al. (2001), Lytton et al. (2001), Kim (1988), and Kim et al. (1997) developed a series of mechanistic theories to model the fatigue life of the asphalt pavements by considering both microfracture and healing based upon the first principles of fracture and healing, viscoelastic correspondence principles, and continuum damage theories. Lytton et al. (2001) calculated that the healing effect accounts for a large portion of the shift factor between laboratory and field fatigue models, and this shift factor can range between about 3 to over 100. Kim et al. (1994) successfully validated that healing is a measurable and repeatable property, both in the laboratory and in the field. Little et al. (1999) also found that the fatigue damage and healing in asphalt pavements are directly related to the surface energy characteristics of the asphalt-aggregate system.

In an industry wide survey conducted by researchers at the University of Maryland, College Park, rutting was rated the most significant distress type regarding damage in pavements (Wittczak, 1998; Christensen et al., 2000, Witczak et al., 2002). A thorough understanding of the rutting phenomenon is required in order to improve pavement design and performance.

The modeling of permanent deformation of AC have been reported by a number of researchers (Sousa et al., 1993; Sousa and Weissman, 1994; Scarpas et al., 1997; Lu and Wright, 1998; Huang et al., 2002; Tashman et al., 2005; Liu et al., 2007; Darabi et al., 2011, 2012a, 2013). Their efforts have played an important role in understanding the mechanisms and factors influencing the AC performance. The different strategies have been utilized to model the individual strain components such as Maxwell-type and Burger-type elements; power law functions of stress, time and number of load repetition; and Perzyna's theory of plasticity, which has successfully used to model the permanent deformation of AC.

The state of permanent deformation (viscoplastic) modeling of AC is still in its formative stages. Uzan (1996) and Schapery (1999) suggested a phenomenological uniaxial viscoplastic model that employed functions of current permanent strain and applied stress. This type of model is found to predict the behavior of AC in tension and compression under monotonic loading (Chehab et al., 2003; Gibson et al., 2003; Levenberg, 2009; Yun and Kim, 2011). However the model is unable to accurately capture minor region behavior in repeated creep and recovery tests. Taking a cue from the field of metal plasticity, many researchers have worked on Perzyna type models with yield and hardening functions but have had limited success in predicting the material behavior under repeated creep and recovery tests (Erkens, 2002; Gibson, 2006; and Dessouky et al., 2006). It will be shown subsequently using experimental data that some of the model forms of the Perzyna-type are not suitable for explaining the behavior of a large number of repeated creep and recovery cycles in compression for AC. One of the main problems with these models is that the effect of load history on permanent deformation is not taken into account properly. The plot of permanent strain versus number of loading cycles on a log–log scale is a straight line for AC