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A thermo-viscoelastic–viscoplastic–viscodamage constitutive model for asphaltic materials

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ABSTRACT

A temperature-dependent viscodamage model is proposed and coupled to the temperature-dependent Schapery's nonlinear viscoelasticity and the temperature-dependent Perzyna's viscoplasticity constitutive model presented in Abu Al-Rub et al. (2009) and Huang et al. (in press) in order to model the nonlinear constitutive behavior of asphalt mixes. The thermo-viscodamage model is formulated to be a function of temperature, total effective strain, and the damage driving force which is expressed in terms of the stress invariants of the effective stress in the undamaged configuration. This expression for the damage force allows for the distinction between the influence of compression and extension loading conditions on damage nucleation and growth. A systematic procedure for obtaining the thermo-viscodamage model parameters using creep test data at different stress levels and different temperatures is presented. The recursive-iterative and radial return algorithms are used for the numerical implementation of the nonlinear viscoelasticity and viscoplasticity models, respectively, whereas the viscodamage model is implemented using the effective (undamaged) configuration concept. Numerical algorithms are implemented in the well-known finite element code Abaqus via the user material subroutine UMAT. The model is then calibrated and verified by comparing the model predictions with experimental data that include creep-recovery, creep, and uniaxial constant strain rate tests over a range of temperatures, stress levels, and strain rates. It is shown that the presented constitutive model is capable of predicting the nonlinear behavior of asphaltic mixes under different loading conditions.

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1. Introduction

Hot Mix Asphalt (HMA) is a highly complex composite which can be considered to be consist of three scales: (a) the micro-scale (mastic), where fine fillers are surrounded by the asphalt binder; (b) the meso-scale, fine aggregate mixture (FAM), where fine aggregates are surrounded by the mastic; and (c) the macro-scale which includes all the coarse aggregates surrounded by FAM. Numerous experimental studies have shown that the material response of HMA is time-, rate-, and temperature- dependent and exhibits both recoverable (viscoelastic) and irrecoverable (viscoplastic) deformations (e.g. Perl et al., 1983; Sides et al., 1985; Collop et al., 2003). It is well recognized that asphalt binders exhibit nonlinear behavior under high strains or stresses. Since the stiffness of aggregates is several orders of magnitude greater than that of the binder, the occurrence of strain localization in the binder phase is a common phenomenon which causes the binder to behave nonlinearly in the HMA. Moreover, rotation and slippage of aggregates and interaction between binder and aggregates during the loading can also contribute to nonlinear behavior of HMA (Masad and Somadevan, 2002; Kose et al., 2000). The evolution of micro-cracks and micro-voids and rate-dependent plastic (viscoplastic) hardening are other major sources of nonlinearity in the thermo-mechanical response of HMA.

The viscoelastic response of HMA can be well-predicted using Schapery's nonlinear viscoelasticity model (Schapery, 1969) as recently shown by Huang et al. (2007) and Huang et al. (in press). In fact, Schapery's single integral model is widely being used to model the behavior of viscoelastic materials such as polymers (e.g. Christensen, 1968; Schapery, 1969, 1974, 2000; Sadkin and Aboudi, 1989; Haj-Ali and Muliana, 2004; Muliana and Haj-Ali, 2008). Furthermore, Touati and Cederbaum (1998), Haj-Ali and Muliana (2004), Sadd et al. (2004) and Huang et al. (2007) have developed numerical schemes for implementation of Schapery's constitutive model in finite element (FE) codes.

In terms of the viscoplastic behavior of asphalt mixes, the Perzyna's theory (Perzyna, 1971) has been used by several researchers for predicting the permanent deformation in HMA. For example, Seibi et al. (2001) and Masad et al. (2005, 2007) have used Perzyna's viscoplasticity along with the Drucker–Prager yield

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