Numerical implementation of elasto-viscoplastic model in bituminous mixtures microstructure

L'implémentation numérique de élastique-visco-plastique pose dans la microstructure de mixtures bitumineuse

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ABSTRACT

Bituminous Mixture (BM) is a granular composite material stabilized by the presence of bitumen. In continuum modeling for BM, the macroscopic response has been lacking the ability to explicitly account for the effect of the microstructure. In this study, an elasto-viscoplastic continuum model is developed to predict BM response and performance in service loading. The model incorporates a Drucker-Prager yield surface that is modified to capture the influence of the directional distribution of aggregates and damage density. The model is converted into a numerical formulation and is implemented in finite element (FE). A fully implicit algorithm in time-step control is used to enhance the efficiency in the FE analysis. The FE model is used in this study to simulate permanent deformation for isotropic and anisotropic structures.

RÉSUMÉ

Les Mixtures Bitumineuses (BM) sont une matière composite granuleuse stabilisée par la présence de bitume. Dans le continuum posant pour le BM, la réponse macroscopic a manqué de la capacité d'explicitement représenter l'effet de la microstructure. Dans cette étude, un modèle de continuum élastique-visco-plastique est développé pour prédire la réponse de BM et la performance dans le chargement de service. Le modèle incorpore une surface de production de Drucker-Prager qui est modifiée pour capturer l'influence de la distribution directionnelle de densité de dommage et d'ensembles. Le modèle est converti en formulation numérique et est exécuté dans l'élément fini (FE). Un algorithme complètement implicite dans le contrôle de pas de temps est utilisé pour améliorer l'efficacité dans l'analyse FE. Le modèle de FE est utilisé dans cette étude pour simuler la déformation permanente pour isotropic et anisotropic des structures.

Keywords: visco-plastic, microstructure, finite element, damage

1 INTRODUCTION

Bituminous mixtures (BM) are particulate composite materials that consist of asphalt binder, particles, and air voids. There has been a long-term interest in relating the macroscopic response of those materials to their microstructure characteristics in terms of particles sizes and properties (Dessouky at al. 2006a), bitumen thin film structure (Dessouky et al. 2006b) and air voids distribution (Tashman et al. 2005), directional distribution of particles, and nucleation and propagation of cracks (Masad et al. 2003). The effect of microstructure distribution has not explicitly considered in continuum modeling of BM to evaluate macroscopic response and performance. This study presents the development of elastic and viscoplastic continuum model that account for important aspects of the microstructure distribution in modeling the macroscopic behavior of BM. Researchers have proved the presence of elastic, viscoelastic, viscoplastic, and plastic components of BM response. Each component is mainly affected by temperature and loading rate (Abdulshafi and Majidzadeh, 1985, Scarpas et al. 1997, Lu and Wright 1998). Bituminous mixtures behavior varies from elastic and linear viscoelastic at low temperatures and/or fast loading rates to viscoplastic and plastic at high temperatures and/or slow loading rate. Since permanent deformation is associated with high temperature and slow loading rate, the model presented in this paper is formulated within the framework of theory of visco-plasticity.

2 MODEL DEVELOPMENT

The objective of the proposed model is to relate the microstructure distribution parameters to the mechanism of permanent deformation. Hence, the following yield function is proposed:

$$f = F(I_1, J_2, J_3, d, \Delta, \xi) - \kappa = 0 \tag{1}$$

where I_1, J_2 & J_3 are the first stress invariant, second deviatoric stress invariant, and third deviatoric stress invariant, respectively. These invariants account for the effect of confinement, the dominant shear stress causing the viscoplastic deformation, and the direction of stress. d, a parameter that reflects the influence of the stress path direction, is defined as the ratio of tensile yield stress to compressive yield stress. ξ is a model parameter that accounts for the effect of damage. κ is a hardening parameter that describes the growth of the viscoplastic yield surface. Δ *is* a microstructure parameter that accounts for the material anisotropy by measuring the directional distribution of particles as function of the angle of inclination (θ) (Figure 1). Utilizing the Perzyna's viscoplastic model and non -associative flow rule the viscoplastic strain rate is defined as follows (Perzyna 1966):

$$\dot{\varepsilon}^{vp} = \Gamma \cdot < \phi(f) > \cdot \frac{\partial g}{\partial \sigma} \tag{2}$$

where Γ is the fluidity parameter, which establishes the relative rate of viscoplastic straining, g is the plastic potential function,

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and $\dfrac{\partial g}{\partial \sigma}$ is a deviatoric vector in stress space which defines the direction of the viscoplastic flow. If $f>0$, $\phi(f)$ is taken as a power law function, f^N, of the viscous flow, where N is a parameter characterizing the material rate-sensitivity (Tashman et al. 2005). A modified formulation of the Drucker-Prager yield function is adopted in the following form:

$$f = \bar{\tau}^e - \alpha \bar{I}_1^e - \kappa = 0 \tag{3}$$

$$\bar{\tau}^e = \frac{\sqrt{\bar{J}_2^e}}{2(1-\xi)}\left[1 + \frac{1}{d} - \left(1 - \frac{1}{d}\right)\frac{\bar{J}_3^e}{\left(\bar{J}_2^e\right)^{3/2}}\right] \tag{4}$$

The parameter α reflects the material frictional properties. It determines the slope of the yield surface. The evolution of α is a result of changes in the aggregate structure associated with friction and dilation when the material is under confinement. κ is a hardening parameter that reflects the combined effect of the cohesion and frictional properties of the material. Granular materials in general develop dilation when they are subjected to deviatoric stresses (Zeinkiewicz et al., 1975). To evaluate the invariants, the modified stress tensor ($\bar{\sigma}_{ij}$) is expressed as a function of stress tensor σ_{ij} and fabric tensor F_{ij} as shown in Eq. (5) (Tobita 1988).

$$\bar{\sigma}_{ij} = \frac{3}{2}\left[\sigma_{ik}F_{kj} + F_{ik}\sigma_{kj}\right] \tag{5}$$

The anisotropic tensor F_{ij} is a function of Δ (Masad et al. 2004).

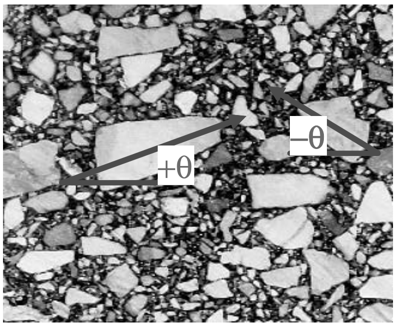

Figure 1. Schematic diagram of anisotropy in a conventional BM microstructure

The effective stress theory (superscript e) is utilized to account for the microstructure damage in terms of microvoids and cracks. Stress components are magnified by dividing them over 1-ξ, where ξ is the damage parameter or area of internal air voids and cracks. ξ is varied from 0 to 1 for complete intact and damaged specimen, respectively, and it is measured using X-ray Computed Tomography of specimens loaded to different strain levels (Masad et al. 2003). The study proposed that damage evolution is a function of confining pressure and plastic deviatoric strain. An exponential form has been used to simulate the degradation response as the material passes the ultimate stresses, Desai (1998).

$$\xi = exp(\xi_1 \cdot \frac{I_1}{3}) \cdot \left[1 - exp(\xi_2 \cdot \varepsilon_{vp} + \xi_3 \cdot \frac{I_1}{3})\right] \tag{6}$$

where ξ_1, ξ_2, and ξ_3 are coefficients to be determined experimentally and ε_{vp} is the effective viscoplastic strain. The first exponential term controls the asymptotic limit of the function, while the last term, which includes the confining pressure, controls the damage rate of growth.

The plastic potential function, g, is assumed to have the same form as the yield function (equ. 3) but with a slope of β which influences the proportions of the volumetric and deviatoric strains. β reflects the dilative potential of the material and therefore, influences the proportions of the volumetric and deviatoric strains. The evolution laws for κ and β are postulated based on the experimental measurements presented by Dessouky et al. (2006a). The study has also shown that β is a function of Δ.

3 MODEL PARAMETERS SENSITIVITY

The fluidity parameter Γ controls the growing rate of the yield surface. It can be seen from Figure 2 that a slight change in the viscosity parameter Γ could produce a significant change in the stress-strain relationship. As the parameter decreases, the yield surface size increases and the ultimate strength is reached at a higher strain level. Γ is associated with the overstress function to account for stresses outside the elastic domain. Another important factor that controls the stress-strain relationship is confining pressure which minimizes the growth of air voids and cracks, and hence reduces damage as illustrated in Figure 3. On other hand, the model parameter ξ is an indicator of the damage percent in the material. The parameter is incorporated in the model through the effective stress theory presented by Kachanov (1958), who introduced for the isotropic case a one-dimensional damage variable. In this theory, damage is interpreted as the effective surface density of microdamage per unit volume. This concept is based on considering a fictitious undamaged configuration of a body and comparing it with the actual damaged configuration.

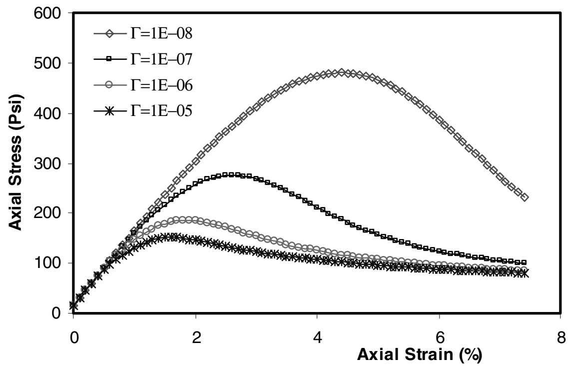

Figure 2. Effect of viscosity parameter on stress-strain relationship

4 MODEL DISCRETE IMPLEMENTATION

The elastic strain increment component can be defined according to Hooke's law and the viscoplastic strain rate defined in Eq. (2) as follows:

$$\begin{aligned} \Delta\sigma &= D : \Delta\varepsilon^e \\ \Delta\sigma &= D : \left(\Delta\varepsilon - \Gamma \cdot <\phi(f)> \cdot \frac{\partial g}{\partial \sigma} \cdot \Delta t\right) \end{aligned} \tag{7}$$

where D is the elastic stiffness matrix. The numerical implementation associated with the elasto-viscoplastic computation is based on the return mapping algorithm, which leads to an elastic predictor-viscoplastic corrector sequence. In time-dependent material, the problem is solved by subdividing the time frame interval into a finite number of time steps. The initial and final time step is referred to increment n and $n+1$, respectively.

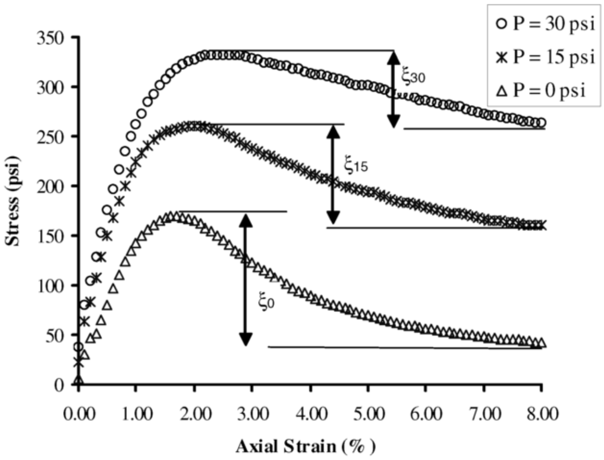

Figure 3. Influence of confining pressure on material softening response. (Confining pressure magnitude is shown in the subscript of ξ, the higher the pressure the smaller the damage factor)

At the initial time step, the trial elastic stress is computed using the elastic predictor that elaborates initial conditions known from the preceding time step. If the trial stress is located inside the yield surface then an elastic response occurs, whereas a stress state outside the yield surface implies development of viscoplastic flow. At this stage the viscoplastic corrector problem is solved by mapping the trial stress to the yield surface to maintain the consistency condition. The algorithmic value of a viscoplastic strain increment over a time interval (Δt) can be defined in implicit form to ensure stability and accuracy for large strain increments. The continuum model of evolution may be written in the following discrete form:

$$\varepsilon_{n+1}^{vp} = \varepsilon_n^{vp} + \Delta t \cdot \Gamma \left\langle \phi\left(f_{n+1}(\sigma, \varepsilon_{vp})\right)\right\rangle \frac{\partial g_{n+1}(\sigma, \varepsilon_{vp})}{\partial \sigma} \tag{8}$$

where the effective viscoplastic strain ε_{vp} is necessary to update the internal state variable of the model evolutions. According to the viscous flow in Eq. (2), a time-step-dependent viscoplastic consistency parameter is introduced in the form:

$$\dot{\gamma}^{vp} = \Delta t \cdot \Gamma \left\langle \phi\left(f_{n+1}(\sigma, \varepsilon_{vp})\right)\right\rangle \tag{9}$$

The algorithm starts by finding a trial value for f_{n+1}^t

$$f_{n+1}^t = F(\sigma_{n+1}^t) - \kappa\left(\varepsilon_{vp}^t\right)_{n+1} \tag{10}$$

where $f_{n+1}^t \leq 0$ implies elastic response; and $f_{n+1}^t > 0$ leads to a positive value for $\dot{\gamma}^{vp}$ according to the condition giving by Alfano et al. (2001)

$$\chi\left(\dot{\gamma}^{vp}\right) = \frac{1}{1-\xi}\left(\bar{\tau} - \alpha \bar{\mathrm{I}}_1\right) - \kappa - \left(\frac{\dot{\gamma}^{vp}}{\Delta t \cdot \Gamma}\right)^{1/N} = 0 \tag{11}$$

Eq. (11) replaces the condition of $f_{n+1} = 0$ in conventional plasticity and the Newton-Raphson iteration scheme is applied to solve its nonlinear form (Masad et al. 2007). Once the viscoplastic multiplier is determined, the corrections for the trial components can be updated at time t_{n+1} as follows:

$$\begin{aligned} \sigma_{n+1} &= D : \left(\varepsilon_{n+1} - \varepsilon_{n+1}^{vp}\right) \\ \varepsilon_{n+1}^{vp} &= \varepsilon_n^{vp} + \dot{\gamma}^{vp} \frac{\partial g_{n+1}(\sigma, \varepsilon_{vp})}{\partial \sigma} \\ \left(\varepsilon_{vp}\right)_{n+1} &= \left(\varepsilon_{vp}\right)_n + \lambda \dot{\gamma}^{vp} \end{aligned} \tag{12}$$

where λ is a scalar quantity defined as the magnitude of the viscoplastic strain vector perpendicular to the potential surface along the axial direction, and it is determined as $\frac{\partial g_{11}(\sigma, \varepsilon_{vp})}{\partial \sigma_{11}}$.

5 EXPERIMENT DESCRIPTION AND RESULTS

The aforementioned parameters were determined for specimen prepared using three sources of aggregates; granite, limestone, and gravel. Two replicates of BM were fabricated to 7.0% air voids using gyratory compaction and tested at 130° F. Five strain rates of 0.0660, 0.318, 1.60, 8.03 and 46.4%/min and three confining pressures of 0, 15 and 30 psi were used for each replicate. Axial and radial stresses and strains were recorded throughout testing. Specimens were loaded up to an axial strain of 8.0% or until failure, whichever occurred first. Triaxial compressive strength test indicated the effect of the strain rate and confining pressure. Higher strengths were associated with higher strain rates and/or confining pressures for all aggregate sources. Example of the stress-strain behavior for granite is shown in Figure 4. More details and complete list of model parameters are found at Dessouky (2005)

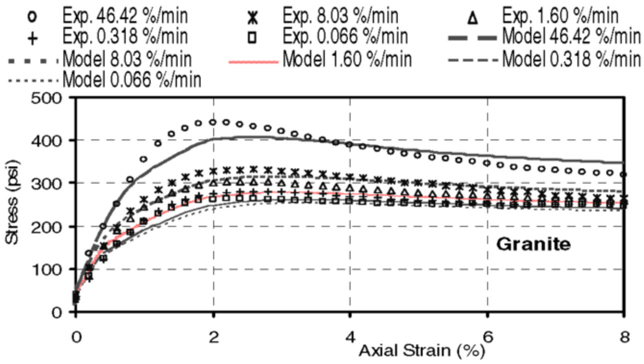

Figure 4. Experimental and model stress-strain relationships in triaxial compression at 30 psi confining pressure

The model has showed good simulation to the experiments, the model parameters are able to distinguish between the granite mixes in terms of their response to different strain rates and confining pressures. Experimental measurements indicated also that elastic modulus varies with respect to loading rate. Material that undergoes a small rate of loading exhibited a small elastic modulus. Figure 5 indicates that granite had the largest modulus, while gravel had the smallest modulus.

6 FE ANALYSIS AND IMPLEMENTATION

The model parameters were implemented in finite element (FE) (Figure 6) using a user-defined material subroutine (UMAT) to link the microstructure properties to BM overall response. The model represents a BM layer exposed to dual-tire loading. Although the anisotropic BM layer developed more shear stress, permanent deformation was found to be less in magnitude when anisotropy is considered as shown in Figure 7. The material also exhibited more dilation in-between and along the tires edges as a result of anisotropy. This is consistent with the findings in

Dessouky (2005) that the angle of dilation increases with anisotropy.

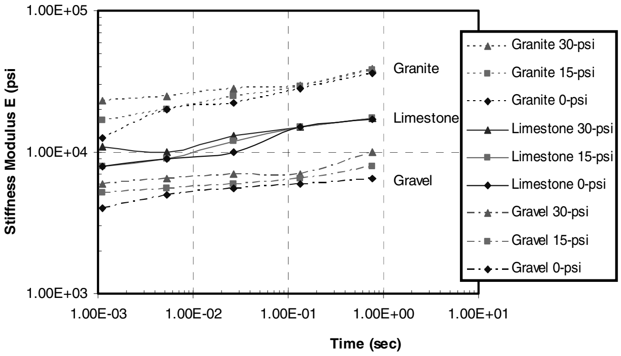

Figure 5. Stiffness modulus evolution as a function of loading time

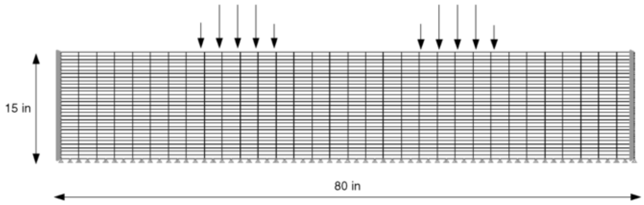

Figure 6. FE Geometric model for a pavement structure

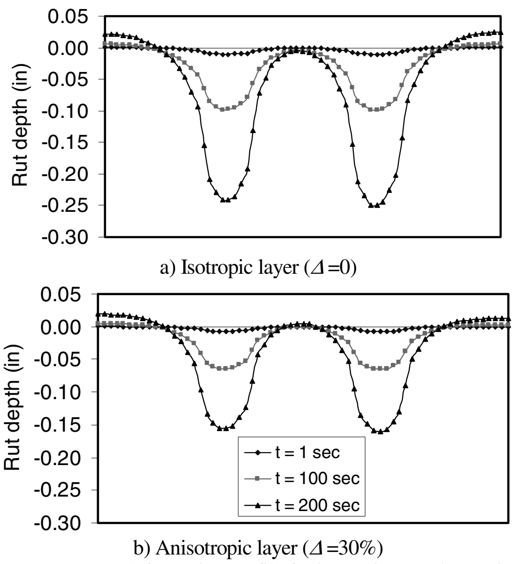

Figure 7. Permanent deformation profile for isotropic vs. anisotropic BM

7 SUMMARY AND CONCLUSION

This study presented the development of an elasto-visco-plastic continuum model to predict BM response and performance under wheel loadings. The model includes microstructure parameters that capture the directional distribution of aggregates and density of cracks. In addition, the model is capable of accounting for the factors affecting the mechanisms of permanent deformation such as shear stress, aggregate structure friction and dilation, confining pressure, and strain rate. The FE results indicated that the elasto-visco-plastic model's parameters and permanent deformation response were sensitive to changes in aggregate orientation.

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