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Constitutive modeling of hardening-relaxation response of asphalt concrete in cyclic compressive loading

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HIGHLIGHTS

- Relaxation of hardening occurs under cyclic loading in asphalt concrete.
- Hardening relaxation increases potential of viscoplastic strain accumulation.
- Hardening relaxation is a function of accumulated recovered viscoelastic strain.
- Viscoelastic-viscoplastic with hardening relaxation-viscodamage model is developed.
- The numerical implementation has been developed for FE modeling.

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ABSTRACT

Cyclic loading on asphalt concrete materials with a longer relaxation time and lower remaining stress lead to higher viscoelastic strain recovery. Consequently, more aggregate reorientation occurs and the rate of viscoplastic strain increases in subsequent cycles. The present study proposes a hardening relaxation constitutive relationship (f_{HR}) as a function of accumulated recovered viscoelastic strain (ε^{rve}) based on experimental observation. This model captures the initiation and evolution of hardening-relaxation during the relaxation time and/or stress reduction under cyclic loading. The model was then coupled with viscoelastic, viscoplastic and viscodamage constitutive relationships. The numerical schemes were implemented in Abaqus finite element software using the user-defined material subroutine. The coupled constitutive relationship was calibrated against cyclic, creep-recovery and creep tests at different stress levels. The proposed hardening-relaxation constitutive relationship was then validated against independent laboratory experiments with different loading scenarios. It was shown that the hardening-relaxation constitutive relationship substantially improved strain prediction at intermediate temperatures.

1. Introduction

Hot mix asphalt (HMA) is a composite material consisting of aggregate, binder and air voids. The rheological properties of binder make the HMA response time-, temperature-, and rate-dependent. At small strain levels, the strain response can be decomposed into viscoelastic and viscoplastic components. Viscoelastic strain recovers during the unloading and rest times while viscoplastic strain is permanent, induces rutting distress in flexible pavements and is more prevalent at high temperatures. Study of the viscoplastic behavior of HMA under both creep (constant stress) and cyclic loading conditions can produce a more comprehensive understanding of this complex material.

Considerable effort has been dedicated to characterization of HMA behavior under creep loading. Schapery [1,2] characterized the nonlinear viscoelastic behavior of polymers using the Boltzmann superposition integral and developed a thermodynamics-based nonlinear viscoelastic constitutive relationship. An experimental study by Seibi et al. [3] showed that the viscoplastic response of HMA can be modeled using linear strain hardening for specific cases. Chehab et al. [4] and Gibson et al. [5] integrated Schapery's viscoelasticity, a strain hardening relationship, and the damage constitutive relationship and referred to it as the viscoelastoplastic continuum damage (VEPCD) model.

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Ali et al. [6] investigated the effect of temperature and traffic speed on pavement rutting using an elastic-viscoplastic constitutive relationship that incorporated the strain hardening effect. Drescher et al. [7] used the dissipation energy-based viscoelastoplastic constitutive relationship to predict a single cycle creep-recovery response of asphalt concrete. Kim et al. [8] cited increased complexity in compression in comparison with tension caused by the contribution of aggregate at high temperatures as well as slow loading rates on the increased need for more robust solutions.

To better distinguish between the evolution of permanent strain in extension and contraction loading and to consider the effect of multi-axial stress states, researchers replaced the strain hardening relationship with Perzyna viscoplasticity [9] to remedy the issues associated with linear strain hardening relationships. The use of different Perzyna-type viscoplastic constitutive relationships improved the accuracy of predicting the permanent deformation in creep tests [10,11,12–20]. A more sophisticated loading pattern than that for creep is required, however, to represent realistic stress states induced in asphalt pavement by traffic.

Saadeh [21] showed that for the same accumulated loading time and stress level, the accumulated permanent deformation during a cyclic creep-recovery test was significantly higher than that during a creep test. Yun and Kim [22] applied different stress levels and rest times to HMA cylindrical specimens and found that, for a given total loading time, the specimens that experienced longer rest times and/or more loading cycles experienced increased permanent deformation. These observations suggest a noticeable effect of resting time on accumulation of the viscoplastic strain; however, the absence of viscoelastic behavior characterization led to long rest times in each cycle to allow the viscoelastic strain to recover completely. In addition, it allowed for permanent deformation to be determined only at the end of the loading time of each cycle.

Yun and Kim [23,24] modeled the viscoplastic behavior of HMA and found that existing viscoplastic models had not been calibrated for different forms of cyclic loading. They used the Boltzmann integral to incorporate the stress history of the yield surface by defining a material-dependent unit yield stress function. The yield surface function ascended during loading and descended during the rest time. While the use of an isotropic yield surface has been common practice when modeling the hardening characteristics of HMA, Nguyan and Nedjar [25] proposed a framework in which the cyclic plasticity behavior of HMA was modeled using single time-dependent restorable kinematic hardening. They extended their proposed rheological model to a three-dimensional constitutive relationship and applied the elastoviscoplastic model to predict viscoplastic strain under cyclic and creep loading scenarios. Hardening restoration was activated when the stress state was inside the yielding surface and the rate of hardening restoration did not depend on the stress state inside the yielding surface. Their proposed constitutive relationship was appropriate for a cyclic square-shaped loading pattern in which the stress was abruptly removed.

Subramanian et al. [26], considered the history-dependent behavior when calculating the viscoplastic response of HMA by means of the Boltzmann integral. Applying this framework, Cao and Kim [27] proposed a coupled viscoelastic-viscoplastic constitutive relationship. They observed variations in the recovered viscoelastic strain in different cycles in triaxial repeated-load permanent deformation test results; therefore, their approach was designed to account for the effect of viscoplastic deflection on non-uniform recovery of viscoelastic strain during the rest times of different cycles.

Darabi et al. [28] also studied the effects of loading and rest times on viscoplastic strain. They proved the inefficiency of the classic Perzyna model for repetitive loading by demonstrating its insensitivity to both rest time and number of cycles for the same accumulated loading time. A supplementary study by Darabi et al. [29] showed that when the stress level was held constant, the strain estimated by classic hardening relationships became saturated after the first few cycles and did not change after subsequent cycles; however, these modeling results for classic hardening viscoplasticity were not in agreement with experimental measurements. They attributed the observed hardening (the decrease in strain rate) during loading to the reorientation of the aggregate to a more compact microstructure. The increase in viscoplastic strain rate at the beginning of a loading cycle was ascribed to the relaxation of residual stresses in the mastic phase of HMA that caused aggregate reorientation to revert to a less compact state during the rest time of the preceding cycle. These changes relaxed the hardening of the specimen induced in the preceding loading time. They argued that, during the rest time, the viscoplastic strain remains constant and the thermodynamic force conjugate to the viscoplastic strain (viscoplastic hardening) should relax during the rest time. It is worth mentioning that although both take place during rest time, hardening-relaxation should not be confused with healing [30]. Hardening-relaxation increases the material potential to experience higher levels of viscoplastic strain [21–25,28–31], while healing enhances the integrity of the material and makes it more resistant to the evolution of viscoplastic strain in subsequent cycles [11,17,30].

The remedy to the classic Perzyna-type viscoplastic constitutive relationship presented by Darabi et al. [28,29] was the introduction of a memory surface containing an internal state variable that incorporated the history of viscoplastic strain as well as the effect of resting time. The evolution rate of this variable depended on the viscoplastic overstrain (its deviation from the effective viscoplastic strain). The shrinkage rate of hardening was set to be linearly proportional to the rate of internal state variable. This time-dependent internal state variable was activated only when the stress state was inside the yield surface ($\dot{\varepsilon}^{vp} = 0$) and was insensitive to the level of the stress inside the yield surface. Benefiting from pavement analysis using the nonlinear damage approach (PANDA), researchers modeled the performance of HMA under various environmental and tire loading conditions [10,14,17,28,32–34]. Rushing et al. [35] incorporated the memory surface model to the PANDA constitutive relationship to predict responses of full-scale airfield pavements for different pavement structures and temperature conditions.

2. Hypothesis and methodology

As inferred from recent studies, it is imperative to develop a constitutive relationship that is capable of predicting the accumulation of viscoplastic strain during cyclic loading by considering the effects of stress level and resting time. To address this issue, this paper proposes a hardening-relaxation constitutive relationship (f_{HR}) as a function of accumulated recovered viscoelastic strain (ε^{rve}) that considers the recovered viscoelastic strain as a measure to capture the change in the position and orientation of aggregate during rest time. This constitutive relationship restores the viscoplastic hardening induced during the loading time and is activated with the recovery of the viscoelastic strain during unloading and relaxation times. The proposed constitutive relationship is then coupled to the Schapery's nonlinear viscoelastic, Perzyna's viscoplastic and Darabi et al.'s [10,11] viscodamage constitutive relationships to represent the response of asphalt concrete subjected to cyclic compressive loading. Carefully conducted lab tests were used to calibrate and validate the coupled constitutive relationship.