Performance Modeling of Asphalt Concrete Pavements

By Y. Richard Kim

Asphalt concrete pavement, one of the largest infrastructure components in the United States, is a complex system that involves multiple layers of different materials, various combinations of irregular traffic loading and varying environmental conditions. Therefore, a realistic prediction of the long-term service life of asphalt pavements is one of the most challenging tasks for pavement engineers. In recent years, research efforts by the Asphalt Materials Analysis and Computational Mechanics Group at North Carolina State University (NCSU) have resulted in some key advances in pavement performance modeling. One such accomplishment is the development of the viscoelastoplastic continuum damage (VEPCD) model.

The structure of the VEPCD model is based on the strain decomposition principle derived by Schapery (1999). Through this principle, strain may be separated and modeled by component, i.e., elastic, linear viscoelastic, viscoplastic, etc. For the VEPCD model, elastic, linear viscoelastic and strains due to microcracking damage are combined in a single term ($\varepsilon_{ve}$), and plastic and viscoplastic strains are combined in another ($\varepsilon_{vp}$). The underlying principles of the VEPCD modeling approach are linear viscoelasticity, continuum damage mechanics and strain-hardening viscoplasticity. Linear viscoelastic (LVE) materials exhibit time- and temperature-dependent behavior. That is to say, the response is dependent on both the current input and all past input (i.e., input history). Continuum damage mechanics considers a damaged body with some stiffness as an undamaged body with a reduced stiffness. Continuum damage theories thus attempt to quantify two values, damage and effective stiffness, and further find the relationship between the two. In the VEPCD modeling approach these two concepts, linear viscoelasticity and continuum damage mechanics, are combined and result in a robust material model that is easy to characterize. For viscoplasticity, the approach thus far has been to utilize a strain-hardening viscoplastic model based on work by others (Uzan et al. 1985 and Schapery 1999).

For a more rigorous treatment of the subject, the reader is referred to previous work (Lee 1996, Daniel 2001, Chehab 2002) and to the work of Schapery (1990, 1999) for linear viscoelasticity and continuum damage mechanics. For a review of strain-hardening viscoplasticity, the reader is directed to the work of Uzan (1996). The full VEPCD model is presented in Equation (1).

$$\varepsilon_{total} = E_R \xi \int \frac{d}{d\tau} \left( \frac{\sigma}{C(S)} \right) d\tau + \left( \frac{p+1}{Y} \right)^{\gamma_{p+1}} \left( \int_0^{\xi} \sigma^\gamma d\xi \right)^{\gamma_{p+1}}$$

where

$E_R$ = reference modulus for dimensional compatibility (usually taken as unity),

$D(\xi)$ = linear viscoelastic creep compliance,

$\xi$ = reduced time,
\[ \sigma = \text{stress}, \]
\[ C = \text{normalized pseudo secant modulus (effective stiffness)}, \]
\[ S = \text{internal state parameter quantifying damage}, \]
\[ \tau = \text{integration variable and} \]
\[ p, q, Y = \text{VP model fitting coefficients}. \]

The major strength of the VEPCD model is in the simplicity of the calibration testing. The calibration testing program is composed of three phases: (1) LVE characterization; (2) VECD characterization; and (3) VP characterization. The complex modulus test at varying temperatures and frequencies is used for LVE characterization, determining \( D(\xi) \) (Underwood et al. 2006). For the VECD and VP model characterization, constant crosshead rate monotonic tests at 5\(^\circ\) and 40\(^\circ\)C, respectively, are used.

The accuracy of the VEPCD model has been assessed in a number of different ways. One of the most robust assessments includes the application of randomly selected cyclic loadings at a temperature (25\(^\circ\)C) not used in characterization. For such tests the loading amplitude, frequency and number of cycles for a given loading are randomly selected. Such a random loading history is shown in Figure 1. Figure 2 presents results of the model prediction for this loading history for four different mixtures. It is noted that the same loading history results in a different fatigue life for each of the mixtures.

An examination of these figures shows that the measured and modeled behaviors closely agree. As the specimen approaches localization the model tends to under-predict the measured data; however, this difference is less than 15\% in the most extreme case (SBS) and could be related to the specimen-to-specimen variability.

An even more rigorous validation of the VEPCD model involves the prediction of Thermal Stress Restrained Specimen Tests (TSRSTs). The TSRST verification is particularly important because these tests were not used in the model development and stresses in TSRSTs are thermally induced whereas mechanically induced stresses are used in the characterization process. Using specimen dimensions, initial temperature, and cooling rates, predictions of stress-time history, stress-temperature history and stress, time, and temperature at failure have been made. These predictions were modeled with three levels of complexity: (1) LVE; (2) VECD; and (3) VEPCD. The predictions are shown in Figure 3. In addition, Figure 4 presents various TSRST failure parameters along with the model predictions. As with the random load tests, the VEPCD predictions are in agreement with the measured responses. For notational brevity, the thermal stress and strain are identified by \( \sigma \) and \( \varepsilon \), respectively.
Figure 1. Random load history used in validation of the VEPCD model

Figure 2. Random load prediction results for ALF mixtures: (a) Control, (b) CR-TB, (c) SBS and (d) Terpolymer
Figure 3: Average measured and predicted stress histories for different material models and cooling rates

Figure 4. Comparison of the TSRST parameters predicted from the VEPCD model with the measured values

Modeling the material behavior alone is not sufficient for pavement performance predictions, however. Experience has shown that the performance of asphalt concrete pavements is also strongly influenced by boundary conditions, such as tire-pavement interaction, temperature gradient along the layer thickness, pavement structural design,
etc. To account for these influences, a structural model must be included in the performance prediction process. This need has led to the development of VEPCD-FEP++, performance modeling software written in C++ that integrates both the fundamental VEPCD material model and a robust finite element model.

Typical analysis results using VEPCD-FEP++ are presented in Figure 5. This figure shows the evolution of damage in a thick asphalt concrete pavement under repeated load applications. It is observed from this figure that the degree of damage increases with load applications. For the thick pavement used in this example, damage initiates from both the bottom of the asphalt layer and the top of the layer right under the tire edge, and propagates simultaneously to form a conjoined damage contour. This conjoined damage contour supports the findings from field studies of top-down cracking (Gerritsen et al. 1987). Also, the conjoined damage contour suggests that the through-the-thickness crack may develop as these bottom-up and top-down microcracks propagate further and coalesce together. VEPCD-FEP++ is currently used in the NCHRP 1-42A project to evaluate the top-down cracking mechanism of various asphalt mixtures and pavements.

![Damage Parameter (Thick AC Thickness)](image)

Figure 5: Damage evolution in a thick asphalt pavement using the viscoelastic continuum damage finite element program.

Pavements with different materials and boundary conditions might not necessarily behave in a similar manner and their performance might be notably different. To the pavement engineer knowing how a given material will perform in a selected structure is of great importance for selecting the appropriate solution. Such a tool has both national and
international implications, as evidenced by two of the current NCSU projects, one funded by the Federal Highway Administration (FHWA) and the other by the Korea Highway Corporation (KHC).

The FHWA project incorporates full-scale Accelerated Loading Facility (ALF) testing on various asphalt mixtures, including polymer-modified mixtures. The KHC Test Road project involves continuous measurement of environmental conditions and traffic loading on a 7.7 km section of instrumented test road on the Jungbu Inland Expressway, as well as periodic measurements of pavement responses under moving loads and the Falling Weight Deflectometer. Both of these projects offer opportunities for validation and calibration of VEPCD-FEP++. Further, the FHWA and several states have also expressed interest in validating and calibrating VEPCD-FEP++ using perpetual pavements in China as well as pavements in those states.

References


