Advanced Characterisation of Pavement and Soil Engineering Materials – Loizos, Scarpas & Al-Qadi (eds)
© 2007 Taylor & Francis Group, London, ISBN 978-0-415-44882-6

Reflective and thermal cracking modeling of asphalt concrete overlays

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ABSTRACT: Although asphalt concrete overlay systems represent a rapid and economical alternative for the repair of deteriorated pavements, reflective cracking continues to be major cause of premature deterioration of these systems. A better understanding of the complex mechanisms behind reflective cracking in asphalt overlays must first be obtained before significant advances in reflective crack prevention and mechanics-based overlay design can be fully realized. Traditional modeling approaches have not provided a direct means for the study of crack initiation and propagation in pavements. The cohesive zone fracture modeling approach provides a rational means for modeling cracking in structural systems consisting of quasi-brittle materials, as a finite length scale associated with the fracturing process is considered. A bi-linear cohesive zone model (Song et al., 2006) was used in the simulation of cracking in three field pavement sections studied in a recent NSF GOALI project. Detailed field performance data, especially crack maps from visual surveys were obtained and compared to the numerical simulation results. The temperature boundary conditions were generated using the *Enhanced Integrated Climatic Model* developed by Dempsey et al. (1990) based upon air temperatures obtained from National Weather Service databases. Viscoelastic bulk and cohesive fracture material properties for these pavement sections were obtained by laboratory testing of specimens fabricated from 150-mm field cores, in accordance with a new, efficient testing suite (Wagoner et al., 2006). A series of numerical simulations were performed using finite element models, which provided new insights towards the mechanisms of cracking in asphalt concrete overlays under thermal and mechanical loads. A series of finite element analyses were performed with hypothetical overlay configurations in an effort to demonstrate the concept of a "simulation-guided" interlayer/overlay design process, which allows the direct consideration of initiating and propagating cracks in one or more overlay layers.

1 INTRODUCTION

When an overlay is placed on an existing pavement, physical tearing of the overlay often takes place as a result of movement at the joints and cracks in the underlying pavement layer. Any movement that takes place in the underlying pavement at a joint/crack will produce stresses in the overlay, which can promote reflective crack propagation if the stresses in the overlay exceed its fracture resistance. Temperature and tire-induced movements, concentrated at underlying joints and cracks in the existing pavement lead to stresses in the overlay, which significantly contribute to reflective cracking. Reflective cracking in the overlay allows water to percolate into the pavement structure and weaken the subbase and also contributes to many forms of pavement deterioration, including

Figure 1. Reflective cracks on US36 near Cameron, MO.

increased roughness and spalling. Figure 1 shows a reflective crack in the field for a pavement section located at US36 near Cameron, MO.

A number of approaches have been developed in an effort to minimize or delay the occurrence of reflective cracking. These approaches include: increased overlay thickness, slab fracturing (crack/seat, break/seat, and rubblization), modification of asphalt properties, crack arresting (reinforcing) interlayers, stress absorbing membrane interlayers (SAMIs), and strain tolerant interlayers. Sometimes approaches utilizing both base-isolation (stress absorbing) and reinforcement techniques are attempted.

Recent work at the University of Illinois has involved work in finite element modeling of asphaltic overlay systems. The modeling includes: innovative use of viscoelastic constitutive models from the Superpave Indirect Tensile Test (IDT); contact interfaces that allow horizontal and vertical slab movements, and crack modeling in various material layers, including he cohesive zone modeling technique. Furthermore, realistic temperature gradients and cooling cycles have been modeled, using the Integrated Climatic Model (ICM). The modeling has contributed to a better understanding of critical factors in the development of reflective cracking.

This paper describes the use of the finite element modeling technique in conjunction with a cohesive zone fracture modeling technique to simulate reflective cracking in asphalt overlays. The paper briefly describes the details regarding the finite-element pavement model and cohesive fracture model. Thereafter, a simulation example is presented, along with a demonstrative parametric investigation directed towards system optimization to prevent reflective cracking. The paper is organized in following sections: field investigation; cohesive fracture modeling; viscoelastic material modeling; experimental characterization; finite-element pavement modeling; simulation results, and; conclusions and recommendations.

2 FIELD INVESTIGATION

Before generating realistic finite-element pavement models, collection of relevant field information is a crucial prerequisite step. The field information that was used for developing simulation models can be summarized as follows:

1. Pavement system (i.e. overlay on rigid pavement, overlay on conventional flexible pavement, etc.)

2. Underlying pavement details (i.e. cracked or uncracked, crack/joint spacing, load transfer characteristics, etc.)
3. Section geometric details (i.e. thicknesses of various layers, pavement width, etc.)
4. Climatic model inputs (i.e. hourly temperatures, latitude, percent sunshine, elevation, etc.)

The climatic information for each pavement section is utilized in determining the thermal loading conditions. The Enhanced Integrated Climatic Model proposed by Dempsey et al. (1990) was used to generate temperature profiles as a function of depth within the various layers in the pavement model. More details are provided in the section entitled *Finite Element Pavement Modeling*.

A total of seven pavement sections were selected, which resided in three main project locations chosen in distinctly different climatic regions as follows:

- Cold climate – IA Rt. 9 (Decorah, Iowa)
- Intermediate climate – US 36 (Cameron, Missouri)
- Warm climate – LA Rt. 34, (Monroe, Louisiana)

Each project included control and interlayer treated overlay sections. The field information for all the sections were collected by means of available construction records and field visits. At least one annual visual crack count survey was conducted at each location each year. Extensive pavement coring was conducted at each site to: 1) collect asphalt pavement and interlayer samples, 2) to verify concrete pavement thickness, 3) to obtain subgrade soil samples, and 4) to investigate crack behavior. The sections located at US State Highway 36 (US36) located near Cameron, MO are discussed in this paper.

3 COHESIVE FRACTURE MODELING

In order to better understand the complex mechanisms underlying the reflective cracking phenomenon, a standard “strength of materials” type analysis is insufficient, due to: 1) the highly nonlinear behavior in the vicinity of the crack tip in this viscoelastic, particulate composite with large aggregate particles, and 2) the importance of the crack in the overall structural response (i.e., the need to model reflective cracking as a moving boundary value problem). For simulation of crack initiation and propagation, a cohesive zone model was selected because of its accuracy and efficiency in accounting for material response ahead of the crack tip in the *fracture process zone* (region of micro-cracking, crack pining, crack branching, material softening, etc.). Soares et al. (2004) and Song et al. (2006) have demonstrated the various capabilities of the cohesive zone model for the simulation of cracking in asphalt concrete materials. More details regarding the cohesive zone modeling approach and the bilinear cohesive zone model are provided in the next section.

3.1 *Cohesive fracture approach*

The cohesive zone model provides a computationally efficient way to predict the damage occurring in a process zone located ahead of a crack tip in a material. This approach, which provides constitutive laws to describe displacement jump/traction behavior along crack surfaces, can capture complex fracture behavior such as crack nucleation, crack initiation and both mode-I and mixed-mode crack propagation. In other words, the cohesive zone model dictates the relationship at any material point between its capacity to transfer load (traction) and potential opening (displacement jump) due to material damage or cracking.

Figure 2(a) illustrates the process zone, modeled herein as the region between the cohesive crack tip (where the traction is at a maximum) and the material crack tip (where the traction is assumed to be zero). Figure 2(b) shows a schematic illustration of the relation between displacement jump and traction along the process zone.

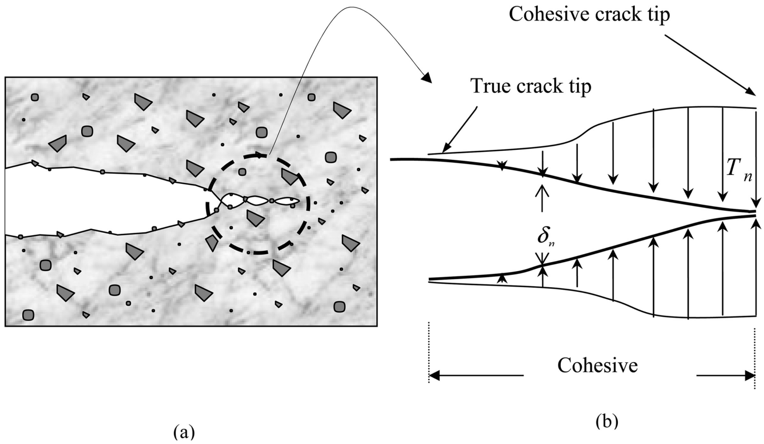


Figure 2. (a) The schematic figure of fracture behavior near crack tip and (b) The displacement jump (δ) and correspondent traction (T_n).

3.2 *Bi-linear cohesive zone model*

A bilinear cohesive zone model (Song et al., 2006) was developed to model cracking behavior in asphalt overlay and interlayer materials in this study. The material parameters used in the cohesive zone model are: material strength (σ_c), critical displacement (δ_c) and cohesive fracture energy (G_c). For modeling purposes, non-dimensional effective displacement and effective traction are used, as follows:

$$\lambda = \sqrt{\left(\frac{\delta_n}{\delta_n^c}\right)^2 + \beta^2\left(\frac{\delta_s}{\delta_s^c}\right)^2} \qquad \text{and} \qquad t(\lambda) = \frac{(1-\lambda)}{(1-\lambda_{cr})}\sigma_c$$

where, β is the ratio between maximum normal and shear tractions; σ_c is the critical traction (strength); δ_n and δ_s denote normal opening and shear sliding displacements, respectively, and δ_n^c are δ_s^c critical displacement values which describe the onset of complete separation, i.e. zero traction, in the normal and shear directions, respectively. Notice that λ_{cr}, which is a non-dimensional parameter, is incorporated adjust the slope of the pre-peak "loading side" of the cohesive law. This parameter is generally set to a very high value to minimize artificial compliance at the crack surface, since the compliance of the loading side of the cohesive law does not describe actual material behavior; rather it is an artifact of *intrinsic* cohesive zone models. Although more elaborate *extrinsic* cohesive zone models have recently been developed (Zhang and Paulino 2005), their employment is far more complex at present. Careful utilization of intrinsic cohesive zone models has been found to yield quite satisfactory results (Song et al., 2006).

The normal and shear tractions are given as:

$$t_n = \frac{\partial\phi}{\partial\delta_n} = \frac{\partial\phi}{\partial\lambda}\frac{\partial\lambda}{\partial\delta_n} = \frac{t(\lambda)}{\lambda}\frac{\delta_n}{\delta_n^c} = \frac{1-\lambda'}{\lambda'}\left(\frac{\delta_n}{\delta_n^c}\right)\frac{\sigma_c}{1-\lambda_{cr}},$$

$$t_s = \frac{\partial\phi}{\partial\delta_s} = \frac{\partial\phi}{\partial\lambda}\frac{\partial\lambda}{\partial\delta_s} = \beta^2\left(\frac{\delta_n^c}{\delta_s^c}\right)\frac{t(\lambda)}{\lambda}\frac{\delta_s}{\delta_s^c} = \beta^2\left(\frac{\delta_n^c}{\delta_s^c}\right)\frac{1-\lambda'}{\lambda'}\left(\frac{\delta_s}{\delta_s^c}\right)\frac{\sigma_c}{1-\lambda_{cr}},$$

where λ' is monotonically increasing and given by

$$\lambda' = \max(\lambda_{max}, \lambda),$$

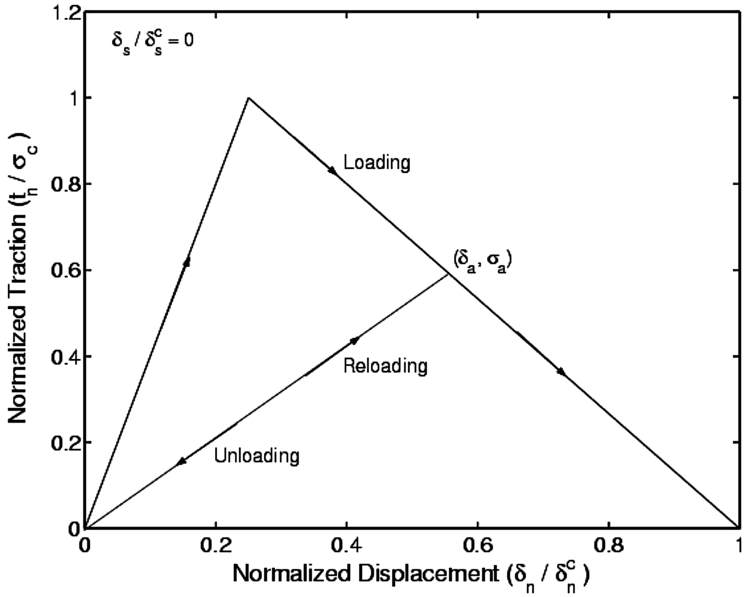


Figure 3. Schematic representation of loading and unloading in terms of displacement jump and traction in the bilinear model.

in which $\lambda_{max} = \lambda_{cr}$ initially and $\lambda_{max} = \lambda$ if $\lambda > \lambda_{max.}$ Figure 3 illustrates a normal displacement jump versus normal traction curve.

4 EXPERIMENTAL TESTING

To obtain accurate fracture (separation) and bulk properties, laboratory tests were conducted on the in-situ materials from cores taken on the pavement sections. Typically, asphalt concrete overlays are placed with relatively thin lifts and often with different mixture designs in each layer. Therefore, a challenge exists in obtaining material properties from thin cylindrical specimens. Wagoner et al. (2005, 2006) described in detail a testing suite for capturing viscoelastic and fracture properties from field cores. The testing suite was capable of measuring four properties: creep compliance, indirect tensile strength, coefficient of thermal expansion, and fracture energy. The creep compliance and indirect tensile strength utilized the Superpave® indirect tension test following the AASHTO T322 specification (2004). The coefficient of thermal expansion was measured using the same instrumentation for the indirect tension test and followed the procedures described by Mehta et al. (1999). The fracture energy was measured using the DC(T) geometry and followed the procedure described by Wagoner et al. (2005).

Figure 4 shows a typical viscoelastic response for asphalt concrete material. The plot shows relaxation modulus master curve as well as time-temperature superposition shift factors for surface and binder courses of US36 Control section at reference temperature (T_{ref}) of −20°C. Laboratory tests for cores from various layers were conducted at 0, −10, and −20°C. Table 1 shows the fracture (separation) properties for the same asphalt materials at −10°C. The current modeling approach utilizes temperature independent fracture properties; however the bulk material response is temperature dependent through the use of a viscoelastic constitutive law. Based on pavement temperature profiles during the coolest climatic event, the fracture properties measured

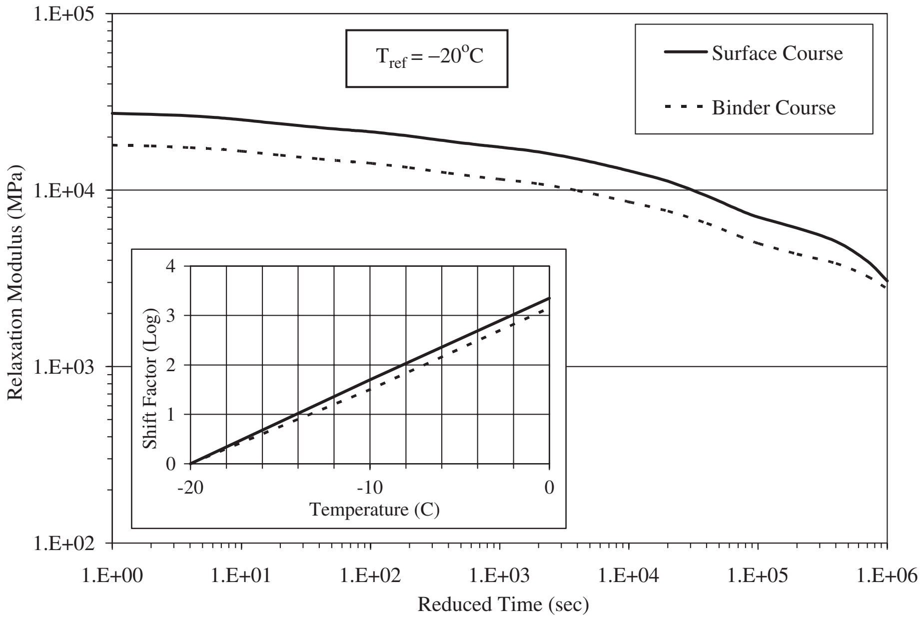


Figure 4. Viscoelastic characterization of asphalt concrete material.

Table 1. Fracture properties of asphalt concrete.

	Surface course	Binder course
Fracture energy (J/m^2)	215	245
Tensile strength (MPa)	1.65	1.76

at −10°C were used as inputs to the cohesive zone fracture model. A rate and temperature dependent fracture model has recently been developed, but the employment of this model is beyond the scope of this paper.

5 VISCOELASTIC MATERIAL MODELING

Asphalt concrete is known to exhibit viscoelastic (time-dependent) material behavior at intermediate and low temperatures. In the current work, a generalized Maxwell model was used to represent relaxation modulus of asphalt concrete, assuming linear viscoelastic behavior at the low temperatures considered in the study (generally 0°C and below). The relaxation moduli were obtained from the creep tests described in the testing suite. Creep tests were performed at three different temperatures and then used to construct a master curve following procedures given by Buttlar et al. (1998). The functional form of the generalized Maxwell model is:

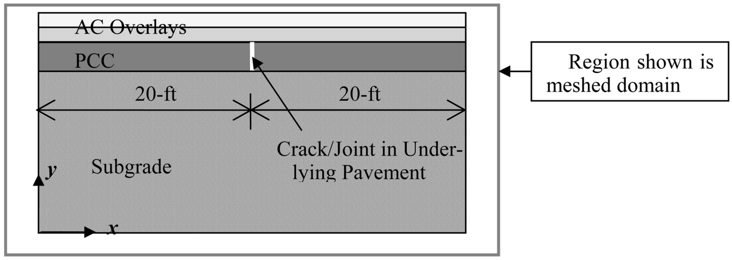
$$E(\xi) = \sum_{i=1}^{n} E_i \, Exp\left[-t/\tau_i \right]$$

Where,
$E(\xi)$ = Relaxation Modulus
E_i = Elastic coefficient of spring in *ith* Maxwell unit
Relaxation time of *ith* spring-dashpot pair, $\tau_i = \eta_i/E_i$
η_i = Viscosity of *ith* dashpot
Reduced time, $\xi = t/a_T$
t = time, and a_T = Time-temperature shift factor

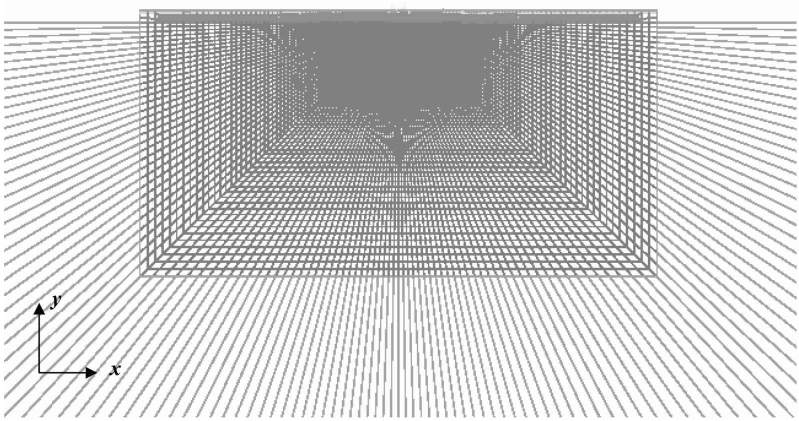
6 FINITE-ELEMENT PAVEMENT MODELING

A commercially available finite element simulation program, *ABAQUS* was used to perform all reflective cracking simulations in this project. A series of user subroutines were developed to employ the viscoelastic and cohesive zone fracture constitutive models developed in this project. The user-subroutine (UEL) option was used to implement the bilinear cohesive zone model described earlier. The basic steps used in the generation of the finite element models were:

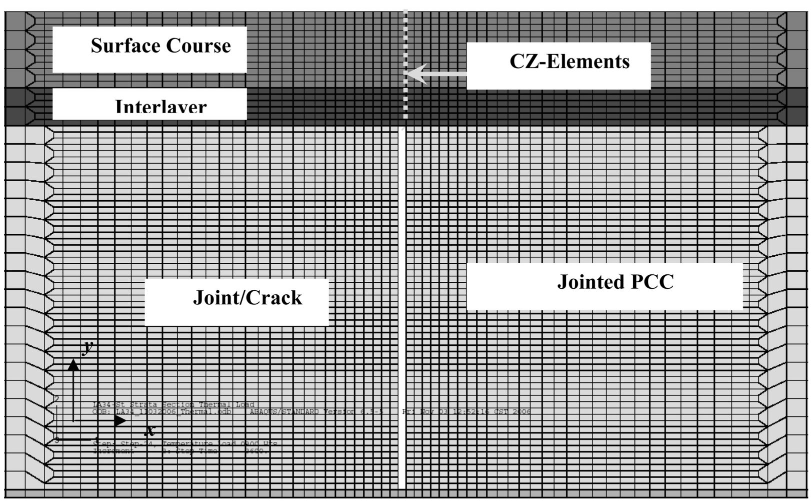
1. Mesh Generation: In the current work, four-noded quadrilateral (Q4) elements were used to represent the pavement structure. Figures 5 shows the finite element discretization and details of the mesh in the vicinity of the underlying pavement crack. Through a domain-extent study it was determined that a domain length extending to 6096-mm (20-ft) on either side of the PCC joint is sufficient.
2. Boundary Conditions: Various constraints are introduced to the model. Specialized "infinite elements" were used to account for the infinite boundary in the subgrade.
3. Loading Conditions: In the current work, two categories of loading were considered: a) thermal loads, and b) mechanical (tire) loads. As temperature within the pavement structure changes continuously with time, the structure undergoes expansion and contraction cycles. As discussed earlier, the temperature profiles can be determined from EICM using climatic information available through the National Oceanic and Atmospheric Administration (NOAA). In addition to thermal loading, the temperature profile input to the finite element model is important, because of temperature dependent properties of asphalt concrete. In the current research, a critical conditions approach was taken, e.g., simulations were performed during cooling cycles having either low pavement temperature and/or a very high rate of cooling. Tire loads were also applied independently and in combination with thermal loading. In the present work, loads were applied on top of the overlay directly over or immediately adjacent to the PCC joint/underlying crack, as this typically creates the most critical loading position for highway pavements.
4. Cohesive Zone Elements: The specialized bi-linear cohesive zone elements implemented by Song et al. (2006) are embedded in the finite element model along pre-defined crack paths. These elements allow for nucleation and propagation of cracks within the model. It is also possible to allow cracks to grow in a non-prescribed manner in the cohesive zone modeling approach, as described by Song et al. (2006); however, this type of CZM implementation is beyond the scope of this paper.
5. Material Properties: Material properties are provided for all the elements within the model. The asphalt concrete material is taken as linear viscoelastic, as described earlier. The underlying concrete slabs and subgrade were modeled as elastic materials, with typical values assigned. For the examples presented herein, subgrade properties were estimated on the basis of the AASHTO classified soil types determined from testing of field collected samples. When possible, it is recommended to utilize falling-weight deflectometer data in the tuning of reflective cracking model parameters to match field responses (Kim and Buttlar, 2002).
6. Analysis and Post-Processing: As mentioned earlier, the commercially available program *ABAQUS*, with added user-subroutines was used for analysis. Once the simulation is complete, the post-processing of data is carried out to determine the extent of reflective cracking and amount and extent of the damage.



(a) Schematic Showing the Meshed Region



(b) Finite-Element Discretization



(c) Details in Vicinity of Crack

Figure 5. Model schematic and finite-element mesh.

7 SIMULATION RESULTS

In this section, typical reflective cracking simulation results are presented for the Cameron, MO (US 36) pavement section. In the latter portion of this section, a hypothetical pavement section is

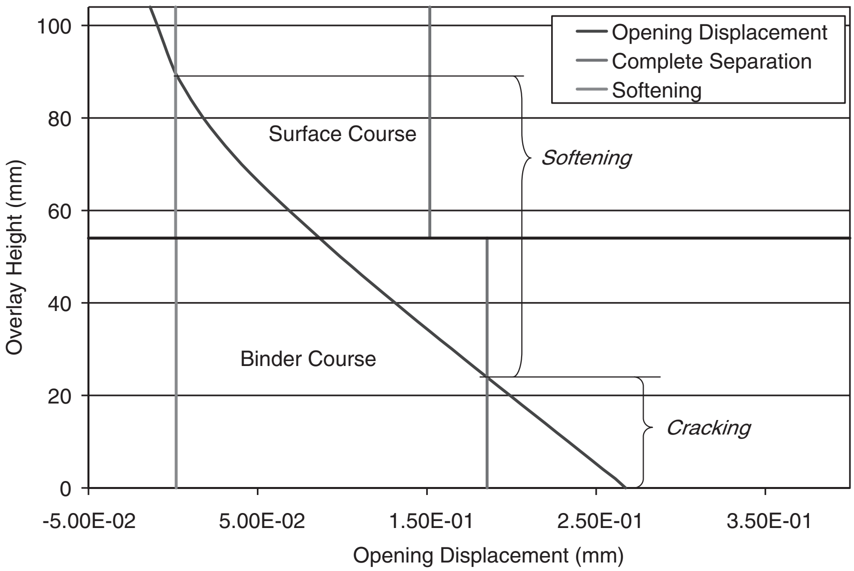


Figure 6. Opening displacement plots for US-36 sections due to single event temperature and single tire load.

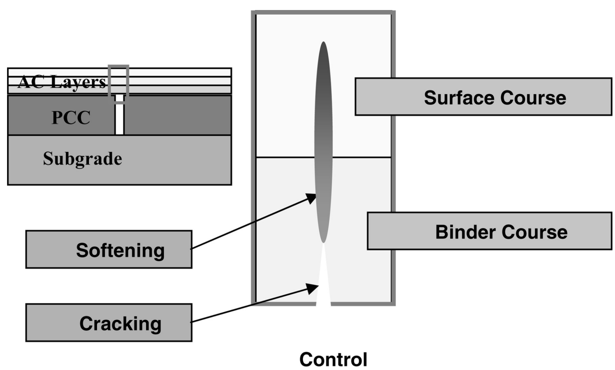


Figure 7. Schematics showing cracking and softening region for US-36 sections under single event temperature and single tire loads.

presented in the context of a design optimization example, whereby the objective was to modify structural and material properties to minimize cracking in the overlay.

7.1 *US36 control section simulation results*

In this simulation series, a single event temperature loading and a single, 9-kip (100-psi) tire load was applied. The single event temperature load extended from pavement surface temperature of 7°C to −15°C. Opening displacements, softening and complete separation (fracture) thresholds for US-36 under thermo-mechanical loading conditions are plotted in Figure 6. This plot shows the opening displacement of the cohesive fracture elements along the crack path, which was used to determine the extent of cracking and region of softening illustrated in Figure 7. In Figure 6 the thresholds for complete separation (fracture) for each material layer are indicated by the red lines and the thresholds for the onset of softening are denoted with magenta lines. Tabulated results summarizing lengths of cracks and softened regions are presented in Table 2.

Table 2. Extent of cracking and softening in US-36 section due to single event temperature and single tire load.

Layers (Thickness)	Length of crack from the bottom of layer (mm)	Length of softened region (mm)
Surface course (50-mm)	–	34
Binder course (54-mm)	24	30

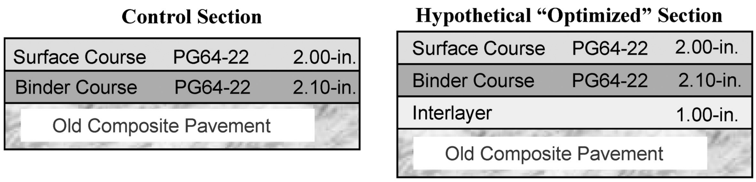


Figure 8. Schematics showing US36 control section and hypothetical section.

Although detailed discussion of field performance data and model calibration is beyond the scope of this paper, a brief summary is appropriate. As shown in Figure 1, the untreated control section in Cameron, MO, consisting of an HMA overlay placed over an existing cracked HMA overlay and underlying PCC pavement, has experienced significant reflective cracking after 5 years of service. The simulation result predicts that, under a critical combination of cold temperatures and a single application of a fully loaded standard tractor trailer, crack propagation and material softening would extend from the bottom of the binder course and into the surface course. Under the single thermo-mechanical loading event, the crack is eventually arrested, due in part to the progression of the crack into a region of compression under the tire load. Findings of a recent National Science Foundation study (NSF Project #0219566, 2002) has demonstrated that repeated combinations of thermal and traffic loads will lead to further crack propagation. The next phase of research will be directed towards bridging between model predictions and field performance through model calibration and validation with additional field observations.

7.2 *Design optimization example*

In the previous simulation example it can be seen that under a single event cooling cycle (temperature drop of −21°C) and a single tire load, significant reflective crack propagation can occur. Once significant cracking such as this has initiated, additional load and temperature cycles will cause the crack to propagate to the surface. A series of finite element runs were performed with hypothetical overlay configurations in an effort to develop a "simulation-guided" interlayer/overlay configuration with reduced or mitigated reflective cracking. The "simulation-guided" hypothetical section is shown in Figure 8.

The hypothetical sections were developed with a highly modified sand-asphalt interlayer placed under the overlay. The results for the optimized section are presented in the form of a displacement plot for the hypothetical section along with the displacement thresholds for fracture and softening, as shown in Figure 9. The model predicts that while the optimized section shows no cracking under the critical thermo-mechanical load, the bottom of the binder course is at the threshold of complete softening and separation. This suggests that the interlayer system: 1) is capable of sustaining the critical thermo-mechanical loading cycle; 2) reduces the critical responses in the overlay system under the aforementioned loading, and; 3) a traditional overlay material may be vulnerable to cracking under repeated applications of critical thermo-mechanical loads, due to the high degree of material softening predicted under a single critical load. This finding also suggests the possible merit of using fracture/fatigue tolerant materials directly above the interlayer.

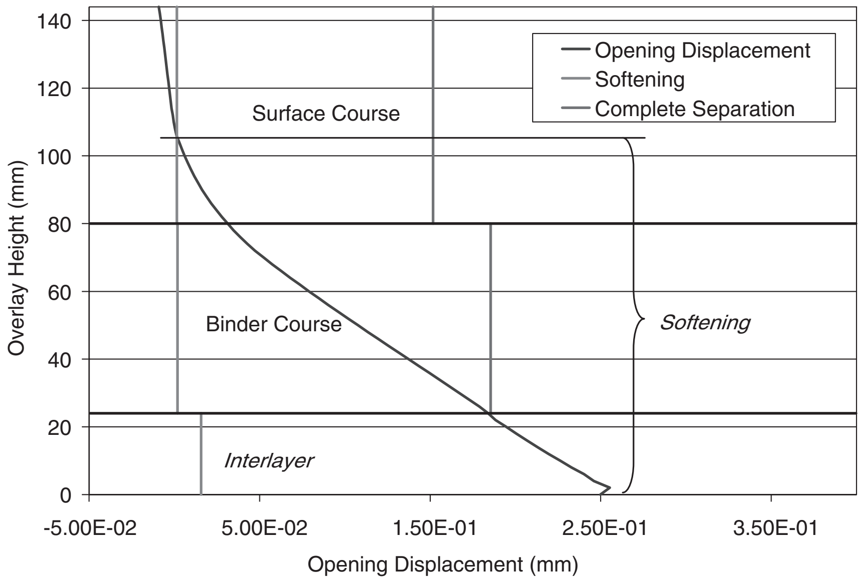


Figure 9. Opening displacement plot for optimized hypothetical section due to single event temperature and single tire load.

Continued research is being directed towards moving the testing and modeling suite described herein towards a mechanistic design procedure for overlay systems. Model calibration and validation will be pursued through additional field sections and accelerated pavement testing. More sophisticated fracture models, including those with improved mixed-mode fracture and fatigue capabilities are under investigation.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 *Conclusions*

Based on the findings presented in this paper, following conclusions can be drawn:

- Finite element simulations with a cohesive zone fracture model provide quantitative measures of predicted softening and cracking under critical thermo-mechanical loading events, which provide useful information for the study of reflective cracking mechanisms
- The testing and modeling approach described herein can be employed as a mechanics-based tool in the design and optimization of overlay systems which resist reflective cracking
- The testing and model approach described herein can be used to characterize and model existing pavement sections, i.e., the system can handle thin pavement lifts, which are often encountered in practice.

8.2 *Recommendations*

Based upon the findings and conclusions presented herein, the following recommendations for future research are suggested:

- Additional work is needed to define how the current model outputs could be used in a mechanistic overlay design procedure. Once established, model calibration and validation will be needed in order to evaluate the predictive accuracy and reliability of the approach.

- The current analysis should be extended by employing temperature and rate dependent cohesive zone fractures models.
- The cohesive zone fracture models should be extended to directly consider fatigue-type damage and cracking under high load repetitions.
- More complex loading configurations, including moving wheel loads with realistic pavement-tire stress patterns should be investigated.
- Additional work in the area of mixed-mode fracture testing and modeling should be pursued.

ACKNOWLEDGEMENT/DISCLAIMER

The authors are grateful for the support provided by SemMaterials, L.P. and the National Science Foundation (NSF) through the GOALI program, award #0219566 (NSF program: Infrastructure Materials and Structural Mechanics; Program manager: Dr. Perumalsamy N. Balaguru). Any opinions expressed herein are those of the authors and do not necessarily reflect the views of the sponsors.

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