PREDICTION OF TOP-DOWN CRACK INITIATION AND CRACK GROWTH IN HOT MIX ASPHALT PAVEMENTS

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Abstract

It has long been accepted that fatigue cracking of hot-mix asphalt pavements is a major mode of premature failure. This paper presents a new viscoelastic crack growth simulator for asphalt pavements. The pavement structure is modelled with a new viscoelastic displacement discontinuity boundary element method. This new numerical method provides an attractive alternative to finite element-based methods for modelling crack initiation and crack growth. Meshes are only required on the boundaries of the pavement system, including cracks. Crack growth is addressed by adding more elements in regions of crack growth. The crack growth law employed was also developed at the University of Florida. A fundamental energy-based threshold is used to determine crack growth and the direction of crack growth, and viscoelastic mixture properties are used to determine the rate of crack growth. The model requires the determination of only four fundamental mixture parameters that can be obtained from less than one hour of testing using the SuperPave\(^{\text{TM}}\) Indirect Tension Test (IDT). These parameters can account for micro-damage, crack propagation, and healing for stated loading conditions, temperatures, and rest periods. The new crack growth simulator is used to model typical Interstate asphalt pavements in Florida. The fracture simulator is shown to predict top-down crack growth patterns in hot mix asphalt pavements observed in the field. Tensile conditions at the top of the modelled pavement due to cyclic tire loads are shown to result in the eventual initiation and growth of vertical cracks that start at the pavement surface and propagate downward. Finally, the predicted cracking performance of several Interstate pavements in Florida is shown to rank in the same manner as observed in the field.

1. Development of a Viscoelastic Fracture Simulator for Asphalt Pavements

Cracking damage in asphalt pavements is typically associated with the fatigue failure characteristics of the pavement. An action of a single truck passing can only cause an unnoticeable amount of cracking damage, i.e. a micro-crack, in the pavement material. However, micro-cracks gradually develop and coalesce into larger macro-cracks that significantly deteriorate the pavement life after years of traffic. Pavement engineers face
the challenge of predicting cracking damage knowing that the amount, rate and direction of the critical cracking failure are the results of the history of traffic loading and environmental effects. Any attempt to understand or to predict the mechanism of the fatigue crack growth in asphalt pavements requires a fracture modelling method that is capable of simulating physical crack development in conjunction with a crack growth rule that resembles the cracking mechanism in asphalt mixtures.

1.1 Viscoelastic Displacement Discontinuity Method

The Displacement Discontinuity (DD) boundary element method provides an attractive solution for modelling crack initiation and crack growth. The DD method requires meshes only on the boundaries of an object or pavement, including cracks. This means that the number of elements required is reduced significantly compared to the finite element method, as discussed in Birgisson et al. (1). Crack growth is addressed simply by adding more DD elements in regions of crack growth. Figure 1 illustrates the DD model of a four-layer pavement structure under two-dimensional plane strain conditions. The pavement boundaries and inter-layers are modelled by a total of 104 elements covering the large extent of pavement geometry presented in the figure. This 104-element DD model was found to yield the stress-displacement solutions at the same level of accuracy as the finite element model with 5,565 solid elements, as presented in Sangpetnagam (2). In addition, the DD method is also implemented using the viscoelastic correspondence principle for solving viscoelastic boundary value problems. This feature allows users to model the time dependent stress-displacement responses of the asphalt mixture in a surface layer due to the application of a truck load. In particular, the asphalt mixture can be represented by either a Burgers viscoelastic material or a viscoelastic material whose compliance is described by the power law.

Fig. 1 – Two-Dimensional Model of a Four-Layer Pavement Structure
At this point, the implemented DD method is capable of modelling a viscoelastic boundary value problem of layered structures including physical cracks. However, an appropriate crack growth rule for asphalt mixtures is still required in order to simulate crack initiation and/or propagation.

1.2 Hot Mix Asphalt Fracture-Mechanics-Based Crack Growth Rule
A new viscoelastic fracture mechanics-based crack growth law, entitled “HMA Fracture Mechanics” was developed recently, based on the observations of results from indirect tensile fracture tests performed on hot mix asphalt samples (3, 4, 5). The crack growth rule suggests that the dissipated creep strain energy (DCSE) limit of asphalt mixtures suitably defines a fracture damage threshold. Damage below the threshold is considered micro-damage (i.e., damage not associated with crack initiation or crack growth) and appears to be fully healable after a resting period, while macro-damage (i.e., damage associated with crack initiation or growth), which does not appear to be healable, occurs when the damage exceeds the threshold. An external load induces the damage increment in the asphalt mixture in the form of strain energy that is dissipated into micro-cracks. Thus the rate of damage increment depends not only on the load magnitude, but also the viscoelastic properties of the mixture. The energy-based limit and viscoelastic properties can be easily determined from the tensile strength test, the resilient modulus test, and the creep test using the Superpave® Indirect Tensile Test following the procedures developed by Roque and Buttlar (6) and Buttlar and Roque (7).

1.3 Hot Mix Asphalt Fracture Simulator
Sangpetngam (2) integrated the HMA fracture mechanics crack growth rule into the viscoelastic boundary element method. The viscoelastic boundary element method determines the amount of dissipated creep strain energy, i.e. incremental damage, which is caused by the applied loads at the critical location, e.g. crack tip. Consequently the crack growth rule is used to determine when a stepwise macro-crack will propagate from that critical location. A study by Sangpetngam (2) suggests that the length of the crack growth increment can be reasonably assumed as one half of the maximum aggregate size of the asphalt mixture, while the crack growth direction is governed by the direction that produces the maximum dissipated strain energy. The resulting hot mix asphalt (HMA) fracture simulator can be used to predict the fatigue crack growth in asphalt mixtures.

2. Prediction of Top-Down Crack Growth in Asphalt Pavements

2.1 Field Pavement Sections
Two pairs of field pavement sections in Florida were chosen to be evaluated as part of an ongoing longitudinal wheel path cracking study. The pavement sections were chosen so that they had experienced the same or very similar traffic volume and environmental conditions. The first pair was selected from two locations of Interstate 110 in Madison County and the second pair was from two locations of Interstate 175 Charlotte County, as shown in Table 1. The evaluation included performance surveying, laboratory testing of samples obtained from coring, and in situ non-destructive testing. Truck traffic was heavy for all sections with annual equivalent single axle loads (ESALs) shown in Table 1. The results of measured layer thicknesses and modulus determinations are given in Table 2. The DCSE limit and viscoelastic properties of asphalt mixtures from all field
sections were obtained from laboratory tests as shown in Table 3. More details about the sections can be found in Sangpetngam (2).

Even though, the cracking damage in reality is a result of cumulative damage that occurs under various environmental conditions throughout the history of a pavement, it is still too complicated for the fracture simulator to account for all of those conditions at this stage. Therefore, we will perform crack growth predictions only to compare the relative performance between two sections in each pavement pair. Thus, rather than performing analysis at various pavement conditions, a pre-selected condition that is considered critical for cracking damage will be used for the crack growth prediction for all sections. For this reason, we shall conduct the cracking predictions of all sections with properties of the asphalt layer at 10°C and properties of other layers as shown in Tables 2 and 3.

Table 1. General Description of Field Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Route / Milepost</th>
<th>Annual ESALs (x1000)</th>
<th>Age (Years)</th>
<th>Crack Depth (mm)</th>
<th>Relative Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>I10MW1</td>
<td>I10 Madison westbound / 24-29</td>
<td>546</td>
<td>10</td>
<td>5</td>
<td>Good</td>
</tr>
<tr>
<td>I10MW2</td>
<td>I10 Madison county westbound / 29-32</td>
<td>546</td>
<td>10</td>
<td>66</td>
<td>Poor</td>
</tr>
<tr>
<td>I75-1U</td>
<td>I75 Charlotte county / 0-12</td>
<td>6702</td>
<td>14</td>
<td>Uncracked</td>
<td>Good</td>
</tr>
<tr>
<td>I75-1C</td>
<td>I75 Charlotte county / 12-28</td>
<td>7443</td>
<td>15</td>
<td>56</td>
<td>Poor</td>
</tr>
</tbody>
</table>

ESALs = Equivalent Single Axle Loads

Table 2. Layer Thickness and Modulus of Field Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Layer Thickness (mm)</th>
<th>Layer Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asphalt</td>
<td>Base</td>
</tr>
<tr>
<td>I10MW1</td>
<td>127</td>
<td>254</td>
</tr>
<tr>
<td>I10MW2</td>
<td>127</td>
<td>254</td>
</tr>
<tr>
<td>I75-1U</td>
<td>159</td>
<td>305</td>
</tr>
<tr>
<td>I75-1C</td>
<td>165</td>
<td>305</td>
</tr>
</tbody>
</table>

Table 3. Properties of Asphalt Mixtures of Field Sections at 10°C

<table>
<thead>
<tr>
<th>Section</th>
<th>Dissipated Creep Strain Energy Limit (KJ/m^3)</th>
<th>Compliance, D(t) = D_0 + D_1 t^m (MPa^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D_0</td>
<td>D_1</td>
</tr>
<tr>
<td>I10MW1</td>
<td>2.262</td>
<td>1.47 x 10^-4</td>
</tr>
<tr>
<td>I10MW2</td>
<td>0.9483</td>
<td>3.08 x 10^-5</td>
</tr>
<tr>
<td>I75-1U</td>
<td>1.813</td>
<td>6.85 x 10^-5</td>
</tr>
<tr>
<td>I75-1C</td>
<td>0.9793</td>
<td>9.48 x 10^-5</td>
</tr>
</tbody>
</table>
2.2 Pavement and Crack Modelling

The DD model in Figure 1 is used for predicting crack growth in all four pavement sections. The thickness and properties of each layer in the pavement model are defined in Tables 2 and 3. To simulate the top-down cracking which was observed in the field, a small discontinuity is introduced at the surface of the pavement model at a location of 570 mm from the centre of tire load, which is the area of critical surface tensile stress during the period of loading (2, 8).

Fig. 2 – Geometry and Rate of Crack Growth of Pavement Section I10MW1
Repeated tire loads with the equal load magnitude of 40-kN and loading period of 0.1 second are applied to the pavement surface at the same location at the beginning of every second. The HMA fracture simulator determines the amount of cracking damage, i.e. dissipated creep strain energy, caused by each tire load and then predicts the stepwise crack growth in conjunction with the number of load applications. The geometry of the predicted crack growth in the asphalt mixture layer along with the corresponding tire loads at each growing step is shown in Figure 2.

**Fig. 3 – Prediction of Crack Growth Rate for the Pavement Sections Studied**
2.3 Comparison between Prediction and Field Performance

Figure 3 shows the predicted crack growth in the four sections studied. The results of crack growth rate predictions suggest that pavement section I10MW1 performs better than I10MW2 and section I75-1U is better than I75-1C. It should be pointed out that the I75-1U section was uncracked in the field, but had predicted cracking damage in the HMA fracture simulator. This is due to the fact that we put a small crack in the tensile zone of all pavement sections in order to initiate crack growth for this study. The existing cracks acted to focus tensile stresses and thus led to crack growth. However, the rate of crack growth between the good and poor performing sections agreed with the observed field performance, shown in Table 1. Thus, we may conclude based on this study that the HMA fracture simulator is successful in predicting the relative performance between pavement sections under the same environmental conditions.

3. Conclusions

This paper presented a new viscoelastic boundary element-based pavement fracture simulator. Cracks are modelled using displacement discontinuity boundary elements. Fracture initiation and rate of crack growth is predicted using HMA Fracture Mechanics, previously presented by Zhang et al. (4,5) and Roque et al. (3). The new fracture simulator is used to predict the relative cracking performance of four Interstate field pavement sections of known relative cracking performance. The resulting crack predictions show that the new fracture simulator predicts the same relative cracking performance as observed in the field, and thus separated well-performing sections from poorly performing sections.

Based on the results presented, it can be concluded that the visco-elastic boundary element method presented provides a promising means of simulating the onset and development of fracture in hot mix asphalt pavements.

Future work will focus on the integration of capabilities for dealing with variable environmental conditions and variable load spectra and load histories.

4. Acknowledgements

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5. References


