Damage Theory Applied to Fatigue Tests in Gap-Graded Asphalt Mixtures with 4th Generation Rubberized Asphalt

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Fatigue Cracking

Classical Approach

Mechanic of Fracture

Continuum Damage

\[ N_f = K_1 \left( \frac{1}{\varepsilon} \right)^{K_2} \]

\[ \frac{da}{dN} = A \cdot \Delta K^n \]

\[ D_m = \left( -\frac{\partial W^R}{\partial D_m} \right)^{\alpha_m} \]
Methodology for Applying CDT

1. The elastic-viscoelastic correspondence principle;

2. The definition of a Pseudo-Energy Density Function; and

3. The definition of a Damage Evolution Law.
Methodology for Applying CDT

**VECD equations:**

<table>
<thead>
<tr>
<th>Pseudo-Strain</th>
<th>( \varepsilon^R = \frac{1}{E_R} \cdot \int_0^t E (t - \tau) \frac{d\varepsilon}{dt} \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-strain relation (E-VE correspondence principle)</td>
<td>( \sigma = C \varepsilon^R )</td>
</tr>
<tr>
<td>Energy equation</td>
<td>( \sigma = \frac{\partial W^R}{\partial \varepsilon^R} ) ( W^R = \frac{1}{2} C \varepsilon^R^2 )</td>
</tr>
<tr>
<td>Damage evolution law</td>
<td>( \frac{dD_S}{dt} = \left(- \frac{\partial W^R}{\partial D_S}\right)^{\alpha_S} )</td>
</tr>
</tbody>
</table>
Methodology for Applying CDT

\[ \dot{D}_S = \left( - \frac{\partial W^R}{\partial D_S} \right)^{\alpha_S} \]

- \( \alpha \) is a material constant;
- Initially, it could be defined as viscoelastic property: relaxation or creep test.

Numerical Integration

\[ D = \sum_{i=1}^{N} \left[ \frac{l}{2} \cdot (\varepsilon^R)^2 \cdot (C_{i-1} - C_i) \right]^\frac{\alpha}{1+\alpha} \cdot (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \]
Damage Characteristic Curve (C-D curve)

\[ C = C_0 - C_1 \cdot D^{C_2} \]

- Proposed as a fundamental material property that governs damage growth under all conditions – stress level, strain level, frequency/rate, and temperature.
Materials and Tests Methods

Five asphalt-rubber mixtures of gap-graded gradation with different 4th generation asphalt-rubber compositions added to the CAP 50/70 binder were produced:

- MAB-R25 with addition of 25% RAR in binder mass
- MAB-P with addition of this material in 30% of binder mass
- MAB-R30-1 with addition of 30% RAR by binder mass
- MAB-R30-2
- MAB-R30-3
Materials and Tests Methods

Five asphalt-rubber mixtures of gap-graded gradation with different 4th generation asphalt-rubber compositions added to the CAP 50/70 binder were produced:
Materials and Tests Methods

<table>
<thead>
<tr>
<th>Test Protocol</th>
<th>Frequency (Hz)</th>
<th>Temperature (°C)</th>
<th>Strain (µε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Modulus (4PB)</td>
<td>EN 12967-24</td>
<td>0.1, 1, 2, 5, 10, 15, 20, 25</td>
<td>5, 15, 25, 35</td>
</tr>
<tr>
<td>Fatigue (4PB)</td>
<td>AASHTO T321</td>
<td>10</td>
<td>5, 12.5, 20</td>
</tr>
</tbody>
</table>
Fatigue tests (flexural)

Laboratory data ($\varepsilon, \sigma, N$)

Pseudo Strain calculation

$$\varepsilon_R = \frac{1}{E_R} \int_0^t E (t - \tau) \frac{d\varepsilon}{dt} \, d\tau$$

Pseudo stiffness calculation

$$C = \frac{\sigma}{\varepsilon_R}$$

Damage Parameter

$$D = \sum_{i=1}^{N} \left[ \frac{1}{2} \cdot (\varepsilon_R)^2 \cdot (C_{i-1} - C_i) \right]^{\frac{1}{1 + \alpha}} \cdot (t_i - t_{i-1})^{\frac{1}{1 + \alpha}}$$

Definition of parameter $\alpha$

Is $C(D)$ unique?

END
Results
Damage evolution with the strain
Mixtures tested at T=20°C
Results

Damage evolution with the strain
Mixtures tested at $T=12.5^\circ C$ and $T=5.0^\circ C$

MAB-R30-2, at $5.0^\circ C$

MAB-R30-3, at $12.5^\circ C$
Results
C-D Curves
Mixtures tested at T=20°C

\[ C = C_0 - C_1 \cdot D^{\alpha} \]

\[ C = C_0 - C_1 \cdot D^{C_2} \]

Model
\[ \alpha = 1.91 \]

\[ \alpha = 2.31 \]

\[ \alpha = 1.79 \]

MAB-P
MAB-R30-1
MAB-R25
Results

C-D Curves
Mixtures tested at T=12.5 and 5.0°C

\[ C = C_0 - C_1 \cdot D^{C_2} \]

MAB-R30-2, at 5.0°C

\[ \alpha = 2.08 \]

MAB-R30-3, at 12.5°C

\[ \alpha = 2.30 \]
For mixtures modified with the same percentage of rubber asphalt, coefficient $C_0$ increases for lower temperatures. Coefficient $C_1$ is closely related to the negative slope of the characteristic curves.

The coefficient $C_0$ is very close to unity as expected. Coefficient $C_1$ is closely related to the negative slope of the characteristic curves. $\alpha$ presented the same trend of parameter $k_2$ for the fatigue.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Temperature</th>
<th>$C_0$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$\alpha$</th>
<th>$k_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAB-P</td>
<td>20°C</td>
<td>0.99</td>
<td>4.36E-04</td>
<td>0.59</td>
<td>1.91</td>
<td>4.32</td>
</tr>
<tr>
<td>MAB-R25</td>
<td>20°C</td>
<td>1.03</td>
<td>7.44E-03</td>
<td>0.37</td>
<td>1.79</td>
<td>5.54</td>
</tr>
<tr>
<td>MAB-R30-1</td>
<td>20°C</td>
<td>1.03</td>
<td>3.88E-03</td>
<td>0.42</td>
<td>2.31</td>
<td>5.96</td>
</tr>
<tr>
<td>MAB-R30-2</td>
<td>5°C</td>
<td>1.00</td>
<td>1.02E-04</td>
<td>0.67</td>
<td>2.08</td>
<td>3.59</td>
</tr>
<tr>
<td>MAB-R30-3</td>
<td>12.5°C</td>
<td>1.01</td>
<td>3.04E-04</td>
<td>0.59</td>
<td>2.30</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Also $k_2$ is lower for lower temperatures!
C-D Curves
Mixtures tested at T=20°C

Comparison should be made using a pavement structural analysis!
Results

C-D Curves
Mixtures modified with RAR tested at 5.0, 12.5 and 20°C

Comparison should be made using a pavement structural analysis!
Conclusions

• The evolution of internal damage in hot mix asphalt (HMA) can be properly evaluated using the framework of the Continuum Damage Theory (CDT) to determine its characteristic curve;

• The characteristic curves proved to be unique for a wide range of strain amplitudes for all compositions asphalt-rubber mixes investigated;

• Tests with different temperatures for the same composition (MAB-R30-1, MAB-R30-2 and MAB-R30-3) and the same temperature for different materials (MAB-P, MAB-R25 e MAB-R30-1) showed α parameter with the similar behavior of the parameter k₂;

• For more conclusions about the damage evolution, numerical analyzes and complementary tests involving the use of the C-D curves are necessary.
THANK YOU!

PROGRAMA DE PÓS-GRADUAÇÃO EM GEOTECNIA – PPG/UnB