Cracking Group Experiment – Evaluation of Laboratory Cracking Tests

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Project Team

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- Fan Yin
  Research Engineer
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  Research Engineer
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  GRA/ Research Engineer
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  GRA
- Chen Chen
  GRA
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  Technician
Cracking Group Experiment

- 7 Test Sections
- Common Structure
  - Subgrade, Aggregate Base, Base and Binder Mixture
- 7 Unique Surface Mixtures
  - Wide Range of Expected Cracking Resistance
- Top-Down, Load-Related Cracking
- Intermediate Temperatures
- Compare Field Cracking Performance to Laboratory Cracking Test Results
- Constructed in 2015
NCAT Test Sections

1 Cycle, 10 MESALs

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Rutting (mm)</th>
<th>Δ IRI (in/mi.)</th>
<th>Δ MTD (mm)</th>
<th>Cracking (% of lane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>20% RAP (Control)</td>
<td>1.7</td>
<td>3</td>
<td>0.4</td>
<td>21.5*</td>
</tr>
<tr>
<td>N2</td>
<td>Control w/ High Density</td>
<td>2.2</td>
<td>7</td>
<td>0.5</td>
<td>6.2*</td>
</tr>
<tr>
<td>N5</td>
<td>Low AC, Low Density</td>
<td>1.2</td>
<td>5</td>
<td>0.4</td>
<td>5.0*</td>
</tr>
<tr>
<td>N8</td>
<td>20% RAP, 5% RAS</td>
<td>1.2</td>
<td>13</td>
<td>0.7</td>
<td>16.9</td>
</tr>
<tr>
<td>S5</td>
<td>35% RAP, PG 58-28</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>S6</td>
<td>Control w HiMA</td>
<td>1.4</td>
<td>10</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>S13</td>
<td>AZ Rubber Mix</td>
<td>2.8</td>
<td>3</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

* = Low Severity Hairline Cracking

- Trafficking will continue in 2018 Research Cycle
Testing Plan

• Mix Types
  ▶ Production Plant Mix (PMLC)
  ▶ Lab-Mixed, Lab-Compacted from Production Raw Materials (LMLC)
  ▶ Density – All specimens to 7% Air Void Except N2 (4%) and N5 (10%)

• Aging Protocols
  ▶ Reheated Plant Mix (RH)
  ▶ Short-term oven aged (STOA)
  ▶ Long-term oven aged (LTOA)
    ▶ a.k.a. ‘Critical Aging’ (CA)
Testing Plan

• Cracking Tests
  ▶ 2 aging conditions (STOA/RH and Critically Aged)
  ▶ X 2 production methods (LMLC and PMLC)
  ▶ X 6 cracking tests (I-FIT, SCB-Jc, ER, OT-TX, OT-NCAT, IDEAL-CT)
  ▶ X 7 unique surface mixes
  ▶ = 168 sets of specimens

• Outlier Analysis performed using ASTM E178-16a
## Testing Plan

<table>
<thead>
<tr>
<th>Energy Ratio</th>
<th>I-FIT</th>
<th>OT - TX</th>
<th>OT - NCAT</th>
<th>SCB-Jc</th>
<th>IDEAL-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH PMLC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>STOA LMLC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>CA PMLC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CA LMLC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
</tr>
</tbody>
</table>

- **X** = Testing Complete
- **O** = Analysis in Progress
Energy Ratio

• Test Temperature = 10°C
• Combination of 3 Tests
  ▶ Resilient Modulus
    ▶ How stiff is my material?
  ▶ Creep Compliance
    ▶ How does it deform under a constant load?
  ▶ Fracture Energy
    ▶ How much energy can my material absorb before it breaks?
▶ Results combined to calculate Energy Ratio
Overlay Tester – TX vs. NCAT

- **OT-TX**
  - 25°C
  - Tex-248-F Parameters
  - 0.1 Hz
  - 0.025” Maximum Opening Displacement
  - Cycles to Failure
  - 93% Reduction in Peak Load
  - AMPT OT Jig

- **OT-NCAT**
  - 25°C
  - Modified Parameters
  - 1 Hz
  - 0.015” Maximum Opening Displacement
  - Cycles to Failure
  - Peak of Load x Cycles Graph
  - AMPT OT Jig
Overlay Test – Failure Analysis

Peak Normalized Load x Cycles

93% Load Reduction

Peak Load (kN) vs Number of Cycles

- Peak Load (kN)
- NL x Cy

Normalized Load x Cycles
Illinois Flexibility Index Test (I-FIT)

- 25°C
- 50 mm/min load rate
- Minimum 4 replicates
- 50 mm wide specimens
- Notch Depth = 15 mm
- Notch Width = 1.5 mm
- Load vs. Axial Deformation
- Test until load drops below 0.1 kN
  ▶ Complete Fracture
I-FIT Flexibility Index

**Specimen A**
- FE = 1,692 J/m²
- Slope = -6.442 kN/mm
- FI = 2.63

**Specimen B**
- FE = 1,683 J/m²
- Slope = -2.220 kN/mm
- FI = 7.58
Semi-Circular Bend – $J_c$ Method

- 25°C
- 0.5 mm/min load rate
- 57 mm wide specimens
- 12 replicates
- 3 notch depths
  - 25.4 mm
  - 31.8 mm
  - 38.1 mm
- 3.0 ± 0.5 mm notch width
Semi-Circular Bend – $J_c$ Method

![Graph showing the relationship between load (kN) and external displacement (mm) for different notch lengths.](image)

- **Increasing Notch Length**

- **Equation for Strain Energy to Failure (kN-mm)**
  
  \[ y = -0.0232x + 1.1052 \]
  
  \[ R^2 = 0.9852 \]
IDEAL-CT

- 25°C
- Indirect Tensile Strength
  - No specimen cutting or notching
- 50 mm/min load rate
- Measure Load-Line Displacement
- Similar Post-Peak Analysis to I-FIT

$CT_{\text{Index}}$
Long-Term Aging Procedure

• Past Research at NCAT and elsewhere
• 70,000 CDD
  - Between 3-5 years of field aging in Alabama
• Dubbed ‘Critical Aging’ (CA)
• Rheological Property Study conducted by Fan Yin and Chen Chen
• 8 hours at 135°C for Test Track Materials
Questions to Answer

• Which laboratory cracking test best relates to field performance?

▶ A: Ongoing. Additional cycle of trafficking required to get full field cracking behavior.

▶ At this point, test should identify N8 (Ctrl + 5% RAS) as most cracking susceptible

▶ S5, S6, and S13 (no cracking) should be among top performers
Questions to Answer

• What are the general trends these tests are showing between the seven unique CG surface mixtures?
I-FIT Flexibility Index

<table>
<thead>
<tr>
<th></th>
<th>RH PMLC</th>
<th>STOA LMLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% RAP Ctrl.</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>High Dens. Ctrl.</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Low Dens./AC Ctrl.</td>
<td>2.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Ctrl + 5% RAS</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>35% RAP PG 58-28</td>
<td>6.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Ctrl + HiMA</td>
<td>4.5</td>
<td>14.7</td>
</tr>
<tr>
<td>AZ Rubber</td>
<td>10.4</td>
<td>15.1</td>
</tr>
</tbody>
</table>
## Texas Overlay Tester

<table>
<thead>
<tr>
<th></th>
<th>RH PMLC</th>
<th>STOA LMLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% RAP Ctrl.</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>High Dens. Ctrl.</td>
<td>59</td>
<td>28</td>
</tr>
<tr>
<td>Low Dens./AC Ctrl</td>
<td>17</td>
<td>59</td>
</tr>
<tr>
<td>Ctrl + 5% RAS</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>35% RAP PG 58-28</td>
<td>61</td>
<td>47</td>
</tr>
<tr>
<td>Ctrl + HiMA</td>
<td>13</td>
<td>229</td>
</tr>
<tr>
<td>AZ Rubber</td>
<td>1725</td>
<td>539</td>
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</tbody>
</table>
NCAT Modified Overlay Tester

<table>
<thead>
<tr>
<th></th>
<th>20% RAP Ctrl.</th>
<th>High Dens. Ctrl.</th>
<th>Low Dens./AC Ctrl</th>
<th>Ctrl + 5% RAS</th>
<th>35% RAP PG 58-28</th>
<th>Ctrl + HiMA</th>
<th>AZ Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH PMLC</td>
<td>516</td>
<td>697</td>
<td>189</td>
<td>12</td>
<td>773</td>
<td>411</td>
<td>3,054</td>
</tr>
<tr>
<td>STOA LMLC</td>
<td>382</td>
<td>688</td>
<td>155</td>
<td>49</td>
<td>672</td>
<td>2,881</td>
<td>4,382</td>
</tr>
</tbody>
</table>
### SCB Critical J-Integral ($J_c$)

The graph shows the 95% CI from the Regression Error Estimate for different conditions. The data is presented in a table below:

<table>
<thead>
<tr>
<th>Condition</th>
<th>SCB-$J_c$ (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% RAP Ctrl.</td>
<td>0.36</td>
</tr>
<tr>
<td>High Dens. Ctrl.</td>
<td>0.61</td>
</tr>
<tr>
<td>Low Dens. /AC Ctrl</td>
<td>0.34</td>
</tr>
<tr>
<td>Ctrl + 5% RAS</td>
<td>0.39</td>
</tr>
<tr>
<td>35% RAP PG 58-28</td>
<td>0.34</td>
</tr>
<tr>
<td>Ctrl + HiMA</td>
<td>0.37</td>
</tr>
<tr>
<td>AZ Rubber</td>
<td>0.51</td>
</tr>
</tbody>
</table>
### Energy Ratio

<table>
<thead>
<tr>
<th></th>
<th>RH PMLC</th>
<th>STOA LMLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% RAP Ctrl.</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>High Dens. Ctrl.</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Low Dens./AC Ctrl.</td>
<td>3.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Ctrl + 5% RAS</td>
<td>12.8</td>
<td>8.1</td>
</tr>
<tr>
<td>35% RAP PG 58-28</td>
<td>7.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Ctrl + HiMA</td>
<td>9.2</td>
<td>6.9</td>
</tr>
<tr>
<td>AZ Rubber</td>
<td>2.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Questions to Answer

• What is the impact of additional laboratory aging on the results of these cracking tests?
• How does additional aging impact relative rankings between mixtures?
Aging Evaluation – 1:1 Plots

- Property Greater with Aging
- R² Gives Sense of Agreement Between Aged and Unaged Mix
- Relative Rankings
- One Unique Mix - Aged vs. Unaged
- Property Reduced with Aging
- Line of Equality
1:1 – I-FIT Flexibility Index

\[ y = 0.447x - 0.261 \]
\[ R^2 = 0.708 \]

\[ y = 0.323x - 0.591 \]
\[ R^2 = 0.927 \]
1:1 – IDEAL-CT (CT_{Index})

\[ y = 0.319x + 2.672 \]
\[ R^2 = 0.981 \]

\[ y = 0.464x - 5.018 \]
\[ R^2 = 0.926 \]
1:1 – OT-TX Cycles to Failure

\[ y = 0.830x^{0.580} \]
\[ R^2 = 0.720 \]

\[ y = 0.505x^{0.664} \]
\[ R^2 = 0.799 \]
1:1 - OT-NCAT Cycles to Failure

\[ y = 0.269x^{0.923} \]
\[ R^2 = 0.715 \]

\[ y = 0.016x^{1.253} \]
\[ R^2 = 0.944 \]
$y = 0.405x + 0.153$

$R^2 = 0.135$
1:1 – Energy Ratio

Energy Ratio - RH/Short-Term Aging

Energy Ratio - Critical Aging

PMLC: \( y = 1.356x + 6.215 \)
\( R^2 = 0.382 \)

LMLC: \( y = 2.365x + 2.470 \)
\( R^2 = 0.513 \)
Questions to Answer

• How do these laboratory cracking test results correlate to one another?
  ▶ A: Pearson Correlation Analysis
  ▶ On average, do these tests correlate to one another when compared using the same aging condition?
Correlation Methodology

• According to Evans (1996)
  ▶ Coefficient of 0.8-1.0 = Very Strong Correlation
  ▶ Coefficient of 0.6-0.8 = Strong Correlation

• Correlation Matrix
  ▶ 22 data sets x 7 unique mixtures
    ▶ SCB-Jc LMLC Data still pending
  ▶ Average Correlation Values
    ▶ Average of 4 aging conditions
    ▶ 4 unique Pearson Coefficients
Average Correlation Example

• Correlation Coefficients
  ▶ RH PMLC I-FIT vs. IDEAL-CT = 0.887
  ▶ STOA LMLC I-FIT vs. IDEAL-CT = 0.941
  ▶ CA PMLC I-FIT vs. IDEAL-CT = 0.829
  ▶ CA LMLC I-FIT vs. IDEAL-CT = 0.939

• ‘Average’ Coefficient
  ▶ Average I-FIT vs. IDEAL-CT = 0.899

• Reduce 22 x 22 Matrix to ‘Average’ 6 x 6 Matrix
Average Correlation – Same Aging

<table>
<thead>
<tr>
<th></th>
<th>I-FIT</th>
<th>IDEAL-CT</th>
<th>OT-TX</th>
<th>OT-NCAT</th>
<th>SCB-Jc*</th>
<th>ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-FIT</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IDEAL-CT</td>
<td>0.899</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OT-TX</td>
<td>0.835</td>
<td>0.984</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OT-NCAT</td>
<td>0.941</td>
<td>0.961</td>
<td>0.947</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCB-Jc*</td>
<td>0.427</td>
<td>0.642</td>
<td>0.687</td>
<td>0.680</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ER</td>
<td>-0.377</td>
<td>-0.500</td>
<td>-0.459</td>
<td>-0.357</td>
<td>-0.273</td>
<td>1</td>
</tr>
</tbody>
</table>

- Average of 2 data sets, not 4 (missing LMLC)
Things We’ve Learned

- Strong Correlation Between 4 of the 6 Laboratory Cracking Tests
  - I-FIT, IDEAL-CT, OT-TX, OT-NCAT
  - Each test has its own idiosyncrasies
    - I-FIT/IDEAL-CT
      - Effect of density on post-peak analysis
    - OT-TX, OT-NCAT
      - Cyclic Test Variability
      - Test Speed (Gluing)
Things We’ve Learned

• I-FIT, IDEAL-CT, OT-TX, OT-NCAT
  ▶ Identified N8 (Ctrl + 5% RAS) as low performer
    ▶ First to crack and highest severity of cracking
  ▶ Had the sections that have not cracked yet among the top performers
    ▶ S5 (35% RAP w/ PG 58-28), S6 (Ctrl w/ HiMA), and S13 (AZ Rubber)
  ▶ S6 (Ctrl w/ HiMA) generally showed better performance with LMLC than the PMLC for these tests
Things We’ve Learned

- For SCB-$J_c$, most PMLC mixes showed an appropriate aging trend, but lower discrimination between mixes
  - Did not distinguish N8 (Ctrl + 5% RAS) as the low performer
  - Still waiting on LMLC data for final analysis
- Energy Ratio showed reverse aging trend
  - Aging the mix improved the cracking resistance parameter
  - Logical aging trends on component tests
Things We Still Want To Learn

- Our Analysis is Ongoing and Evolving
  - Field cracking data from 2018 cycle to finalize lab to field comparisons
    - Recommend Test or Test(s) that best match field performance
  - Additional Statistical Analysis
  - Analysis of Additional Cracking Parameters
    - New Texas OT Curve Parameters
  - Density Correction Factors
    - I-FIT and IDEAL-CT
THANKS!

FHWA Mixture ETG – May 2018