Develop Mix Design and Analysis Procedures for Asphalt Mixtures Containing High-RAP Contents – TPF 5(294)

Louay N. Mohammad
Wei Cao
Department of Civil and Environmental Engineering
Louisiana Transportation Research Center
Louisiana State University

FHWA Asphalt Binder Expert Task Group
Salt Lake City, Utah
April 25 – 27, 2016
Outline

- Update

- Mixture Experiment
  - ALF Experiment
    - Direct Tension Cyclic Fatigue – SVECD
      - 10 Lanes
    - SCB
      - L3, L5, L7
    - Texas Overlay
**Objective**

- Evaluate fatigue/fracture tests that can be conducted on plant mixtures (lab or field compacted) from participating states
  - ranking the quality of RAP and or RAP/RAS mixtures as compared to virgin mixtures.
  - Develop score card
Scope

- Two field projects
  - Each field project
    » Two mixtures: Conventional, RAP and/or RAS
      • Conventional may include 15% RAP
  - Four mixtures

- Collect Mix Design / Pavement Design Record
  - JMF
  - Loose mixtures
  - Cores
    » Challenging

- Materials Characterization
  - Mixture Experiment
    » Cracking tests
  - Binder Experiment
    » Rheology and Chemistry
Binder Experiment

- Binder Rheology
  - PG grading
  - MSCR
  - GPC (Gel permeation chromatography)
  - SARA
  - Others

GPC

- GPC separates molecules on the basis of size (like sieving!).
- When a mixture of molecules dissolved in a solvent is applied to the top of the column, the smaller molecules are distributed through a larger volume of gel than is available to the large molecules. Consequently, the large molecules move more rapidly through the column, and in this way the mixture can be separated (fractionated) into its components.
Mixture Experiment

- Specimen Types
  - Plant produced laboratory compacted (PL)
  - Plant Produced Field Compacted (PF, Cores)
    » Challenging
  - Triplicates

- Fracture/fatigue testing
  - Semi-circular bend test, SCB
  - Overlay tester test, OT
  - Energy Ratio Test
  - Beam Fatigue Test
  - Direct Tension Cyclic Fatigue
    » SVECD

- Per mixture and Specimen type
  - 5 tests x 3 = 15 mixes
Field Projects

FHWA
- **Advance Use of Recycled Asphalt in Flexible Pavement Infrastructure: Develop and Deploy Framework for Proper Use and Evaluation of Recycled Asphalt in Asphalt Mixtures**
  - 10 Lanes

FLDOT
- SR 21 Clay County
- Hubbard Construction
- West Palm Beach area
- Mix 1: Mix with 40% RAP
- Mix 2: Mix with ~20% RAP
Data Analysis

- Each test will be ranked
- Develop a score card
Data Analysis

- Each test will be ranked
  - Specimen preparation
  - Instrumentation
  - Standard test method
  - Testing
  - Training
  - Interpretation
  - Sensitivity to mix composition parameters
  - Routine Application
  - Correlation to field performance
  - Data Analysis
  - Repeatability

| 3. Testing | 1: Testing is very involved and requires substantial oversight. | 2: Testing requires heavy oversight. | 3: Testing requires moderate oversight. | 4: Testing is very straightforward and requires little oversight. |
FHWA ALF Overview

➢ Materials and structures.

Average Thickness = 4.37 in.*

Asphalt Layer Thickness (in.)

<table>
<thead>
<tr>
<th>Lane</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.60</td>
</tr>
<tr>
<td>2</td>
<td>4.59</td>
</tr>
<tr>
<td>3</td>
<td>4.42</td>
</tr>
<tr>
<td>4</td>
<td>4.55</td>
</tr>
<tr>
<td>5</td>
<td>4.08</td>
</tr>
<tr>
<td>6</td>
<td>4.60</td>
</tr>
<tr>
<td>7</td>
<td>4.27</td>
</tr>
<tr>
<td>8</td>
<td>4.50</td>
</tr>
<tr>
<td>9</td>
<td>4.15</td>
</tr>
<tr>
<td>11</td>
<td>4.05</td>
</tr>
</tbody>
</table>

*Data from presentation by Dr. Nelson Gibson at 2014 ETG Fall meeting.
Fracture/fatigue testing

- Direct Tension Cyclic Fatigue – SVECD
- AASHTO TP 79-15: Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)
  - Stiffness
- AASHTO TP 107-14: Standard Method of Test for Determining the Damage Characteristic Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests
  - Damage characteristic curve (C vs. S)
Dynamic Modulus Test

- 150 mm X 170 mm
- Air void: 7.0 ± 0.5%
- 3 replicates

<table>
<thead>
<tr>
<th>Frequency (HZ)</th>
<th>25, 10, 5, 1, 0.5, 0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. (°C)</td>
<td>4.4, 25, 37.8</td>
</tr>
</tbody>
</table>

- Target on-specimen strain: 50-75 µε
Dynamic Modulus Test Results

![Graphs showing the dynamic modulus test results for different lanes.](image)
**Dynamic Modulus Test Results**

Effect of RAP/RAS content (PG 64-22, HMA)

![Graph showing the dynamic modulus test results for different lanes with varying RAP/RAS content.](image-url)
Dynamic Modulus Test Results

- Effect of WMA technologies (PG 58-28, 40%RAP)
Dynamic Modulus Test Results

- **Binder PG58-28**

![Graph showing dynamic modulus test results for Lane 7 (20% RAS, 58-28, HMA) and Lane 8 (40% RAP, 58-28, HMA).](image-url)
Dynamic Modulus Test Results

- Binder PG 64-22

Lane 3: 20% RAS, 64-22, HMA
Lane 5: 40% RAP, 64-22, HMA
Direct Tension Cyclic fatigue Test

- Test Condition
- Temperature: 18°C
- Frequency: 10 Hz
- Initial on-specimen strain level: 190-260 με
- Failure determined by phase angle drop
Direct Tension Cyclic fatigue Test

C(S) Damage characteristic curves

Lane 1
Lane 2
Lane 3
Lane 4
Lane 5
Lane 6
Lane 7
Lane 8
Lane 9
Lane 11
**Direct Tension Cyclic fatigue Test**

**Strain-Based SVECD Fatigue Simulation**

- For a given strain level input, perform S-VECD fatigue simulation* and produce the cyclic history of normalized pseudo stiffness $C$ for each mix.
  - Temperature: 20°C**
  - Frequency: 10 Hz
  - Failure criterion: $C_f = 0.25$

- Plot fatigue life versus strain level in a log-log space for each mix.

---


**The ALF full scale sections were tested under controlled temperature of 20°C, according to Li, X. and Nelson, G., *Comparison of Asphalt Mixture Performance Tester Fatigue Characteristics with Full Scale Pavement Cracking for Recycled and Warm Mix Asphalts*. Transportation Research Board, doi: 10.3141/2576-11.
Direct Tension Cyclic fatigue Test
Strain-Based SVECD Fatigue Simulation

Ranking is indicated by the legend below

From top to bottom: good to poor fatigue resistance.

*The ALF data for Lane 2 and 8 are not available yet.
Direct Tension Cyclic fatigue Test
Strain-Based SVECD Fatigue Simulation

Effect of RAP/RAS content (PG 64-22, HMA)

Stiffness: L5 > L3 > L6 > L1.

Fatigue resistance reduces with RAP/RAS content: L1 > L6 > L3 > L5.
**Direct Tension Cyclic fatigue Test**

Strain-Based SVECD Fatigue Simulation

- **Effect of WMA technologies** (PG 58-28, 40%RAP)

<table>
<thead>
<tr>
<th>Lane 11: WMA Evotherm</th>
<th>Lane 2: WMA Foam</th>
<th>Lane 8: HMA</th>
</tr>
</thead>
</table>

- **Stiffness:** L11 > L2 > L8
- **Fatigue resistance:** L8 & L2 > L11
Direct Tension Cyclic fatigue Test
Strain-Based SVECD Fatigue Simulation

Effect of soft binder
Direct Tension Cyclic fatigue Test
SVECD Ranking Based on alpha

Damage evolution rate – $\alpha$
  - Pseudo strain energy density: $W^R = f(\varepsilon^R, S)$
  - Damage evolution law
    \[ \frac{dS}{dt} = \left( -\frac{\partial W^R}{\partial S} \right)^\alpha \quad \text{with} \quad \alpha = \frac{1}{n} + 1 \]
  - Larger $\alpha$-values indicate faster damage evolution

\[ \text{where } n = \text{maximum log-log slope of relaxation modulus} \]

\[ \text{with } \alpha = \frac{1}{n} + 1 \]
**Direct Tension Cyclic fatigue Test**

**SVECD Ranking Based on alpha**

- Ranking based on damage evolution rate

<table>
<thead>
<tr>
<th>Ranking</th>
<th>SVECD using $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Three</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$L1$</td>
</tr>
<tr>
<td>2</td>
<td>$L2$</td>
</tr>
<tr>
<td>3</td>
<td>$L11$</td>
</tr>
<tr>
<td><strong>Middle Four</strong></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$L8$</td>
</tr>
<tr>
<td>5</td>
<td>$L4$</td>
</tr>
<tr>
<td>6</td>
<td>$L9$</td>
</tr>
<tr>
<td>7</td>
<td>$L6$</td>
</tr>
<tr>
<td><strong>Worst Three</strong></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$L3$</td>
</tr>
<tr>
<td>9</td>
<td>$L5$</td>
</tr>
<tr>
<td>10</td>
<td>$L7$</td>
</tr>
</tbody>
</table>

![Graph showing damage evolution rate vs. reduced frequency for various lanes](image-url)
Direct Tension Cyclic fatigue Test
SVECD Ranking Based on \(\alpha\)

- Effect of RAP/RAS content (PG 64-22, HMA)

Stiffness: L5 > L3 > L6 > L1.
Fatigue resistance reduces with RAP/RAS content: L1 > L6 > L3 > L5.
**Direct Tension Cyclic fatigue Test**
SVECD Ranking Based on alpha

- **Effect of WMA technologies (PG 58-28, 40%RAP)**

  - Fatigue resistance: $L_8 < L_{11} < L_2$.
  - WMA better than HMA.
  - Stiffness: $L_{11} > L_2 > L_8$
  - Fatigue resistance: $L_8 < L_{11} < L_2$.
  - WMA better than HMA.
Semi Circular Bend (SCB) Test

- LADOTD TR 30/Proposed ASTM WK48574
- Temperature: 25°C
- Half-circular Specimen
  - Laboratory prepared
  - Field core
  - 150mm diameter X 57mm thickness
  - simply-supported and loaded at mid-point
- Notch controls path of crack propagation
  - 25.4-, 31.8-, and 38.0-mm
- LTA: 5 days, 85°C
- Loading type
  - Monotonic
  - 0.5 mm/min
  - To failure
- Record Load and Vertical Deformation
- Compute Critical Strain Energy: $J_c$
**SCB Test – Analysis**

- Apply load to specimen in displacement control
  - 0.5 mm/min (slow rate);
- Collect force and displacement
  - sampling rate of 10 Hz;
- Plot force versus displacement
- Compute $U$: area under the curve up to peak load
  - For each notch depth
- Plot notch depth versus the corresponding $U$
- Determine slope of the line (notch depth vs $U$ graph)
- Compute $J_c$: slope of line + sample thickness

$$J_c = \frac{1}{b} \frac{dU}{da}$$

$J_c =$ critical strain energy release rate (kJ/m$^2$);
$b =$ sample thickness (m);
$a =$ notch depth (m);
$U =$ strain energy to failure (kilo-Joule, kJ); and
$dU/da =$ change of strain energy with notch depth, KJ/m.
**SCB @ Intermediate Temperature**

- Fracture Energy COV ~ 15%

<table>
<thead>
<tr>
<th>Test</th>
<th>Peak Load (KN-mm)</th>
<th>Peak Disp (mm)</th>
<th>Area (Km-mm²)</th>
<th>Thick (mm)</th>
<th>Area (mm²)</th>
<th>Area (Km-mm²)</th>
<th>Stdev</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>1.574</td>
<td>0.603</td>
<td>0.652</td>
<td>60.5</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>15%</td>
</tr>
<tr>
<td>53</td>
<td>1.626</td>
<td>0.744</td>
<td>0.771</td>
<td>60.1</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>15%</td>
</tr>
<tr>
<td>54</td>
<td>1.483</td>
<td>0.632</td>
<td>0.668</td>
<td>60.3</td>
<td>0.011</td>
<td>0.011</td>
<td>0.011</td>
<td>15%</td>
</tr>
<tr>
<td>55</td>
<td>1.669</td>
<td>0.866</td>
<td>0.901</td>
<td>60.3</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>15%</td>
</tr>
<tr>
<td>56</td>
<td>1.396</td>
<td>0.627</td>
<td>0.625</td>
<td>60.2</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>15%</td>
</tr>
<tr>
<td>57</td>
<td>1.326</td>
<td>0.541</td>
<td>0.523</td>
<td>60.4</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>15%</td>
</tr>
<tr>
<td>58</td>
<td>1.323</td>
<td>0.640</td>
<td>0.602</td>
<td>60.1</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>15%</td>
</tr>
<tr>
<td>59</td>
<td>1.480</td>
<td>0.643</td>
<td>0.675</td>
<td>53.6</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>15%</td>
</tr>
</tbody>
</table>

**Graph:**
- Area (Km-mm²) / Thickness (mm) vs. Notch Depth (mm)

**Regression Equation:**
- \( y = -0.00005 \times x + 0.0267 \)
- \( R^2 = 0.5666 \)
SCB @ Intermediate Temperature

- Fracture Energy COV ~ 15%

<table>
<thead>
<tr>
<th>Integration</th>
<th>Peak Load (Kn)</th>
<th>Peak Disp (Kn-mm)</th>
<th>Area (mm)</th>
<th>Thick (mm)</th>
<th>Area Thick</th>
<th>Area Avg</th>
<th>Area Stdev</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4</td>
<td>1.680</td>
<td>0.962</td>
<td>0.897</td>
<td>57.0</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.751</td>
<td>0.869</td>
<td>0.894</td>
<td>57.0</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.520</td>
<td>1.061</td>
<td>0.980</td>
<td>57.0</td>
<td>0.017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.502</td>
<td>0.949</td>
<td>0.804</td>
<td>57.0</td>
<td>0.014</td>
<td>0.016</td>
<td>0.001</td>
<td>8.020</td>
</tr>
<tr>
<td>31.8</td>
<td>1.211</td>
<td>0.756</td>
<td>0.569</td>
<td>57.0</td>
<td>0.010</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.055</td>
<td>0.763</td>
<td>0.488</td>
<td>57.0</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.212</td>
<td>0.716</td>
<td>0.534</td>
<td>57.0</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.240</td>
<td>0.789</td>
<td>0.622</td>
<td>57.0</td>
<td>0.011</td>
<td>0.010</td>
<td>0.001</td>
<td>10.177</td>
</tr>
<tr>
<td>38.0</td>
<td>0.888</td>
<td>0.630</td>
<td>0.358</td>
<td>57.0</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.987</td>
<td>0.750</td>
<td>0.478</td>
<td>57.0</td>
<td>0.008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.978</td>
<td>0.703</td>
<td>0.429</td>
<td>57.0</td>
<td>0.008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.862</td>
<td>0.597</td>
<td>0.331</td>
<td>57.0</td>
<td>0.006</td>
<td>0.007</td>
<td>0.001</td>
<td>16.784</td>
</tr>
</tbody>
</table>

Dr. Erv Dukatz ASTM work item :WK48574 Ruggedness testing between four laboratories has shown the Jc for split samples to have a within laboratory COV of 9.9%
**SCB @ Intermediate Temperature**

- Specimen Preparation QC Sheet

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Target Notch</td>
<td>25.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Notch Depth (mm)</td>
<td>Deviation from Target (mm)</td>
<td>Notch Width, 3.0 mm</td>
<td>Thickness (mm)</td>
<td>Diameter (mm)</td>
<td>Left center</td>
<td>Right center</td>
<td>middle height</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>25.5</td>
<td>0.1</td>
<td>1.0</td>
<td>2.7</td>
<td>1.0</td>
<td>57.4</td>
<td>1.0</td>
<td>149.3</td>
<td>73.5</td>
<td>73.3</td>
<td>72.9</td>
</tr>
<tr>
<td>9</td>
<td>2.0</td>
<td>25.6</td>
<td>0.2</td>
<td>2.0</td>
<td>2.8</td>
<td>2.0</td>
<td>57.4</td>
<td>2.0</td>
<td>149.2</td>
<td>74.5</td>
<td>73.8</td>
<td>72.8</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>24.0</td>
<td>1.4</td>
<td>3.0</td>
<td>2.8</td>
<td>3.0</td>
<td>57.3</td>
<td>3.0</td>
<td>149.3</td>
<td>74.1</td>
<td>73.7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>AVG</td>
<td>25.0</td>
<td>0.4</td>
<td>AVG</td>
<td>2.8</td>
<td>AVG</td>
<td>57.4</td>
<td>AVG</td>
<td>149.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Image of Specimen Preparation QC Sheet](image1.png)

![Image of Specimen Preparation QC Sheet](image2.png)
SCB Test Results

- Completed L3, L5, L7

Graph showing Jc, kJ/m² for different asphalt mixtures:
- L3 64-22 20% RAS HMA
- L5 64-22 40% RAP HMA
- L7 58-28 20% RAS HMA
## Correlation to field performance

**ALF vs. S-VCED and SCB**

<table>
<thead>
<tr>
<th>Ranking</th>
<th>ALF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Three</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>L1</td>
</tr>
<tr>
<td>2</td>
<td>L9</td>
</tr>
<tr>
<td>3</td>
<td>L6</td>
</tr>
<tr>
<td><strong>Middle Two</strong></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>L4</td>
</tr>
<tr>
<td>5</td>
<td>L11</td>
</tr>
<tr>
<td><strong>Worst Three</strong></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>L3</td>
</tr>
<tr>
<td>7</td>
<td>L5</td>
</tr>
<tr>
<td>8</td>
<td>L7</td>
</tr>
</tbody>
</table>
## Correlation to field performance

**ALF vs, S-VCED and SCB**

<table>
<thead>
<tr>
<th>Ranking</th>
<th>ALF</th>
<th>S-VECD simulation $C_f = 0.25$</th>
<th>S-VECD Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Three</strong></td>
<td>1</td>
<td>L1</td>
<td>L1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>L9</td>
<td>L9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>L6</td>
<td>L4</td>
</tr>
<tr>
<td><strong>Middle Two</strong></td>
<td>4</td>
<td>L4</td>
<td>L11</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>L11</td>
<td>L9</td>
</tr>
<tr>
<td><strong>Worst Three</strong></td>
<td>6</td>
<td>L3</td>
<td>L3</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>L5</td>
<td>L7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>L7</td>
<td>L7</td>
</tr>
</tbody>
</table>
Correlation to field performance
ALF vs, S-VCED and SCB

<table>
<thead>
<tr>
<th>Ranking</th>
<th>ALF</th>
<th>S-VECD simulation Cf = 0.25</th>
<th>S-VECD Alpha</th>
<th>SCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Three</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>L1</td>
<td>L1</td>
<td>L1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>L9</td>
<td>L9</td>
<td>L11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>L6</td>
<td>L4</td>
<td>L$</td>
<td></td>
</tr>
<tr>
<td>Middle Two</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>L4</td>
<td>L11</td>
<td>L9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>L11</td>
<td>L6</td>
<td>L6</td>
<td></td>
</tr>
<tr>
<td>Worst Three</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>L3</td>
<td>L3</td>
<td>L3</td>
<td>L3</td>
</tr>
<tr>
<td>7</td>
<td>L5</td>
<td>L7</td>
<td>L5</td>
<td>L5</td>
</tr>
<tr>
<td>8</td>
<td>L7</td>
<td>L5</td>
<td>L7</td>
<td>L7</td>
</tr>
</tbody>
</table>
Texas Overlay
Test method: Tex-248-F
- AMPT
Texas Overlay
Test method: Tex-248-F

- AMPT