NCHRP 9-49A Project
Performance of WMA Technologies:
Stage II – Long-term Field Performance

FHWA Mix ETG

Oklahoma City, OK
September 17, 2015
Project Background

- Duration: 04/2011-07/2016

- Team Members
  - Haifang Wen - Washington State University (Prime)
  - Louay Mohammad - Louisiana State University
  - Shihui Shen - Penn State University at Altoona
  - Braun Intertech
  - Bloom Companies
Outline

- Objectives & Research Progress
- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Property Changes Over Time
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- Summary and Future Work
Research Objectives

- To identify the material and engineering properties of WMA pavements that are *significant determinants* of their long-term field performance, and

- To recommend *best practices* for the use of WMA technologies.
Research Progress

Phase I
- Task 1: Selection of WMA Candidate Projects
- Task 2: Design of Experiment

Phase II
- Task 3: Field Characterization of WMA Projects
- Task 4: Lab Characterization of WMA/HMA Specimens
- Task 5: Analysis of Experimental Data in the Field
- Task 6: Identification of Significant Determinants of Field Performance

Phase III
- Task 7: Final Report Preparation and Recommendation for Best Practice and Revision of AASHTO Specifications and Test Methods
New (2011 Construction) Pavement Projects

- 5 Projects = 10 HMA-WMA pairs
- 1st round: pre-overlay distress survey, construction monitoring, on-site sample compaction, field cores, and falling weight deflectometer tests
- 2nd round: field cores and distress survey
In-service (as of 2011) Pavement Projects

• 22 field projects + 1 HVS = 40 HMA-WMA pairs
• 1\textsuperscript{st} round: distress survey, field cores and falling weight deflectometer tests
• 2\textsuperscript{nd} round: distress survey
Projects Distribution

- Organic WMA Technology
- Chemical WMA Technology
- Foaming WMA Technology

- <3M Traffic (ESALs)
- >=3M Traffic (ESALs)

- [4,5) Age, Years
- [6,7) Age, Years
- [8,10) Age, Years

- Flexible Pavement Structure
- PCC/Cement Stabilized Pavement Structure
<table>
<thead>
<tr>
<th>Project</th>
<th>MT I-15</th>
<th>TN SR 125</th>
<th>IA US 34</th>
<th>TX FM 973</th>
<th>LA US 61</th>
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<td>2011</td>
<td>2011</td>
<td>2011</td>
<td>2011</td>
<td>2012</td>
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<td>Warm Mix</td>
<td>Sasobit, Evotherm DAT, Foaming</td>
<td>Evotherm 3G</td>
<td>Sasobit, Evotherm 3G</td>
<td>Evotherm 3G, Foaming</td>
<td>Sasobit, Evotherm 3G</td>
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<td>0.39 million (3,470 AADT, 13% truck)</td>
<td>3 million (6,450 AADT, 10.9% truck)</td>
<td>3 million (11,300 AADT, 4.3% truck)</td>
<td>9 million (34,138 ADT, 14% truck)</td>
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<td>Gravel &amp; Sand</td>
<td>Limestone, Quartzite &amp; Sand</td>
<td>Gravel, Limestone &amp; Dolomite</td>
<td>Granite &amp; Limestone</td>
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<td>1/2</td>
<td>1/2</td>
<td>3/4</td>
<td>1/2</td>
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<td>Asphalt Binder</td>
<td>PG 70-28</td>
<td>PG 70-22</td>
<td>PG 58-28</td>
<td>PG 70-22</td>
<td>PG 76-22</td>
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<td>AZZ-MAZ, 0.3%</td>
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<td>None</td>
<td>0.6%</td>
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<td>$G_{mm}$</td>
<td>HMA (2.458) Sas (2.466) Evo (2.459) Foam (2.453)</td>
<td>HMA (2.352) Evotherm (2.355)</td>
<td>HMA (2.423) Sasobit (2.428) Evotherm (2.429)</td>
<td>HMA (2.406) Evotherm (2.405) Foaming (2.420)</td>
<td>HMA (2.464) Sasobit (2.468) Evotherm (2.464)</td>
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<td>17% RAP</td>
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<td>2.5&quot; overlay + 7&quot; existing HMA + 16.2&quot; base (non-stabilized) + infinite subgrade</td>
<td>1.25&quot; overlay + 8&quot; bituminous base + 6&quot; min. aggregate base + infinite subgrade</td>
<td>HMA &amp; Sasobit: 1.5&quot;overlay + 5&quot; existing HMA + 7&quot; PCC + subgrade Evotherm: 1.5&quot; overlay + 3&quot; existing HMA + 9&quot; PCC + subgrade</td>
<td>2&quot; overlay + 8&quot; existing HMA + 10&quot; base + 141.1&quot; subgrade (lean clay)</td>
<td>2&quot; overlay + 8&quot; existing HMA + 8&quot; PCC + 6&quot; cement treated soil subgrade</td>
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<td>MO Hall St.</td>
<td>MO Rte. CC</td>
<td>MN TH 169</td>
<td>OH SR 541</td>
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<td>Warm Mix (content, %, by weight of binder)</td>
<td>Sasobit (1.5%); Evo ET; Asph (0.3%)</td>
<td>Sasobit (1.5%); Evo ET (5.3%); Asp (0.3%)</td>
<td>LEA, Gencor (0.5%)</td>
<td>Astec DBG</td>
<td>Astec DBG</td>
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<td>Production Temp., °F</td>
<td>HMA (310-350); Sasobit (270-310)</td>
<td>HMA (320), Sas (240); Evo (225); Aspha (275)</td>
<td>HMA (320); Evo (280-290)</td>
<td>HMA (320), Sas (260); Evo (235); Asp (245)</td>
<td>H (290-310); Gen (250-265); LEA (240-260)</td>
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<td>Steel Slag</td>
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<td>3/8</td>
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<td>64-22</td>
<td>58-28</td>
<td>70-22</td>
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<td>ARR MAZ, 0.25%</td>
<td>Pave Bond Lite, 0.25%</td>
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<td>Asphalt Content, %</td>
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<td>5.3</td>
<td>5.4</td>
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<td>6.1</td>
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<td>$G_{mm}$</td>
<td>2.519</td>
<td>2.451</td>
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<td>7/17/12</td>
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<td>6/18/12</td>
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<tr>
<td>RAP</td>
<td>15%</td>
<td>10%</td>
<td>20%</td>
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<td>15%</td>
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<td>Structure</td>
<td>2&quot;+5&quot; HMA + 8&quot;Macadam stone</td>
<td>1.75&quot;+12&quot; PCC + 0-3&quot; base</td>
<td>3.75&quot;+7&quot; PCC + 6&quot; base</td>
<td>2&quot;+8&quot; HMA + 6&quot; base</td>
<td>1.25&quot;+6.75&quot; HMA+9&quot; Granular Base</td>
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<td>Wet No-Freeze</td>
<td>SC US 178</td>
<td>TN SR 46</td>
<td>TX FM 324</td>
<td>LA 116</td>
<td>LA 3191</td>
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<td>Warm Mix</td>
<td>Evotherm DAT</td>
<td>Sasobit, Evotherm DAT, Astec DBG, and Advera</td>
<td>Sasobit, Evotherm DAT, Rediset, Advera</td>
<td>Foam</td>
<td>Astec Foam</td>
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<td>Production Temp., °F</td>
<td>HMA (295), Evotherm (240)</td>
<td>HMA Danley (320-350); HMA Franklin (320-350), Sasobit (250); Evotherm DAT (240); Advera (250); DBG (260)</td>
<td>H (330)</td>
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<td>2600</td>
<td>ADT 200</td>
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<td>NMAS, in.</td>
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<td>1/2</td>
<td>3/8</td>
<td>1/2</td>
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<tr>
<td>Asphalt Binder</td>
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<td>70-22</td>
<td>64-22</td>
<td>70-22</td>
<td>70-22</td>
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<tr>
<td>Anti-stripping Agent</td>
<td>N/A</td>
<td>Franklin (AD-Here 77-00, 0.3%); Astec DBG (Pavegrip 650, 0.3%)</td>
<td>1% Lime</td>
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<td>Asphalt Content, %</td>
<td>H (5.3), W (5.4)</td>
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<td>4.6</td>
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<td>5.2</td>
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<tr>
<td>Gmm</td>
<td>H (2.460), W (2.463)</td>
<td>HMA Danley (2.428), Sasobit (2.411), Evotherm (2.410), Astec DBG (2.444), Advera (2.422) HMA Franklin (2.425)</td>
<td>HMA, Sas, Evo (2.508) Adv, Rediset (2.498)</td>
<td>H (2.525) W (2.541)</td>
<td>H (2.453) W (2.486)</td>
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<td>07/24/12</td>
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<td>None</td>
<td>15</td>
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<tr>
<td>Structure</td>
<td>2&quot; overlay + 5.7&quot; HMA + 7.1&quot; PCC + Sand Clay Base</td>
<td>1.25&quot; Overlay + 4.26&quot; HMA + 6&quot; crushed stone</td>
<td>1.5&quot; Overlay + 5.7&quot; HMA + 10&quot; base</td>
<td>1.5&quot; Overlay + 5&quot; HMA +8.5&quot; Base</td>
<td>2&quot; HMA + 6&quot; HMA+ 7&quot; PCCP</td>
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<td>Dry- Freeze</td>
<td>WA I-90</td>
<td>WA SR 12</td>
<td>CO IH 70</td>
<td>NE US 14</td>
<td>NV</td>
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<tr>
<td>Warm Mix</td>
<td>Sasobit</td>
<td>Aquablack</td>
<td>Sasobit (1.5%); Evotherm DAT (0.5%); Advera (0.3% of mix)</td>
<td>Advera, Evotherm DAT</td>
<td>Ultrafoam</td>
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<tr>
<td>Production Temp., °F</td>
<td>HMA (330), Sasobit (276)</td>
<td>HMA (325), Aquablack (275)</td>
<td>HMA (mixing 310, compaction 280); Sasobit (255, 235); Evotherm (250, 230); Advera (255, 235)</td>
<td>H (330), W (275)</td>
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<td>Basalt</td>
<td>Crushed River Rock</td>
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<tr>
<td>Anti-stripping Agent</td>
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<td>Superbond (0.25%)</td>
<td>Hydrated Lime (1% by mass of aggregate blend)</td>
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<td>Hydrated Lime, 1.5%</td>
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<td>6.3</td>
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<tr>
<td>$G_{mm}$</td>
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<td>2.596</td>
<td>2.45</td>
<td>H-Adv (2.439), H-Evo (2.441)</td>
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<td>10/18/12</td>
<td>10/14/12</td>
<td>10/19/12</td>
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<tr>
<td>Structure</td>
<td>3&quot; Overlay + 11.28&quot; HMA + 6.5&quot; base (HMA)/5&quot; base (Sasobit)</td>
<td>3&quot; Overlay + 7.8&quot; HMA + 9&quot; base</td>
<td>2.5&quot; Overlay + 10-11&quot; HMA</td>
<td>3&quot; Overlay + 4&quot; HL Slurry Stabilization + 1.5&quot; Existing Asphalt + 4” Bit Sand Base</td>
<td>6&quot; HMA + 9&quot; Aggregate Base</td>
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<td>Dry No-Freeze</td>
<td>TX SH 251</td>
<td>TX SH 71</td>
<td>CA HVS 3a</td>
<td>CA HVS 3b</td>
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<tr>
<td><strong>Warm Mix</strong></td>
<td>Astec DBG</td>
<td>Evotherm DAT</td>
<td>Gencor, Evotherm DAT, Cecabase</td>
<td>Sasobit, Advera, Astec DBG, Rediset</td>
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<tr>
<td><strong>Production Temp., °F</strong></td>
<td>H (310), W (270)</td>
<td>H (330), W (240)</td>
<td>HMA (320), Gencor (284), Evotherm (248), Cecabase (266)</td>
<td>HMA (335, 279), Sasobit (300,279), Advera (295,266), Astec DBG (295,257), Rediset (285,258)</td>
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<td>57,000</td>
<td>HMA (74,000), Gencor (159,000), Evotherm and Cecabase (160,000)</td>
<td>HMA, Sasobit, Astec DBG and Rediset (160,000), Advera (50,000)</td>
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<td>Granite</td>
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<td>1/2</td>
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<td>76-22</td>
<td>64-16</td>
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<td>1% Akzo</td>
<td>0.8% Liquid</td>
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<tr>
<td><strong>Asphalt Content, %</strong></td>
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<td>4.8</td>
<td>7.0</td>
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<tr>
<td><strong>G&lt;sub&gt;mm&lt;/sub&gt;</strong></td>
<td>H (2.45), W (2.4)</td>
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<td>H (2.503)</td>
<td>H (2.505)</td>
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<td>Rubber (18% of binder)</td>
<td>Rubber (18% of binder)</td>
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<td><strong>Structure</strong></td>
<td>2.0&quot; Overlay + 4.3&quot; HMA</td>
<td>2&quot; Overlay + HMA</td>
<td>2.5&quot; Gap-graded Rubberized HMA + 2.5&quot; HMA + 15.6&quot; Base</td>
<td>2.5&quot; Gap-graded Rubberized HMA + 2.5&quot; HMA + 15.6&quot; Base</td>
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# Field Work Progress

## New Projects

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<tr>
<th>Items</th>
<th>MT I-15</th>
<th>IA US 34</th>
<th>TN SR 125</th>
<th>TX FM 973</th>
<th>LA US 61</th>
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<td>1 2 3</td>
<td>1 2 3</td>
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<td>Distress Survey</td>
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<tr>
<td>FWD/Coring</td>
<td>✔ ✔ ✔ ✔ ✔ ✔ ✔ - ✔ ✔</td>
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## In-service Projects

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<td>FWD/Coring</td>
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## In-service Projects (continued)

<table>
<thead>
<tr>
<th>Items</th>
<th>TX SH 251</th>
<th>NE US 14</th>
<th>TX FM 324</th>
<th>LA 3121</th>
<th>LA 116</th>
<th>LA 3191</th>
<th>NV Bravo</th>
<th>IL 147</th>
<th>PA SR 2006</th>
<th>TX SH 71</th>
<th>CA HVS</th>
</tr>
</thead>
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<tr>
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<tr>
<td>Distress Survey</td>
<td>✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔</td>
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<tr>
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<td>✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔</td>
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</table>

Notes: “✔”: completed; blank cells: to be completed; “-”: not planned or not available.
<table>
<thead>
<tr>
<th>Mixture Test</th>
<th>IDT Dynamic Modulus/Creep Compliance</th>
<th>Fatigue-IDT Fracture at Room Temp</th>
<th>Thermal Cracking-IDT Fracture at Low Temp</th>
<th>Rutting/Moisture - Hamburg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing Conditions</td>
<td>Temp.: −4, 14, 32, 50, 68, 86ºF; Frequency: 20, 10, 5, 1, 0.1, 0.01 Hz Duration: 100 seconds</td>
<td>Temp.: 68ºF Loading rate: 2 in./min</td>
<td>Temp.: 14ºF Loading rate: 0.1 in./min</td>
<td>Temp.: 122ºF Wet condition</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Dynamic modulus; Creep compliance</td>
<td>IDT strength; Fracture work density; Vertical failure deformation Horizontal failure strain</td>
<td>IDT strength; Fracture work density; Vertical failure deformation; Horizontal failure strain</td>
<td>Rut depth; Stripping inflection point (SIP); Cycles</td>
</tr>
<tr>
<td>References/Standards</td>
<td>AASHTO T322 Wen et al. 2002</td>
<td>AASHTO T322</td>
<td>AASHTO T322 Wen 2012</td>
<td>AASHTO T324</td>
</tr>
</tbody>
</table>

**Vertical Failure Deformation**

![Graph of Vertical Failure Deformation](image)

**Peak Stress**

**Load**

**Fracture Work**

**Vertical Displacement**
Rutting Resistance Index (RRI)

\[ \text{RRI} = \text{No. of Cycles @ end of test} \times (1" - \text{Rut Depth}) \]

(1) Good rutting performance: 0.1 in. @ 20,000 cycles, RRI=18,000

(2) Average rutting performance: 0.3 in. @ 20,000 cycles, RRI=14,000

(3) Poor rutting performance: 0.5 in. @10,000 cycles, RRI=5,000
## Binder Test Summary

<table>
<thead>
<tr>
<th>Binder Test</th>
<th>PGs</th>
<th>Rutting: MSCR</th>
<th>Fatigue: Monotonic at Room Temp</th>
<th>Thermal Cracking: Monotonic at Low Temp</th>
</tr>
</thead>
</table>
| Testing Conditions | Different temp depending on the test (DSR, BBR) | Stress: 0.1, 3.2kPa  
Temp.: 98%  
Reliability from LTPP Bind | Temp.: 68°F  
Shear strain rate: 0.3 s⁻¹ | Temp.: 41°F  
Shear strain rate: 0.01s⁻¹ |
| Material Properties | PG; BBR stiffness; m-value | Jnr₀.₁, Jnr₃.₂; R₀.₁, R₃.₂ | Maximum stress; Fracture energy; Failure strain | Maximum stress; Fracture energy; Failure strain |
| References/Standards | AASHTO MP1/T240/T313 | AASHTO T350 | Wen et al. 2010 | Wen 2012 |
Outline

■ Objectives & Research Progress

■ Preliminary Findings
  ■ Transverse Cracking
  ■ Top-down Longitudinal Cracking
  ■ Rutting & Moisture Susceptibility
  ■ Effects of WMA on construction practices
  ■ Material Properties Changes
    □ MT I-15 Project
    □ TN SR 125 Project
    □ IA US 34 Project

■ Summary and Future Work
Transverse Cracking

- Field Performance Comparison between HMA and WMA
  - 1st Round Survey
  - 2nd Round Survey

- Significant Determinants for Transverse Cracking
  - 1st Round Results
  - 2nd Round Results

- Use Determinant to Compare HMA and WMA
Transverse Cracking

Existing crack in the shoulder

Reflective

Surface-initiated

Evotherm

Underlying

Overlay

Advera

Overlay

Underlying
1st Round HMA/WMA Transverse Cracking Comparison

14 (21 H-W Pairs) out of 28 projects exhibited transverse cracking

**Graph:**
- **y-axis:** Project Number
- **Legend:**
  - H>W
  - H=W
  - H<W

**Map:**
- **Regions:**
  - Dry Freeze
  - Wet Freeze
  - Dry No-Freeze
  - Wet No-Freeze

- **Counts:**
  - 3/6
  - 5/10
  - 1/4
  - 5/8
2nd Round HMA/WMA Transverse Cracking Comparison

22 (35 H-W pairs) out of 28 projects exhibited transverse cracking.
Significant Determinants of Transverse Cracking

- Compare Material Properties
  - $H > W$, $H = W$, $H < W$ (t-test)

- Compare Field Performance
  - $H > W$, $H = W$, $H < W$ (t-test)

- Compare the two rankings
  - Consistent trend
  - No consistent trend

- Summarize the number of pairs with consistent trend and determine the promising indicator
Significant Determinants for Transverse Cracking Based on 1st Round Results

15 out of 21 HMA/WMA pairs
Verification: Significant Determinants for Transverse Cracking Based on 2nd Round Results

25 out of 35 HMA/WMA pairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBR stiffness</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Binder shear strength (41°F)</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>Binder shear strength (68°F)</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Binder fracture energy (41°F)</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Mix E* (41°F)</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>Mix work density (14°F)</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Mix horizontal failure strain (68°F)</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Mix vertical failure deformation (68°F)</td>
<td>14</td>
<td>21</td>
</tr>
</tbody>
</table>

Diagram: Bar chart showing the number of positive and negative pairs for various parameters.
Use of Fracture Work Density as Indicator for Transverse Cracking Performance

HMA and WMA are comparable.
# Pairs of HMA and WMA Whose FWD are not comparable

<table>
<thead>
<tr>
<th>WMA</th>
<th>Project</th>
<th>FWD</th>
<th>Air Void</th>
<th>Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasobit</td>
<td>MT I-15</td>
<td>H &lt; W</td>
<td>H (2.7%) = W (3.0%)</td>
<td>H (5.0%) &gt; W (4.4%)</td>
</tr>
<tr>
<td>CA 3b</td>
<td>H &lt; W</td>
<td>H (9.4%) &gt; W (7.4%)</td>
<td>H (6.7%) = W (6.4%)</td>
<td></td>
</tr>
<tr>
<td>CA3a</td>
<td>H &gt; W</td>
<td>H (4.4%) &lt; W (7.1%)</td>
<td>H (7.2%) = W (7.5%)</td>
<td></td>
</tr>
<tr>
<td>Evotherm</td>
<td>TN SR 125</td>
<td>H &gt; W</td>
<td>H (5.9%) &lt; W (7.8%)</td>
<td>H (6.4%) &gt; W (6.0%)</td>
</tr>
<tr>
<td>MT I-15</td>
<td>H &lt; W</td>
<td>H (2.7%) = W (2.0%)</td>
<td>H (5.0%) &gt; W (4.6%)</td>
<td></td>
</tr>
<tr>
<td>Water-based</td>
<td>VA I66</td>
<td>H &gt; W</td>
<td>H (4.5%) &lt; W (5.3%)</td>
<td>H (5.5%) = W (5.4%)</td>
</tr>
<tr>
<td>Foaming</td>
<td>TN SR 46</td>
<td>H &gt; W</td>
<td>H (5.0%) &lt; W (6.9%)</td>
<td>H (5.4%) &gt; W (5.2%)</td>
</tr>
<tr>
<td></td>
<td>TX SH 71</td>
<td>H &gt; W</td>
<td>H (6.7%) = W (7.2%)</td>
<td>H (4.6%) = W (4.9%)</td>
</tr>
<tr>
<td></td>
<td>MT I-15</td>
<td>H &lt; W</td>
<td>H (2.7%) = W (2.5%)</td>
<td>H (5.0%) &gt; W (4.4%)</td>
</tr>
</tbody>
</table>

\[
y = -45.34 \ln(x) + 128.54 \\
R^2 = 0.472
\]

\[
y = 3.0982e^{0.4907x} \\
R^2 = 0.2872
\]
Implementation of the Use of Significant Determinants in Mix Design

\[ FWD = -91.38 + 0.387VFA + 66.74G_{se} + 8.08\varepsilon_b + 15.76P_b + 2.97P_{50} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWD</td>
<td>mixture fracture work density tested at 14°F, kPa</td>
<td></td>
</tr>
<tr>
<td>G_{se}</td>
<td>aggregate effective specific gravity</td>
<td>0.006</td>
</tr>
<tr>
<td>VFA</td>
<td>voids filled with asphalt, %</td>
<td>0.006</td>
</tr>
<tr>
<td>\varepsilon_b</td>
<td>binder failure strain tested at 41°F</td>
<td>0.000</td>
</tr>
<tr>
<td>P_b</td>
<td>asphalt content, %</td>
<td>0.000</td>
</tr>
<tr>
<td>P_{50}</td>
<td>percentage passing No. 50 sieve size</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Higher FWD, if
- ductile asphalt binder (i.e., a higher level of failure strain),
- relatively more asphalt (i.e., higher asphalt content, VFA)
- contains more aggregate passing the No. 50 sieve,
- contains hard aggregate (high $G_{sb}$).
Measured Work Density Vs Calculated Work Density

\[ y = 0.9742x \]

\[ R^2 = 0.7748 \]
Summary of Transvers Cracking Study

- The transverse cracking may be a combination of thermal cracking and reflective cracking.
- In general, HMA and WMA have comparable transverse cracking performance in the field.
- Fracture work density and dynamic modulus are found to be a significant determinant of transverse cracking.
- Fracture work density is very sensitive to air void and asphalt content.
Summary of Transvers Cracking Study

To achieve high fracture work density and good resistance to transverse cracking:

- a high asphalt content and VFA,
- a ductile asphalt binder,
- hard aggregates
- a fine gradation.
Outline

- Objectives & Research Progress
- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project

- Summary and Future Work
Top-down Longitudinal Cracking

- Field Performance Comparison between HMA and WMA
  - 1st Round Survey
  - 2nd Round Survey

- Significant Determinants for Top-down Cracking
  - 1st Round Results
  - 2nd Round Results

- Use Determinant to Compare HMA and WMA

- Implementation in Mix Design
Top-down Fatigue Cracking
8 (17 H-W pairs) out of 24 projects exhibited top-down longitudinal cracking.
2nd Round HMA/WMA Top-down Cracking Comparison
14 (24 H-W pairs) out of 28 projects exhibited top-down longitudinal cracking.

![Bar chart showing the comparison of HMA/WMA top-down cracking]

- **3/6**: 18 projects with H=W
- **5/10**: 5 projects with H>W
- **6/8**: 6 projects with H<W

![Map showing the distribution of HMA/WMA top-down cracking across the USA]

- **Dry Freeze**
- **Dry No-Freeze**
- **Wet Freeze**
- **Wet No-Freeze**
Significant Determinants for Top-down Longitudinal Cracking Based on 1st Round Results

**Vertical failure deformation**
(68°F), 15 out of 17 pairs

- **Mix IDT strength (68°F)**
- **Mix creep compliance (68°F)**
- **Mix horizontal failure strain (68°F)**
- **Mix vertical failure deformation (68°F)**
Verification: Significant Determinants for Top-down Cracking Based on 2\textsuperscript{nd} Round Results

Vertical failure deformation and horizontal failure strain (68ºF), 17 out of 24 pairs
Use of Vertical Failure Deformation as Indicator for Top-down Longitudinal Cracking Resistance

HMA vs Sasobit

Pairs of HMA vs WMA

HMA vs Chemical

Pairs of HMA vs WMA

HMA vs Water-based Foaming

Pairs of HMA vs WMA

HMA vs Water-containing Foaming

Pairs of HMA vs WMA
**Pairs of HMA and WMA Whose VFD are not comparable**

<table>
<thead>
<tr>
<th>WMA</th>
<th>Project</th>
<th>VFD</th>
<th>Air Void</th>
<th>Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasobit</td>
<td>WA I90</td>
<td>H &gt; W</td>
<td>H (2.5%) &lt; W (3.1%)</td>
<td>H (5.4%) = W (5.6%)</td>
</tr>
<tr>
<td></td>
<td>PA SR 2006</td>
<td>H &gt; W</td>
<td>H (5.0%) &lt; W (6.0%)</td>
<td>H (6.1%) = W (5.8%)</td>
</tr>
<tr>
<td>Water-based</td>
<td>TX SH 251</td>
<td>H &lt; W</td>
<td>H (4.2%) = W (4.1%)</td>
<td>H (5.3%) = W (5.1%)</td>
</tr>
<tr>
<td>Foaming</td>
<td>TX SH 71</td>
<td>H &gt; W</td>
<td>H (6.6%) &lt; W (7.7%)</td>
<td>H (4.6%) = W (4.9%)</td>
</tr>
</tbody>
</table>

**Graphs:**
- **Left:**
  - Equation: $y = -0.366\ln(x) + 2.0454$
  - $R^2 = 0.1517$
- **Right:**
  - Equation: $y = 0.2979e^{0.2854x}$
  - $R^2 = 0.3514$
Implementation of the Use of Significant Determinants in Mix Design

VFD = -3.285 + 0.361P_b - 0.000152σ_b + 0.0172P_{30} + 0.0988G_{sb}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFD</td>
<td>vertical failure deformation of mix 68°F, mm</td>
<td></td>
</tr>
<tr>
<td>P_b</td>
<td>binder content, %;</td>
<td>0.000</td>
</tr>
<tr>
<td>σ_b</td>
<td>binder shear strength tested at 68°F, kPa</td>
<td>0.000</td>
</tr>
<tr>
<td>P_{30}</td>
<td>percentage passing No. 30 sieve size</td>
<td>0.002</td>
</tr>
<tr>
<td>G_{sb}</td>
<td>aggregate bulk specific gravity</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Higher VFD, if the mix has
- a relatively higher asphalt content,
- lower binder shear strength,
- finer gradation (more aggregate passing the No. 30 sieve)
- harder aggregate (high G_{sb}).
Summary of Top-down Fatigue Cracking Study

- In general, HMA and WMA have comparable top-down fatigue cracking performance in the field, except in a few cases organic and water-containing WMA have more cracking than HMA.

- The use of vertical failure deformation to represent field performance to remove the effects of other factors shows that HMA and WMA have comparable top-down fatigue cracking performance.

- Vertical failure deformation and horizontal failure strain of a mix are found to be the significant determinants of top-down fatigue cracking.
Summary of Top-down Fatigue Cracking Study

- Vertical failure deformation is sensitive to air void and asphalt content.

- To achieve a high vertical failure deformation and good resistance to top-down fatigue cracking, a mix have:
  - a relatively high asphalt content
  - a soft binder
  - fine aggregate gradation
  - hard aggregates.
Outline

- Objectives & Research Progress
- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project

- Summary and Future Work
Rutting Performance

- Field Performance Comparison between HMA and WMA
  - 2nd Round Survey
- Significant Determinants for Rut Depth
  - 2nd Round Results
- Use Determinant to Compare HMA and WMA
- Implementation in Mix Design
Rutting
2nd Round HMA/WMA Rutting Performance Comparison

23 projects (43 H-W pairs) exhibited measurable rut depth.

HMA and WMA are comparable in rut depth.
Significant Determinants for Rutting Resistance

- 34 out of 41 HMA/WMA pairs
- 39 out of 43 HMA/WMA pairs

Bar chart showing:
- Positive and Negative No. of Pairs
- Mix RRI
- High and Low PG
- Mix creep compliance (86°F)
- Hamburg Rutting Resistance Index
- Binder high temp PG
- Binder low temp PG
- Mix E* (86°F)
Use of RRI as Indicator of Rutting Performance

HMA vs Sasobit

HMA vs Chemical

HMA vs Water-based

HMA vs Water-containing
### Pairs of HMA and WMA Whose RRI are not comparable

<table>
<thead>
<tr>
<th>WMA</th>
<th>Project</th>
<th>RRI</th>
<th>Air Void</th>
<th>Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasobit</td>
<td>PA 2006</td>
<td>H &lt; W</td>
<td>H (7.0%) = W (6.8%)</td>
<td>H (6.1%) = W (5.8%)</td>
</tr>
<tr>
<td>Chemical</td>
<td>NE US 14</td>
<td>H &gt; W</td>
<td>H (8.0%) = W (8.4%)</td>
<td>H (4.7%) = W (4.8%)</td>
</tr>
<tr>
<td>Water-containing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foaming</td>
<td>MO Hall St.</td>
<td>H &lt; W</td>
<td>H (6.0%) = W (6.25%)</td>
<td>H (5.8%) = W (5.5%)</td>
</tr>
<tr>
<td>Water-based Foaming</td>
<td>LA 116</td>
<td>H &gt; W</td>
<td>H (5.4%) &lt; W (6.7%)</td>
<td>H (4.4%) = W (4.6%)</td>
</tr>
</tbody>
</table>

**Graphs**

1. **Asphalt Content vs. Air Void**
   - Equation: $y = -1299.8x + 20368$
   - $R^2 = 0.1558$

2. **Asphalt Content vs. Rutting Resistance Index**
   - Equation: $y = 2E+06e^{-0.967x}$
   - $R^2 = 0.3256$
## Implementation of the Use of Significant Determinants in Mix Design

RRI = 3700.555 + 2187.602P_{100} + 122.027R_{3.2} – 323.71P_{16} – 73.374VFA +2054.665P_{ba}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRI</td>
<td>rutting resistance index, RRI = N × (1 - RD)</td>
<td></td>
</tr>
<tr>
<td>P_{100}</td>
<td>percentage passing No. 100 sieve</td>
<td>0.000</td>
</tr>
<tr>
<td>R_{3.2}</td>
<td>percentage of recovery of binder at stress level of 3.2 kPa from MSCR test</td>
<td>0.000</td>
</tr>
<tr>
<td>P_{16}</td>
<td>percentage passing No. 16 sieve</td>
<td>0.000</td>
</tr>
<tr>
<td>VFA</td>
<td>voids filled with asphalt</td>
<td>0.003</td>
</tr>
<tr>
<td>P_{ba}</td>
<td>asphalt binder absorption</td>
<td>0.013</td>
</tr>
</tbody>
</table>
Measured RRI Vs Calculated RRI

y = 1.0165x
R² = 0.70
Summary of Rutting Study

- In general, HMA and WMA have comparable rutting performance in the field.

- The mix’s rutting resistance index (RRI) is recommended to be a significant determinant of rutting performance.

- To develop a rutting resistant mix, a mix has
  - a high percent recovery from MSCR test
  - a low VFA
  - a high asphalt absorption rate
  - a gap-graded aggregate.
Moisture Susceptibility

For the projects that show SIP, it is found that anti-stripping agents were not applied in most cases.
Summary of Rutting Study

- In general, HMA and WMA have comparable rutting performance in the field.

- The mix’s rutting resistance index (RRI) is recommended to be a significant determinant of rutting performance.

- To develop a rutting resistant mix, a mix needs to have a high percent recovery from MSCR test, a low VFA, a high asphalt absorption rate, and a gap-graded aggregate.

- A mix without anti-stripping agent is likely to have a stripping inflection point.
Outline

- Objectives & Research Progress

- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project

- Summary and Future Work
Air Void: WMA/HMA

Air Void Content Ratio, WMA/HMA

Frequency

0.65-0.75 0.75-0.85 0.85-0.95 0.95-1.05 1.05-1.15 1.15-1.25 1.25-1.35 1.35-1.45 1.45-1.55 1.55-1.65 1.65-1.75 1.75-1.85 1.85-1.95 1.95-2.05

AV Ratio = 1

Air Void Content Ratio
Binder Content: WMA/HMA
Fractured Aggregate after Testing
Summary

- As a whole, WMA has a tendency to have slight higher air void and lower asphalt content.
- The mix design results in the laboratory based on gyratory compactor may not be translated into the field.
- The compaction pressure may be too high and does not distinguish different mixes.*
Outline

- Objectives & Research Progress
- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- Summary and Future Work
TN SR 125 Project: HMA Pavement

Before Construction

During Construction

After Construction

3 years After Construction
TN SR 125 Project: 2014 Vs 2011 Field Cores
Dynamic Modulus
2014 field cores shows higher $E^*$ than 2011
TN SR 125 Project: 2014 Vs 2011 Field Cores
Air Void

Air Void, %

HMA 2011
HMA 2014
Evotherm 2011
Evotherm 2014

HMA
Evotherm
Creep Compliance

Creep Compliance Master Curve at 68°F Reference Temperature

HMA F3 2014 (6.4%)
HMA M3 2014 (6.3%)
HMA T1 2014 (7.0%)
HMA #3 2011 (5.7%)
HMA #5 2011 (6.0%)
HMA #17 2011 (6.6%)

Evo F3 2014 (9.3%)
Evo M2 2014 (8.6%)
Evo T3 2014 (7.5%)
Evo #5 2011 (6.2%)
Evo #8 2011 (8.3%)
Evo #18 2011 (9.0%)
TN SR 125 Project: 2014 Vs 2011 Field Cores

Creep Compliance

2014 field cores shows lower creep compliance than 2011
TN SR 125 Project: 2014 Vs 2011 Field Cores

IDT Test at Intermediate Temperature

- **IDT Strength, kPa**
  - HMA: 2011 HMA (7.5%), 2014 HMA (5.9%)
  - Evotherm: 2011 Evotherm (7.2%), 2014 Evotherm (8.0%)

- **Work Density, kPa**
  - HMA: 2011 HMA (7.5%), 2014 HMA (5.9%)
  - Evotherm: 2011 Evotherm (7.2%), 2014 Evotherm (8.0%)

- **Vertical Failure Deformation, mm**
  - HMA: 2011 HMA (7.5%), 2014 HMA (5.9%)
  - Evotherm: 2011 Evotherm (7.2%), 2014 Evotherm (8.0%)

- **Horizontal Failure Strain**
  - HMA: 2011 HMA (7.5%), 2014 HMA (5.9%)
  - Evotherm: 2011 Evotherm (7.2%), 2014 Evotherm (8.0%)
TN SR 125 Project: 2014 Vs 2011 Field Cores

IDT Test at Low Temperature

- 2011 HMA (6.0%)
- 2014 HMA (5.9%)
- 2011 Evotherm (7.0%)
- 2014 Evotherm (7.8%)
Binder MSCR Tests

TN SR 125 Project: 2014 Vs 2011 Field Cores
TN SR 125 Project: 2014 Vs 2011 Field Cores

Binder Fracture Tests at Intermediate Temperature
TN SR 125 Project: 2014 Vs 2011 Field Cores

Binder Fracture Tests at Low Temperature

![Graph showing failure strain comparison between HMA and Evotherm in 2011 and 2014.](image)
# Summary of Material Properties between HMA and WMA (TN SR125 Project)

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Property</th>
<th>HMA Vs. WMA</th>
<th>2011</th>
<th>2014</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>14°F</td>
<td>68°F</td>
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<tr>
<td>Mix</td>
<td>Dynamic Modulus</td>
<td>Evotherm</td>
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<td>&gt;</td>
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<tr>
<td></td>
<td>Creep Compliance</td>
<td>Evotherm</td>
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<tr>
<td></td>
<td>Vertical Failure Deformation (68°F)</td>
<td>Evotherm</td>
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<td>Fracture Work Density (14°F)</td>
<td>Evotherm</td>
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<td>Binder</td>
<td>PGs</td>
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<td>MSCR-R₃,₂</td>
<td>Evotherm</td>
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<td>Fracture Energy (68°F)</td>
<td>Evotherm</td>
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<tr>
<td></td>
<td>Failure Strain (41°F)</td>
<td>Evotherm</td>
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<td>=</td>
</tr>
</tbody>
</table>
Summary of Change of Material Properties

- The oxidation leads to higher modulus, smaller creep compliance and slopes, higher PG, compromised cracking resistance and improved rutting resistance.
- The application of chip seal significantly slowed down the oxidation.
- There is no clear trend of significant change of ranking between HMA and WMA after 2 or 3 years in service.
Outline

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Summary:

- In general, there is no significant difference of field performance between HMA and WMA pavements.
- Fracture work density, vertical failure deformation (and/or dynamic modulus), and rutting resistance index are recommended to be the significant determinants of transverse cracking, top-down fatigue cracking and rutting, respectively.
- Reducing the asphalt content based on laboratory compaction may compromise the cracking performance of a mix and should be discouraged.
Summary:

- A mix is more resistant to transverse cracking if it has a relatively high binder content and VFA, a ductile binder, hard aggregates and a fine aggregate gradation.
- A mix is more resistant to top-down cracking if it has a relatively high binder content, a soft binder, hard aggregates and a fine aggregate gradation.
- A mix is more resistant to rutting if it has a binder with high percent recovery, a low VFA, a gap-graded aggregate gradation, and a high asphalt absorption rate.
- Use of anti-stripping agent may be beneficial to avoid the moisture damage.
Summary:

- The aging of HMA and WMA does not significantly affect the property ranking.
Recommendations for implementations

- Implementation of findings
  - Develop mix design criteria based on significant determinants
    - Fracture work density for transverse cracking
    - Vertical failure deformation or horizontal failure strain for top-down cracking
    - Rutting resistance index for rutting
  - Use of anti-stripping agent
    - How much?
  - Procedure to ensure WMA has sufficient asphalt content
  - Adjustment of laboratory compaction
    - Compaction pressure, etc.
  - Use the material and field data to calibrate the Pavement ME models for rutting, top-down cracking, etc.
  - Develop binder specifications based on binder, mix and field data.
Thank You!
Any questions?