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

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Asphalt Mixture ETG Meeting
Fall Rivers, MA

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Project Information

- Project Duration: 05/2011-05/2016
- Project Team:
  - Haifang Wen, PI
  - Shihui Shen, Co-PI (PSU-Altoona)
  - Louay Mohammad, Co-PI (LTRC)
  - Bloom Companies – Field Distress Survey
  - Braun Intertec – Field Cores, FWD
Outline

- Background & Objectives
- Projects Overview & Tests
- Field Performance & Significant Determinants
  - Transverse cracking
  - Top-down longitudinal cracking
  - Rutting
- Summary and Future Work
Background

- **WMA categories:**
  - Wax additives: e.g. Sasobit
  - Chemical additives: e.g. Evotherm
  - Foaming: Water-based (Astec DBG, Ultrafoam)
    - Water containing (Aspha-min, Advera, Rediset)

- **How about the long-term field performance?**
  - Potential issues (rutting, moisture susceptibility, etc)
  - Lack of sufficient data

- Significant material and engineering property (determinants) to characterize WMA long-term performance?
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.
Outline

- Background & Objectives
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New Pavement Project (2011/2012)

5 Projects = 10 HMA-WMA pairs

- Sasobit, Evotherm DAT, Foaming
  3,170 AADT
  2.5”Overlay + 7”HMA + 16.2”base

- Sasobit, Evotherm 3G
  6,450 AADT
  1.5”Overlay + 5”HMA + 7-9”PCC

- Evotherm 3G, Foaming
  11,300 AADT
  2”Overlay + 8”HMA + 10”base

- Evotherm 3G
  3,470 AADT
  1.25”Overlay + 8”HMA + 6”based

- Sasobit, Evotherm 3G
  34,138 ADT
In-service Pavement Project
Different Ages, structures, traffic, material types, RAP content

Total: 22 in-service projects +1 HVS = 40 HMA-WMA pairs
Field Distress Survey

- LTPP distress identification manual: cracks, rut depth
- Cores taken at the tip of crack
- Three 200-feet segments

Wheel-path longitudinal cracking

Transverse crack
## Field Cores Test Summary

<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, 86°F; Frequency: 20, 10, 5, 1, 0.1, 0.01 Hz; Duration: 100s</td>
<td>Temp.: 68°F; Loading rate: 2 in./min</td>
<td>Temp.: 14°F; Loading rate: 0.1 in./min</td>
<td>Temp.: 122°F; 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)</td>
</tr>
</tbody>
</table>

![Diagram of load vs. vertical displacement](image-url)
## 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>
<tbody>
<tr>
<td>Testing Conditions</td>
<td>Different temp depending on the test (DSR, BBR)</td>
<td>Load: 0.1, 3.2kPa Temp.: high pavement temp 98% reliability</td>
<td>Temp.: 68ºF Shear strain rate: 0.3 s⁻¹</td>
<td>Temp.: 41ºF Shear strain rate: 0.01s⁻¹</td>
</tr>
<tr>
<td>Material Properties</td>
<td>PG; BBR stiffness; m-value</td>
<td>Jnr₀.₁, Jnr₃.₂; R₀.₁, R₃.₂</td>
<td>Maximum stress; Fracture energy; Failure strain</td>
<td>Maximum stress; Fracture energy; Failure strain</td>
</tr>
</tbody>
</table>

![Shear Stress Diagram](image)

- **Fracture energy**
- **Failure strain**
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Transverse Crack Length Comparison

- Weighted or Unweighted? (consider crack severity)
  - Use weighted factor (Wu et al. 2010 FHWA report)

\[ TotalCrack = 1.0 \times Crack_{low} + 3.4 \times Crack_{medium} + 7.7 \times Crack_{high} \]
HMA/WMA Transverse Cracking Comparison (1st Survey)

14 out of 24 projects exhibited transverse cracking (21 H-W pairs)

WMA better or comparable in transverse cracking performance

Note: H>W: HMA has more cracking than WMA
Transverse Cracking Comparison in terms of WMA Technology

HMA vs Sasobit
- H=W: 1/40
- H>W: 3/40
- H<W: 1/40

HMA vs Foaming
- H=W: 3/40
- H>W: 5/40
- H<W: 1/40

HMA vs Chemical
- H=W: 1/40
- H>W: 3/40

HMA vs Water based
- H=W: 1/40
- H>W: 3/40

HMA vs Water containing
- H=W: 2/40
- H>W: 2/40

14
Significant Determinants for Transverse Cracking (1st Round Survey)  

16 out of 21 pairs

- BBR stiffness
- Binder shear strength (41°F)
- Mix E* (14°F)
- Binder shear strength (41°F)
- Binder shear strength (68°F)
- Mix work density (14°F)
- Binder failure strain (41°F)
- BBR m-value
- Mix IDT strength (14°F)
- Mix horizontal failure strain (68°F)
- Mix vertical failure deformation (68°F)
Transverse Cracking Regression Model

\[ TC = 540.64 - 1846.17 \text{FWD} + 0.019T_{low} - 185.00D_{OL} + 0.29D_{HMA} \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>Transverse cracking length, ft/200ft segments</td>
</tr>
<tr>
<td>FWD</td>
<td>Mixture fracture work density tested at 14°F, MPa</td>
</tr>
<tr>
<td>( T_{low} )</td>
<td>8-year low temperature hour, (the total hours of low temperature below 15°F, direct output from Pavement ME based on the location of the site)</td>
</tr>
<tr>
<td>( D_{OL} )</td>
<td>Overlay thickness, in.</td>
</tr>
<tr>
<td>( D_{HMA} )</td>
<td>Total HMA thickness, in.</td>
</tr>
</tbody>
</table>

![Field Measured vs. Predicted Transverse Cracking](image)

- \( y = 1x \)
- \( R^2 = 0.60 \)
- Line of Equality
Implementation of the Use of Significant Determinants in Mix Design

\[ FWD = -291.38 + 0.387VFA + 66.74G_{se} + 8.08\varepsilon_b + 15.76P_b + 2.97P_{50} \]

<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 14ºF, kPa</td>
<td></td>
</tr>
<tr>
<td>VFA</td>
<td>Voids filled with asphalt</td>
<td>0.006</td>
</tr>
<tr>
<td>G_{se}</td>
<td>aggregate effective specific gravity</td>
<td>0.006</td>
</tr>
<tr>
<td>\varepsilon_b</td>
<td>binder failure strain tested at 41ºF</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>
Measured Vs Predicted Fracture Work Density

y = 0.9742x
R² = 0.7748
Line of equality
Outline

- Background & Objectives
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  - Top-down longitudinal cracking
  - Rutting
- Summary and Future Work
Top-down Longitudinal Cracking (Wheel-path)

Surface-initiated
8 out of 24 projects exhibited top-down longitudinal cracking (18 H-W pairs).

HMA better or comparable in top-down fatigue cracking performance
Top-down Longitudinal Cracking Comparison in terms of WMA Technologies (1st Round)

HMA vs. Sasobit

- $H=W \ 1/40$
- $H<W \ 3/40$

HMA vs. Foaming

- $H=W \ 3/40$
- $H<W \ 2/40$
- $H>W \ 1/40$

HMA vs. Chemical

- $H=W \ 2/40$
- $H<W \ 5/40$
- $H>W \ 1/40$

HMA vs. Water based

- $H=W \ 2/40$
- $H<W \ 2/40$

HMA vs. Water containing

- $H=W \ 1/40$
- $H>W \ 1/40$
Significant Determinants for Top-down Longitudinal Cracking (1\textsuperscript{st} Round)

12 out of 17 HMA/WMA pairs

- Binder maximum stress (68\degree F)
- Mixture IDT strength (68\degree F)
- Mixture IDT creep compliance (68\degree F)
- Mixture vertical failure deformation (68\degree F)
- Mixture horizontal failure strain (68\degree F)
- Binder Failure Strain (68\degree F)
Top-down Cracking Regression Model

\[ LC = -1514.14 + 129.86 \text{Age} - 16.55 \text{VFD} + 107.84 \text{DOL} + 0.012 \text{AADT} + 0.075 \text{UV} \]

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>Top-down longitudinal crack length, ft/200-ft segment</td>
</tr>
<tr>
<td>Age</td>
<td>Service years</td>
</tr>
<tr>
<td>VFD</td>
<td>Vertical failure deformation of mix tested at 68°F, mm</td>
</tr>
<tr>
<td>D_{OL}</td>
<td>Overlay thickness, in.</td>
</tr>
<tr>
<td>AADT</td>
<td>Average annual daily traffic</td>
</tr>
<tr>
<td>UV</td>
<td>Cumulative UV index during the service period, obtained from the National Oceanic and Atmospheric Administration (NOAA).</td>
</tr>
</tbody>
</table>

\[ y = 1.086x \]
\[ R^2 = 0.8467 \]

Line of equality
Implementation of the Use of Significant Determinants in Mix Design

\[
VFD = 1.65 - 0.034PG_{\text{inter}} + 0.01VFA + 0.009P_{16}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFD</td>
<td>Mixture vertical failure deformation 68ºF, mm</td>
<td></td>
</tr>
<tr>
<td>(PG_{\text{inter}})</td>
<td>Binder intermediate temperature PG</td>
<td>0.000</td>
</tr>
<tr>
<td>VFA</td>
<td>Void filled with asphalt</td>
<td>0.013</td>
</tr>
<tr>
<td>(P_{16})</td>
<td>Percentage passing No. 16 sieve size</td>
<td>0.027</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between measured and predicted vertical failure deformation with the line of equality and the equation \(y = 1.0045x\) and \(R^2 = 0.7237\).]
Outline

- Background & Objectives
- Projects Overview & Tests
- Field Performance & Significant Determinants
  - Transverse cracking
  - Top-down longitudinal cracking
  - Rutting
- Summary and Future Work
HMA/WMA Rut Depth Comparison (2nd Round)

- Use 1/16” to compare averaged rut depth of HMA and WMA pavements
Rut Depth Comparison in terms of WMA Technologies (2nd Round)

- **HMA vs. Sasobit**
  - $H > W$: 1/40
  - $H = W$: 8/40

- **HMA vs. Foaming**
  - $H > W$: 1/40
  - $H = W$: 15/40

- **HMA vs. Chemical**
  - $H < W$: 1/40
  - $H = W$: 11/40

- **HMA vs. Water-based**
  - $H > W$: 1/40
  - $H = W$: 9/40

- **HMA vs. Water containing**
  - $H = W$: 6/40
Rutting Resistance Index (RRI)

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

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

(1) Average rutting performance: 0.5 in. @ 20,000 cycles, RRI=10,000

(1) Poor rutting performance: 0.5 in. @ 10,000 cycles, RRI=5,000
Significant Determinants for Rutting Performance (2nd Round)

30 out of 32 HMA/WMA pairs

- Jnr0.1
- Jnr3.2
- Mix creep compliance (86°F)
- Hamburg Rutting Resistance Index R0.1
- R3.2
- Binder high temp PG
- Binder low temp PG
- Mix E* (86°F)
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</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>Binder percent recovery of binder @3.2 kPa</td>
<td>0.000</td>
</tr>
<tr>
<td>( P_{16} )</td>
<td>Percentage passing No. 16 sieve size</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>

\[ y = 1.0165x \]
\( R^2 = 0.70 \)
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Conclusions: Transverse Cracking

- Transverse crack may result from a combination of thermal cracking and reflective cracking.

- WMA shows better or comparable transverse cracking performance than HMA.

- Mixture work density (14°F) is found to be a significant determinant of transverse cracking in overlay.

- For implementation, if a mix has a ductile binder, relatively more asphalt, contain more aggregate passing No.50 sieve, and hard aggregate, the mix is more crack resistance.
Conclusions: Top-down cracking

- Most of the cracks in the wheel path are surface-initiated, indicating that these cracks are top-down fatigue cracking.

- HMA shows better or comparable top-down cracking performance than WMA.

- The mixture vertical deformation obtained from IDT tests (68°F) are found to be the significant determinants of top-down fatigue cracking.

- For implementation, if a mix has relatively lower intermediate PG, higher VFA, and more % passing No.16 sieve, the mix has better top-down cracking resistance.
Conclusions: Rutting

- HMA and WMA show comparable rutting performance.

- Mixture rutting resistance index is a good indicator for rutting performance.

- If a mix has a rutting-resistant binder (higher $R_{3.2}$), relatively lower VFA (dry mix), less aggregate passing No.16 and more passing No.100 (like SMA), a relatively higher binder absorption rate, the mix is more rutting resistance.
Future Work

- Data analysis on the 2\textsuperscript{nd} round field distress survey results
- Testing on new-pavement project (2\textsuperscript{nd} round sampling)
- Validation of previous findings
Acknowledgements

- NCHRP (09-49A) for Sponsoring the Study

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

- State Highway Agencies
Thank You!
Any questions?
How to compare based on what criteria?

- High variation of crack in three segments
- t-test may overshadows the difference
- Dual criterion

  (1) Absolute difference: 18.9 ft/200 ft
  (2) Difference ratio: 15%

For example:
HMA: 114.7 ft/200 ft
WMA: 71.7 ft/200 ft

  (1) Absolute difference = 114.7 - 71.7 = 43 > 18.9
  (2) Difference ratio = (114.7 - 71.7)/93.2*100 = 46.2% > 15%

Crack length: HMA > WMA
Significant Determinants of Transverse Cracking

**Compare Material Properties**
- $H > W$, $H = W$, $H < W$
- Effect size ($d = 1.6$)

**Compare Field Performance**
- $H > W$, $H = W$, $H < W$
- $15\%$ and $18.9\text{ft}/200\text{ft}$ Transverse
- $15\%$ and $10\text{ft}/200\text{ft}$ Top-down

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

- Summarize the number of pairs with consistent trend and determine the promising indicator;
- Evaluate other possible influencing factors
Fracture Work Density

\[ \text{Fracture Work Density} = \frac{\text{Fracture Work}}{\text{Volume of Specimen}} \]

The higher fracture work density, the better transverse cracking resistance.
Significant Material Properties Determination Procedure

Compare Material Properties

- \( H > W \), \( H = W \), \( H < W \)
- Effect size \( (d = 1.6) \)

Compare Field Performance

- \( H > W \), \( H = W \), \( H < W \)
- 15% and 18.9ft/200ft Transverse
- 15% and 10ft/200ft Top-down

Compare the two rankings

- Consistent trend
- No consistent trend

- Summarize the number of pairs with consistent trend and determine the promising indicator;
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