Performance Modeling and Design for Highly Modified Asphalt Pavement

Bob Kluttz, Kraton Polymers
Raj Dongré, Dongre Lab Services
Buzz Powell, NCAT
Richard Willis, NAPA
Richard Kim, North Carolina State U

Mid Atlantic Quality Asphalt Workshop
February 14, 2018
Outline

- What is highly modified asphalt?
- NCAT test track section performance
- AASHTOWare™ Pavement ME Design modeling
- FLEXPave™ software
- FLEXPave modeling
- Conclusions and where we go from here
What Is Highly Modified Asphalt?

Highly Modified Asphalt is exactly what it says, asphalt with more than double the normal amount of SBS polymer.

This gives a much denser polymer network with up to 10X rutting and fatigue cracking resistance.

Over 3,000,000 tons in over 70 projects around the world have demonstrated superior performance at reduced thickness.
PMA Producer’s Perspective

- Polymer Handling
- Blending
- Storage & Pumping
- Transport

- For all, no problem—handles like normal PMA.
## HiMA Specifications North America

<table>
<thead>
<tr>
<th>Standard</th>
<th>AASHTO M 320</th>
<th>AASHTO T301</th>
<th>AASHTO M 332</th>
<th>AASHTO T 350</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PG specification</td>
<td>Elastic Recovery</td>
<td>PG specification</td>
<td>MSCR Recovery</td>
</tr>
<tr>
<td>Alabama</td>
<td></td>
<td></td>
<td>PG 76E-22</td>
<td>95%</td>
</tr>
<tr>
<td>Alaska</td>
<td></td>
<td></td>
<td>PG 64E-40</td>
<td>90%</td>
</tr>
<tr>
<td>Florida</td>
<td></td>
<td></td>
<td>PG 76E-28</td>
<td>90%</td>
</tr>
<tr>
<td>Georgia</td>
<td></td>
<td></td>
<td>PG 76E-22</td>
<td>90%</td>
</tr>
<tr>
<td>Missouri</td>
<td></td>
<td></td>
<td>PG 76E-22</td>
<td>90%</td>
</tr>
<tr>
<td>Oklahoma</td>
<td></td>
<td></td>
<td>PG 76E-28</td>
<td>95%</td>
</tr>
<tr>
<td>Tennessee</td>
<td></td>
<td></td>
<td>PG 76E-28</td>
<td>90%</td>
</tr>
<tr>
<td>Utah</td>
<td></td>
<td></td>
<td>PG 70E-34</td>
<td>90%</td>
</tr>
<tr>
<td>Virginia</td>
<td></td>
<td></td>
<td>PG 76E-28</td>
<td>90%</td>
</tr>
<tr>
<td>Florida</td>
<td>PG 82-22</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Iowa</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Minnesota</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Ohio</td>
<td>PG 88-22M</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Oregon</td>
<td>PG 76-28</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>New York City</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Utah</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Vermont</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Washington</td>
<td>PG 76-34</td>
<td></td>
<td></td>
<td>90%</td>
</tr>
</tbody>
</table>
National Center for Asphalt Technology Test Track

- 5 trucks, 16 h/day, 5 days/week
- Axle load: 18 kip
- Speed: 45 mph
National Center for Asphalt Technology Test Track

- Track cycle of 10 million ESALs simulates the design lifetime of damage in 2+ years
- ESAL = Equivalent Single Axle Load = 1 pass of 18 kip axle
- Highly Modified Asphalt (HiMA) project started in 2009 cycle
- Part of Performance Group study—6 sections including control
- Continued in 2012 cycle
- Total 20 million ESALs
Control (S9) and HiMA (N7) Section Designs

**Section S9 - Control**
178 mm Standard Hot Mix
- 32 mm (PG 76-22; 9.5 mm NMAS; 80 Gyrations)
- 70 mm (PG 76-22; 19 mm NMAS; 80 Gyrations)
- 70 mm (PG 76-22; 19 mm NMAS; 80 Gyrations)

**Section N7**
145 mm Highly Modified Hot Mix
- 32 mm (7.5% SBS; 9.5 mm NMAS)
- 57 mm (7.5% SBS; 19 mm NMAS; 80 Gyrations)
- 57 mm (7.5% SBS; 19 mm NMAS; 80 Gyrations)

Dense Graded Crushed Aggregate Base
- $M_c = 85$ MPa
- $n = 0.40$

Lift thicknesses limited by 3:1 thickness:NMAS requirement

Test Track Soil
- $M_c = 200$ MPa
- $n = 0.45$

Courtesy Prof. David Timm, Auburn U.
## Crack Maps at 17 Million ESALs

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Rutting</th>
<th>Lane</th>
<th>Left Wheel Path</th>
<th>Right Wheel Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>S9</td>
<td>3/14</td>
<td>6.0 mm</td>
<td>9%</td>
<td>12%</td>
<td>21%</td>
</tr>
<tr>
<td>N7</td>
<td>1.6 mm</td>
<td></td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**2/14 Crack Maps**

- **S9**: 6.0 mm
  - Lane: 9%
  - Left Wheel Path: 12%
  - Right Wheel Path: 21%

- **N7**: 1.6 mm
  - Lane: 0%
  - Left Wheel Path: 0%
  - Right Wheel Path: 0%
Rutting over 20 Million ESALs
N7 Crack Map at 20 Million ESALs

S9 resurfaced at 17 million ESALs

N7 cracking is superficial top-down
AASHTOWare™ Pavement ME Design

- Traditional layered elastic model
- Comprehensive input data

- Fatigue cracking model
  \[ N_{f-HMA} = k_{f1}(C)(C_H)b_{f1}(\varepsilon_t)^{kf2}b_{f2}(E_{HMA})^{kf3}b_{f3} \]

- Permanent deformation model
  \[ D_{p(HMA)} = \varepsilon_{p(HMA)}h_{HMA} = b_{r1}k_{z}\varepsilon_{r(HMA)}^{kr1}\eta^{kr2}b_{r2}T^{kr3}b_{r3} \]
Fatigue Global Calibration Parameters

\[ y = k_f (1/\varepsilon_0)^{k_f} \]

\( k_f = \text{modulus coefficient} \)
# Fatigue Calibration Factors for Section N7

<table>
<thead>
<tr>
<th></th>
<th>$k_{f_1}$</th>
<th>$k_{f_2}$</th>
<th>$k_{f_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEPDG Standard Values</td>
<td>7.566E-3</td>
<td>3.9492</td>
<td>1.2810</td>
</tr>
<tr>
<td>S9 Calculated Values</td>
<td>1.4964E-2</td>
<td>3.9492</td>
<td>1.2810</td>
</tr>
<tr>
<td>N7 Calculated Values</td>
<td>7.5721E-5</td>
<td>7.3135</td>
<td>2.3655</td>
</tr>
<tr>
<td>Ratios</td>
<td>0.9762</td>
<td>0.7595</td>
<td>0.0491</td>
</tr>
<tr>
<td>N7 Adjusted Values</td>
<td>7.386E-3</td>
<td>2.9994</td>
<td>0.0630</td>
</tr>
</tbody>
</table>
Rutting Global Calibration Parameters

$k_{r1}$ is the y-axis intercept
$k_{r2}$ is the x versus y slope
$k_{r3}$ is the $k_{r1}$ versus temperature slope
## Rutting Calibration Factors for Section N7

<table>
<thead>
<tr>
<th></th>
<th>$k_{r1}$</th>
<th>$k_{r2}$</th>
<th>$k_{r3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEPDG Standard Values</td>
<td>-3.3541</td>
<td>0.4719</td>
<td>1.5606</td>
</tr>
<tr>
<td>S9 Calculated Values</td>
<td>-3.7902</td>
<td>0.4719</td>
<td>1.5606</td>
</tr>
<tr>
<td>Ratios</td>
<td>0.8045</td>
<td>0.4791</td>
<td>1.0000</td>
</tr>
<tr>
<td>N7 Adjusted Values</td>
<td>-2.6985</td>
<td>0.2261</td>
<td>1.5606</td>
</tr>
</tbody>
</table>
Predicted Cracking

Predicted AC Bottom-Up Cracking

- 50% Reliability
- Specified Reliability

Measurement Dates

KRATON
### Predicted damage summary

<table>
<thead>
<tr>
<th>Pavement Distress</th>
<th>S9</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Permanent Deformation, mm</td>
<td>10.2</td>
<td>8.4</td>
</tr>
<tr>
<td>AC Permanent Deformation, mm</td>
<td>6.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Bottom-Up Cracking, % Area</td>
<td>18</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Measured damage summary

<table>
<thead>
<tr>
<th>Pavement Distress</th>
<th>S9</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Permanent Deformation, mm</td>
<td>6.0</td>
<td>1.6</td>
</tr>
<tr>
<td>AC Permanent Deformation, mm</td>
<td>6.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Bottom-Up Cracking, % Area</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>
FlexPAVE™ 1.0

- Three dimensional layered viscoelastic analysis for moving loads and thermal stresses
- Fatigue performance analysis based on Viscoelastic Continuum Damage (VECD) Model
- Rutting performance analysis based on the shift model
- Support for multiple axle and multiple wheel loading
- Integrated with EICM software to capture temperature variation for thermal stress analysis and material properties
- Integrated GUI that includes pre and post processors
General Information
Damage Contour
FlexPAVE™ Simulation

NCAT Test Track 2009 Performance Group
FlexPAVE™ Simulation
NCAT Test Track 2009 Section N7
FlexPAVE™ Simulation
NCAT Test Track 2009 Section N7 Expanded Scale

% Damage (Top-down)

ESALs
NCAT Test Track Prediction

![Graph showing the comparison between measured and predicted damage]
Conclusions

- NCAT section N7 developed fine surface cracking late in its life, but forensic analysis showed that the cracking was minor top down cracking not impacting the structural integrity of the pavement.

- Highly modified asphalt may be useful in perpetual pavement design.

- Demonstrated performance up to 20 million ESALs shows that the thickness of pavement structures may be reduced while retaining or even improving long term performance.
Conclusions

- AASHTO M332 specifications (plus elastic recovery) have been effective to specify HiMA binders for commercial applications.
- Standardized test methods in increasingly common use are adequate to characterize HiMA mixtures for the purpose of pavement design.
- The current Pavement ME Design protocol is suited to designing perpetual pavements with highly modified asphalts. Relative global calibration factor adjustment with Level 1 design gives performance predictions that agree well with actual field performance relative to known structures.
Conclusions

- Both AASHTOWare Pavement ME Design™ and FlexPAVE™ are effective design tools.
- ME Design currently lacks a validated model for top-down cracking.
- FlexPAVE currently lacks a built-in aging model and so required aged material properties.
- We will be doing follow up modeling with both to compare!
HiMA Market Applications - Where Does it Add Value?

- **Structural Applications**
  - With a sound base, thinner pavements with lower upfront cost
  - Demonstrated in many field applications & Ohio University APLF
  - With weak base, much longer lifetime can be achieved

- **Thin Overlays**
  - Superior resistance to reflective cracking BUT requires finer, richer mix.

- **Preservation Surfacing such as micro surfacing**

- **Open Grade Mixes for Reduced Raveling**

- **SAMI Layers**

- **High Stress Applications - ramps, intersections**

- **AASHTOWare® Pavement ME Design works for HiMA designs**
In General Terms, What Does HiMA Do to Mixture and Performance Characteristics?

- Modulus
- Cracking Resistance
- Rutting Resistance
- Cracking Versus Rutting
- Structural Integrity
Dynamic Modulus Testing Results - 9.5 mm NMAS Mixtures
Four Point Bending Beam Fatigue Results

Full sinusoidal loading. Cited strains are $\frac{1}{2}$ amplitude.
TX DOT Overlay Specifications - Coarse Dense Mix

12.5 mm max Hamburg TX DOT specification
TX DOT Overlay Specifications - Fine Rich Mix

12.5 mm max Hamburg  750 min Overlay  TX DOT specification
Thickening Reduction Capability

Good quality sub base

(1) Thickness determined by asphalt strain criterion
(2) Thickness determined by sub grade strain criterion

Poor quality sub base

HiMA = Highly Modified Asphalt
HiMA Mixture and Pavement Design Concepts

- So how should these observations apply to design principles?
- Structural Pavement - Strong Base
- Structural Pavement - Weak Base
- Overlay - Undamaged Pavement
- Overlay - Damaged Pavement
- Waterproof Bridge Deck
- SAMI
Structural Pavement - Strong Base

- Lowest strain. Best Case!
- Key distress—bottom up fatigue cracking
- Solution—standard mix design, perhaps slightly richer, 0.2-0.3%.
- Thinner pavement design for lower up front cost and life cycle cost for a perpetual pavement.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Mix Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ¼”</td>
<td>PG 76-22 E, 9.5 mm NMAS, 80 gyrations</td>
</tr>
<tr>
<td>2 ¼”</td>
<td>PG 76-22 E, 19mm NMAS; 80 gyrations</td>
</tr>
<tr>
<td>2 ¾”</td>
<td>PG 76-22 E; 19mm NMAS; 80 gyrations</td>
</tr>
</tbody>
</table>
**Structural Pavement - Weak Base**

- Moderate strain.
- Key distress—risk of subbase, subgrade damage, bottom up cracking.
- Solution—rich bottom layer, little or no thickness reduction.
- Likely more expensive up front cost, but perpetual pavement vs. rehab every few years.

<table>
<thead>
<tr>
<th>1¼” (7½% polymer; 9.5 mm NMAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3¼” (7½% polymer; 19mm NMAS; 80 Gyraions)</td>
</tr>
<tr>
<td>1½” (7½% polymer; 9.5mm NMAS; 80 Gyraions)</td>
</tr>
</tbody>
</table>
Overlay - Undamaged Pavement

- Low strain.
- Key distress—should be able to achieve substantial thickness reduction, but be aware of potential for rutting below surface.
- Solution—standard mix design, perhaps 0.2-0.3% richer to be on the safe side.
- Thinner pavement for lower up front cost and life cycle cost.
Overlay - Damaged Pavement

- Very high localized strain.
- Key distress—reflective cracking.
- Solution—take advantage of rutting resistance with a finer, richer mix than standard, e.g., New Jersey HPTO mix
- Mix expensive up front mix, but much better life cycle cost analysis.

SECTION 406 – HIGH PERFORMANCE THIN OVERLAY (HPTO)

406.01 DESCRIPTION
This Section describes the requirements for constructing high performance thin overlay (HPTO).

406.02 MATERIALS

406.02.01 Materials
Provide materials as specified:

Tack Coat: Emulsified Asphalt; Grade RS-1, SS-1, SS-1h, Grade CSS-1 or CSS-1h……………………………...902.01.03
HPTO……………………………………………………………………………………………………………………902.08
Waterproof Bridge Deck Mix

- Key distress—fatigue cracking, water permeation
- Solution—very rich fine mix with <2% voids.
- Lower cost & far better workability than alternatives.

SECTION 555 - BRIDGE DECK WATERPROOF SURFACE COURSE

555.01 DESCRIPTION
This Section describes the requirements for constructing bridge deck waterproof surface course (BDWSC).

555.02 MATERIALS
555.02.01 Materials
Provide materials as specified:
- Tack Coat 64-22, PG 64-22 ...............................................................902.01.01
- Tack Coat:
  - Cut-Back Asphalt, Grade RC-70 ....................................................902.01.02
  - Emulsified Asphalt, Grade RS-1, SS-1, SS-1h, Grade CSS-1 or CSS-1h ........................................902.01.03
  - Joint Sealer, Hot Pour ....... .........................................................914.02
- Polymerized Joint Adhesive .................................................................914.03
Stress Attenuating Mix Interlayer (SAMI)

- High strain. Low voids.
- Key distress—reflective cracking.
- Solution—very rich fine mix with low voids.
- Lower cost than thick structural layer.

Assessment of Asphalt Interlayer Designed on Jointed Concrete
Legal Disclaimer

Kraton Corporation and all of its affiliates, including Arizona Chemical, believe the information set forth herein to be true and accurate, but any recommendations, presentations, statements or suggestions that may be made are without any warranty or guarantee whatsoever, and shall establish no legal duty on the part of any Kraton affiliated entity. The legal responsibilities of any Kraton affiliate with respect to the products described herein are limited to those set forth in Kraton’s Conditions of Sale or any effective sales contract. NOTE TO USER: by ordering/receiving Kraton product you accept the Kraton Conditions of Sale applicable in the region. All other terms are rejected. Kraton does not warrant that the products described herein are suitable for any particular uses, including, without limitation, cosmetics and/or medical uses. Persons using the products must rely on their own independent technical and legal judgment, and must conduct their own studies, registrations, and other related activities, to establish the safety and efficacy of their end products incorporating any Kraton products for any application. Nothing set forth herein shall be construed as a recommendation to use any Kraton product in any specific application or in conflict with any existing patent rights. Kraton reserves the right to withdraw any product from commercial availability and to make any changes to any existing commercial or developmental product. Kraton expressly disclaims, on behalf of all Kraton affiliates, any and all liability for any damages or injuries arising out of any activities relating to the use of any information set forth in this publication, or the use of any Kraton products.

*KRATON and the Kraton logo are either trademarks or registered trademarks of Kraton Corporation, or its subsidiaries or affiliates, in one or more, but not all countries.

©2018 Kraton Corporation