SBS Modified Base Courses for Enhanced Pavement Performance

Bob Kluttz, Kraton Polymers

Northeast Asphalt User Producer Group Meeting – October 8-9, 2008
Outline

- Kraton Polymers
- How SBS Works in Bitumen and Asphalt Pavement
- Background of the Study
- Framework
- Testing phases
- Results
- Advanced Modeling
- Conclusions
Kraton Polymers

- Inventor and world’s leading producer of styrenic block copolymers ("SBCs")
  - First commercialized as part of Shell Elastomers in the 1960s

- Produces over 1000 products from six plants in the US, Europe, Latin America and Asia

- Serves three groups of end-uses:
  - Paving & Roofing
  - Adhesives, Sealants & Coatings
  - Advanced Materials
SBS in Bitumen
Phase Morphology

- Bitumen + 2½% polymer
- Bitumen + 5% polymer
- Bitumen + 7½% polymer
Crack Propagation in Toughened Composite

Source: www.scielo.br/img/fbpe/mr/v4n3/a13fig5a.gif
How SBS Works in Asphalt Pavement

Common Road Structure

High wheel loads → permanent deformation top-down cracking

Delta T → thermal contraction thermal fatigue surface cracking

WEARING COURSE
SBS to increase $G^*/\sin\delta$, decrease $J_{nr}$

BINDER COURSE
SBS to increase low T flexibility and fracture toughness

BASE COURSE
SBS to increase fracture toughness

Traffic induced deflections → fatigue
Background of the Study

- Higher traffic intensities and pavement loadings require more durable pavements
- Higher traffic intensities also command longer maintenance intervals to increase availability of the road
- Environmental pressure is increasing; reduction of use of natural resources such as aggregate and less emissions are highly desired
- SBS modification has proven benefits in wearing courses over the past decades in every relevant property

Use the benefits of SBS to create a polymer modified base course asphalt that can fulfill the requirements of today and tomorrow

Technical challenge: compatibility and workability with relatively hard base bitumen
2004: start of a joint research program with Road Engineering Section of Delft University of Technology

Asphalt mix knowledge of DUT combined with polymer-bitumen technology of Kraton Polymers to investigate whether SBS modification of base layers would increase life time and/or enable layer thickness reductions of the asphalt pavement
Participants

- Kraton Polymers
  - Willem Vonk
  - Erik Jan Scholten
  - Bob Kluttz

- Technical University Delft – Road & Railways
  - Andre Molenaar
  - Martin van de Venn
  - Tariq Medani

- Technical University Delft - Mechanics
  - Tom Scarpas
  - Xueyan Liu
Testing Phases

- **2004 (phase 1):**
  Asphalt mix testing by DUT of base course asphalt containing standard Kraton® polymer grades

- **2005:**
  Binder testing by Kraton Polymers Research of best performing mixes
  Selection of additional polymer grades for testing in phase 2
Results Phase 1

- All SBS modified asphalt mixes outperformed unmodified reference in 4 point bending test; best results were with mix 42.
Testing Phases

- **2006 (phase 2):**
  Fundamental asphalt mix testing using standard base course mix with selected binders: monotonic uniaxial compression and tensile tests, indirect tensile tests

- **2007:**
  Use of fundamental asphalt mix data in advanced modeling to compare damage development in pavement
Advanced Modeling

- Asphalt Concrete Response (ACRe) model developed at Delft University
- Desai response surface for hardening and softening
- Crack plane response simulation with Hoffman surface
- CAPA 3D Finite Element Code developed at Delft University

Desai Response Surface – Compressive Behavior

\[
F = \frac{J_2}{P_a^2} \left[ -\alpha \left( \frac{I_1 - R}{P_a} \right)^n + \gamma \left( \frac{I_1 - R}{P_a} \right)^2 \right] = 0
\]

- \( I_1 \) = first stress invariant
- \( J_2 \) = second stress invariant
- \( P_a \) = atmospheric pressure
- \( \alpha, \gamma, n, R \) = material dependent model parameters
- \( \alpha \) - controls size of flow surface
- \( \gamma \) - related to ultimate strength
- \( n \) - apex of flow surface, where response changes from compaction to dilation
- \( R \) - triaxial strength in tension

Hoffman Surface – Crack Plane Response

\[ \sigma^2 + q\left(\tau_s^2 + \tau_t^2\right) = f_t^2\left(\delta, T, \kappa\right) \]

- \( \sigma \) = normal stress on crack plane
- \( \tau_s, \tau_t \) = shear components
- \( f_t \) = tensile strength after crack initiation
- \( q \) = material constant
- \( \kappa \) = softening parameter
- \( \delta \) - controls size of flow surface
- \( T \) - temperature

Definition of Damage for Model

\[ \xi = \sqrt{\text{deviatoric} : \text{deviatoric}} = \sqrt{\text{volumetric} \cdot \text{volumetric} + \text{volumetric} \cdot \text{volumetric} + \text{volumetric} \cdot \text{volumetric} + \text{volumetric} \cdot \text{volumetric} + \text{volumetric} \cdot \text{volumetric} + \text{volumetric} \cdot \text{volumetric}} \]
Shear Strength from Tension & Compression

Tension + Compression = Shear
Interaction Between Desai and Hoffman Aspects of ACRe Model

End in Hoffman region? ready

End in Desai region?
Submit new stresses to Desai: INTERACTION!

Desai regime=
Isotropic damage (permanent deformation)

Hoffman regime=
cracking

Apply Hoffman

Principal Stress Space

Back to xyz

Results Phase 2

- Low strain rate / high temperature (rutting!)

\[ T = 40 \, ^\circ C \text{ and strain rate} = 0.01\%/s \]
Results Phase 2

- high strain rate / low temperature (cracking!)

\[ T = 5 \, ^\circ\text{C} \text{ and strain rate } = 0.1\%/\text{s} \]

\[ \text{I}_1 \, \text{[N/mm}^2\text{]} \]

\[ \text{sqrt(J}_2 \text{)} \, \text{[N/mm}^2\text{]} \]
Crack Growth Behavior

Schapery theory

\[
\frac{dc}{dN} = A \cdot K_{eff}^n
\]

\[
\log \frac{dc}{dN} = \log A + n \log K
\]

The higher A, the faster cracks will grow

\[
A = f\left\{ \frac{1}{f_t^2}, \left(\frac{1}{\Gamma}\right)^{\frac{1}{m}}, \left(\frac{1}{E^2}\right)^{\frac{1}{m}}, \left(1 - \mu^2\right)^{\frac{1}{m}} \right\}
\]

Tensile strength
Fracture energy
Slope of compliance curve
### A-ratio; Improvement over Unmodified Reference

- **Ratio of A unmodified reference / modified mix**
  - $T = 20 \, ^\circ\mathrm{C}$ and strain rate = 1 %/s

<table>
<thead>
<tr>
<th>Modification type</th>
<th>Improvement (A-ratio) (m, based on $E^*$ vs. frequency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46 – experimental SBS</td>
<td>68 (0.38)</td>
</tr>
<tr>
<td>45 – speciality SBS</td>
<td>58 (0.38)</td>
</tr>
<tr>
<td>47 – experimental SBS</td>
<td>34 (0.38)</td>
</tr>
<tr>
<td>43 – standard SBS</td>
<td>13 (0.38)</td>
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<tr>
<td>42 – standard SBS</td>
<td>8  (0.38)</td>
</tr>
<tr>
<td>41 – standard SBS</td>
<td>2  (0.41)</td>
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</tbody>
</table>
Pavement Structure and Loading

Three layers structure:
- Bound layer - $E_1 = 1000 \text{ MPa (145,000 psi)}$; $h = 6$” or 10”
- Unbound subbase - $E_2 = 300 \text{ MPa (43,500 psi)}$; $h = 12$”
- Subgrade - $E_3 = 100 \text{ MPa (14,500 psi)}$; $h = 50$’

Constant temperature: $T = 20 \degree C (68 \degree F)$

Stationary dynamic load:
800 kPa (115 psi) – 25 ms
Proposed System

1 3/4" (PMA) wearing course
1 3/4" binder course
6 1/2" base course
subbase
subgrade

This an example; depending on local conditions other types may apply
## Cost Comparison: Base Case with Unmodified Wearing Course

<table>
<thead>
<tr>
<th>mix type</th>
<th>thickness</th>
<th>cost per ton</th>
<th>per sq yd</th>
<th>total</th>
<th>cost reduction per sq yd</th>
<th>% cost reduction</th>
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</thead>
<tbody>
<tr>
<td>unmodified wearing course</td>
<td>1.75 &quot;</td>
<td>$70.00</td>
<td>$13.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unmodified binder course</td>
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<tr>
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<td>$30.68</td>
<td>$63.73</td>
<td>$11.30</td>
<td>15%</td>
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</tbody>
</table>

*Based on example from previous slide, material costs only*

**base data:**
- SMA unmodified wearing mix: $70/ton
- unmodified base mix: $65/ton

**assumptions:**
- PMA wearing mix + 20%
- PMA base mix + 40%
Cost Comparison: Base Case with Modified Wearing Course

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base data:
SMA unmodified wearing mix: $70/ton
unmodified base mix: $65/ton

assumptions:
PMA wearing mix + 20%
PMA base mix + 40%
Intense volumetric damage of compressive nature occurs in the vicinity of the wheel, indicating the gradual development of rutting.

Intense tensile volumetric damage at the bottom of the layer under the wheel; gradual development of tensile crack at the bottom of the pavement.

Deviatoric damage starting in the top of the pavement (inclined cracking).
Volumetric damage of compressive nature occurs in the vicinity of the wheel, indicating the gradual development of rutting.

No tensile volumetric damage at the bottom of the pavement.

Significantly lower levels of damage (note factor 10 in scales)
Modeling Results

**Kraton Polymer Modified (6”)**

- **total damage**
  - N=1000
  - N=5000
  - N=9000

**Unmodified (10”)**

- **total damage**
  - N=1000
  - N=9000
Rutting Profile

40-2 = 10” unmodified asphalt
45-1 = 6” SBS modified asphalt

>4X reduction in permanent deformation at 60% thickness
Initial Wheel-Tracking Results
Deviatoric Deformation

Deviatoric damage distribution in thicker unmodified pavement
Max = 2.05E-2

Deviatoric damage distribution in thinner modified pavement
Max = 0.78E-2
Initial Wheel-Tracking Results
Compressive Deformation

Compressive damage distribution in thicker unmodified pavement
Max = 1.27E-2

Compressive damage distribution in thinner modified pavement
Max = 0.70E-2
Initial Wheel-Tracking Results
X Direction Cracking

Crack projected in x direction in thicker unmodified pavement
Max = 1.31E-3

Crack projected in x direction in thinner modified pavement
Max = 0.02E-3
Initial Wheel-Tracking Results
Y Direction Cracking

Crack projected in y direction in thicker unmodified pavement
Max = 7.72E-4

Crack projected in y direction in thinner modified pavement
Max = 4.41E-4
Initial Wheel-Tracking Results
Z Direction Cracking

Crack projected in z direction in thicker unmodified pavement
Max = 8.65E-4

Crack projected in z direction in thinner modified pavement
Max = 0.79E-4
Conclusions

- The proven performance of SBS modified asphalt in wearing courses can now be extended to base courses.
- Reduction of the asphalt pavement thickness in combination with an improved performance has proven to be feasible.
  - Base course layer thickness can be reduced which creates a saving on energy, natural resources and potentially even overall costs.
  - Significantly increased performance can be used to construct perpetual pavements.
- To achieve this performance, while having acceptable workability and compatibility with the hard base bitumen, specially designed polymers are required.
Discussions underway with several agencies in US and Europe for potential test sections.

Wheel tracking trials in planning for 2009 at TRL, the UK Transportation Research Laboratory and/or ATREL facility at University of Illinois at Urbana-Champaign

Full test track trial in planning for NCAT 2009 cycle.
Future work

- More tested asphalt mixes will be evaluated in Finite Element Modeling (FEM)
- FEM evaluations with lower subgrade E-modulus for sensitivity analysis
- Stationary dynamic loading and wheel loading FEM with different pavement structures
- Efforts will be made to correlate advanced testing results to standard asphalt mix testing
- Implement FEM results into pavement design
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