SBS Modified Base Courses for Enhanced Pavement Performance

Bob Kluttz, Kraton Polymers

Southeast Asphalt User Producer Group Meeting – November 18-20, 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

Delta T $\rightarrow$ thermal contraction
thermal fatigue
surface cracking

High wheel loads $\rightarrow$
permanent deformation
top-down 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 $\rightarrow$ 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
Framework of the Study

- 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

\[ \xi = \sqrt{\varepsilon_{ij}^P : \varepsilon_{ij}^P} = \sqrt{\varepsilon_{xx}^P \cdot \varepsilon_{xx}^P + \varepsilon_{yy}^P \cdot \varepsilon_{yy}^P + \varepsilon_{zz}^P \cdot \varepsilon_{zz}^P + \varepsilon_{xy}^P \cdot \varepsilon_{xy}^P + \varepsilon_{xz}^P \cdot \varepsilon_{xz}^P + \varepsilon_{yz}^P \cdot \varepsilon_{yz}^P} \]
Shear Strength from Tension & Compression

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

Principal Stress Space

Apply Hoffman

End in Hoffman region? ready

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

Desai regime=
Isotropic damage (permanent deformation)

Hoffman regime=
cracking

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 °C and strain rate = 0.1%/s
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.

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

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

Ratio of A unmodified reference / modified mix

\[ T = 20 \, ^\circ\text{C} \text{ and strain rate } = 1 \, \%/\text{s} \]

<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>
</tr>
<tr>
<td>42 – standard SBS</td>
<td>8 (0.38)</td>
</tr>
<tr>
<td>41 – standard SBS</td>
<td>2 (0.41)</td>
</tr>
</tbody>
</table>
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: $T = 20 \, ^\circ\text{C (68 \, ^\circ\text{F})}$

Stationary dynamic load: $800 \, \text{kPa (115 psi)}$ – $25 \, \text{ms}$
Proposed System

1\(\frac{3}{4}\)” (PMA) wearing course

1\(\frac{3}{4}\)” binder course

6\(\frac{1}{2}\)” base course

subbase

subgrade

old

This an example; depending on local conditions other types may apply

1\(\frac{3}{4}\)” PMA wearing course

1\(\frac{3}{4}\)” PMA binder course

3” PMA base course

subbase

(thickness depending on local conditions)

subgrade

new

6\(\frac{1}{2}\)”
## 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>
</tr>
</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>
<td>1.75 &quot;</td>
<td>$70.00</td>
<td>$13.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unmodified base course</td>
<td>6.5 &quot;</td>
<td>$65.00</td>
<td>$47.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>10.0 &quot;</td>
<td></td>
<td></td>
<td>$75.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>modified wearing course</td>
<td>1.75 &quot;</td>
<td>$84.00</td>
<td>$16.52</td>
<td></td>
<td>-$24.50</td>
<td>-33%</td>
</tr>
<tr>
<td>modified binder course</td>
<td>1.75 &quot;</td>
<td>$84.00</td>
<td>$16.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>modified base course</td>
<td>6.5 &quot;</td>
<td>$91.00</td>
<td>$66.48</td>
<td>$99.52</td>
<td>-$24.50</td>
<td>-33%</td>
</tr>
<tr>
<td></td>
<td>5.5 &quot;</td>
<td>$91.00</td>
<td>$56.25</td>
<td>$89.29</td>
<td>-$14.27</td>
<td>-19%</td>
</tr>
<tr>
<td></td>
<td>5.0 &quot;</td>
<td>$91.00</td>
<td>$51.14</td>
<td>$84.18</td>
<td>-$9.16</td>
<td>-12%</td>
</tr>
<tr>
<td></td>
<td>4.5 &quot;</td>
<td>$91.00</td>
<td>$46.02</td>
<td>$79.07</td>
<td>-$4.05</td>
<td>-5%</td>
</tr>
<tr>
<td></td>
<td>4.0 &quot;</td>
<td>$91.00</td>
<td>$40.91</td>
<td>$73.95</td>
<td>$1.07</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>3.5 &quot;</td>
<td>$91.00</td>
<td>$35.80</td>
<td>$68.84</td>
<td>$6.18</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>3.0 &quot;</td>
<td>$91.00</td>
<td>$30.68</td>
<td>$63.73</td>
<td>$11.30</td>
<td>15%</td>
</tr>
</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

## Table:

<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>
</tr>
</thead>
<tbody>
<tr>
<td>modified wearing course</td>
<td>1.75 &quot;</td>
<td>$84.00</td>
<td>$16.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unmodified binder 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 base course</td>
<td>6.5 &quot;</td>
<td>$65.00</td>
<td>$47.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>10.0 &quot;</td>
<td></td>
<td></td>
<td></td>
<td>$77.77</td>
<td></td>
</tr>
</tbody>
</table>

<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>
</tr>
</thead>
<tbody>
<tr>
<td>modified wearing course</td>
<td>1.75 &quot;</td>
<td>$84.00</td>
<td>$16.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>modified binder course</td>
<td>1.75 &quot;</td>
<td>$84.00</td>
<td>$16.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>modified base course</td>
<td>6.5 &quot;</td>
<td>$91.00</td>
<td>$66.48</td>
<td>$99.52</td>
<td>-$21.75</td>
<td>-29%</td>
</tr>
<tr>
<td></td>
<td>5.5 &quot;</td>
<td>$91.00</td>
<td>$56.25</td>
<td>$89.29</td>
<td>-$11.52</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>5.0 &quot;</td>
<td>$91.00</td>
<td>$51.14</td>
<td>$84.18</td>
<td>-$6.41</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>4.5 &quot;</td>
<td>$91.00</td>
<td>$46.02</td>
<td>$79.07</td>
<td>-$1.29</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>4.0 &quot;</td>
<td>$91.00</td>
<td>$40.91</td>
<td>$73.95</td>
<td>$3.82</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>3.5 &quot;</td>
<td>$91.00</td>
<td>$35.80</td>
<td>$68.84</td>
<td>$8.94</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>3.0 &quot;</td>
<td>$91.00</td>
<td>$30.68</td>
<td>$63.73</td>
<td>$14.05</td>
<td>19%</td>
</tr>
</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%
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”)

- N=1000
- N=5000
- N=9000

Unmodified (10”)

- N=1000
- N=9000

2008 SEAUPG CONFERENCE-BIRMINGHAM, ALABAMA
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
Kraton® and the Kraton logo and design are trademarks of Kraton Polymers LLC.

Disclaimer

We believe the information set forth above to be true and accurate, but any recommendations or suggestions that may be made in the foregoing text are without any warranty or guarantee whatsoever, and shall establish no legal duty or responsibility on the part of the authors or their employer. Furthermore, nothing set forth above shall be construed as a recommendation to use any product in conflict with any existing patent rights. Kraton Polymers expressly disclaims any and all liability for any damages or injuries arising out of any activities relating in any way to this publication.