ARC Project Update

Asphalt Binder Lubricity, Impacts of WMA on Energy and Emissions

Hussain U. Bahia, Andrew Hanz, and Scott Schwandt

Warm Mix Technical Working Group Meeting
May 18, 2010
Auburn, AL
Outline of Talk

• Asphalt Binder Lubricity
  – New Procedure for Higher Temperatures
  – Preliminary Results
  – Relationship with Mixture Workability Parameters

• Impact of Reduced Production Temperatures
  – Energy Consumption
  – Emissions: Laboratory Measurements and Field
Study Main Objectives

• Verify Warm Mix Additives (WMA) Effects
  ▪ Reducing viscosity
  ▪ Lubrication

• Determine how much is needed.
  ▪ WMA content versus temperature reduction
  ▪ Cost is based on content, justify use by saving heat energy and recuing emissions
Asphalt Binder Lubricity – Previous Results

• Presented procedure to measure Coefficient of Friction for Asphalt Binders.
• Results showed potential to differentiate between binder grades and WMA Additives
• Due to machine limitations testing was limited to <100°C
Asphalt Binder Lubricity – New Efforts

• Modify Testing Fixture
  – Allow for testing at higher temperatures.
  – Requires use of different DSR in UW Madison Laboratories

• Modify Test Procedure
  – Control Gap, Speed, and Temperature During Testing.
  – Increase thermal equilibration time.
  – Monitor Normal Force and Torque.

• Test at temperatures consistent with lab mixture compaction
  – 90, 110, and 135°C
Asphalt Lubricity Test – Based on ASTM Standards for oils

**Stribeck**: Friction a function of viscosity (Z), pressure (P), and speed (N).

**Measurement Tool**
Asphalt Binder Lubricity – New Fixture

Cup machined for torsion bar geometry in TA DSR.

Balls are fixed by lid that screws into cup.
Asphalt Binder Lubricity – New Fixture

Torque and normal force applied by chuck from top of machine.

Before testing zero gap is established using cup and chuck.
Asphalt Binder Lubricity – Test Procedure

• After gap is zeroed, a sample of asphalt (4 gm) is placed in the cup and melted at 90°C.
• Chuck is lowered until a normal force of ~15N is established.
• Thermal equilibration for 45 minutes – 1 hour.
• Test is conducted at speeds of 10, 20, and 40 RPM.
• Procedure is repeated for 110°C and 135°C
Asphalt Lubricity Test - Calculations

- Torque and normal force are monitored under constant speed and gap.
- The coefficient of friction (μ) is obtained from the normal force and torque measured

\[ \mu = C \times \frac{T}{P \times d} \]

- Where:
  - C = 2.842 – Value of constant for the four ball testing fixture geometry, T = Torque (N), P = Normal Force (N), d = diameter (m)
Asphalt Lubricity Test – Example Data

Controlling the gap allows for consistent values of torque and normal force.

Statistics

<table>
<thead>
<tr>
<th></th>
<th>Avg</th>
<th>Stdev</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.16</td>
<td>0.003</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td>14.56</td>
<td>0.125</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
Experimental Design – Example Data to Date

• One Warm Mix Additive:
  ▪ Viscosity Reducer (RV).
  ▪ Two concentrations: X% and 2x%

• Two base binders:
  ▪ Unmodified PG64-22 and
  ▪ SBS modified PG 76-22

• Two Mixture Gradations: Fine and Coarse
Experimental Plan - Testing

• **Binder Workability:**
  - Asphalt Binder **Viscosity** – Rotational Viscometer
  - Asphalt Binder **Lubricity** – New DSR test

• **Mixture Workability:**
  - Gyratory **Compaction Indices:**
    > Construction Force Index using the GPDA - (CFI)
    > Number of Gyrations to 92 % Gmm- N92
Effect of WMA Additive on Viscosity

VR-2 results in a PG 76-22, with similar viscosity to unmodified PG 64-22.
Viscosity and Compaction Effort

\[ y = 0.0004x + 12.656 \]
\[ R^2 = 0.3585 \]
New Test Method “Asphalt Lubricity Test” – Initial Results – Temperature Dependence

- Effect of Additive and temperature most significant at 90°C.
- Effect of binder: Clear reduction in friction due to PG 64.
Results: Coefficient of Friction vs. Stribeck Number

- VR-2 behaves similarly to PG 64.
- Due to differing viscosities, Stribeck number is much higher for PG 76. Temperature reduction of ~15°C needed for other materials to demonstrate μ similar to PG 76.
Mixture Workability

— Evaluation Criteria

- Gyratory Compaction indices
  > Gyrations to 92% Gmm
  > Construction Force Index (CFI) using the GPDA
Effects of WMAs on CFI (Mixture Workability) – Fine Gradation

- Major WMA effects at 90°C.
- VR-2 at 2x% show more effects at all temperatures.
Effect of WMA on CFI – Coarse Gradation

- **WMA Effects** – similar to fine gradation.
- **Effect of gradation on workability.**
  - CFI (FINE) Range: 150-500
  - CFI (COARSE) Range: 300-800

**Graph**

- HMA
- PG 64-22
- PG 76-22
- PG 76 + 2x % VR
- PG 76 + x % VR

**Temperature [°C]**

**CFI**

**Graph**

- HMA
- PG 64-22
- PG 76-22
- PG 76 + 2x % VR
- PG 76 + x % VR

**Temperature [°C]**
Regression Analysis

• Model Parameters
  – Asphalt Binder Workability
    ▪ Viscosity: Estimated at 90C, tested at 110C and 135C
    ▪ Lubricity: Tested at 90, 110, and 135C. Avg of three speeds.
  – Gradation
    ▪ Quantified using Beta
      ▪ Fine: 4.29
      ▪ Coarse: 6.34

• Response
  – Mixture Workability – CFI and N92
Gradation Analysis and Modeling

Weibull distribution

\[ F(x, \alpha, \beta) = 1 - e^{-\left(\frac{x}{\beta}\right)^\alpha} \]
Regression Results (Compaction Force Index)

- Regression Analysis: CFI = F(Coef Fric, Visc, Beta)
- CFI = -108 + 106 Beta -1036 Coef Fric + 0.0202 Visc

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-108</td>
<td>89.66</td>
<td>-1.2</td>
<td>0.224</td>
</tr>
<tr>
<td>Beta</td>
<td>106</td>
<td>13.24</td>
<td>8.03</td>
<td>0.000</td>
</tr>
<tr>
<td>Coef. Friction</td>
<td>-1036</td>
<td>302.2</td>
<td>-3.43</td>
<td>0.003</td>
</tr>
<tr>
<td>Visc</td>
<td>0.02</td>
<td>0.004</td>
<td>6.34</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Regression Results (CFI)

\[ y = 0.8599x + 39.171 \]
\[ R^2 = 0.8983 \]

Overall
- PG 64-22
- PG 76-22
- Viscosity Reducer

Linear (Overall)
Regression Results (N92)

- \( N92 = -5.55 + 8.455 \beta - 89.8 \text{ Coef. Friction} - 0.00167 \text{ Visc} \)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-5.55</td>
<td>7.504</td>
<td>-0.74</td>
<td>0.468</td>
</tr>
<tr>
<td>Beta</td>
<td>8.455</td>
<td>1.108</td>
<td>7.63</td>
<td>0.000</td>
</tr>
<tr>
<td>Coef. Friction</td>
<td>-89.81</td>
<td>25.3</td>
<td>-3.55</td>
<td>0.002</td>
</tr>
<tr>
<td>Visc</td>
<td>0.00163</td>
<td>0.00026</td>
<td>6.24</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Regression Results (N92)

\[ y = 0.8493x + 4.3877 \]

\[ R^2 = 0.8497 \]
Summary of Interim Findings

• Warm Mix Additive affect laboratory compaction.
  – Main affect at lower temperatures (<100 C).
  – Reduction in viscosity and coefficient of friction both identified as significant.

• Results were consistent with classification of WMA additive as a viscosity reducer.

• Cost need to be justified by energy savings & environmental impact.
Next Steps

• More Lubricity Testing is needed
  – Establish repeatability of procedure.
  – More WMA additives.
  – Wider range of temperatures?

• Potential to use lubricity and viscosity to classify WMA additives
  – Confirm findings with other viscosity reducers (Sasobit)
  – Establish similar relationship for other WMA mechanisms
Impacts of WMA Additives on Energy Consumption
Energy Consumption in Production of HMA

Opportunities for Energy Reduction

• Reduce production temperature: Warm Mix, Half Warm Mix, Cold Mix.
• Reduce/control moisture content of aggregates prior to production.
Benefits of Warm Mix Asphalt: Conceptual Reduction in Energy

Energy Reduction Relative to HMA

WMA: ~25%-40%
HWMA: ~60%-80%

Source: FHWA
Tools Available to Quantify Environmental Impacts of WMA

• **Plant Diagnostic Tool**
  – Pennsylvania Asphalt Pavement Association (PAPA)

• **Estimation Tool**
  – Models Developed by the World Bank
PAPA Plant Diagnostic Tool

- Generalize plant operations: Focused on drying costs and exhaust gases in a web-based interface.
World Bank Estimation Tools

• Estimate Emissions and Energy Consumption as a function of:
  – Aggregate Moisture Content
  – Fuel Type
  – Production Temperature

• Tool to quantify importance and relative impacts of production related factors.
Impacts of Moisture Content and Fuel Type on Energy Consumption – 3 models

Impact of M C (5% to 2%): ~35%
Impact of Fuel Type: ~20%
Impact of Temp: 0.25 gal/50F/ton
Reduction in Fuel Consumption Based on Three Existing Models

![Graph showing fuel consumption vs mix temp for 5% and 2% moisture with a note of 0.25 gallon per 50 F](image)

- **5% Moisture**
- **2% Moisture**

*0.25 gallon per 50 F*
Impacts of Moisture Content and Fuel Type on Emissions—3 Models

Impact of Moisture Content (5% to 2%): ~40%
Impact of Fuel Type: ~20%
Impact of Temp: 5 lbs/50F/ton
Conclusions – Opportunities to Reduce Emissions and Energy Consumption

• **Energy Consumption**
  - Use of WMA alone can result in 40% reduction.
  - Super heating of aggregates reduced or eliminated.
  - Control of aggregate moisture content.

• **Emissions**
  - Cleaner fuel types.
  - Lower production temperatures.
Next Steps

• Life-cycle perspective.
  – Performance of WMA must be similar to HMA for environmental benefits to be realized.

• Field Projects with WisDOT (4-6 this summer)
  – Laboratory Performance: Binder and Mixture
  – Fuel Consumption
  – Estimate of Emissions
  – Monitoring of Pavement Performance
Laboratory Measurement of Emissions and Impacts of Reduced Temperatures
Study Objective / Scope

- **Laboratory Testing**
  - Model asphalt fume PAH emission vs. temperature

- **Laboratory & Field (asphalt plant stack) Testing**
  - Corroborate WMA usage benefits regarding emissions
  - Corroborate Jullien (LCPC) results
  - Corroborate EPA emission factors
  - Quantify asphalt and burner fuel emission fractions

![Graph showing PAH Emission vs. Temperature](image)
Study Objective / Scope

Emissions of Interest

- Asphalt Plant Emissions
  - CO
  - CO\textsubscript{2}
  - SO\textsubscript{2}
  - NO\textsubscript{x}
  - CH\textsubscript{4}

- Occupational Health Emissions
  - Polycyclic Aromatic Hydrocarbons (PAH)
    - Anthracene
    - Benzo(a)anthracene
    - Benzo(a)Pyrene
    - Chrysene
    - Coronene
    - Fluoranthene
    - Methyl Cholanthrene (3-)
    - Naphthalene
    - Perylene
    - Phenanthrene
    - Pyrene

*Testing resulted in no measurable quantity*
Experimental Design (Laboratory)

• Testing
  – 40 *Extended OSHA 58 Method* tests by Wisconsin Occupational Health Laboratory (WOHL)

• Two Phase Analysis (20 tests each)
  – Phase I: Design of Experiment (DOE)
    ▪ Factorial Design: $2^4$ (2 Level, 4 Factors)
      > $2^4 = 16$
      > 4 “Blanks” (contamination check)
  – Phase II: PAH/Temperature Modeling
    ▪ 4 sample types @ 5 temperatures
# Experimental Design (Laboratory)

## Experimental Factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Level</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt Source</td>
<td>Flint Hills</td>
<td>Citgo</td>
</tr>
<tr>
<td>Flask Rotation ($\omega$/min)</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td>Test Duration (min)</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Test Temperature (°C)</td>
<td>130</td>
<td>180</td>
</tr>
</tbody>
</table>

## Experimental Design

<table>
<thead>
<tr>
<th>StdOrder</th>
<th>RunOrder</th>
<th>AC Source</th>
<th>Rotation</th>
<th>Test Duration</th>
<th>Test Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>8</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Blank samples were run prior to runs: 1, 5, 9, 13
Laboratory Testing

- UW-Madison Test Setup

Overall Setup
Laboratory Testing

• UW-Madison Test Setup
Laboratory Testing

- UW-Madison Test Setup
Laboratory Testing

• Testo 350

The total solution for emission testing and combustion analysis

www.testo350.com

<table>
<thead>
<tr>
<th>Range</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>0 to 25% vol.</td>
<td>&lt; 0.2% of m.v.</td>
<td>0.1 vol. %</td>
</tr>
<tr>
<td>CO</td>
<td>0 to 10,000 ppm</td>
<td>&lt; 5 ppm (0 to 50 ppm)</td>
<td>1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (100 to 2,000 ppm)</td>
<td>1 ppm</td>
<td>40 s (typ)</td>
</tr>
<tr>
<td></td>
<td>&lt; 10% of m.v. (2,001 to 10,000 ppm)</td>
<td>1 ppm</td>
<td>40 s (typ)</td>
</tr>
<tr>
<td>CO₂ ppm</td>
<td>0 to 500 ppm</td>
<td>&lt; 2 ppm (0 to 20 ppm)</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (50 to 500 ppm)</td>
<td>0.1 ppm</td>
<td>30 s (typ)</td>
</tr>
<tr>
<td>NO</td>
<td>0 to 3,000 ppm</td>
<td>&lt; 5 ppm (0 to 50 ppm)</td>
<td>1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (50 to 2,000 ppm)</td>
<td>1 ppm</td>
<td>40 s (typ)</td>
</tr>
<tr>
<td></td>
<td>&lt; 10% of m.v. (2,001 to 3,000 ppm)</td>
<td>1 ppm</td>
<td>40 s (typ)</td>
</tr>
<tr>
<td>NO₂ ppm</td>
<td>0 to 300 ppm</td>
<td>&lt; 2 ppm (0 to 20 ppm)</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (50 to 300 ppm)</td>
<td>0.1 ppm</td>
<td>30 s (typ)</td>
</tr>
<tr>
<td>SO₂</td>
<td>0 to 5,000 ppm</td>
<td>&lt; 5 ppm (0 to 50 ppm)</td>
<td>1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (50 to 2,000 ppm)</td>
<td>1 ppm</td>
<td>30 s (typ)</td>
</tr>
<tr>
<td></td>
<td>&lt; 10% of m.v. (2,001 to 5,000 ppm)</td>
<td>1 ppm</td>
<td>30 s (typ)</td>
</tr>
<tr>
<td>H₂S</td>
<td>0 to 500 ppm</td>
<td>&lt; 2 ppm (0 to 50 ppm)</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% of m.v. (50 to 200 ppm)</td>
<td>0.1 ppm</td>
<td>30 s (typ)</td>
</tr>
<tr>
<td>C₆H₆</td>
<td>0.01 to 4%</td>
<td>&lt; 0.05 ppm (0.05 to 4.00 ppm)</td>
<td>0.001 vol. %</td>
</tr>
<tr>
<td></td>
<td>&lt; 10% of m.v. (4.001 to 20 ppm)</td>
<td>0.001 vol. %</td>
<td>40 s (typ)</td>
</tr>
<tr>
<td>CO₂</td>
<td>0 to 5% vol.</td>
<td>±0.3% vol. ±1% of m.v. (0 to 25% vol.)</td>
<td>0.01% vol.</td>
</tr>
<tr>
<td></td>
<td>±0.5% vol. ±1.6% of m.v. (25 to 50% vol.)</td>
<td>0.01% vol.</td>
<td>10 s (typ)</td>
</tr>
<tr>
<td>CO₂</td>
<td>0 to CO₂ max. vol. %</td>
<td>Calculated from O₂</td>
<td>0.1 vol. %</td>
</tr>
<tr>
<td>Dry Press. 1</td>
<td>± 15° H₂O</td>
<td>&lt; 1% m.v. (±20° to ±15° H₂O)</td>
<td>0.01° H₂O</td>
</tr>
<tr>
<td>Dry Press. 2</td>
<td>± 18° H₂O</td>
<td>&lt; 1% m.v. (±20° to ±18° H₂O)</td>
<td>0.01° H₂O</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0 to 100%</td>
<td>± 0.5% m.v. (±1% to ±0.5% H₂O)</td>
<td>0.1%</td>
</tr>
<tr>
<td>Flow Veloc.</td>
<td>0 to 7500 rpm</td>
<td>± 0.01 m³</td>
<td>10 m³/min</td>
</tr>
<tr>
<td>Current Vel.</td>
<td>0 to 20 mA</td>
<td>± 0.04 mA</td>
<td>± 0.01 mA</td>
</tr>
<tr>
<td>Current Vel.</td>
<td>0 to 10 V</td>
<td>± 0.01 V</td>
<td>± 0.01 V</td>
</tr>
<tr>
<td></td>
<td>20 to 20,000 rpm</td>
<td>± 1 rpm</td>
<td>1 rpm</td>
</tr>
<tr>
<td>Temp</td>
<td>-40 to 212°F</td>
<td>± 0.8°F (±40° to ±212°F)</td>
<td>± 0.5 m.v. (±122° to ±212°F)</td>
</tr>
</tbody>
</table>
Laboratory Testing

- **OSHA Versatile Sampler Tubes (OVS Tube)**
  - Designed to trap aerosols and adsorb vapors
  - Typical Flow Rate of 1.0 L/min
  - Tubes analyzed for PAHs by high performance liquid chromatography (HPLC)* with a fluorescene (FL) detector

  *Performed by WOHL
Data Analysis

• Preliminary Models developed
  - Emission Gas = Constant + a[Source] + d[Temperature]
  - PAH = Constant + d[Temperature]

![Graphs showing CO emission vs temperature and asphalt source](image1.png)

![Graph showing fitted line plot for Anthracene](image2.png)
Conclusions

- Laboratory process evaluation
  - “Blank” sample analysis
    - Possible residual contamination from previous test
      - Affected measurements: NO, SO$_2$, NO$_x$, Naphthalene
    - Incorporate a “cleaning cycle” between tests
  - Lab setup components
    - System air flow control
    - Heated rotating flask
    - Testo 350 collection/measurement
    - OVS Tube collection / analysis
    - All worked well
Conclusions

• DOE Results
  – Significant Factors: Asphalt Source, Test Temperature
  ➢ Future Testing: use slow flask rotation speed and 15 min test duration

• Phase I of the study complete
Study Continuation

• Begin Phase II
  – Create Asphalt emission development vs temperature models
  – Conduct field stack testing
    ▪ Corroborate WMA benefits
    ▪ Corroborate Jullien results
    ▪ Corroborate EPA emission factors
    ▪ Quantify asphalt/burner fuel emission fractions