University of Nevada Reno  
*Presented by: Elie Y. Hajj, Ph.D.*

Updates on ARC Work Element E2d:  
Thermal Cracking Testing of Asphalt Mixtures  

*Asphalt Mixture & Construction Expert Task Group*  
*Wisconsin – Madison*  
*September 20-21, 2010*
ARC Work Element E2d

A. Environmental conditions within intermountain region
B. TSRST – SGC cylindrical specimens
C. TSRST – Cooling Rates Experiment
A. Environmental Conditions

- Collect & report actual pavement temperature history & profile throughout the depth of HMA pavements within & outside intermountain region.
  - Identified HMA pavements:
    - LTPP SMP sites in the intermountain region: 10 sections
    - LTPP SMP sites outside the intermountain region: 5 sections
    - WesTrack project (NATC): 3 sections
A. Environmental Conditions

Sites Locations
A. Environmental Conditions

Temp. Rates Definitions

- Average Daily Warming Rate
- Average Daily Cooling Rate
- Hourly Cooling Rate
- Hourly Warming Rate

Temperature (°C)

Cumulative Hours

Hourly Temperature
A. Environmental Conditions

Summary of Daily Cooling and Warming Rates

<table>
<thead>
<tr>
<th>Sensor Depth</th>
<th>12.5 mm</th>
<th>25.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Daily Cooling Rate (°C/hr)</td>
<td>-2.2</td>
<td>-1.8</td>
</tr>
<tr>
<td>Max Daily Warming Rate (°C/hr)</td>
<td>4.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

(Whiskers represent 95% confidence interval)
A. Environmental Conditions

Hourly Cooling/Warming Rate – Sensor depth = 12.5 mm

- Cooling Rates
  - Inside Intermountain Region
  - Outside Intermountain Region

- Warming Rates
  - Inside Intermountain Region
  - Outside Intermountain Region

Intermountain: dry-no freeze (2), dry-freeze (5)
Outside: wet-no freeze (2)
A. Environmental Conditions

Hourly Cooling/Warming Rate – Sensor depth = 25 mm

Intermountain: dry-no freeze (4), dry-freeze (2) wet-no freeze (1)
Outside: wet-no freeze (1), wet-freeze (1), dry-freeze (1)
A. Environmental Conditions

**Binary Cooling Rate**

FIGURE. High rate and low rate calculation of the maximum hourly cooling rate for section 040113 (Kingman, AZ) of 4.9°C/hour of pavements temperatures 10°C and colder at a sensor depth of 12.5 mm (Whiskers represent 95% CI).
A. Environmental Conditions

Summary of Findings

- Pavement Temp histories:
  - Lower temp. rates at deeper pavement depths (i.e. 12.5 vs. 25.0 mm).
  - At 12.5 mm depth: higher average hourly cooling/warming rates for sections within intermountain region.
  - At 25.0 mm depth: similar cooling/warming rates for sections within & outside intermountain region.
A. Environmental Conditions

Summary of Findings

- Within Intermountain Region:
  - Maximum DAILY:
    - cooling rates: 2-3°C/hr range
    - warming rates: 4-5°C/hr range
  - Maximum HOURLY:
    - cooling rates: 4-6°C/hr.
    - warming rates: 6-10°C/hr.
A. Environmental Conditions

Summary of Findings

• Pavement Temp histories:
  – Daily cooling periods can typically be divided into two phases:
    ▪ initial period of high cooling rate: ~ 4°C/hr
    ▪ followed by a much lower cooling rate ~ 0.5°C/hr.
B. TSRST – Cylinders vs. Beams

**Objective**

- Effect of: Geometry (cylinder vs beam) & Compaction method (SGC vs kneading compactor) on TSRST results
B. TSRST – Cylinders vs. Beams

Specimen Geometries

Different TSRST specimen geometries (a) Beam, (b) 1-in-1 Cylinder (c) 3-in-1 Cylinder, (d) Side Cylinder
B. TSRST – Cylinders vs. Beams

PG64-22 Mix
B. TSRST – Cylinders vs. Beams

Results – PG64-22 Mix

(Whiskers represent 95% confidence interval)
B. TSRST – Cylinders vs. Beams

Results – PG64-22 Mix

(Whiskers represent 95% confidence interval)
B. TSRST – Cylinders vs. Beams

Results – Low temp. grade comparison PG64-22 mix

Comparison of TSRST fracture temperatures to asphalt binder low temperature grades for 64-22 mixture (whiskers represent 95% confidence interval)
B. TSRST – Cylinders vs. Beams

2D Image Analysis (PG64-22 mix)

2D image analysis (a) fracture strength versus aggregate contact points and (b) aggregate contact points versus specimen type (numbers represent mean values and whiskers represent 95% confidence interval).
B. TSRST – Cylinders vs. Beams

Summary

• TSRST side cylinders:
  – Cored sideways from SGC samples (perpendicular to compaction direction).
  – Improved repeatability of test results.
  – Can be cored out of field core samples from different lifts within asphalt layer parallel to traffic direction
    ▪ Preserve specimens’ orientation to simulate actual thermal loading conditions in the lab by subjecting tensile stresses parallel to traffic direction.
C. TSRST Cooling Rate Experiment

*Experimental Plan*

- **Effect of Monotonic Cooling Rate:**
  - Standard Cooling Rate: **10°C/hr**
  - Average Daily Cooling Rate: **2.5°C/hr**

- **Effect of starting test temperature**
  - 5°C vs. 20°C starting temperature

- **Effect of Binary Cooling Rate:** **3.7°C/hr to 0.4°C/hr**

- **Effect of Temperature Cycling** *(soon to start)*
C. TSRST Cooling Rate Experiment

*Effect of Monotonic Cooling Rate (Starting Test Temp. = 5°C)*

Only fracture temp. was affected by cooling rate
### C. TSRST Cooling Rate Experiment

*Effect of Monotonic Cooling Rate (Starting Test Temp. = 5°C)*

<table>
<thead>
<tr>
<th>TSRST Property</th>
<th>Cooling Rate</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10°C/hr</td>
<td>2.5°C/hr</td>
</tr>
<tr>
<td>Fracture strength (MPa)</td>
<td>Mean</td>
<td>1.627</td>
<td>1.584</td>
</tr>
<tr>
<td></td>
<td>STD*</td>
<td>0.135</td>
<td>0.245</td>
</tr>
<tr>
<td></td>
<td>CV*</td>
<td>8.3</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>95% CI'</td>
<td>0.133</td>
<td>0.240</td>
</tr>
<tr>
<td>Fracture temperature (°C)</td>
<td>Mean</td>
<td>-26.3</td>
<td>-23.5</td>
</tr>
<tr>
<td></td>
<td>STD*</td>
<td>0.475</td>
<td>0.360</td>
</tr>
<tr>
<td></td>
<td>CV*</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>95% CI'</td>
<td>0.466</td>
<td>0.352</td>
</tr>
<tr>
<td>Transition temperature (°C)</td>
<td>Mean</td>
<td>-12.0</td>
<td>-11.0</td>
</tr>
<tr>
<td></td>
<td>STD*</td>
<td>1.274</td>
<td>0.866</td>
</tr>
<tr>
<td></td>
<td>CV*</td>
<td>10.6</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>95% CI'</td>
<td>1.248</td>
<td>0.848</td>
</tr>
<tr>
<td>Slope of non relaxation period (MPa/°C)</td>
<td>Mean</td>
<td>-0.070</td>
<td>-0.080</td>
</tr>
<tr>
<td></td>
<td>STD*</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>CV*</td>
<td>7.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>95% CI'</td>
<td>0.006</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* STD denotes “Standard Deviation”
* CV denotes “Coefficient of Variation”
* 95% confidence interval
C. TSRST Cooling Rate Experiment

Effect of Starting Test Temperature

- Temperature (°C)
- Stress (Mpa)

- 2.5°C/hr-20°C
- 10°C/hr-20°C
C. TSRST Cooling Rate Experiment

Effect of Starting Test Temperature

![Graph showing the effect of starting test temperature on TSRST cooling rate experiment. The graph plots Stress (MPa) against Temperature (°C) for two cooling rates: 10°C/hr-5°C and 10°C/hr-20°C. The graph illustrates the relationship between stress and temperature for different cooling rates.](image)
C. TSRST Cooling Rate Experiment

Effect of Starting Test Temperature

![Graph showing the effect of starting test temperature on TSRST cooling rate experiment.](image)

- Stress (Mpa) versus Temperature (°C)
- Three lines with different cooling rates:
  - 2.5°C/hr-5°C
  - 2.5°C/hr-10°C
  - 2.5°C/hr-20°C

Temperature range from -40°C to 20°C, Stress range from 0.0 to 2.5 Mpa.
C. TSRST Cooling Rate Experiment

Effect of Starting Test Temperature

<table>
<thead>
<tr>
<th>Starting Test Temp., °C</th>
<th>Cooling Rate, °C/hr</th>
<th>Fracture Strength, Mpa</th>
<th>Fracture Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>2.5</td>
<td>1.58</td>
<td>-23.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.63</td>
<td>-26.3</td>
</tr>
<tr>
<td>20.0</td>
<td>2.5</td>
<td>1.10</td>
<td>-20.9</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.94</td>
<td>-25.8</td>
</tr>
</tbody>
</table>
C. TSRST Cooling Rate Experiment

*Effect of Binary Cooling Rate*

- Binary Cooling Rate: 3.7°C/hr to 0.4°C/hr
- Field: average cooling period approx. 14 hrs
  - initial high rate avg. approx. 3 hrs
  - secondary low rate approx. 11 hrs
- Test duration approx. 25 hours
  - 6 hours at 3.7°C/hr
  - Remainder at 0.4°C/hr
C. TSRST Cooling Rate Experiment

Effect of Binary Cooling Rate

![Graph showing the effect of binary cooling rate on stress vs. temperature.](image)

- **Stress (Mpa)**
- **Temperature (°C)**

- **2.5°C/hr**
- **3.7°C/hr - 0.4°C/hr incomplete 1**
- **3.7°C/hr - 0.4°C/hr incomplete 2**

[Asphalt Research Consortium]
C. TSRST Cooling Rate Experiment

Preliminary Findings

• TSRST testing: For monotonic cooling rates at a starting test temp of 5°C:
  – Warmer fracture temperature was observed but similar build-up of thermally induced stresses.

• Binary cooling rate showed similar thermally induced stress accumulation behavior for initial rate (at a start temp of 5°C).
C. TSRST Cooling Rate Experiment

Preliminary Findings

• A starting test temp of 5°C was not warm enough to see any difference in the *thermally induced stress-temperature plots* for the various rates.

• Warmer starting test temperature allowed additional thermal stresses to accumulate in specimens subjected to a higher cooling rate.
  – longer relaxation period for specimen during test
Acknowledgment

– This work is part of the overall effort in the Asphalt Research Consortium (ARC) work element E2d. (www.arc.unr.edu)

– Authors gratefully acknowledge the FHWA support.