Acknowledgements

• NCHRP 9-60
  • Ed Harrigan
  • The Panel and the Team

• FHWA
  • Fundamental Properties of Asphalts (FPIII) and Products Validation
  • Asphalt Research Consortium (ARC)
  • Jack Youtcheff

• Infravation
  • https://www.fhwa.dot.gov/research/resources/infravation.cfm
  • http://www.infravation.net/

• Commercial clients
  • AIRC
• NCHRP 9-60 Introduction / Project organization
  • Concept of Age-Induced Surface Damage
  • Liaison with 9-59

• Experimental work plan
  • Binder selection
  • Binder physical-chemical characterization
  • Binder mechanical & mixture testing
  • Oxidative and physical aging
  • Relation to field performance
NCHRP 0960 - [RFP]

- **Addressing Impacts of Changes in Asphalt Binder Formulation and Manufacture on Pavement Performance through Changes in Asphalt Binder Specifications**

- **Funds:** $1,000,000

- **Contract Time:** 30 months
  - End planned: 12/2018

- **Staff Responsibility:** Edward T. Harrigan
OBJECTIVE

• Propose changes to the current performance graded asphalt binder specifications, tests, and practices

• Remedy gaps and shortcomings related to the premature loss of asphalt pavement durability in the form of cracking and raveling

SHRP Superpave binder specifications

• Performance grade spec / test methods

• Designed in the 90’s for asphalt from the 90’s

• ... not adapted to today’s and tomorrow’s binders...
Asphalt variability context

- **Reasons:** economics, geopolitics, sustainability, specs
  - Change in crude oils and in processes
  - Blends of various refining bases
  - New world of additives, incl. biomass
  - High rate recycling
    - RAP / RAS / REOB (re-refined engine oil bottoms)
    - GTR ground tire rubber, ...
  - Impact of specifications
    - Asphalt: Superpave and empirical – no true performance related
    - Other petroleum products specs: 2020 Marine fuels % Sulfur
  → Huge binder variability, inconsistent quality, not captured by current specs and leading to early field failures
  → Pavement issues: lower durability - premature cracking and raveling

- **Current and future binders need true PG specs**
A new pavement damage model consistent with the observed distresses of surface raveling and cracking

The hypothesis

- **Thermal stresses** lead to cracking and raveling damages as an aged asphalt mixture cools to low pavement temperatures, *even when* there is no external restraint.
- **Thermal cycling without complete healing** (thermal fatigue), and load-induced stresses developing at the edge of a rolling tire further contribute to accumulating damage at the pavement surface.
- **In-situ changes in asphalt rheology** caused by oxidative aging and physical hardening amplify damage rates until serious visible distress appears in the form of block or top-down cracking.
Aged induced surface damage

• Importance of:
  • Physical hardening and oxidative aging
  • Thermal healing

### Types of Cracking

<table>
<thead>
<tr>
<th>9-59</th>
<th><strong>Load-Induced</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Classic Fatigue – Bottom-up</td>
</tr>
<tr>
<td></td>
<td>Slippage</td>
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</table>

<table>
<thead>
<tr>
<th>9-59</th>
<th><strong>Load/Thermal</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reflective</td>
</tr>
<tr>
<td></td>
<td>Top-down</td>
</tr>
<tr>
<td></td>
<td>Tire-stress on surface already damaged by cooling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9-60</th>
<th><strong>Thermal: Cooling</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Restrained: Transverse Thermal Cracking</td>
</tr>
<tr>
<td></td>
<td>Unrestrained: Age-induced Surface Damage Leading to Block Cracking</td>
</tr>
</tbody>
</table>

- Details presented in a White Paper by G. King and JP. Planche
Concept

Age-Induced Surface Damage

Cooling With No External Restraint: Questions Unanswered

- Do waxes “Physical Hardening” impact the damage mechanism or potential for healing?
- Can the Hirsch Model be used to quantify damage?
- If no tensile stress is applied to aggregate contact points during unrestrained cooling, should mixture rheology tests replace fracture tests?
- What binder properties relate to:
  - Damage: low temperature mechanism
  - Healing: intermediate temperature mechanism
Liaison with NCHRP 9-59 – Research Results

- Relationships between phase angle, healing, and thermal cracking

The relationships among phase angle, adhesive healing and non-load associated cracking in asphalt pavements will be investigated through the NCHRP Project 9-60
Concepts and liaison with 9-59

NCHRP 9-59: Potential fatigue/fracture tests

- SDENT or LAS for ensuring adequate inherent fatigue/fracture resistance
- Binder phase angle for limiting damage persistence (ensuring healing)

- Details presented in a White Paper by D. Christensen
Links with NCHRP projects

- **9-59** Binder Fatigue (WRI)
- **9-58** RAP - rejuvenation (TAMU, GHK, WRI)
- **9-55** RAS with WMA (NCAT, WRI)
- **9-52** Short term aging of Mixtures (TAMU, WRI, GHK, DAA)
- **9-54** Long term aging of Mixtures (NCSU, WRI, GHK, DAA)
- **9-60** Binder Specs & Tests for Thermal cracking (WRI, AAT, NCAT, GHK, DAA)
- **9-61** Binder aging (AAT, WRI, GHK, DAA)
Project Organization

- **Literature Review** 86 pages – 238 ref. - worldwide
  - Changes in today’s and tomorrow binders compared to SHRP era
- **Agency Survey** 37 agency responses / 9 w binder issues / 5 w samples
  - Identify pavements exhibiting premature surface damage (20)
  - Select pavements & binders to be sampled and evaluated (11)
- **Experimental Work plan**
  - Binder evaluation: *binder drivers for cracking and healing*
  - Mixture tests: *what causes mixture damage?*
  - Physical and oxidative aging on binders and mixtures
  - Pavement performance – agencies info on cracking / raveling
  - Relationships: Binder chemical / mechanical / Mixture / Pavement
**Expected deliverables**
- Proposition of a binder specification parameter to control surface cracking and raveling
  - One binder specification test with appropriate failure limits, and success rates comparable to other positive PG specs
  - AASHTO format and consistent with current PG
- Informal binder formulation guidelines

**Dissemination and Training**
- Workshops and training seminars
- Coordination with Binder ETG, AI TAC, TRB, AAPT, PARC, and regional user-producer group meetings

**Input for Research needs and Perspectives**
- Design of RAP mixes, Pavement preservation timing
- Tools for ME-PDG aging effects models
- Streamlined field sampling procedures
**Task 1.1 – Literature review**

- Problematic binders: High $\Delta T_c$ and generally “out of balance”, incompatible, inhomogeneous blends
  - REOB blends
  - Airblown, oxidized blends
  - Hard SDA / soft blends
  - Visbroken residues (IMO 2020)
  - Waxy binders
  - Incompatible blends – fracking crudes / heavy crudes
  - Inhomogeneous modified binders
    - Polymers - EVA, SBS, Terpolymers
    - Additives - PPA, wax, biomass
  - High RAP / RAS

- Complex structure and rheological behavior
Binder selection process

Where to get the binders?

- Ideally T 1.2 (Agency survey) would have provided most problematic binders identified in T 1.1 (Lit. survey)
- **Impossibility**: lack of information and unavailability

Constitution of a Binder pool

- SHRP asphalts for references from the SHRP era
- Asphalts from 9-59 and 9-58 for bridging and crossfertilizing projects
- FAA binders for proof of concept
- WRI and partners contacts for filling out gaps
- Asphalt with field performance data, original & aged binders for field validation of the findings vs. specification criterions
  - Agency survey binders
  - ARC binders
Summary of the Agency survey

- Identified issues
  - Longitudinal cracking
  - Transverse cracking
  - Block cracking
- Miscellaneous surface cracking
- Raveling

+ Ontario (all issues)
Summary of the Agency survey

- Potential binder issues
  - REOB
  - Oxidized asphalts
  - Oxidized, RAP, RAS
  - Others (combinations…)

Potential Binder Issues

- Oxidized asphalt
- REOB and related materials
- PPA modified asphalt
- Excessive RAP
- Excessive RAS
- Others

Number of Responses

+ Ontario (All)
### 11 Binders from Agencies with field performance + original binders

<table>
<thead>
<tr>
<th>Agency</th>
<th>Premature Distresses</th>
<th>Binder Blend</th>
<th>Pavement Sections PG and $\Delta T_c$ ($^\circ$C)</th>
<th>In-Place</th>
<th>Original Binder</th>
<th>Field Coring</th>
<th>Other Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME DOT</td>
<td>Longitudinal cracks, Raveling</td>
<td>Unknown</td>
<td>Route 1 Presque Isle PG 64-28 ?</td>
<td>Yes</td>
<td>Same source + PG, Different sampling t</td>
<td>Yes</td>
<td>DSR, FTIR, $\Delta T_c$</td>
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<tr>
<td></td>
<td>DOT / FHWA Investigation</td>
<td></td>
<td>Route 11, Wallagrass PG 58-28 ?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I 295 SB, Portland PG 70-28 ?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH DOT</td>
<td>Transverse, localized fatigue cracks</td>
<td>REOB</td>
<td>Route 12, Westmorland PG 52-34 ?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON MTO</td>
<td>Ext. transverse, longitudinal + alligator cracks</td>
<td>REOB</td>
<td>Hwy 655 P1 (Sect. 4) PG 58-34 -3.2</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Distress report</td>
</tr>
<tr>
<td></td>
<td>Good perf.</td>
<td>N/A</td>
<td>Hwy 655 P1 (Sect. 1) PG 58-34 0.7</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
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<tr>
<td></td>
<td>Good perf.</td>
<td>1% PPA + 2% SBS</td>
<td>Hwy 655 – P2 (Sect. 10) PG 64-34</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>CTAA 2015</td>
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<tr>
<td></td>
<td>Good perf.</td>
<td>2.5% Elvaloy</td>
<td>Hwy 655 P2 (Sect. 12) PG 64-34</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>CTAA 2015</td>
</tr>
<tr>
<td></td>
<td>Good perf.</td>
<td>7% SBS</td>
<td>Hwy 655 P2 (Sect. 13) PG 76-34</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>CTAA 2015</td>
</tr>
<tr>
<td></td>
<td>Good perf.</td>
<td>3.5% SBS</td>
<td>Hwy 655 P2 (Sect. 14) PG 58-64</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>CTAA 2015</td>
</tr>
<tr>
<td></td>
<td>Good perf.</td>
<td>Control/REOB</td>
<td>Hwy 655 P2 (Sect. 15) PG 52-34</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>CTAA 2015</td>
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Asphalts with field performance data

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>AZ-1-1</td>
<td>AZ-1-2</td>
</tr>
<tr>
<td>PG</td>
<td>76-16</td>
<td>76-16</td>
</tr>
<tr>
<td>Modif.</td>
<td>Air-blown</td>
<td>N/A</td>
</tr>
<tr>
<td>Asph. (%)</td>
<td>13.6</td>
<td>25</td>
</tr>
<tr>
<td>DTc (°C)</td>
<td>-9.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Field issues</td>
<td>High cracking</td>
<td>Moderate cracking</td>
</tr>
<tr>
<td>Perf.</td>
<td>Bad</td>
<td>Average</td>
</tr>
</tbody>
</table>
### Binder selection

- **SHRP reference binders** – unmodified binders

<table>
<thead>
<tr>
<th>Asphalts</th>
<th>AAA-1</th>
<th>AAG-1</th>
<th>AAK-1</th>
<th>AAM-1</th>
<th>ABA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Lloydminster</td>
<td>Ca Valley</td>
<td>Boscan</td>
<td>WTI</td>
<td>WTI/S</td>
</tr>
<tr>
<td>Modifier</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Airblown</td>
</tr>
<tr>
<td>PG grade</td>
<td>58-28</td>
<td>58-10</td>
<td>64-22</td>
<td>64-16</td>
<td>64-16</td>
</tr>
<tr>
<td>Asphaltenes n-C7 (%)</td>
<td>16.2</td>
<td>5</td>
<td>20.1</td>
<td>4</td>
<td>15.7</td>
</tr>
<tr>
<td>Wax (Intevep) (%)</td>
<td>1.62</td>
<td>1.13</td>
<td>1.17</td>
<td>4.21</td>
<td>4.85</td>
</tr>
<tr>
<td>$\Delta T_c$ (°C)</td>
<td>2.5</td>
<td>4.9</td>
<td>1.8</td>
<td>-5.4</td>
<td>-10</td>
</tr>
<tr>
<td>Performance (assumed)</td>
<td>Good</td>
<td>Average</td>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
</tr>
</tbody>
</table>

- **Note:** $DT_c$ calculated from SHRP A-645 data (Jones, 1993)
- **Red figures** estimated from a different grade of the same crude
**Binder selection**

- Asphalts from 9-59 – mainly modified binders

<table>
<thead>
<tr>
<th>Binder Number (9-59)</th>
<th>Performance</th>
<th>Modifier</th>
<th>PG grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Good</td>
<td>SBS</td>
<td>76-28</td>
</tr>
<tr>
<td>3</td>
<td>Good</td>
<td>SBS/PPA</td>
<td>76-22</td>
</tr>
<tr>
<td>5</td>
<td>Good</td>
<td>SBR</td>
<td>70-22</td>
</tr>
<tr>
<td>6</td>
<td>good/moderate (average)</td>
<td>EVA</td>
<td>76-22</td>
</tr>
<tr>
<td>12</td>
<td>Poor (bad)</td>
<td>Oxidized</td>
<td>76-16</td>
</tr>
<tr>
<td>14</td>
<td>Poor (bad)</td>
<td>REOB</td>
<td>58-28</td>
</tr>
<tr>
<td>15</td>
<td>Good</td>
<td>Terpolymer</td>
<td>58-34</td>
</tr>
<tr>
<td>16</td>
<td>Poor (bad)</td>
<td>PPA</td>
<td>70-22</td>
</tr>
</tbody>
</table>
**Binder selection**

- Asphalts for proof of concept

<table>
<thead>
<tr>
<th></th>
<th>FAA/AI study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Study</strong></td>
<td>AAPTP 05-07</td>
</tr>
<tr>
<td><strong>Binder</strong></td>
<td>WTX</td>
</tr>
<tr>
<td></td>
<td>GSE</td>
</tr>
<tr>
<td></td>
<td>WC</td>
</tr>
<tr>
<td><strong>PG</strong></td>
<td>64-16</td>
</tr>
<tr>
<td></td>
<td>64-22</td>
</tr>
<tr>
<td></td>
<td>64-28</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>WTS</td>
</tr>
<tr>
<td></td>
<td>Gulf Southeast</td>
</tr>
<tr>
<td></td>
<td>Western Canadian</td>
</tr>
<tr>
<td><strong>Modif.</strong></td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td><strong>ΔTc (°C)</strong></td>
<td>-3.1</td>
</tr>
<tr>
<td></td>
<td>-1.3</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Field issues</strong></td>
<td>Block cracking</td>
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<tr>
<td></td>
<td>Block cracking</td>
</tr>
<tr>
<td><strong>Perf.</strong></td>
<td>Bad</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Good</td>
</tr>
</tbody>
</table>
Binder selection Summary

- **Binder pool**
  - Variety of binder compositions and performance levels to cope with most problematic cases from the lit. survey

- **Various sources**
  - SHRP, ARC (AZ, MN), FAA, NCHRP 9-59, NCHRP 9-58, WRI-AIRC
  - 3 agencies (ME, MTO, NH)

- **Composition variables**
  - Refining process: straight run vacuum residues, and blends with airblown, visbroken, SDA, and fluxed hard pen residues.
  - Modification process: REOB, SBS, EVA and terpolymers
  - High RAP/RAS mixes
  - Various asphaltene and wax contents

- **Total of 43 different binders**
  - Wide range of performance levels - field documented or assumed ($\Delta T_c$ and engineering judgment) - $\Delta T_c$ from +5 to -24°C
  - “Good, average, bad” – fairly even for a sound statistical analysis
  - Need for dedicated feasibility studies and test selections
Categorical mapping

Notes:
- Assumed perf: **Blue** = SHRP binders – **Purple** = European special grades
- Recorded perf: all others
- Perf level: 3 is good, 2 average, and 1 bad
- Delta Tc on PAV-1 residues – from literature, BBR and DSR 4mm
- In progress
**Binder Physical – Chemical characterization (WRI)**

- **Chemical analysis** – Chicken and egg?
  - SAR-AD: generic fractions based on solubility
  - IR: oxidation, polymer, additive identification / semi-quantitative dosage
  - DSC: glass transition and crystallinity
  - SEC: MW, sol-gel, polymer (neat, crosslinked or degraded)
  - AFM: phase behavior – polymers, wax, REOB

- **Relationships** with rheology and other mechanical binder and mix properties and pavement perf. data
  - ExpliFit chemometrics software

- **Note**: Approach used at WRI on a wider scale
  - WRI-AIRC (55 binders)
  - Infravation (FEHRL/FHWA): Alterpave and Biorepavation proj.
Binder Physical – Chemical characterization (WRI)

Saturates, Aromatics, Resins-Asphaltene Determinator - SAR-AD™

Fully automated SAR separation (chromatography) coupled to AD asphaltene fractionation (solubility)

Polarity & Aromaticity

- Cyclohexane (1)
- Toluene (2)
- CH₂Cl₂:MeOH (3)

Patented
SAR-AD – Asphalt Finger Printing

- Already used to correlate with asphalt binder composition with rheology and follow aging
Physical – Chemical Test
Differential Scanning Calorimetry (DSC)

Glass Transition (T_g), Modulated

Crystallizable Fraction, Unmodulated

Intermediate T thermal event
Relation with crossover parameters / healing?

Widening with oxidation – Relation with ΔT_c?
Binder and mixture mechanical testing

NCHRP 9-60 rheology & failure binder and mixture tests
- Binder grading (AAT)
- DSR master curves (WRI)
- BBR (AAT)
- Direct tension (AAT)
- ABCD (WRI)
- SDENT(AAT)
- LAS when material limited? (AAT)
- Sliver test (NCAT)

Binder/mixture tests: summary
- A wide range of binder tests: DSR, BBR, DTT, SDENT (LAS?), ABCD
- RTFOT/PAV20, RTFOT/PAV40
- Physical Hardening, 1h to 3d at PGL+10°C
- Quantity may be limited for some field materials
- Sliver test for field cores
- Information for thermal stress/fatigue analysis, rheological parameters

Sliver test for unrestrained mix specimen
Binder rheological testing

- Black space diagram / Phase angle & stiffness modulus relationships
- Glover-Rowe
- Delta Tc
- R-value
- Crossover T and f
Physical and chemical aging

Oxidized Asphalt

- In-situ Pavement Aging
- Recycling: High RAP/RAS with \( \geq 0.3\% \) RBR
- (Semi or Partially) Air Blown Bitumen
- Overheating Mix at HMA Plant
- Asphalt Extracted from Shingles - TOAS

Hypothesis: Sliver Test should pick up damage induced by physical hardening?

- Need for extensive binder oxidative aging and low temperature conditioning
  - PAV up to 80 hrs
  - Isothermal cond. Up to 3 days at PGLT + 10°C (MTO procedure)

Impact of Waxes

1. Waxes precipitate to form amorphous solid:
   - Temp Range: +25° to +80°C:
   - R-value increases as wax separates
2. Waxes transform from amorphous to crystalline solid: “Physical Hardening”
   - Temp range: from Tg to +20°C:
   - Wax crystallization increases AC density
   - \( G^* \) increases, \( \delta \) drops, R value increases

Similar for sliver test mix
# RECAP: Binder Physical – Chemical characterization (WRI)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Ref.</th>
<th>Output Characteristics</th>
<th>Un-aged</th>
<th>RTFO</th>
<th>PAV-1</th>
<th>PAV-2</th>
<th>PAV-4 2 binders</th>
<th>Extracted</th>
<th>PH-1h (PAV-2)</th>
<th>PH-3d (PAV-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic compo.</td>
<td>SAR-AD</td>
<td>FHWA-HRT-15-055</td>
<td>8 solubility fractions &amp; ratios S1,S2,Ar1,Ar2,R,As1,As2,As3 / CII, TPA, AI</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chem function</td>
<td>IR</td>
<td>AASHTO T302</td>
<td>Oxidation products (carbonyl + sulfoxide contents), polymer / additive nature</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>X</td>
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</tr>
<tr>
<td>Thermal prop.</td>
<td>DSC</td>
<td>WRI SOP</td>
<td>Glass Transition, wax, Tg, DTg, %wax</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Molecular weight</td>
<td>GPC</td>
<td>FP III Product: FP 22</td>
<td>Molecular weight distribution, Mw, Mn, PI</td>
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<td>x</td>
<td></td>
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<tr>
<td>Micro-structure</td>
<td>AFM</td>
<td>ACS Fuel chemistry preprints, 46 (2), 104-110</td>
<td>Phases, Wax Bees, REOB Peaks, Polymer nodules, Phase inversion</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
### RECAP:

**Binder mechanical testing**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Test method</th>
<th>Ref.</th>
<th>Lab</th>
<th>Output Characteristics</th>
<th>Un-aged</th>
<th>RTFO</th>
<th>PAV-1</th>
<th>PAV-2</th>
<th>PAV-4</th>
<th>Extracted</th>
<th>PH-1hr PAV-2</th>
<th>PH-3d PAV-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG grading</td>
<td>DSR</td>
<td>M320-T315</td>
<td>AAT</td>
<td>High &amp; Int. continuous PG</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BBR</td>
<td>M320-T313</td>
<td>AAT</td>
<td>Low continuous PG, ΔTc, Ts, Tm</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td>Size</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rheology</td>
<td>DSR</td>
<td>T315</td>
<td>WRI</td>
<td>Black space, Mastercurve, R-value, G-R, crossover parameters</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DSR-4mm</td>
<td>TRB-2010</td>
<td>WRI</td>
<td>ΔTc, Ts, Tm, mastercurve, Rheological Tg, Black space</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adhesion</td>
<td>DSR</td>
<td>Christensen, 2017</td>
<td>AAT</td>
<td>Adhesion/healing parameters (phase angle)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture</td>
<td>DTT</td>
<td>T314</td>
<td>AAT</td>
<td>Critical cracking temperature: FFPR</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>Size</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Failure</td>
<td>SDENT</td>
<td>TP113 modified</td>
<td>AAT</td>
<td>Failure energy at equi-stiffness point; FFPR</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>Size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal stress build up</td>
<td>ABCD</td>
<td>TP092-11</td>
<td>WRI</td>
<td>Critical cracking temperature, Fracture stress</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>Size</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Properties</td>
<td>Test meth</td>
<td>Ref.</td>
<td>Lab</td>
<td>Output Charact.</td>
<td>Oxidation LT-2</td>
<td>Oxidation-LT</td>
<td>Physical Hardening</td>
<td>Temp. cycling</td>
<td>Field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
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<tr>
<td>Thermal cracking</td>
<td>Sliver Test</td>
<td>AASHTO TP 125-16</td>
<td>NCAT</td>
<td>Sliver creep / strength using BBR or BBR-Pro</td>
<td>x (2 mixes)</td>
<td>AAA-1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cracking Acoustic Emission (AE)</td>
<td>Sliver Test</td>
<td>NCHRP IDEA-144, Butlar, 2011</td>
<td>?</td>
<td>AE based embrittlement temp.</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>Thermal fatigue</td>
<td>Sliver Test</td>
<td>None TBD</td>
<td>NCAT</td>
<td>Thermal cycle number to failure</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
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<td></td>
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</tbody>
</table>
### RECAP: Binder physical and chemical aging

<table>
<thead>
<tr>
<th>Binder Conditioning</th>
<th>Test Method</th>
<th>Reference</th>
<th>Lab</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxidation-Short Term</strong></td>
<td>RTFO</td>
<td>T240</td>
<td>WRI</td>
<td>85 min at 163°C</td>
</tr>
<tr>
<td></td>
<td>PAV-1</td>
<td>R028</td>
<td>WRI</td>
<td>20 hrs at 100°C</td>
</tr>
<tr>
<td></td>
<td>PAV-2</td>
<td>R028 modified</td>
<td>WRI</td>
<td>40 hrs at 100°C</td>
</tr>
<tr>
<td></td>
<td>PAV-4</td>
<td>R028 modified</td>
<td>WRI</td>
<td>80 hrs at 100°C - mini study on 2 binders / sliver test</td>
</tr>
<tr>
<td><strong>Physical Hardening (PH)</strong></td>
<td>PH / BBR</td>
<td>TP122/MTO</td>
<td>AAT</td>
<td>1 hr at temp. LT PG+10°C</td>
</tr>
<tr>
<td></td>
<td>PH / BBR</td>
<td>TP122/MTO</td>
<td>AAT</td>
<td>3 days at temp. LT PG+10°C</td>
</tr>
<tr>
<td></td>
<td>PH / DSR-4mm</td>
<td>T315 mod/MTO</td>
<td>WRI</td>
<td>1 hr at temp. LT PG+10°C</td>
</tr>
<tr>
<td></td>
<td>PH / DSR-4mm</td>
<td>T315 mod/MTO</td>
<td>WRI</td>
<td>3 days at temp. LT PG+10°C</td>
</tr>
</tbody>
</table>
## RECAP: Mixture conditioning

<table>
<thead>
<tr>
<th>Mixture Conditioning</th>
<th>Test Method</th>
<th>Ref.</th>
<th>Lab</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long term Oxidation</td>
<td>Long Term Oven Aging</td>
<td>9-59 Interim report, 2017</td>
<td>NCAT</td>
<td>LT: 5 days at 95°C on the loose mix / Aging equivalent to 40hr PAV LT-2: 10 days at 95°C / 2 mixes</td>
</tr>
<tr>
<td>Physical Hardening</td>
<td>Sliver test</td>
<td>NCHRP Idea 151 / MTO</td>
<td>NCAT</td>
<td>3 days at temp. LT PG+10°C</td>
</tr>
<tr>
<td>Temp. cycling</td>
<td>Sliver test</td>
<td>N/A</td>
<td>NCAT</td>
<td>Temperature range?</td>
</tr>
<tr>
<td>Field</td>
<td></td>
<td></td>
<td>NCAT</td>
<td>observation / measurement of crack lengths / differentiation of cracks / years in service</td>
</tr>
<tr>
<td>Coring</td>
<td>NCAT</td>
<td>NCAT</td>
<td></td>
<td>Shoulder cores</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Undamaged by traffic, less compacted (no post compaction)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface course and depth?</td>
</tr>
<tr>
<td>Extraction</td>
<td>NCAT</td>
<td>NCAT</td>
<td></td>
<td>Solvent: Trichloroethylene</td>
</tr>
<tr>
<td>Microcoring</td>
<td>WRI</td>
<td>FPIII: FP09</td>
<td>WRI</td>
<td>Microcoring of field cores</td>
</tr>
<tr>
<td>Microextraction</td>
<td>WRI</td>
<td>FPIII: FP09</td>
<td>WRI</td>
<td>Solvent: 85% toluene, 14.25% ethanol, 0.75% water</td>
</tr>
</tbody>
</table>
Relation to Field Performance

- Results analysis from binder analysis to mix properties
  - As they relate to each other and to understand how they affect pavement performance
  - Pavement performance data: two possibilities
    - Categories (good, average, bad) --- Model the probability
    - Vector of different variables describing performance: multivariate regressions
    - The predictor variables will be the rheological properties (up to 10) and the mechanical properties (up to 5)
  - Regression output: most important predictors from the properties (at most 2 to 4)

Deliverable: development or modification of specifications and informal guidelines for suppliers
Relation to Field Performance

- **Partial least squares to assess the correlations**
  - Examples of expected correlations
    - Binder chemistry and binder rheology (or fracture) properties
    - Binder rheology (or fracture) properties and mixture properties

- **Using the ExpliFit software**
  - Developed by WRI (under FPIII)
  - Does chemometrics correlations
    - Based on a multivariable linear regression algorithm
    - Originally developed for FTIR spectra
  - Generates equations
    - such as (for DSR vs. SAR-AD)

\[
\log G^* (T, f) = C_0 + C_1 \times [\text{Saturates}] + C_2 \times [\text{Naphthene}] + \ldots
\]
Thank You!  Questions?