Performance-Based Mix Design

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Integration between PBMD and PRS

- Same test methods and same underlying principles and models used in PBMD and PRS
- Index properties can be used in PBMD whereas full models are used in PRS.
- Integration necessary to apply incentive/disincentive to contractors
- PBMD index properties allow go/no-go decisions during construction
- Allows changes in mix production during construction
DALY
Disability Adjusted Life Year is a measure of overall disease burden, expressed as the cumulative number of years lost due to ill-health, disability or early death.

\[ \text{DALY} = \text{YLD} + \text{YLL} \]

- YLD: Years Lived with Disability
- YLL: Years of Life Lost

Healthy life
Disease or Disability
Early death
Expected life years

PRS
Predict Pavement Performance
How much life was lost? Gained?
Make it simpler

PBMD
Hit the target.
Walk away.
Calibrated to performance data.

Binder Content

a number

a number
PBMD Framework
Performance-Based Mix Design

Cracking Resistance

Rutting Resistance

Minimum Required

Minimum Required

Candidate Performance Optimum
Performance-Based Mix Design

- Cracking Resistance
- Rutting Resistance

Volumetric optimum

Predictive Equations

Candidate Performance Optimum
PBMD Framework

- Step 1: Perform Superpave volumetric mix design to determine the volumetric optimum.
- Step 2: Conduct performance tests on the volumetric optimum using AMPT.
- Step 3: Check against the minimum performance criteria.
- Step 4: If okay, the volumetric optimum becomes the final optimum.
- Step 5: If not okay, adjust the asphalt content using predictive equations.
- Step 6: Conduct performance tests on the adjusted optimum.
- Step 7: Check against the minimum performance criteria.
- Step 8: If okay, the adjusted optimum becomes the final optimum.
- Step 9: If not okay, use different aggregate gradation and repeat the above steps.
Possible Scenarios for PBMD

- Pavement structure *unknown*
  - Pre-approval of mix design
  - Use index properties to determine pass/fail
  - Or run LVECD program on critical pavement designs with measured mixture properties to check against the minimum required pavement performance

- Pavement structure *known*
  - Run LVECD program on known pavement design with measured mixture properties to check against the minimum required pavement performance.
Test Methods and Models for PBMD and PRS
Asphalt Mixture Performance Tester
38 mm Cores for AMPT Cyclic Fatigue Testing

Only 1 gyratory specimen needed for PBMD fatigue testing
Horizontal Cores from Field Core

AC
Base
Subgrade
S-VECD Material Functions

These characteristic relationships remain the same under different modes of loading, different temperatures, different stress/strain amplitudes, and different loading histories.
# S-TSS for Rutting Test

<table>
<thead>
<tr>
<th>Test Method</th>
<th>S-TSS</th>
<th>TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>-</td>
<td>1 (TH)</td>
</tr>
<tr>
<td>Temp.</td>
<td>2 (TH and TL)</td>
<td>3 (TH, TI, and TL)</td>
</tr>
<tr>
<td>Pulse Time (s)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Rest Period (s)</td>
<td>3.6 (TH)</td>
<td>10 (TH)</td>
</tr>
<tr>
<td>Deviator Stress (psi)</td>
<td>100, 70, and 130 (TH)</td>
<td>70, 100, and 130 (TL)</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Testing Time (days)</td>
<td>1.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Permanent strains determined from machine displacements. No on-specimen LVDTs necessary.
Shift Model as the Rutting Model

Accounts for the effects of stress level, temperature, and loading time on rutting

\[
E_{vp} = \frac{\varepsilon_0 N_{red}}{N_{f}}
\]

\( a_{\xi_p} = p_1 \log(\xi_p) + p_2 \)

\( a_{\sigma_v} = d_1 \log(\sigma_v / P_a) + d_2 \)
LVECD for Pavement Model

3-dimensional viscoelastic analysis under moving load and changing temperature
Damage after 20 Years Loading

Damage Factor ($N/N_f$) Distribution - @ September 1, 2021

- **Control**
- **Advera**
- **Sasobit**
- **Evotherm**
Rut Depth Prediction in LVECD

Time History
# Required Testing Time

<table>
<thead>
<tr>
<th>Property</th>
<th>Operation</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Dynamic Modulus Test</td>
<td>1 day</td>
</tr>
<tr>
<td>Cracking</td>
<td>AMPT Cyclic Fatigue Test (TP-107)</td>
<td>1 day</td>
</tr>
<tr>
<td>Rutting</td>
<td>S-TSS Test (TP-116 Option B&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>1.5 days</td>
</tr>
<tr>
<td>Pavement Performance&lt;sup&gt;a&lt;/sup&gt;</td>
<td>LVECD Program</td>
<td>40 min.</td>
</tr>
<tr>
<td>Total Time for PBMD Performance Testing</td>
<td>For Index Properties</td>
<td>2.5 days</td>
</tr>
<tr>
<td></td>
<td>For Pavement Performance</td>
<td>3.5 days</td>
</tr>
</tbody>
</table>

Note:  
<sup>a</sup> Only needed when the pavement performance analysis is desired. 
<sup>b</sup> AASHTO specification being developed.
Validation Using Field Data
Laboratory-to-Field Correlation

FHWA-ALF (100 mm Pavement)

LVECD Analysis

Field Cracking Data

Damage Area (%) vs No. of Cycles

Crack Area (%) vs No. of Cycles

Control
SBS
Crumb Rubber (Terminal Blend)
Terpolymer

Crushed Stone Aggregate Base
Fatigue Prediction

NCAT Test Track
Fatigue Prediction

MIT-WMA
Rutting Performance Prediction

Field Measured

LVECD Predicted

Pavement Sections (MIT-RAP)

Pavement Sections (MIT-WMA)
Rutting Performance Prediction

Field Measured

LVECD Predicted

FHWA ALF

NCAT

Pavement Sections (ALF)

Pavement Sections (NCAT)
Index Property for Pass/Fail
S@$\text{C}_{\text{avg}}$ as Cracking Index Property

- $S@$C$\text{avg}$ is ‘cumulative effective dissipated pseudo strain energy’
- Use the temperature recommended in TP 107 as the reference temperature.
- $S@$C$\text{avg} = 80,000$ is the preliminary minimum required value.
$S_{@C_{avg}}$ for ALF Mixtures

![Graphs showing $S_{@C_{avg}}$ for ALF mixtures.](image)
Factors Affecting $S@C_{avg}$

**Binder Content**

- **NH6440-opt**
- **NH6440-opt**
- **NH6440+opt**

**Binder Grade**

- **NH5840-opt**
- **NH6440-opt**
MSR for Rutting Index Property

*TP-116 by Azari and Mohseni*

MSR = a(T×P)^b = 10^{-7} \times TP^b

where T= temperature (°C) and P=deviatoric stress (MPa)

FHWA ALF Mixtures
# Classification of Mixtures

## Traffic Level Design ESALs (million)

<table>
<thead>
<tr>
<th>Traffic Level</th>
<th>Maximum MSR Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Standard</td>
<td>&gt; 1 to 3</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt; 3 to 10</td>
</tr>
<tr>
<td>Very Heavy</td>
<td>&gt; 10 to 30</td>
</tr>
<tr>
<td>Extreme</td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>

## NCDOT QMS Manual

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Design ESALs (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S9.5B</td>
<td>&gt; 0.3 to 3</td>
</tr>
<tr>
<td>I19B</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>B25B</td>
<td>&lt; 3</td>
</tr>
</tbody>
</table>

## NCDOT 2016 QMS Manual

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Design ESALs (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS9.5B</td>
<td>13.96</td>
</tr>
<tr>
<td>RI19B</td>
<td>21.14</td>
</tr>
<tr>
<td>RB25B</td>
<td>4.08</td>
</tr>
</tbody>
</table>
Predictive Equations
Materials and Mix Designs

- **Accelerated Loading Facility (ALF) Lane 6**
  - Superpave 12.5 mm HMA mixture
  - 23% RAP
  - PG 64-22 binder

- **Volumetric Design Target**
  - Design VMA: 13, 14, 15%
  - Design AV: 3, 4, 5%
  - In-Place AV: 5, 7, 9%

- **Total of 21 Mix Designs**

- **AMPT Cyclic Fatigue and TSS Testing Completed**
Predictive Equations for Damage Characteristic Curve

\[ C = \exp (a \cdot S^b) \]

\[ a = 0.0018026 + 0.00046641 \times V_a - 0.0021855 \times V_{MA} \]

\[ b = 2.3088 + 0.014604 \times V_a - 0.1235 \times V_{MA} - 0.1452 \times V_{beff} + 0.010241 \times V_{MA} \times V_{beff} \]
Prediction Results for Mix B

**B 9-15.0-5.3**

- $y = 0.9809x$
- $R^2 = 0.9966$

- Log(Dynamic Modulus) vs. Log(Reduced Frequency)
- % Damage (Measured Coefs) vs. % Damage (Predicted Coefs)
- Log(C) vs. Temp (C)
- Log(NF) vs. Log(C)
Prediction Results for Mix O

\[ y = 0.8611x \]

\[ R^2 = 0.954 \]
LVECD Prediction for 21 Pavements

12 Months Loading

\[ y = 0.99x \]
\[ R^2 = 0.6947 \]

24 Months Loading

\[ y = 1.0145x \]
\[ R^2 = 0.7919 \]
Current PBMD Database

**Relative** not absolute distress

Applicable for a particular structure and traffic
BUT we can generate a catalog with LVECD

准入点是标准Superpave
• Minimum VMA for NMAS
• 4% Design Air Voids
• 7% Air Voids In-Place Density
Generalization to Any Mixture

• Other mixes will be different

• The pattern should be the same

• We need to verify with other mixes, incl. WesTrack
Summary of PBMD

- Starts with Superpave volumetric mix design
- AMPT cyclic fatigue and S-TSS tests as the performance tests
- LVECD program for pavement performance analysis
- Either index properties or pavement performance as the pass/fail criteria
- Predictive equations to adjust the mix design
Additional Remarks

- PBMD is a necessity in adequately implementing PRS.
- PBMD and PRS must be based on the same test methods and engineering properties.
- PBMD and PRS models have been successfully validated using the field data.
- Excel programs to be available for determination of material properties
- Predictive equations are being developed by testing additional mixtures at different volumetrics.
Thank you!
Questions?