Selection Of A Durable, Sustainable And Cost Effective Asphalt Mixture For Pavements In Oregon

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Sponsor:
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Outline

- Introduction
- Problem statement
- Objectives
- Methodology
- Strategies for Mix Design
- Results
- Major conclusions
Asphalt mixture?

**Additional Additives**

- Warm Mix
- Latex
- Rubber
- Recycled Plastic
- Lime
- Fibers

https://www.pinterest.com/pin/671528994411571559

pavementinteractive.org

parkleasandsoil.com.au
Asphalt Surfaced Pavement Distresses

- Rutting
- Low temperature cracking
- Fatigue cracking

[Link 1](https://www.pavementinteractive.org) [Link 2](https://www.wolfpaving.com/blog/what-to-do-when-you-see-alligator-cracking-in-asphalt)
Problem Statement

Ideal mix design
✔ Excellent performance
✔ Pavement longevity
✔ Environment

Factors affecting current Mix Design:
• Aggregate source and gradation,
• Asphalt source and grade,
• Air voids,
• Voids in mineral aggregate (VMA)
• Voids filled with asphalt (VFA)

Existing analysis and design methods → empirical
• Need for holistic evaluation and design of asphalt mixture based on performance
✔ Cracking
✔ Rutting

Volumetric Properties
Objectives

✔ Design three trial asphalt mixtures
✔ Evaluate the trial mixes for cracking and rutting performances
✔ Determine design binder content range for each mix using the balanced asphalt mix design method developed for Oregon
✔ Determine the cost and environmental impact of all three mixtures

✔ Recommend the “best” asphalt mixture for the given conditions by considering the cost-effectiveness, sustainability and the long-term performance of the mixes
Balanced Mix Design

“asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure”.

Volumetric Mix Design vs Balanced Mix Design (Example)

Note: Example for Illustration Purposes.

Source: NCAT Balanced Mix Design Training Course
Balanced Mix Design Approaches

1. Volumetric Design with Performance Verification
2. Performance-Modified Volumetric Mix Design
3. Performance Design
Approach 1: Volumetric Design with Performance Verification

Current method:

1. **Start**
   - Select trial gradations; check aggregate blend properties
   - Conduct volumetric analysis. Select design binder content and volumetric properties
2. Conduct moisture damage test
3. Pass moisture damage test?
   - Yes: Production / Validate JMF
   - No: Decrease moisture susceptibility
4. Conduct performance tests: rutting, cracking
5. Pass performance tests?
   - Yes
   - No: Redesign mix

- Existing mix criteria retained
- Criteria for rutting and cracking tests added
**Strategies for Mix Design**

**Mix1. Density Effect**
- Mastic
- Aggregate
- Air voids
- Source: Presti et al. (2015)

Mix compacted to

- 5% AV
- 7% AV

30% RAP mixture

**Mix2. High RAP content**

RAP content increased to 45%


**Mix3. Warm-Mix Asphalt**

Source: FHWA
Mix1: Density Effect

- Volumetric mix design with current process and Superpave 5 process i.e., mix designed at and compacted to 5% airvoid.

- Impact on stripping and permeability not investigated but Superpave 5 mix is expected to have higher cracking and rutting resistance.

Mix with 5% target airvoid (Superpave5)  Mix with 7% target airvoid (conventional)
Mix2: High RAP content

- Reduction in pavement life cycle costs, conserves natural resources, protects the environment
- Currently in Oregon, 20-30% Reclaimed Asphalt Pavement is commonly used in pavements.
- For this strategy, RAP content was increased to 45%
Mix3: Warm Mix Asphalt

- Evotherm® was used as a warm-mix additive

- The chemical additive dosage was calculated according to the following equation:

\[
\% \text{Adjusted Evotherm dosage} = \frac{(% \text{Target Evotherm dosage}) \times (% \text{Total binder})}{(% \text{Total binder} - \% \text{Binder from RAP})}
\]

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Mixing Temperature (°C)</th>
<th>Compaction Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA (Mix1)</td>
<td>173</td>
<td>160</td>
</tr>
<tr>
<td>WMA (Mix3)</td>
<td>140</td>
<td>126</td>
</tr>
</tbody>
</table>
## Experimental Plan and Production Mixture Information

<table>
<thead>
<tr>
<th>ID</th>
<th>Binder Grade</th>
<th>RAP (%)</th>
<th>AC&lt;sub&gt;RAP&lt;/sub&gt; (%)</th>
<th>AC (%)</th>
<th>BR (%)</th>
<th>P&lt;sub&gt;be&lt;/sub&gt; (%)</th>
<th>P&lt;sub&gt;200&lt;/sub&gt;/P&lt;sub&gt;be&lt;/sub&gt; f Ratio</th>
<th>Addi.g</th>
<th>VMA&lt;sub&gt;j-VFA&lt;/sub&gt; k %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix1_AV5</td>
<td></td>
<td>30</td>
<td></td>
<td>5.6</td>
<td>26.9</td>
<td>4.63</td>
<td>1.4</td>
<td>1% Li&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16.1-69</td>
</tr>
<tr>
<td>Mix1_AV7</td>
<td>PG 70-22ER</td>
<td>30</td>
<td>5.02</td>
<td>5.6</td>
<td>26.9</td>
<td>4.63</td>
<td>1.4</td>
<td>1% Li&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16.1-69</td>
</tr>
<tr>
<td>Mix2</td>
<td></td>
<td>45</td>
<td></td>
<td>5.3</td>
<td>42.6</td>
<td>4.38</td>
<td>1.6</td>
<td>1% Li&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15.6-68</td>
</tr>
<tr>
<td>Mix3</td>
<td></td>
<td>30</td>
<td></td>
<td>5.6</td>
<td>26.9</td>
<td>4.63</td>
<td>1.4</td>
<td>1% Li&lt;sup&gt;b&lt;/sup&gt;, 0.68% Evm&lt;sup&gt;i&lt;/sup&gt;</td>
<td>16.1-69</td>
</tr>
</tbody>
</table>

a All mixtures had dense gradation and aggregates with a nominal maximum aggregate size of 12.5mm;

b RAP = Reclaimed asphalt pavement added by weight;

c AC = Total asphalt content by weight from volumetric design for 65 gyrations;

d BR = Binder replacement;

e P<sub>be</sub> = Effective asphalt content present by weight in the total mix;

f P<sub>200</sub>/P<sub>be</sub> = Dust to binder ratio in the mix;

g Addi. = Additive;  h Li = Lime;  i Evm = Evotherm warm mix additive;  j VMA = Voids in mineral aggregate;

k VFA = Voids filled with asphalt.
Semi Circular Bend Test
Semi Circular Bend Test – Oregon spec.

- Loading rate: **0.5 mm/min**
- Output parameters:
  - ✔ Fracture energy ($G_f$)
  - ✔ Flexibility Index (FI)

\[ G_f = \frac{W_f}{A_{lig}} \]

\[ FI = \frac{G_f}{\text{abs}(m)} \]

(Ozer et al. 2016)
Hamburg Wheel-Tracking Test (HWTT)
# Experimental plan

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Mix ID b</th>
<th>Test</th>
<th>Temperature (°C)</th>
<th>Asphalt Content (%)</th>
<th>Replicates</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMLC</td>
<td>Mix1_AV5, Mix1_AV7, Mix3</td>
<td>SCB</td>
<td>25.0</td>
<td>OBC c, - 0.5%, + 0.5%</td>
<td>4</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HWTT</td>
<td>50.0</td>
<td></td>
<td>4</td>
<td>36</td>
</tr>
<tr>
<td>Mix2</td>
<td></td>
<td>SCB</td>
<td>25.0</td>
<td>OBC c, + 0.5%, + 1%</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HWTT</td>
<td>50.0</td>
<td></td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

a LMLC = Laboratory mixed, and laboratory compacted;  
b Mix1_AV5 – Mix3 = LMLC samples from three trial mixes;  
c OBC = Optimum binder content obtained from volumetric mix design.
Balanced Mix Design Thresholds for Oregon

Coleri et al. 2020

FI threshold of 6 was recommended for Level 3 mixes while the threshold for Level 4 was selected as 8.

RD threshold of 3mm was recommended for Level 3 mixes while the threshold for Level 4 was selected as 2.5mm.

Competition traffic level: 20 year design ESAL of 7,500,000

Level 4 mixes are for high/heavy traffic volumes in Oregon (> 3 million ESALs for a 20-year design) – ODOT Pavement Design Guide, 2019
RESULTS – SCB Flexibility Index

Flexibility Index

WMA

45% RAP

Denser Mix
RESULTS – HWTT

Average Rut Depth (mm)

Mix1_5.1_AV5
Mix1_5.6_AV5
Mix1_6.1_AV5
Mix1_5.1_AV7
Mix1_5.6_AV7
Mix1_6.1_AV7
Mix2_5.5_AV7
Mix2_5.8_AV7
Mix2_6.3_AV7
Mix3_5.1_AV7
Mix3_5.6_AV7
Mix3_6.1_AV7

Lowest rut-depth
High rut-depth
Highest rut-depth
RESULTS – Balanced mix design process – Mixture 3 (WMA) results

- BMD AC = 5.3%
- Volumetric design AC = 5.6%
# RESULTS – Volumetric properties for the three mixes based on BMD design binder content

<table>
<thead>
<tr>
<th>ID a</th>
<th>Binder Grade</th>
<th>RAP b (%)</th>
<th>AC&lt;sub&gt;RAP&lt;/sub&gt; (%)</th>
<th>AC c (%)</th>
<th>BR d (%)</th>
<th>P&lt;sub&gt;be&lt;/sub&gt; e (%)</th>
<th>P&lt;sub&gt;200/Pbe&lt;/sub&gt; f Ratio</th>
<th>VMA&lt;sub&gt;ij&lt;/sub&gt;-VFA&lt;sub&gt;k&lt;/sub&gt;%</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix1_AV 5</td>
<td>PG 70-22ER</td>
<td>30</td>
<td>6.00</td>
<td>25.1</td>
<td>4.96</td>
<td>1.30</td>
<td>16.2-69</td>
<td>VMA: JMF Target ± 1.0%</td>
<td></td>
</tr>
<tr>
<td>Mix1_AV 7</td>
<td></td>
<td>30</td>
<td>6.05</td>
<td>24.9</td>
<td>4.99</td>
<td>1.28</td>
<td>16.2-69</td>
<td>12.5 - 17.0 (3/4&quot; Mix)</td>
<td></td>
</tr>
<tr>
<td>Mix2</td>
<td></td>
<td>45</td>
<td>5.02</td>
<td>37.0</td>
<td>5.04</td>
<td>1.27</td>
<td>15.4-68</td>
<td>13.5 - 17.0 (1/2&quot; Mix)</td>
<td></td>
</tr>
<tr>
<td>Mix3</td>
<td></td>
<td>30</td>
<td>5.30</td>
<td>28.4</td>
<td>4.37</td>
<td>1.46</td>
<td>16.4-70</td>
<td>VFA: 65 - 75 (3/4&quot; and 1/2&quot; Mix in Level 3 and 4)</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> All mixtures had dense gradation and aggregates with a nominal maximum aggregate size of 12.5mm;

<sup>b</sup> RAP = Reclaimed asphalt pavement added by weight;

<sup>c</sup> AC = Design BMD asphalt content added by weight;

<sup>d</sup> BR = Binder replacement;

<sup>e</sup> P<sub>be</sub> = Effective asphalt content present by weight in the total mix;

<sup>f</sup> P<sub>200/Pbe</sub> = Dust to binder ratio in the mix;

*ODOT ACP Manual (2015)*
RESULTS – Cost Calculation

Cost of materials from previous years production:
- RAP: $20/ton
- Aggregate: $13/ton
- PG70-22ER binder: $490/ton
- Evotherm P25: $70/ton
RESULTS – Life Cycle Cost Analysis

\[ \text{NPV} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \]

Where:
- \( C_t \) = estimated agency costs at year \( t \),
- \( r \) = interest rate, and
- \( T \) = number of time periods.

NPVs for all the mixes – Without burner fuel consumption cost

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Mix ID</th>
<th>Initial cost ($)</th>
<th>NPV-1 ($)</th>
<th>NPV-2 ($)</th>
<th>NPV ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mix1_AV5</td>
<td>27,823</td>
<td>12,698</td>
<td>5,795</td>
<td>46,316</td>
</tr>
<tr>
<td>2.</td>
<td>Mix1_AV7</td>
<td>28,005</td>
<td>12,781</td>
<td>5,833</td>
<td>46,619</td>
</tr>
<tr>
<td>3.</td>
<td>Mix2</td>
<td>26,167</td>
<td>11,942</td>
<td>5,450</td>
<td>43,560</td>
</tr>
<tr>
<td>4.</td>
<td>Mix3</td>
<td>27,299</td>
<td>12,459</td>
<td>5,686</td>
<td>45,444</td>
</tr>
</tbody>
</table>

NPVs for all the mixes – With burner fuel consumption cost

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Mix ID</th>
<th>Initial cost ($)</th>
<th>NPV-1 ($)</th>
<th>NPV-2 ($)</th>
<th>NPV ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mix1_AV5</td>
<td>32,416</td>
<td>14,794</td>
<td>6,752</td>
<td>53,962</td>
</tr>
<tr>
<td>2.</td>
<td>Mix1_AV7</td>
<td>32,599</td>
<td>14,878</td>
<td>6,790</td>
<td>54,267</td>
</tr>
<tr>
<td>3.</td>
<td>Mix2</td>
<td>30,761</td>
<td>14,039</td>
<td>6,407</td>
<td>51,207</td>
</tr>
<tr>
<td>4.</td>
<td>Mix3</td>
<td>29,597</td>
<td>13,508</td>
<td>6,165</td>
<td>49,269</td>
</tr>
</tbody>
</table>
**METHODOLOGY – Life Cycle Assessment (Pavement LCA)**

- Define pavement geometry and material inputs (binder content, binder type, WMA/HMA, etc.)
- Define rehabilitation schedule as maintenance every 20 years until the 60-year lifespan has been reached
- Run software and export global warming markers to excel

### Lanes

<table>
<thead>
<tr>
<th>Lanes</th>
<th>Lane 1 Lift 1</th>
<th>Lane 2 Lift 1</th>
<th>Lane 3 Lift 1</th>
<th>Lane 1 Lift 2</th>
<th>Lane 2 Lift 2</th>
<th>Lane 3 Lift 2</th>
<th>Lane 1 Lift 3</th>
<th>Lane 2 Lift 3</th>
<th>Lane 3 Lift 3</th>
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</thead>
<tbody>
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<tr>
<td>Granular Layer 1</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Activity Timing

<table>
<thead>
<tr>
<th>Year After Initial Construction</th>
<th>Expected Lifespan [Years]</th>
<th>Activity Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>Asphalt Milling</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>Asphalt Paving</td>
</tr>
</tbody>
</table>

### Model: B3-R6-BC6

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Materials and Equipment</th>
<th>Transport</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Warming Potential</td>
<td>kg CO₂-eq</td>
<td>469.955,33</td>
<td>498138,5946</td>
<td>519773,8722</td>
</tr>
<tr>
<td>Acidification Potential</td>
<td>kg SO₂-eq</td>
<td>4.977,53</td>
<td>5025220314</td>
<td>4580366696</td>
</tr>
<tr>
<td>PM₁₀ Particulates</td>
<td>kg PM₁₀</td>
<td>247,60</td>
<td>261782047</td>
<td>2733870679</td>
</tr>
<tr>
<td>Eutrophication Potential</td>
<td>kg N-eq</td>
<td>173,58</td>
<td>1319910511</td>
<td>2047762385</td>
</tr>
<tr>
<td>Ozone Depletion Potential</td>
<td>kg CFC-11</td>
<td>0,00</td>
<td>1175635860</td>
<td>7,08015058</td>
</tr>
<tr>
<td>Snop Potential</td>
<td>kg O₃-eq</td>
<td>42615,98</td>
<td>1593833377</td>
<td>5854981465</td>
</tr>
<tr>
<td>Total Primary Energy</td>
<td>MJ</td>
<td>30,450,605,29</td>
<td>722007,2163</td>
<td>311726312,51</td>
</tr>
<tr>
<td>Fossil Fuel Consumption</td>
<td>MJ</td>
<td>25,867,573,70</td>
<td>720560,7824</td>
<td>30558143,48</td>
</tr>
</tbody>
</table>

### Table:

- The table shows the environmental impacts for each component and the total impact for the model B3-R6-BC6.
RESULTS – Life Cycle Assessment (Pavement LCA)

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Global Warming Potential (kg CO₂ eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Mix</td>
<td>928,452.01</td>
</tr>
<tr>
<td>RAP30_AVS</td>
<td>695,029.40</td>
</tr>
<tr>
<td>RAP45</td>
<td>674,945.31</td>
</tr>
<tr>
<td>WMA</td>
<td>668,003.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Typical Mix</th>
<th>RAP30_AVS</th>
<th>RAP45</th>
<th>WMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential</td>
<td>kg CO₂ eq</td>
<td>928,452.01</td>
<td>695,029.40</td>
<td>674,945.31</td>
<td>668,003.82</td>
</tr>
</tbody>
</table>
RESULTS – Life Cycle Assessment (Pavement LCA)

![Graph showing Acidification Potential for different Mix Types]

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Acidification Potential (kg SO₂ eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Mix</td>
<td>8,455.31</td>
</tr>
<tr>
<td>RAP30 AVS</td>
<td>6,381.97</td>
</tr>
<tr>
<td>RAP45</td>
<td>6,134.03</td>
</tr>
<tr>
<td>WMA</td>
<td>6,001.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Typical Mix</th>
<th>RAP30 AVS</th>
<th>RAP45</th>
<th>WMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidification Potential</td>
<td>kg SO₂ eq</td>
<td>8,455.31</td>
<td>6,381.97</td>
<td>6,134.03</td>
<td>6,001.86</td>
</tr>
</tbody>
</table>
RESULTS – Life Cycle Assessment (Pavement LCA)

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Eutrophication Potential (kg N eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Mix</td>
<td>390.30</td>
</tr>
<tr>
<td>RAP30 AVS</td>
<td>303.00</td>
</tr>
<tr>
<td>RAP45</td>
<td>288.52</td>
</tr>
<tr>
<td>WMA</td>
<td>282.97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Typical Mix</th>
<th>RAP30 AVS</th>
<th>RAP45</th>
<th>WMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eutrophication Potential</td>
<td>kg N eq</td>
<td>390.30</td>
<td>303.00</td>
<td>288.52</td>
<td>282.97</td>
</tr>
</tbody>
</table>
Major Conclusions

• Mix3 has cracking resistances significantly higher than all other mixtures;
• It is possible that Mix 3 with warm-mix additives can have better “compactibility”;
• The most cost-effective mix is the warm mix asphalt (Mix 3) considering the reduced production temperature;
• Mix 3 (warm-mix) is also the most environmentally friendly mix with lower expected GWP, EP, and AP values for a 60 year analysis period;
• Based on the balanced mix design plots for the four mixes, the required asphalt content for Mix1_AV5, Mix1_AV7, Mix2 and Mix3 are 6.00%, 6.05%, 6.10% and 5.30%.

The mixture with warm-mix additives (Mix 3) is selected as the best asphalt mixture with lowest cost and lowest environmental impact.
Thank You
GO BEAVS!