AAPA’s 14th International Flexible Pavements Conference

Sydney
25–28 September 2011

Design of Recycled Asphalt Mixtures

André A.A. Molenaar
Professor of Road Engineering
Delft University of Technology NL
Co-Authors

Mohamad Mohajeri
Martin F.C. ven de Ven

Delft University of Technology
Contents

• Recycling of hot mix asphalt in the Netherlands
• Mix design issues of mixtures with high RAP content; effects of moisture and mixing method
• Effect of RAP content, moisture and mixing method on mechanical characteristics
Some Statistics about the Netherlands

- 16 million people
- 3 million tons of RAP
- 15 million tons of CDW
- No natural aggregates
- No space for dumping waste
- Recycling is a must
Government policy

- Recycling is a must.
- Costs per ton for dumping RAP are very high, close to costs of producing new mixture.
- Active policy in development of techniques, specifications, test methods etc.
- Since 1990, recycled asphalt mixtures are in the Dutch standards.
- Since 1990, RAP is treated as “normal” material.
Some early Developments

• 1976 Renofalt process; recycling with up to 100% RAP
• 1990 MARS process; recycling with up to 100% RAP
State of the Art Recycling in the Netherlands

- Asphalt production of $9 \times 10^6$ ton/year mostly for binder and surface layers.
- Consumption of bitumen $0.37 \times 10^6$ ton/year.
- At the moment $3.5 \times 10^6$ ton/year of RAP.
- 80% of the RAP is used in hot mix.
- 65% of new HMA production contains RAP.
State of the Art Recycling in the Netherlands

- Recycling in STAC (base layer) maximum 50%.
- Recycling in OAC (binder layer) maximum 50%.
- Recycling in DAC (wearing course) maximum 50%.
- Recycling in Porous Asphalt (wearing course) maximum 20%.
- No recycling in SMA.
- Log pen rule is used for the combined penetration (old - new bitumen) in the mix design for all mixes.

\[ a \log \text{pen}_{\text{RAP}} + b \log \text{pen}_{\text{virgin}} = (a + b) \log \text{pen}_{\text{mix}} \]
\[ a + b = 1 \]
Hot Mix Asphalt plants (partial recycling PR) in the Netherlands

<table>
<thead>
<tr>
<th>Type of plant</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch plant with parallel drum</td>
<td>38</td>
</tr>
<tr>
<td>Batch plant with cold RAP feed</td>
<td>1</td>
</tr>
<tr>
<td>Drum mixer suitable for PR</td>
<td>5</td>
</tr>
<tr>
<td>Double barrel drum</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45</strong></td>
</tr>
</tbody>
</table>
Some Issues

• From max 50% to 70% recycling in base layers

• Many PA layers are to be replaced in a first or second maintenance cycle. This is RAP with extremely hard bitumen (pen < 15).

• How to keep the temperature of virgin aggregate at reasonable level at higher RAP contents.

• For surface layers, requirements PSV stone are increased (>57). Is aggregate in current RAP good enough?
CE marking effective since January 2009

• Functional requirements in CE marking also for RAP mixtures:
  - water sensitivity (retained ITS),
  - stiffness (4 point bending),
  - fatigue (4 point bending),
  - permanent deformation (triaxial test).
Important Research questions

- Fatigue properties of mixtures with very high RAP contents.
- Healing of mixes with RAP.
- How to recycle mixtures with PMB (can log (pen) rule be used).
- Re-use of Porous Asphalt RAP.
- More general: increase amount of RAP in the top layers
Fatigue and Healing Tests

Mortar samples $h = 10 \text{ mm}$ $\phi = 6 \text{ mm}$

Mortar means all aggregates with $\phi < 0.5 \text{ mm} + \text{bitumen}$
Fatigue and Healing Results of Virgin and Aged Mortars

MO02/03 and MO04

Healing factor 3 - 4

Sample stress [MPa]

Fat. MO02/03

Hea. MO02/03

Fat. MO04

Hea. MO04

Effect of rest periods

Effect of ageing

y = 2263.7x^{-4.843}

y = 6919x^{-4.795}

y = 39084x^{-6.424}

y = 121191x^{-5.02}
Consequences for Recycling

- Aged mortar has better fatigue resistance than virgin mortar
- Ageing does seem to have bad effect on healing

CAREFUL!!!!

- Results are obtained on artificial aged mortars
- However, rheological and chemical characteristics of artificial aged binder were the same as those of binder extracted from RAP
Comparison Lab vs “Field”

- Rheological properties of lab aged binder = rheological properties of binder recovered from RAP
- Chemical composition lab aged binder = chemical composition binder from RAP
- Fatigue characteristics were the same (no rest periods)
- Healing lab aged mortar 3 - 4
- Healing mortar with RAP (field aged) binder 1.8
- In all cases mortar aggregates were the same
Blending

Will this binder blend with new binder?

“naked” stone “black rock”?
Nano-indentation Tests to measure Blending

Difficult to measure blending via nano-indentation

CT scanning may be the way to go

Hard binder 20/30
Soft binder 160/200

Modulus at Max Load
Expectations

- Full blending will not occur
- Some kind of layered structure will develop
- Fines will influence layer development
## Recycling in Europe

<table>
<thead>
<tr>
<th>Country</th>
<th>Available Reclaimed asphalt mix [tons]</th>
<th>% re-used in hot mix</th>
<th>% re-used in cold mix</th>
<th>% of new hot mix production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>$14 \times 10^6$</td>
<td>82</td>
<td>18</td>
<td>60</td>
</tr>
<tr>
<td>Spain</td>
<td>$2.25 \times 10^6$</td>
<td>8</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Italy</td>
<td>$14 \times 10^6$</td>
<td>18</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>$6.5 \times 10^6$</td>
<td>13</td>
<td>&lt; 2</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Norway</td>
<td>$0.59 \times 10^6$</td>
<td>7</td>
<td>26</td>
<td>8</td>
</tr>
<tr>
<td>Netherlands</td>
<td>$3 \times 10^6$</td>
<td>80</td>
<td></td>
<td>63</td>
</tr>
</tbody>
</table>
The Problem

- Mixture design process in laboratory ≠ Field conditions
- Simulate in the lab as good as possible real mixing conditions
- BUT CURRENTLY in the lab, RAP is preheated to same temperature as virgin materials!
- Field: Hot Recycling:
  - Warm feed: Parallel drum preheats RAP to 130 °C
  - Cold feed: Cool and moist RAP is added to the mixing unit
- In both cases virgin aggregates have to be heated to high temperatures
- High temperature virgin aggregates might harm mixture quality
Goals

• Determine effects of:
  - amount of RAP
  - moisture content RAP
  - preheating of virgin aggregates on
  - mechanical characteristics of recycled asphalt mixture.

• Derive a laboratory mixture design method that simulates as close as possible the mixing procedures that are used in practice.
Virgin Materials

- Base course mixture
- Norwegian granite $\phi_{\text{max}} = 20 \text{ mm}$

<table>
<thead>
<tr>
<th>Properties bitumen</th>
<th>Unit</th>
<th>Q8 pen 40/ 60</th>
<th>Q8 pen 70/ 100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nominal values</td>
<td>Measured values</td>
</tr>
<tr>
<td>Penetration @ 25° C</td>
<td>0.1mm</td>
<td>40-60</td>
<td>50</td>
</tr>
<tr>
<td>Softening point $T_{r&amp;b}$</td>
<td>° C</td>
<td>48-56</td>
<td>51</td>
</tr>
<tr>
<td>Penetration Index</td>
<td></td>
<td>-1</td>
<td>-0.96</td>
</tr>
<tr>
<td>Density at 25° C</td>
<td>kg/ m³</td>
<td>1035</td>
<td>1035</td>
</tr>
</tbody>
</table>
RAP

- 2.9% moisture
- Crushed to maximum size of 20 mm and fractionized

RAP was fractionized to get better control on composition.
### RAP fractions & binder content

<table>
<thead>
<tr>
<th>Fraction size [mm]</th>
<th>0 - 2</th>
<th>2 - 5</th>
<th>5 - 8</th>
<th>8 - 11</th>
<th>11 - 16</th>
<th>16 - 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass percentage of total aggregate fraction</td>
<td>22</td>
<td>21</td>
<td>15</td>
<td>18</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Percentage of binder in that fraction</td>
<td>33</td>
<td>25</td>
<td>11</td>
<td>13</td>
<td>13</td>
<td>5</td>
</tr>
</tbody>
</table>
RAP and Virgin Aggregates

- RAP
  - 16-22mm
  - 11-16mm
  - 8-11mm
  - 5.6-8mm
  - 2-5.6mm
  - 0-2mm

- Virgin Aggregate
  - 16-22mm
  - 11-16mm
  - 8-11mm
  - 5.6-8mm
  - 2-5.6mm
  - 0-2mm
# Mixture Compositions

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>RAP</th>
<th>0% RAP Virgin material</th>
<th>30% RAP Virgin material</th>
<th>60% RAP Virgin material</th>
<th>Target Virgin material</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; C22.4</td>
<td>0,0</td>
<td>1,2</td>
<td>0,0</td>
<td>0,0</td>
<td>1,2</td>
</tr>
<tr>
<td>C22.4 - C16</td>
<td>6,0</td>
<td>12,2</td>
<td>1,8</td>
<td>10,4</td>
<td>8,6</td>
</tr>
<tr>
<td>C16 - C11.2</td>
<td>11,0</td>
<td>6,6</td>
<td>3,3</td>
<td>3,3</td>
<td>6,6</td>
</tr>
<tr>
<td>C11.2 - C8</td>
<td>14,0</td>
<td>20,2</td>
<td>4,2</td>
<td>16,0</td>
<td>11,8</td>
</tr>
<tr>
<td>C8 - C5.6</td>
<td>9,2</td>
<td>7,0</td>
<td>2,8</td>
<td>4,2</td>
<td>1,5</td>
</tr>
<tr>
<td>C5.6 - C2</td>
<td>16,3</td>
<td>9,8</td>
<td>4,9</td>
<td>4,9</td>
<td>9,8</td>
</tr>
<tr>
<td>River Sand (0/2)</td>
<td>35,7</td>
<td>37,0</td>
<td>10,7</td>
<td>26,3</td>
<td>21,4</td>
</tr>
<tr>
<td>&lt; 0.063</td>
<td>7,8</td>
<td>6,0</td>
<td>2,3</td>
<td>3,7</td>
<td>4,7</td>
</tr>
<tr>
<td>Total (%)</td>
<td>100,0</td>
<td>100,0</td>
<td>30,0</td>
<td>70,0</td>
<td>60,0</td>
</tr>
<tr>
<td>bitumen</td>
<td>4,3</td>
<td>4,5</td>
<td>1,3</td>
<td>3,2</td>
<td>2,6</td>
</tr>
</tbody>
</table>

Total (%)
# Mixing Methods

<table>
<thead>
<tr>
<th>Laboratory mixing method</th>
<th>code</th>
<th>Related actual plant</th>
<th>Preheating conditions and temperatures (°C)</th>
<th>RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard method</td>
<td>SM</td>
<td>-</td>
<td>170, 170</td>
<td></td>
</tr>
<tr>
<td>Partial Warming</td>
<td>PW</td>
<td>Conventional partial warming</td>
<td>&gt; 170, 130</td>
<td></td>
</tr>
<tr>
<td>Upgraded method</td>
<td>UPG</td>
<td>Astec double barrel</td>
<td>&gt;&gt; 170, 23</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Virgin Agg</th>
<th>RAP</th>
<th>Moisture</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%, 4%</td>
<td>0%</td>
<td>0, 30, 60</td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td>4%</td>
<td>30, 60</td>
<td></td>
</tr>
</tbody>
</table>
# Mixing Temperatures

**Final mixing temperature 170 °C**

<table>
<thead>
<tr>
<th>Mixing method</th>
<th>Virgin aggregate preheating temp (+ 30% RAP)</th>
<th>Virgin aggregate Preheating temp (+ 60% RAP)</th>
<th>RAP preheating temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>170 °C</td>
<td>170 °C</td>
<td>170 °C</td>
</tr>
<tr>
<td>PW</td>
<td>240 °C</td>
<td>330 °C</td>
<td>130 °C</td>
</tr>
<tr>
<td>UPG 0% moisture</td>
<td>290 °C</td>
<td>430 °C</td>
<td>25 °C</td>
</tr>
<tr>
<td>UPG 4% moisture</td>
<td>345 °C</td>
<td>515 °C</td>
<td>25 °C</td>
</tr>
</tbody>
</table>
Observation

- Mixing 60% RAP which is at ambient temperature and containing 4% moisture with very hot aggregates is a violent process
- Steam develops
- Does foaming occur in outer drum of double barrel?
Temperature during mixing

UPG

SM
Temperature Change in Time
Stiffness testing

Frequency sweeps at 5, 10, 15, 23 and 35 °C
Fatigue Testing by means of ITT

- 20 °C / 10 Hz
- Only one stress level: 220 kPa
- Reason: limited availability of specimens
Fatigue “dry” and “wet”

Fatigue “wet”: fatigue test sample is kept under water during fatigue test

Possible reason: low void content of mixture (appr. 3%)

<table>
<thead>
<tr>
<th>Material</th>
<th>Dry IT fatigue</th>
<th>Saturated IT fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM0</td>
<td>4.9</td>
<td>5.1</td>
</tr>
<tr>
<td>SM30</td>
<td>6.0</td>
<td>5.3</td>
</tr>
<tr>
<td>SM60</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td>PW30</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td>PW60</td>
<td>5.6</td>
<td>6.1</td>
</tr>
<tr>
<td>UPG30</td>
<td>5.3</td>
<td>5.5</td>
</tr>
<tr>
<td>UPG60</td>
<td>5.7</td>
<td>5.8</td>
</tr>
<tr>
<td>UPG4-30</td>
<td>5.5</td>
<td>5.8</td>
</tr>
<tr>
<td>UPG4-60</td>
<td>6.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Conclusions

- The amount of RAP as well as its moisture content does not have negative effects on the mechanical properties of the investigated recycled mixtures.
- Even when the virgin aggregate is preheated to (very) high temperatures there seems to be no negative effect.
- It takes quite a while for relatively cool RAP to take the same temperature as the entire mixture when mixed with super heated aggregates.
- Effect of shorter mixing times on the mechanical characteristics of the recycled mixtures should be studied.
- The ADBM mixing process is very difficult to simulate in the laboratory.
- The UPG method allows studying the effect of mixing super heated aggregates with cool, moist RAP on the mechanical properties of recycled mixtures.
Thank you for your attention