Asphalt Diffusion

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Understand RAP-Virgin Binder Diffusion

Objective
- Understand diffusion between RAP and Virgin binder
- Understand impact of binder blending on rheological properties

Approach
- Understand diffusion kinetics
- Verify the approach for asphalt mix
- Translate findings to mix production & paving conditions
Section 1
Binder Diffusion
RAP-Virgin Binder Diffusion Key to Performance

- Diffusion rate depends on molecular mobility → temperature & molecular structure

![Diagram showing RAP-aggregate, RAP binder, and Virgin binder diffusion into a mix with test in rheometer and results for RAP aggregate, RAP-virgin binder diffusion, and Virgin binder diffusion corrected for effects of oxidation & evaporation.](image)
Diffusion Coefficient Calculated from Viscosity

\[ \phi_{RAP}(y, t) = (1 - \alpha)(1 - \phi_0^{\text{Virgin}}) - \frac{2(1 - \phi_0^{\text{Virgin}})}{\pi} \sum_{n=1}^{\infty} \frac{\sin(n\pi\alpha)}{n} \cos\left(\frac{n\pi y}{L}\right) \exp\left\{-\left(\frac{n \pi}{L}\right)^2 D t\right\} \]

- **RAP conc. in distance y at time t**
- **Average RAP conc. in the specimen**
- **Distance from the top plate**
- **Total sample thickness**
- **Diffusion coefficient**

Experimental Results

\[ \eta(t) = \frac{L}{\int_0^L \frac{\eta_{RAP}}{\eta_{\text{Virgin}}} dy} \]

\[ \eta(t) \] = Experimental Results

Model Fit

\[ \eta(t) \] = Model Fit

Time [s]
Diffusion is Faster at Higher Temperature

- Faster Brownian motion at higher temperature increases diffusion rate & reduces time to equilibrium (homogenous blend)
Binder Blending in Mix is More Complex

Film thickness & time at temperature define blending in the mix
• Distribution of thicknesses exists
• Proper binder contact may not be reached by mixing

Understanding effective binder thickness in mix is essential
Section 2

Mix Diffusion

“Finding the Distance”
Specific Mixes Prepared to Study Diffusion

<table>
<thead>
<tr>
<th>ID</th>
<th>Binder Added</th>
<th>Aggregate</th>
<th>RAP</th>
<th>Air Voids %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Virgin</td>
<td>Same in all mixes</td>
<td>None</td>
<td>30%</td>
</tr>
<tr>
<td>AD</td>
<td>Asphalt Diffusion</td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Same in all mixes</td>
<td>RAP aggregate</td>
<td>None</td>
<td>2.7</td>
</tr>
<tr>
<td>BC</td>
<td>Blended Control</td>
<td>Lab Blend (Virgin+ RAP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Same in all mixes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Superpave 12.5mm Mix Design (OPSS.MUNI 1151)
Mix Briquette Cut & Conditioned

Conditioning in N₂ purged PAV at constant temperature (90, 120, 150 °C) & variable time
Testing in DSR – High Variability is a Challenge

- Test in torsion, 10 rad/s, 20 °C, constant strain (LVE)
  - Small size specimen selected as a compromise to manage time & effort
  - Larger aggregate significantly contribute to variability
- 5-10 repeats, COV remained high
RAP Mix is Softer than Control (pre-blended binders)

EXPERIMENTAL DATA FOR DIFFUSING (AD) & CONTROL MIX (BC)

Significant hardening attributed to binder absorption & evaporation
Diffusion Only Partially Responsible for Mix Hardening

Shaded Area = Contribution of diffusion to complex viscosity increase

Separated contribution of diffusion to complex viscosity increase
Binder Diffusion Model Fits Mix Data Well

MODEL FIT OF EXPERIMENTAL MIX DATA

90 °C

120 °C

150 °C

Diffusion distance = 800µm
Diffusion = Lengthy Process at Mix/Pavement Temperatures

In realistic mix production & placement scenario incomplete blending results in lower complex viscosity

**COMPLEX VISCOSITY INCREASE (DIFFUSION CONTRIBUTION)**

Fraction of Homogenous Viscosity

- **Time, days**
  - $10^{-4}$
  - $10^{-2}$
  - $10^{0}$
  - $10^{2}$
  - $10^{4}$

- HMA
- WMA

- mix
- silo
- transport
- paving
- service

100 days
Extent of Blending is Critical for RAP Mix Performance & Virgin PG Selection

Binder film thickness & time at temperature are critical parameters for diffusion in the asphalt mix

Diffusion may not be completed during mix production

• Effective binder viscosity is lower than expected (“lubrication”)

Silo storage at higher temperature can assist diffusion

Asphalt mix is a dynamic system

• Caution should be used during mix testing
Thank you
Appendix
Proper Binder Contact is Essential for Good Blending

<table>
<thead>
<tr>
<th>Factors: Contact</th>
<th>Factors: Blending</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP temperature</td>
<td>Diffusion rate (D(T))</td>
</tr>
<tr>
<td>Mixing energy/time</td>
<td>Film thickness (distance)</td>
</tr>
<tr>
<td>Virgin binder viscosity</td>
<td>Time</td>
</tr>
</tbody>
</table>

**Poor contact**
- Poor blending

**Good contact**
- Good blending

Virgin Aggregate  | RAP Aggregate  | Virgin Binder  | RAP Binder  | Binder Blend

**Factors:**
- RAP temperature
- Mixing energy/time
- Virgin binder viscosity

**Blending Factors:**
- Diffusion rate (D(T))
- Film thickness (distance)
- Time
RAP-Virgin Binder Blending is Critical to Mix Rheology

Viscosity of two discrete layers of RAP & virgin binder is significantly lower than that of homogenous blend.
Diffusion Rate Can Be Estimated From Viscosity-Temperature Profile

The free volume theory was used to relate diffusion coefficient to viscosity-temperature profile, $\eta(T)$
Relatively accurate estimations of diffusion coefficients are possible from Newtonian viscosity-temperature profiles (Brookfield at 100-140 °C)
Experimental Results Sensitive to Test Setup

Density differences between binders impact diffusion rates. Higher test strains result in artificially higher diffusion rates.

- **Effect of RAP Layer Position**
  - Denser RAP **top** layer = faster
  - Denser RAP **bottom** layer = slower

- **Effect of Test Strain on Diffusion Rate**
  - Higher strain $\rightarrow$ mechanical mixing
Simulating Diffusion Rate at Realistic Conditions

Diffusion coefficient decreases with mix cooling

- Mixing
- Storage
- Transport
- Placement
- Service
Mix Temperature Profile Determined to Assess Extent of Diffusion Before Testing

![Temperature Profile Graph]

- **Mixing**
- **Quenching**
- **Storage**

**Axes:**
- **Time, min**
- **Temperature, °C**

**Samples:**
- VC
- RC
- BC
- AD