Rheology considerations for recycled and recovered binder

Geoffrey M. Rowe

PAVEMENT PERFORMANCE PREDICTION
SYMPOSIUM - Binder Issues Affecting the Durability of RAP and WMA Pavements

Sponsored by Federal Highway Administration — Organized by Western Research Institute
Hilton Garden Inn & University of Wyoming Conference Center — July 12, 2012, Laramie, Wyoming
Objectives

- To consider what rheology is needed with some recycled and recovered products
  - Master curves
    - Binder
    - Mix
    - Ultimate properties
- Durability case study
  - Airport example
- Suggestions for development
Why rheology

- Rheology provides an excellent tool to help understand the behavior of asphalt binders
- Objective is to discuss what parameters may be of interest to help us understand the effectiveness of recycled products
Binder
Binders

○ As binders age rheological properties change
  ● Well know
  ● Changes in shape and location of master curve
  ● Can quantify by R-value (rheological index), cross-over frequency, defining temperature and temperature susceptibility
Binder aging

Example from SHRP project of what occurs as material ages. From aged section in WY compared to Original and PAV.
Cross over frequency

- Crossover frequency reduces as material ages
- Example with various products – extended aging
Temperature susceptibility

- Degree of shift changes between isotherms as material ages
- In all cases C2 increases – controls slope of WLF or Kaelble relationships
Temperature susceptibility

- Can consider three parameters for description of temperature susceptibility from rheology:
  - $\beta$ and $R$ (CA model) linked via simple relationship: $R = \log_2/\beta$
  - $C_1$ parameter in WLF/Kaelble sets location
  - Note $C_1$ and $C_2$ are not constant values but depend upon material

\[ y = 1.1482e^{0.0061x} \quad R^2 = 0.9248 \]
\[ y = 0.2622e^{-0.0061x} \quad R^2 = 0.9248 \]
Temperature susceptibility

- The temperature susceptibility is captured in the slope of the shift factor.
- PVN60 had the best $r^2 (0.74)$ compared to an Arrhenius gradient.
Temperature susceptibility

What about our old parameters

- Measured Pen, 25 and 50°C and ring & ball softening point
- Calculated Penetration Index, PI
- PI with SP provided best correlation with observed behavior
Temperature susceptibility

- Compare against old measures, for example = PI
- PI reduces for SBS modified materials as solid structure is lost with age
- May increase if further aged!!??
- For non-SBS in study PI increases with aging time
Rheological changes

- Aging changes more reliably seen with polymer modified binders by looking at rheological parameters
Aging shift factor

BBR and DSR Combined Data

Complex Modulus - $G^*$, MPa

Reduced Frequency, rad/s (reduced to 25°C and shifted further by aging factor)
Aging shifts

- Shifts apply both to horizontal position and shape (R-value or $\beta$)
- Data from study looking at application of rejuvenators
Rheological data

- Define master curve – CAM good model to fit if working with most RAP supplies
- Define CAM with Kaelble parameters
  - Kaelble enables a fast a rapid evaluation of the defining temperature
  - Make use of BBR data to define cold end of data

\[
G^*(\omega) = G_0[1+(\omega_0 / \omega)\beta]^{-\kappa/\beta}
\]
\[
\delta = 90 / [1+(\omega / \omega_0)\beta]
\]
\[
\log a_T = -C_1\left(\frac{T-T_k}{C_2+|T-T_k|} - \frac{T_r-T_k}{C_2+|T_r-T_k|}\right)
\]
Mix data
Mix data

- As mixes age the master curve changes
  - Hardens (gets stiffer)
  - Cross over point moves
    - how can we look at this!
  - Temperature susceptibility changes

- Are these the same as the binder?
RAP in HMA – master curves

Increasing rap

Log $E^*$, psi vs. Log reduced frequency, Hz

Rap percent
- 0
- 20
- 30
- 40

19
Temperature susceptibility

- Temperature susceptibility should be either related as a function of Arrhenius of WLF (C2) parameter.
Position of master curve

- Inflection point frequency has similar value to the cross over frequency for binders
- Aged/hardened materials will be move to lower values
Models

○ Generalized sigmoid with modified Kaelble fits most data well

\[
\log(E^*) = \delta + \frac{\alpha}{(1 + \lambda e^{(\beta + \gamma \log \omega)})^{1/\lambda}}
\]

\[
\log a_T = -C_1 \left( \frac{T - T_k}{C_2 + |T - T_k|} - \frac{T_r - T_k}{C_2 + |T_r - T_k|} \right)
\]

\[\delta = \text{lower asymptote} \quad -(\beta/\gamma) = \text{inflection point/frequency} \]
\[\delta + \alpha = \text{upper asymptote}\]
Mix vs. binder master curve

Can use functional forms to describe mix and binder master curves.

Several methods available to look at efficiency of mixing.
Ultimate properties
Heukelom (1966)

- Tensile strength of binder as function of binder stiffness presented as master curve
- Binder stiffness considers time of loading and temperature
Heukelom (1966)

- Extended to tensile strength of mixes (8-mix types)
Ferry’s book (T. Smith data)

- Styrene-butyadiene rubber
- Tensile strain
- Data is shifted to a reduced strain rate

FIG. 19-3. Tensile strain at break plotted against logarithm of strain rate (in sec\(^{-1}\)) reduced to 263ºK for a cross-linked styrene-butyadiene rubber at 14 temperatures as indicated (Smith.\(^{106}\))
Ferry’s book (T. Smith data)

- Styrene-butadiene rubber
- Tensile strength
- Data is shifted to a strain rate

FIG. 19-4. Tensile strength in force per unit initial cross-section area, $\sigma_T(b)/\lambda_b$, plotted against logarithm of strain rate, both reduced to $T_r = 263^\circ K$ for the material of Fig. 19–3 at the same 14 temperatures. (Smith.\textsuperscript{106})
SHRP A-369, Anderson et. al (1994)

- Failure master curves of stress, strain and energy for conventional binders
- Functional form for energy

\[ F(\xi) = A + \beta_1 [(Z)^{\beta_4 - 1}] [\exp( -(Z)^{\beta_4})] \]

\begin{itemize}
  \item \(F(\xi)\) = failure strain or failure energy
  \item \(A\) = constant
  \item \(\beta_1\) = magnitude parameter
  \item \(Z = (\log(\xi) - \beta_3)/\beta_3\)
  \item \(\beta_2\) = location parameter
    \begin{itemize}
      \item \(= 0.5392\beta_3\) for failure strain master curve
      \item \(= 0.5011\beta_3\) for failure energy master curve
    \end{itemize}
  \item \(\beta_4\) = scale parameter
  \item \(\beta_4\) = shape parameter, fixed (constant) at 10
  \item \(\log(\xi)\) = common log of reduced time, \(\xi = t/a(T)\)
  \item \(a(T)\) = shift factor obtained from rheological measurements
\end{itemize}
DTT vs. Vialit

This shift is just related to loading time!
Three methods

- Look at fracture properties as function of a reduced parameter
  - Binder Stiffness
  - Reduced Strain Rate
  - Reduced Time

- My preference – binder stiffness
- Needs more work in this area....
Durability case study
Example - airport

- Case study – data from airport – 10 years old - revisited
Airport observed a surface distress in the inner part of runway ends and taxiways, where Polymer-Modified Asphalt Concrete (PMAC) mixtures were paved.

Adjacent to these premium mixes (PG82-22 and PG76-28), in the outer part of the runway and taxiway, a conventional mix (with PG 64-22 binder) was paved.

The distress is in the form of exposed coarse aggregate, absence of fines (raveling) and a graying or whitening of the surface (weathering).
Work conducted

- **Binder**
  - Detailed master curves on recovered binders
  - Creep recovery tests

- **Mix**
  - SST FS
  - Sliver testing FS
# Grades obtained

<table>
<thead>
<tr>
<th>Grade</th>
<th>Location</th>
<th>PG High</th>
<th>$\Delta$ from PG grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG64-22</td>
<td>T</td>
<td>68.6</td>
<td>+2.6</td>
</tr>
<tr>
<td>PG64-22</td>
<td>B</td>
<td>65.3</td>
<td>+1.3</td>
</tr>
<tr>
<td>PG64-22</td>
<td>T</td>
<td>67.3</td>
<td>+3.3</td>
</tr>
<tr>
<td>PG64-22</td>
<td>B</td>
<td>65.5</td>
<td>+1.5</td>
</tr>
<tr>
<td>PG76-28</td>
<td>T</td>
<td>85.1</td>
<td>+8.1 (+1 grade)</td>
</tr>
<tr>
<td>PG76-28</td>
<td>B</td>
<td>74.5</td>
<td>-1.5 (-1 grade)</td>
</tr>
<tr>
<td>PG76-28</td>
<td>T</td>
<td>85.5</td>
<td>+8.5 (+1 grade)</td>
</tr>
<tr>
<td>PG76-28</td>
<td>B</td>
<td>74.2</td>
<td>-1.8 (-1 grade)</td>
</tr>
<tr>
<td>PG82-22</td>
<td>T</td>
<td>90.4</td>
<td>+8.4 (+1 grade)</td>
</tr>
<tr>
<td>PG82-22</td>
<td>B</td>
<td>85.2</td>
<td>+3.2</td>
</tr>
<tr>
<td>PG82-22</td>
<td>T</td>
<td>94.8</td>
<td>+12.8 (+2 grades)</td>
</tr>
<tr>
<td>PG82-22</td>
<td>B</td>
<td>81.3</td>
<td>-0.7 (-1 grade)</td>
</tr>
</tbody>
</table>
Initial summary

- The stiffness of the materials at the bottom of the layer are lower than that obtained at the top in all cases.
- The PG64-22 has the highest stiffness at 5°C for the bottom of the core but the lowest value at the top of the core.
- Modified materials age to a greater extent.
- The PG64-22 showed little change in high temperature PG.
- The modified binders showed significant change in properties.
2\textsuperscript{nd} analysis

- Why?
  - Initial analysis not satisfactory
  - Decided to reanalyze data looking again at rheology and durability parameters
  - Have well defined data
Rheological changes

- The change with position (more aging in surface)
  - R-value increases
  - Crossover frequency reduces
Data compared to G-R parameter in Black space

- Sensitivity to cracking
- Two modified systems showed poor performance “dull appearance and show potential for early distress” noted in 2004
- Pavement surface gave poor performance for modified products
Data compared to SHRP cracking parameter

- \( G^* \times \sin(\delta) \) added to graph did not capture issue with binder performance
Value of rheology

- Good rheological data allows review and 2nd analyses in this case
- Data shows importance of both stiffness and relaxation properties
- Plausible results to explain observed distresses
Suggestions/summary

- Kaelble model and others to be further developed
- Need to extend more analysis to ultimate properties
- Better understanding of intermediate properties
- Detailed rheological analysis provides a better understanding
- Some of the newer parameters may help us to fill in gaps in understanding
- Use good definitions for master curves that allow good flexibility and definition of parameters
Questions/discussion?

Missing Laramie and all the fun in wild west!

Looking forward to 2013 – in Laramie ....