Interrelationships in Rheological Parameters

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Overview

- Work collected data, BBR DSR
- Review of Interconversions analysis
- DSR, use of $G^*$ and $\delta$ instead of $S$ and $m$ – and what values?
- Black space – R value key
- Short cuts to R and cross-over
- Binder properties estimation – short cuts estimated from CAM parameters
- Summary
Work collected data, BBR DSR

- Limitation and guidance on master mastercurve production
- Limit on ranges for models
Initial model – several approximations
- Split temperature susceptibility analysis around defining temperature, Td with Arrhenius below and WLF above – with temperature susceptibility values same for all binders
- Assumed glassy modulus = 1e9 Pa
- Shift factor confounded in model parameter fits

RHEA analysis removes the approximations
- New analysis uses Kaelble modified WLF to calculate Td – with single function above and below
- No assumption of glassy modulus
- Calculates all CAM parameters
- Shifting independent of model fit
Initial analysis

- Initial analysis of model properties showed errors of +10% on rms fit
- Model fit does not work well for all stiffness range with all binders
  - However, previous work with TSAR BBR shows very good fit for
    - Fit error <6%
    - Ave. <3%

<table>
<thead>
<tr>
<th>Sample</th>
<th>Aged</th>
<th>No. of Analysis</th>
<th>Root Mean Square Error (%)</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>CA</td>
</tr>
<tr>
<td>1</td>
<td>RTFO</td>
<td>13</td>
<td>3.50</td>
</tr>
<tr>
<td>2</td>
<td>RTFO</td>
<td>13</td>
<td>1.30</td>
</tr>
<tr>
<td>2</td>
<td>PAV</td>
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<tr>
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<td>2.84</td>
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<tr>
<td>4</td>
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<tr>
<td>11</td>
<td>PAV</td>
<td>11</td>
<td>1.65</td>
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Average  2.45  0.07  1.07  0.01  1.22  0.00
Black space plot of binder AAM (original condition) with data from BBR and DSR
SHRP Core binders, PAV aged
Reducing error

- At last working group meeting we decided to rerun analysis but removing high temperature data
  - Result – similar error ranges for obtained for BBR
  - If AAM is curtailed at 1e+05 then error changes to 3.49%
R-value calculation

- R calculation robust but depends upon assumptions in process
- Example shows range in results for one binder
  - Same binder data set – AAA PAV

\[
R = \frac{(\log 2) \log \frac{G^*(\omega)}{G_g}}{\log\left(1 - \frac{\delta(\omega)}{90}\right)}
\]

<table>
<thead>
<tr>
<th>R₁₀rad, 15C, Gg=1e9</th>
<th>2.15</th>
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<tbody>
<tr>
<td>R₁₀rad, 25C, Gg=1e9</td>
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<td>R₁₀rad, 15C, Gg Calc.</td>
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<td>R₁₀rad, 25C, Gg Calc.</td>
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<td>R_all data</td>
<td>2.47</td>
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<td>R_reduced</td>
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R-value, differences in data

- R-value – why the difference in data
R–value

- Easy to compute from single data points
- Place in Black space linked to R
- Cross–over frequency, VET, G–R or other parameters such as NCSU \( \delta = 45 \) all related to R–value
- Field performance shows cracking is related to R
- All interrelated via VE–time temperature functions
Based upon the analysis the CAM model has limitations which should be applied in modeling

Applicability of CAM master curve model fit and parameters, $G^* \geq 1e5$ Pa

R value and cross-over frequency should only be expresses reliability when data in range 1e5 to 1e9 Pa

Use free shifting to produce master curve
  - Don’t fit for time and temperature properties at same time

Data acceptable if rms % error $\leq 2.25%$ !!!
Review of Interconversions analysis

- During SHRP
  - Some detailed inter–conversions
  - Some approximations via $E = 3G$
  - General assumption that $\nu = 0.5$ for liquid appears reasonable
  - Note – nearly all testing is conducted at temperatures significantly above glass transition temperatures

- Recent work
  - Use relaxation and retardation spectra to perform inter–conversions between BBR and DSR
Spectra analysis

Relaxation Spectra Model

\[ G'(\omega) = G_o + \sum_{i=1}^{\infty} \frac{G_i (\omega \tau_i)^2}{1 + (\omega \tau_i)^2} \]

Retardation Spectra Model

\[ G''(\omega) = \sum_{i=1}^{\infty} \frac{G_i \omega \tau_i}{1 + (\omega \tau_i)^2} \]
BBR data is fitted with the CA, CAS and CAM models and the software determines the fit with the lowest error.

Hopkins and Hamming method is used to convert the master curve to the relaxation modulus $E(t)$.

The $E(t)$ data is then fitted with a CAM model using the glassy modulus determined from the previous fitting. This gives a function which describes an $E(t)$ fit.

The discrete spectra is calculated for the $E(t)$ fitted function.

The reciprocal of the observed times are substituted into the function to estimate the $E', E''$ data points.

The data points are shifted using the original shift values obtained along with a reverse density correction to obtain dynamic isotherms corresponding to the original data.

$E', E''$ extensional data is then output to a data file converting to $G', G''$ (or $G^*$).

**Note:** $G^* \neq S(t)/3$
Conversion of $S(t) = 300$ to $G^*$ and $m = 0.30$ to $\delta$

- Equivalency is binder specific BBR vs. DSR
- $S(t) \ @ \ 60s$
  - $300\text{MPa} \approx G^*$
  - $111\ \text{MPa}$
- $0.3 \text{ m} \approx 26.2^\circ$
  - $\delta$ is a bit more variable

Data is AAD, AAF, AAG, AAK & AAM (all PAV)
Conversions

- These conversions are robust and pass the test of engineering reasonableness
- Not to dissimilar to what we had in SHRP
Parameters in linear region

- G–R
- Use of BBR + 2 intermediate DSR master curve
- Alternate approach to BBR
  - Use G* and δ
  - Use G–R definition – single value
- VET
Intermediate temperature binder specification

- Two important parameters
  - The existing Superpave criteria $G^\star \sin \delta$ ensures rheology of binder in range from low to intermediate range
  - $G-R$ parameter $[G^\star(\cos \delta)^2 / \sin \delta]$ adds to existing specification and prevents excessive age related cracking
    - Relates well to cracking on airports
    - Used to evaluate performance of RAP mixes in Netherlands
    - Corresponds to surface cracking (top down) of mixes in Indiana Study

Note – here the G–R uses $15^\circ$C and 0.005 rads/sec
PAV master curve from standard M320 testing

(a) raw data, 3 BBR isotherms and 2 DSR data points

(b: master curve of $G^*$ and $\delta$

DSR data
DSR, use of $G^*$ and $\delta$ instead of $S$ and $m$ – and what values?

- If we go to alternate rheology for defining cold temperature properties – what are the choices?
  - Can we use a single BBR isotherm and intermediate value DSR?
  - Can use intermediate value and model predictions
    - G–R for cold temperature !?
    - $G^*$ and $\delta$ !?
  - Can we use 4mm plate?

- Why all of this – folks want to age less binder and speed up testing time!!!
DSR and BBR are interrelated
- A method of calculation exists that will enable use to express BBR data (S, m) in DSR format (G*, δ)
  - S and G* both describe a stiffness
  - m and δ – both describe the binders viscous component and ability to relax stresses

Conversion → BBR t=60 seconds to DSR
- ω=10rads/sec
  - S 300MPa ≈ G* 111 MPa
  - 0.3 m ≈ 26.2°
    - δ is a bit more variable
BBR $\rightarrow$ DSR

- Same data – plotted on two graphs
- R value of 1.923 divides what we would consider as S and m controlled binders
A better definition of pass/fail!

- Failure line based upon adaption of G–R parameter = 184 MPa
- Intersection of red box and line has same meaning as current BBR S and m specification
- No need to use numerical Interconversions
- Simple specification concept – consistent with current M320 specification MSCR version
VET Concept

Development
- Initial concept developed by French workers
  - Saw relationships between binder properties and fatigue cracking
- Used 7.8Hz

Adopted in UK specifications
- 0.4 Hz
- $T_{VET}$
- $G^*_{VET}$
UK data

Aging definitions
Symbols A50 to E10 - tested in Orginal, RFTOT and HiPAT condition. HiPAT is PAV but at 65hrs at temperature of 85°C. SHRP core asphits (symbols AAA, AAG, AAK & AAM) - Tested in Orginal, RFTOT and PAV condition. GSE - Tested in Orginal, PAV and extended PAV (40 and 80 hours).
SHRP core asphalts

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Interrelationship from CAM to VET

- If $G^* = 1 \text{e9} \text{ Pa}$
  
  $$G^*_{VET} = 10^{(9-R)}$$

- If CAM model with Kaelble shift

  $$T_{VET} = T_d + \chi \left( \frac{C_2}{[1 - |\chi|]} \right)$$

  $$\chi = \frac{T_r - T_d}{C_2 + |T_r - T_d|} - \frac{\log \omega_c - \log \omega_{VET}}{C_1}$$

  $$G^*_{VET} = G_g \cdot 2^{(-\kappa/\beta)}$$

- VET parameters are an expression of R-value and hardness/temperature susceptibility
Summary – Analysis

- Free shifting – keep analysis for temperature dependency and time dependency as two steps
- CAM model fit works well in limited range 1e5 to 1e9 Pa with Kaelble modification to WLF
  - Density inclusion in shifting is important
  - Data acceptable if rms % error ≤ 2.25%
- Combination of BBR data seems reasonable using interconversion via spectra fit, Hopkins and Hamming, etc.
- R value and cross–over frequency is only expressed reliability when data is in range (as above)
- Use free shifting to produce master curve
  - Don’t fit for time and temperature properties at same time
- Can develop master curve from standard PAV data set collected with M320 analysis using BBR and DSR data
Summary – Specifications

- **Low temp**
  - Options exist with regard to extrapolation and how we can determine a critical parameter
  - \( \text{Value of } G^*(\cos\delta)^2 / \sin\delta \leq 184 \text{ MPa} \) – would satisfy both \( S \) and \( m \) criteria

- **Intermediate**
  - Material still in linear visco-elastic range
  - Important to be careful in modeling if we use stiffness which are low – use \( \geq 10^5 \text{ Pa} \)
  - Various parameters can be used to define cracking of different formats, \( G^* \cdot \sin\delta \), \( G^*(\cos\delta)^2 / \sin\delta \), \( \Delta(T) \), \( G^*_{\text{VET}} \), \( T_{\text{VET}} \), etc., etc.
  - Parameters are dependent upon \( R \)-value, cross-over frequency and temperature susceptibility

- **High temperature**
  - Note – we are beyond region were we can extrapolate from models with good accuracy
  - Models loose accuracy when this data is included
Thanks for listening ...

Questions?
Comments!