New methods for assessing rheology data such as $\Delta T_c$ and G-R Parameter and their relationship to performance of REOB in asphalt binders and other materials

Dr. Geoffrey M. Rowe
Abatech

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Objectives

• Update on document development
• Information on $\Delta T_c$ from CA model
• Thoughts on “point” vs. “shape” parameters
Task Group

- Geoffrey M. Rowe (Abatech) (growe@abatech.com)
- Louay Mohammad (LSU) (louaym@lsu.edu)
- Bill Ahearn (VT Agency of Transportation) (bill.ahearn@vermont.gov)
- Mark Buncher (Asphalt Institute) (MBuncher@asphaltinstitute.org)
- Gerald Reinke (MTE Services) (Gerald.Reinke@mteservices.com)
- Walaa Mogawer (UMass) (wmogawer@umassd.edu)
- Nelson Gibson (FHWA) (Nelson.Gibson@dot.gov)
- Tom Bennert (Rutgers) (bennert@rci.rutgers.edu)
- Jean-Pascal Planche (WRI) (jplanche@uwyo.edu)
- Imad Al-Qadi (U of IL) (alqadi@illinois.edu)
- Pamela Marks (Ontario Ministry of Transportation) (pamela.marks@ontario.ca)
- Laci Tiarks-Martin (PRI) (ltiarks@priasphalt.com)
- John D’Angelo (Consultant) (johndangelo@Dangeloconsulting.com)
- David A. Anderson (Consultant) (da.sc@comcast.net)
Document status

- Redrafted with input from task-group members
- Forwarded for circulation to wider ETG for final review
- Some additional background provided
- Details on $\Delta T_c$ calculation from CA model added with a worked example using data from Anderson et al. (2011) paper
Interconversions

• CA model defines rheology in region of $10^5$ to $10^9$ Pascals to a good accuracy

• From this possible to calculate G-R and $\Delta T_c$
  • Calculation of $\Delta T_c$ more complex
  • Can calculate from BBR or DSR data
  • Example using BBR data

• Method on next few slides
CA equation

- Form of CA within RHEA
  \[ S = \text{Stiffness modulus} \]
  \[ S_g = \text{Glassy stiffness modulus} \]
  \[ t = \text{Time of interest} \]
  \[ \lambda, \beta = \text{Fitting parameters in the CA equation} \]
  \[ R = \log2 / \beta \]

- Time at a given stiffness is given by
  \[ t(S) = \lambda \left[ \left( \frac{S}{S_g} \right)^{-\beta} - 1 \right]^{1/\beta} \]
  \[ S(t) = S_g \left[ 1 + \left( \frac{t}{\lambda} \right)^{\beta} \right]^{-1/\beta} \]
Determination of $\Delta T_c$ from the CA equation

- Further rearrangement provides for the determination:
  - The slope, $m(t)$, were the time is set
  - The time, $t(m)$ at when the slope is set

- In this formulation we have assumed an Arrhenius function – ok for BBR data in stiffer region of master curve (could consider linearized form or Keakle – in further development)

  \[ m(t) = \frac{1}{1 + \left(\frac{t}{\lambda}\right)^{-\beta}} \]

  \[ t(m) = \lambda \left[\left(\frac{1}{m}\right) - 1\right]^{-1/\beta} \]

  \[ \ln a_T = c \left(\frac{1}{T} - \frac{1}{T_r}\right) \]

$a_T = \text{Time – temperature shift function}$,
$c = \text{Constant determined via regression analysis}$
$T = \text{Temperature, } ^\circ\text{K}$
$T_r = \text{reference temperature, } ^\circ\text{K}$
The CA and Arrhenius equation result

- Combining the two equations we can develop two further equations
  - Stiffness at a temperature, $T$, which corresponds to a loading time of 60 seconds
  - Temperature ($T$) that corresponds to a stiffness at defined at 60 seconds

- Now we can do the steps to calculate $\Delta T_c$ using a stepwise process

$$S(T, 60) = S_g \left[ 1 + \left( \frac{60}{\lambda \exp \left[ c \left( \frac{1}{T} - \frac{1}{T_r} \right) \right]} \right)^{\beta} \right]^{-1/\beta}$$

$$T(S, 60) = \left[ \ln \left( \frac{60}{\lambda \left[ \left( \frac{S_g}{S} \right)^{\beta} - 1 \right]^{1/\beta}} \right) /C + \frac{1}{T_r} \right]^{-1}$$
Example

• Data from Anderson et al. (2011)
  • Computed values for $S_g = 2,638.1$ MPa, $\lambda = 4,787.93$ seconds, $\beta = 0.183734$, $T_r = -18^{\circ}$C and Arrhenius constant $= 29,680.4$ (“0” aging condition)

1. Obtain parameters as noted above
2. Use $T(S)$ to get Temperature for $S=300$ when loading time is fixed as 60 seconds [ = -16.9 $^{\circ}$C]
3. Use $t(m)$ to obtain the loading time when $m=0.300$ at the reference temperature [ = 47.6 sec]
4. Use $S(t)$ to obtain the stiffness value when the loading time is associated with $m=0.300$ at the reference temperature [for $t=47.6$ sec, $S(t)= 378.6$ MPa at $T_{ref}$]
5. Use $T(S)$ to obtain the temperature for the condition at which $S(t)$ at the reference temperature corresponds to $m=0.300$ [$S=378.6$ which results in $T(m) = -18.5^{\circ}$C]
6. Subtract $T(S) - T(m)$ to get $\Delta T_c$. [-16.9 - (-18.5) = +1.4]
Point vs. shape

• Need to consider what is defined as a point property versus a parameter that defines a shape of the master curve or part of the master curve
What is $\Delta T_c$?

- $T_{S(60s)} - T_{m(60s)}$
- $\Delta T_c$ defines the slope of the stiffness curve in the temperature domain
- Is a shape parameter in the higher stiffness region – related to temperature susceptibility and the rheological index
What is Glover-Rowe (G-R) parameter?

• $G-R = G^* (\cos \delta)^2/G^* \cdot \sin \delta$
  - Defined at 15°C and 0.005 rads/sec
• This defines a point within a Black space plot of $G^*$ vs. phase angle
• Is a point property in a similar manner to $S$, $m$, $G^* \cdot \sin \delta$, $G^*/\sin \delta$, $J_{nr}$, etc.
**Point versus shape**

- Will not necessarily correlate since they are defining different parameters
- Initial relationship shown for $\Delta T_c$ versus G-R does not apply to many materials
  - Which is a more reliable indicator of performance?
  - In our existing specifications we have not used a shape parameter without a point parameter!

<table>
<thead>
<tr>
<th>Point</th>
<th>Shape</th>
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</thead>
<tbody>
<tr>
<td><strong>Rheology</strong></td>
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</tr>
<tr>
<td>S, m, G$^<em>$/$sin\delta$, G</em>/$sin\delta$, $J_{nr}$</td>
<td>R, WLF/Arrhenius, $\Delta T_c$, A+VTS, etc.</td>
</tr>
<tr>
<td><strong>Empirical</strong></td>
<td><strong>Empirical</strong></td>
</tr>
<tr>
<td>Pen, R&amp;B SP, Frass</td>
<td>PI, PVN, etc.</td>
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Thanks for listening ...

Questions?

Comments!