Interrelationships in Rheology for Asphalt Binder Specifications

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Overview

- Interrelationships
- Results
- Options for specifications
  - Glover–Rowe Concept
  - VET approach
  - $S$ & $m$ versus $G^*$ and $\delta$
  - …. Other ideas
- Summary
Lots of equations!

Relaxation Spectra Model

Interconversion via spectra fit

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

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

\[ G(t) = \sum_{i=1}^{\infty} g_i e^{-t/\lambda_i} \]

Rouse density correction

\[ G(T_n, t) = \frac{T_R}{T} \rho(T_R) G\left( T, \frac{t}{\alpha_T} \right) \]

Hopkins and Hamming

\[ \int_0^t E(\xi) D(t - \xi) d\xi = t \]

\[ E(t_{n+1}) = \frac{t_{n+1} - \sum_{i=0}^{n-1} E(t_{i+\frac{1}{2}})[f(t_{n+1} - t_i) - f(t_{n+1} - t_{i+1})]}{f(t_{n+1} - t_n)} \]

\[ f(t_{n+1}) = f(t_n) + \frac{1}{2} [D(t_{n+1}) + D(t_n)] [t_{n+1} - t_n] \]

Retardation Spectra Model

\[ \delta_{(T,w)} = \frac{90}{1 + \left( \frac{\omega_r}{\omega_0} \right)^\beta} \]

\[ R = \log \frac{2}{(\beta)} \]

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Complex modulus master curve

\[ G^*(T, \omega_r) = G_g \left[ 1 + \left( \frac{\omega_c}{\omega_r} \right)^\beta \right]^\frac{-\kappa}{\beta} \]

\[ R = \log \frac{2}{(\beta)} \]

\[ \delta_{(T,w)} = \frac{90}{1 + \left( \frac{\omega_r}{\omega_0} \right)^\beta} \]

\[ R = \log \frac{2}{(\beta)} \]

Stiffness modulus master curve

\[ \frac{1}{D(T, t)} = S(T, t) = S_g \left[ 1 + \left( \frac{t}{\lambda} \right)^\beta \right]^\frac{-\kappa}{\beta} \]

Time–temperature superposition

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

Glover–Rowe

\[ G-R = \frac{G^*(\cos \delta)^2}{\sin \delta} \]

\[ G^* ((\cos \delta)^2 / \sin \delta) = 180 \text{ kPa} \]

\[ G^* ((\cos \delta)^2 / \sin \delta) = 450 \text{ kPa} \]

Visco–Elastic Transition

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

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

\[ G^*_{VET} = G_g \cdot 2^{\left( \frac{-\kappa}{\beta} \right)} \]

When \( G_g = 1 \times 10^9 \)

\[ G^*_{VET} = 10^{(9-R)} \]
What now !!!???

Let’s explore some ideas!
Master curve quality

- Limits 1GPa to 10kPa
  - Error in mastercurve $< 3.5\%$ rms
    - Cracking parameters all calculated within this range
      - Thermal, fatigue and durability cracking

- Result $\rightarrow$ can use interconversions for all cracking parameters

Beyond this range binders can have transitions that results in lack of thermo-rheologically simple behavior

CAM Model, $R=2.05$
Extended data analysis
Master curve from M320 QC data

- BBR data and intermediate DSR data can be used to construct master curve
- Extended usefulness of data collection with current specifications as additional parameters relating to binder quality can be obtained
  - R-value, cross over modulus, temperature susceptibility parameters
Relationship between $G^*$ and $S$; and $\delta$ and $m$

- Data for AAD, AAF, AAG, AAK and AAM
  - PAV aging
- Relationships robust
  - $S \ 300 \ MPa$
    - $= G^* \ 111 MPa$
  - $m \ 0.300$
    - $= \delta \ 26.2^\circ$

\[ G^* = 0.3759 \ S(t)^{0.9992} \]
\[ R^2 = 0.9893 \]

\[ \delta = -28.239 (m)^2 + 96.858 (m) \]
\[ R^2 = 0.924 \]
Thermal Cracking

- BBR parameters can be substituted with $G^*$ and $\delta$ with equivalent meaning
  - Original calibrations would apply
- $S$ or $m$ controlled is related to R-value
  - Low $R = S$ controlled
  - High $R = m$ controlled
  - Cut-off around $\approx 1.92$
If 4mm rheology is adopted -- then -- we have no need to use complex interconversions to $S(t)$ and $m$

Just use $G^*$ and $\delta$ collected at the appropriate conditions
G–R parameter suggested as method for assessing durability cracking

If R<3 (most typical binders) the G–R critical values are all in the range captured by linear visco–elastic analysis and suggested limits on interrelationships

- >1e5 Pa

Parameters can be determined via use of standard M320 tests

- BBR + int. DSR

Noted to work well with RAP mixes !!!!

- More on this later ....
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 $\delta = 45$ all related to R-value
- Field performance shows cracking is related to R
- All interrelated via VE– time temperature functions
VET concept

- Visco-elastic transition temperature based on concept of $G' = G''$ when expressed as a function of temperature
  - In draft specifications in UK
  - French workers noted that $\delta = 45^\circ$ related to cracking

Questions
- How linked to performance?
- How is this related to other parameters such as R-value and those of CA model?
  - Key $\rightarrow$ via understanding of interrelationships...
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 asphlts (symbols AAA, AAG, AAK & AAM) - Tested in Orginal, RTFOT and PAV condition. GSE - Tested in Orginal, PAV and extended PAV (40 and 80 hours).
Performance is grouped depending on material.
Lower $G^{*}_{VET}$ and higher $T_{VET}$ generally poorer performance.
Captures similar concept to G-R but is criteria is grade dependent!

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VET and G–R concept

- G–R and VET approaches can be interrelated
- G–R parameter can be plotted within VET space and explains VET cracking parameter
- VET cracking approach is related to R–value, stiffness and relaxation properties
  - Concept reversed with VET numbers
    - Lower $E^*_\text{VET} = \text{more blown and harder asphalt}$
    - Higher $T_{\text{VET}} = \text{harder material}$
  - VET criteria will be different for different binder grades
- Both methods describe stiffness and relaxation but in different ways
Extending the G–R concept – to cold temperature cracking

- A single parameter could conceptually define the same region as controlled by S and m.
- Key \( \rightarrow \) is the control of stiffness and relaxation properties.
- As binders age, the R-value increases and the cross over frequency reduces.
- Rejuvenation should produce opposite effect.
Aging vs. rejuvenation

![Graph showing the relationship between R-value and crossover frequency for different asphalt binders under various aging and rejuvenation conditions.](image)
RAP Rejuvenation

- Concept applied to assessment of rejuvenated product
- Effectiveness of rejuvenation
- Assessment of cracking potential associated with durability
- Part of evaluation
  - Assumes blending, etc., etc.
  - Not full assessment!

![Graphs showing data and analysis of rejuvenation effectiveness.](https://example.com/graphs.png)
Summary – Analysis

- Model fit works well in limited range 1e5 to 1e9 Pa
  - 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 temperature cracking**
  - Options exist with regard to extrapolation and how we can determine a critical parameter
  - Value of $G^* (\cos \delta)^2 / \sin \delta \leq 184$ MPa – would satisfy both $S$ and $m$ criteria

- **Intermediate (cracking parameters)**
  - Material still in linear visco-elastic range
  - Important to be careful in modeling if we use stiffness which are low – use $\geq 10^5$ Pa
  - Various parameters can be used to define cracking of different formats, $G^* \sin \delta$, $G^* (\cos \delta)^2 / \sin \delta$, $\Delta(T)$, $G^*_{VET}$, $T_{VET}$, 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

- LVE analysis explains significant potential for cracking
Thank you for listening.

Questions?
Comments?