Historical and Current Rheological Binder Characterization vs. Binder Performance

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Why Characterize Binder Rheology With Mathematical Models?

- Provide mathematical formula that can be manipulated for purpose of calculation
- Provide quantitative parameters that can be used to characterize rheology and changes in rheology
- Provide rational basis for specification criteria
- Provide link between binder and mixture

Models – What Is Needed?

- Needs vary with application
- From binder perspective binder need model that:
  - Captures changes in binder rheology caused by long-term aging
    - Must be compatible with molecular/structure changes at molecular level
- Links binder and mixture properties
- Is related to binder “quality” – a forgotten issue
- Many possibilities – focus on CA model

Explicit Models – Pre SHRP

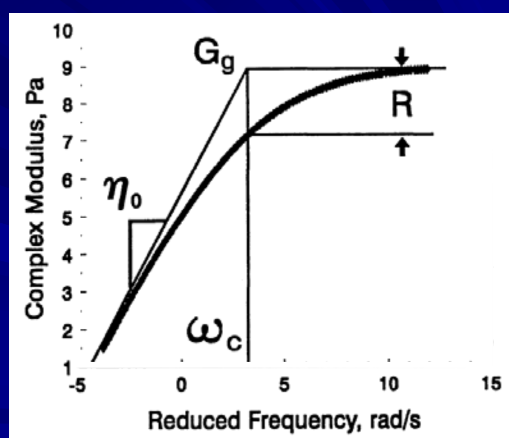
- Jongepier and Kuilman
  - Relaxation spectra as log normal distribution
- Dobson (1969)
  - Based on empirical relationships between modulus and phase angle
- Dickenson and DeWitt (1974)
  - Based on hyperbolic representation
  - Recognized relaxation spectra skewed

Models – Christensen-Anderson

- Developed during SHRP
- Genesis was the need to describe relaxation modulus
  - All other rheological functions can be generated from relaxation modulus
- Christensen recognized that relaxation modulus is skewed, not symmetric
  - Concluded that skewed function was needed

CA Model

- Christensen-Anderson - CA model (1993)
  - Relates $G^*(\omega)$ to G_g, ω_c and R



Weibul Function to Model Relaxation Spectrum

$$F(x) = \frac{m}{b} \exp\left\{\frac{x-a}{b}\right\}\left[1 + \left\{\frac{x-a}{b}\right\}\right]^{-(m+1)}$$

$F(x)$ = Probability density function

m = Skewness parameter

x = Independent parameter

b = Scale parameter

a = Location parameter

Cumulative Weibull Function

- Integrate to obtain cumulative function:

$$P(x) = 1 - \left[1 - \left\{\frac{x-a}{b}\right\}^{b}\right]^{-m}$$

- or:

$$1 - P(x) = \left[1 + \left\{\frac{x-a}{b}\right\}^{b}\right]^{-m}$$

CA Model for $G^*(\omega)$

- Substituting rheological parameters:

$$G^*(\omega) = G_g\left[1+\left\{\frac{\omega}{\omega_c}\right\}^{(\log 2/R)}\right]^{-R/\log 2}$$

$G^*(\omega)$ = Measured complex modulus

G_g = Glassy modulus

R = Rhelogical Index (shape factor)

ω = Test frequency

ω_c = Crossover frequency (location parameter)

CA Model for $\delta(\omega)$

- Rewriting and substituting rheological parameters:

$$\delta(\omega) = 90/\left[1+\left\{\frac{\omega}{\omega_c}\right\}^{(\log 2)/R}\right]$$

$\delta(\omega)$ = Measured phase angle

Temperature Dependency

- WLF based on free volume concepts
  - Good results above T_g
- Arrhenius based on rate theory
  - Necessary below glass transition temperature
- Polynomial
  - Useful over small temperature range only
  - Works well with BBR data

R and Delayed Elastic Response

$$1/G^*(\omega) = 1/G_E + 1/G_{DE}(\omega) + 1/G_V(\omega)$$

$$1/G_{DE}(\omega) = 1/G^*(\omega) - 1/G_E - 1/G_V(\omega)$$

- $1/G^*(\omega)$ ↓ Measured at some T and ω
- $1/G_E$ ↓ $1/G_g$
- $1/G_V(\omega)$ ↓ $1/(\omega\eta_o)$

Estimate for Rheological Index

- Model can be rewritten as:

$$\log G^*(\omega) = \log G_g + (R/\log 2)\log[1 - \delta(\omega)/90]$$

- $G^*(\omega)$ versus log[1- $\delta(\omega)$ / 90)]
  - slope R/log2
  - Can be estimated from a single DSR measurement
- Relationship works well when:

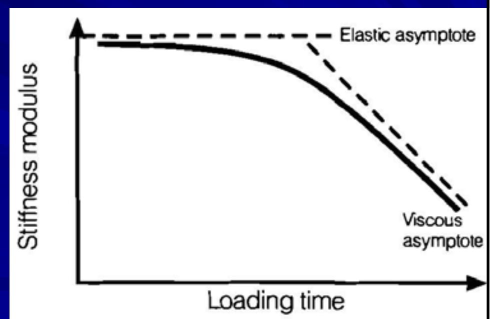
  $10° < \delta(\omega) < 70°$

Estimation of η_o and ω_c

- Similar shortcuts
- Full mastercurve is not needed to estimate model [parameters
- Useful in following aging studies

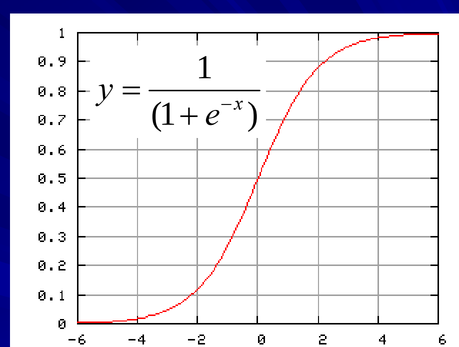
Other Models – van der Poel

- Predicts stiffness from Pen and vis
- Recognized hyperbolic relationship S vs.T
- Model implicit in development of nomograph
  - Viscous asymptote
  - Elastic asymptote



Mix models - Witczak

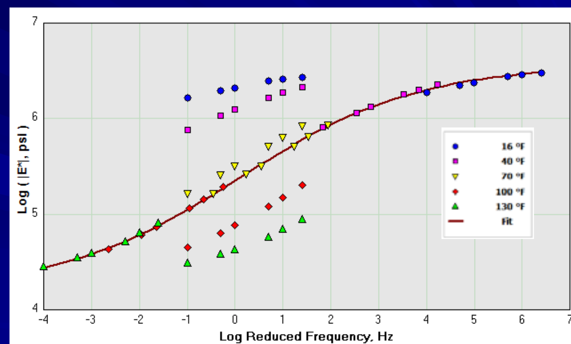
- Basic symmetric sigmoid function
- Basis of Witczak model for asphalt mixture E* data



Witczak model

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

- Two asymptotes and the central/inflection point of the sigmoid
- Model is limited in shape to a symmetrical sigmoid



Temperature Susceptibility Parameters

- $PI_{R\&B}$ (Pfeiffer and van Doormaal, 1936
  - Ring and ball and pen
- PI_{logPen} (Huekelom and Klomp, 1964)
  - Slope of log pen vs temperature
- PVN (McLeod, 1972)
  - Pen at 25°C and viscosity at 60 or 135 60°C
- VTS (Puzinauskas)
  - Viscosity at 60 and 135 60°C

Comments - Temperature Susceptibility Parameters

- Based on measurements at two temperatures
- Shear rates not same at multiple temperatures
- Confound time and temperature effects
- Studies show that different indices are not equivalent and vary differently with aging
  - Indices reflect time and temperature susceptibility

Temperature Susceptibility

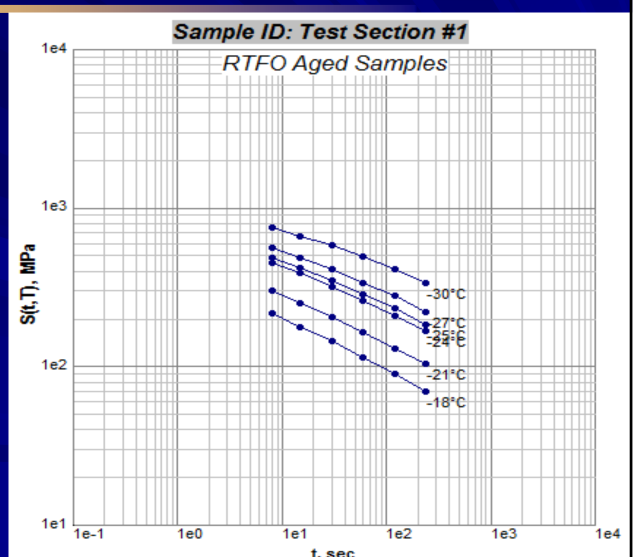
- In old specifications captures via PI, PVN etc
- How do we capture this in the newer specifications/testing
- Example – five data sets from Lamont Road

BBR data using CAM Model

- Analysis of 5 data examples from Lamont test road
- Master curve construction using AASHTO PP42
  - CAM model

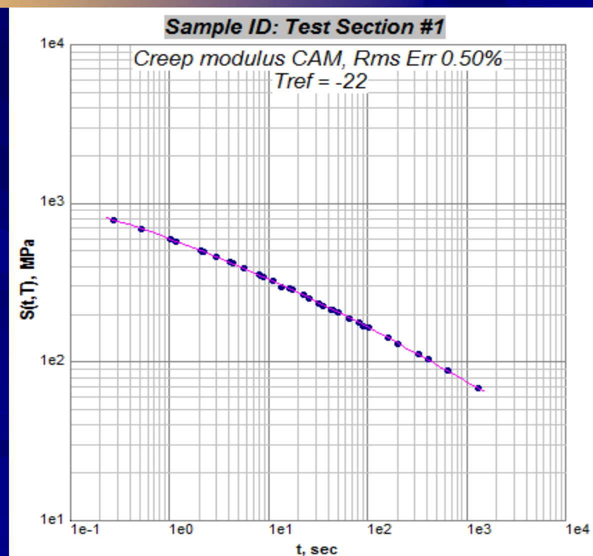
BBR data

- Five sections considered
- Typical example of data
- Used all data available



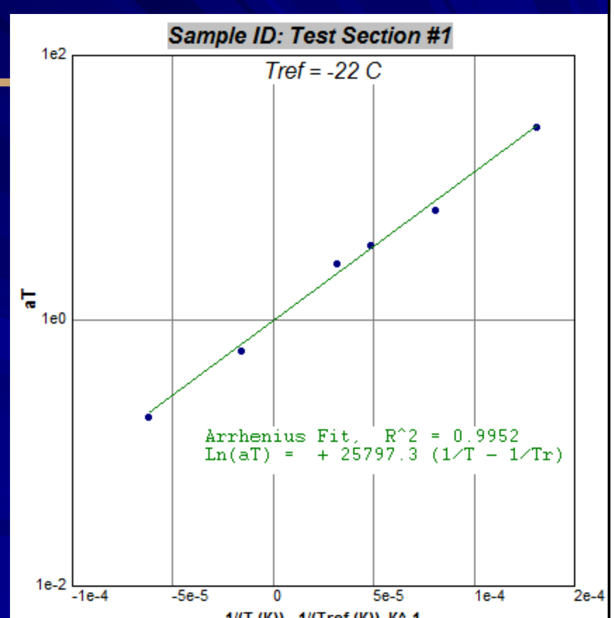
Master Curve Construction

- Used AASHTO PP42 to construct master curves



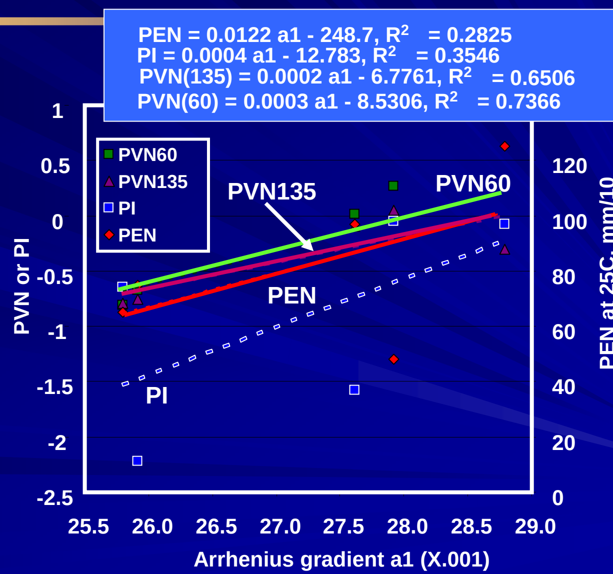
Shift factors

- Shift factors obtained in Arrhenius form



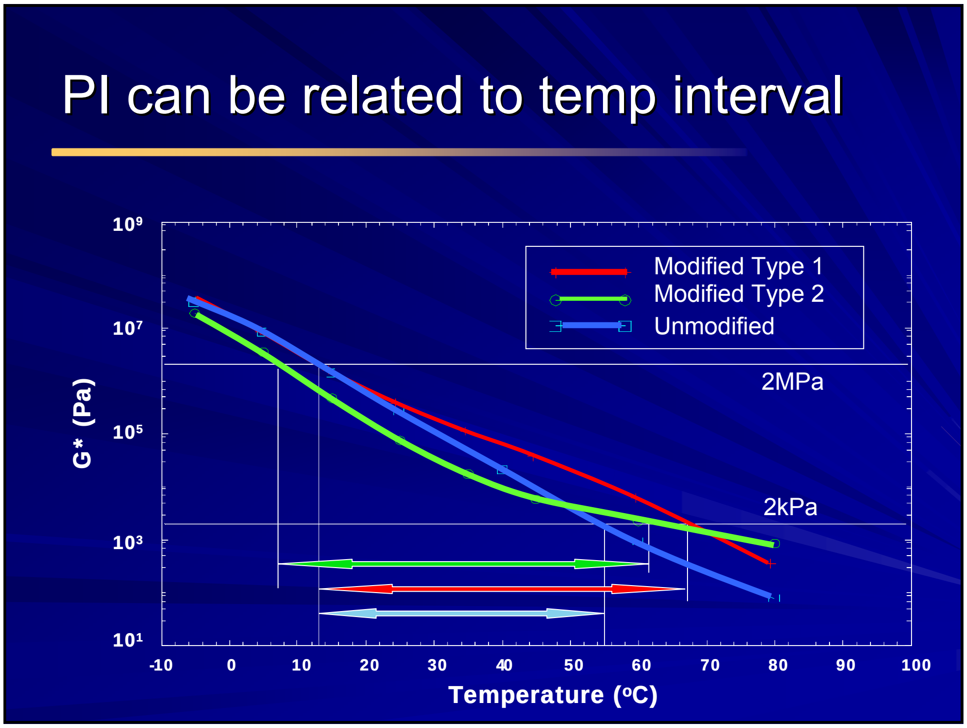
Temperature susceptibility

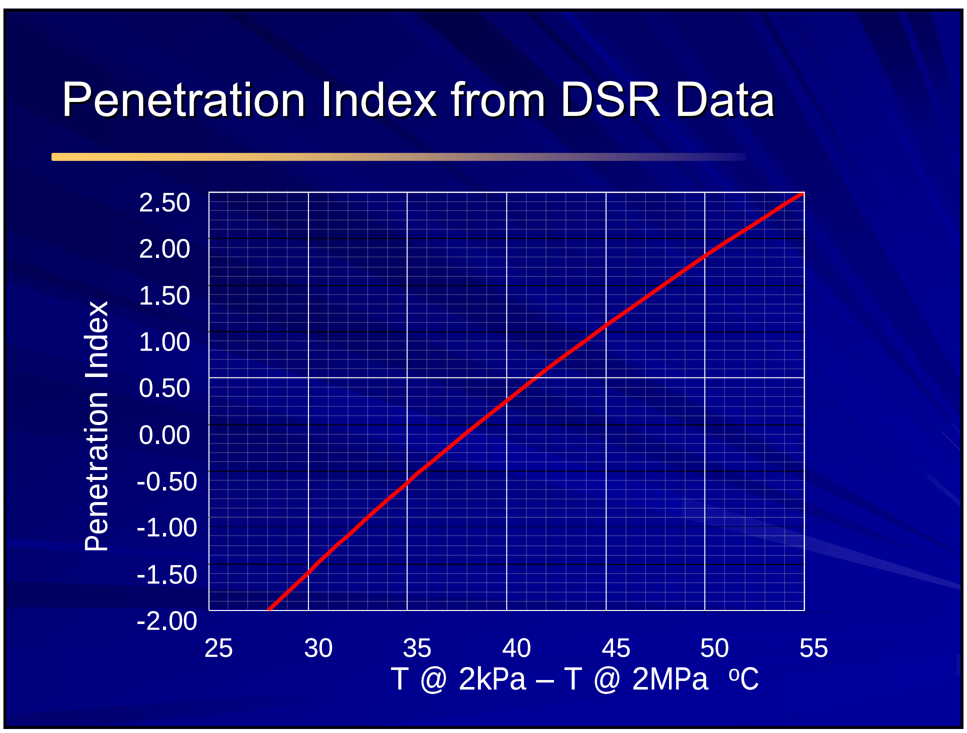
- The temperature susceptibility is captured in the slope of the shift factor
- The better r^2 results from the data obtained to compute the empirical parameter closest to the rheological measurements



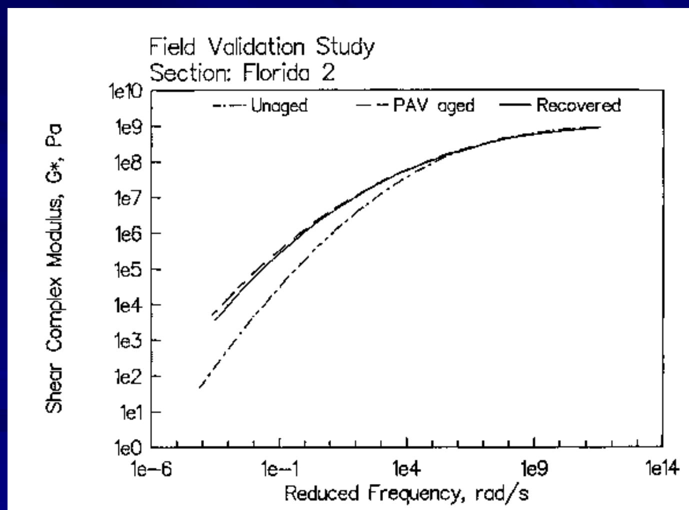
Temperature intervals

- Similar to US absolute grade (PG)
- Used in Europe – particularly UK

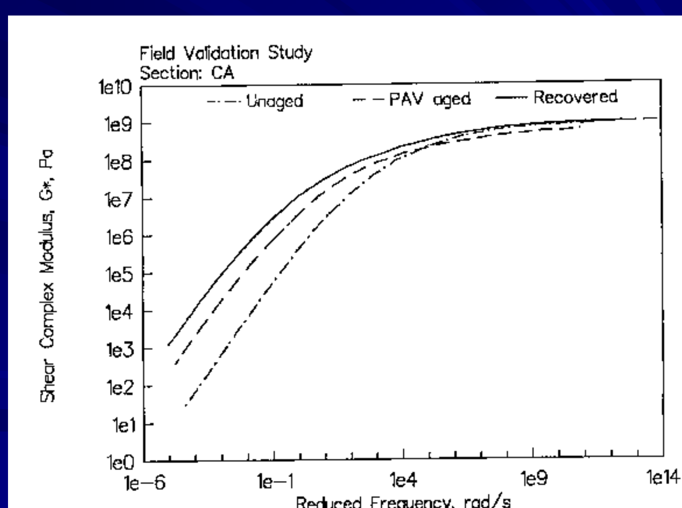

PI can be related to temp interval
Modified Type 1
Modified Type 2
Unmodified
2MPa
2kPa
G* (Pa)
10⁹
10⁷
10⁵
10³
10¹
-10
0
10
20
30
40
50
60
70
80
90
100
Temperature (ºC)


Penetration Index from DSR Data
Penetration Index
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
25
30
35
40
45
50
55
T @ 2kPa – T @ 2MPa ºC

Model Parameter Changes with Aging



Model Parameter Changes with Aging



R and ω_c May Both Change

- Changes in R reflect changes in relaxation Modulus
  - Shape of mastercurve
- Changes in Infinite number of combinations ω_c reflect hardening
  - Location of mastercurve

Closing Comments

- Many different models are available for characterizing rheological properties of binders
  - Model selected depends on application
- Skewed function is needed to model mastercurve
- Shortcut methods can be used to generate CA model parameters
- Temperature Susceptibility parameters can be related to CA model parameters
- R and or ω_c can change with aging

Acknowledgements

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