Master curve properties interrelationships with mix and binder data

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Presented at the

RAP ETG Meeting

Phoenix, AZ

October 28-29, 2008

Objective

- To discuss basic properties of the master curves for binder and mixes
- To demonstrate how all properties for MEPDG input can be derived from the mix master curve

Why?

- MEPDG based on viscosity aging profiles
- Viscosity is estimated from G* and phase angle

2.2.14 after log-log transformation of the viscosity data and log transformation of the temperature data.

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \quad (2.2.13)$$

$$\log\log\eta = A + VTS\log T_R \quad (2.2.14)$$

where

G*	=	binder complex shear modulus, Pa.
δ	=	binder phase angle, °.
η	=	viscosity, cP.
T_R	=	temperature in Rankine at which the viscosity was estimated.
A, VTS	=	regression parameters.

It is possible to derive all this information from the mixture master curve

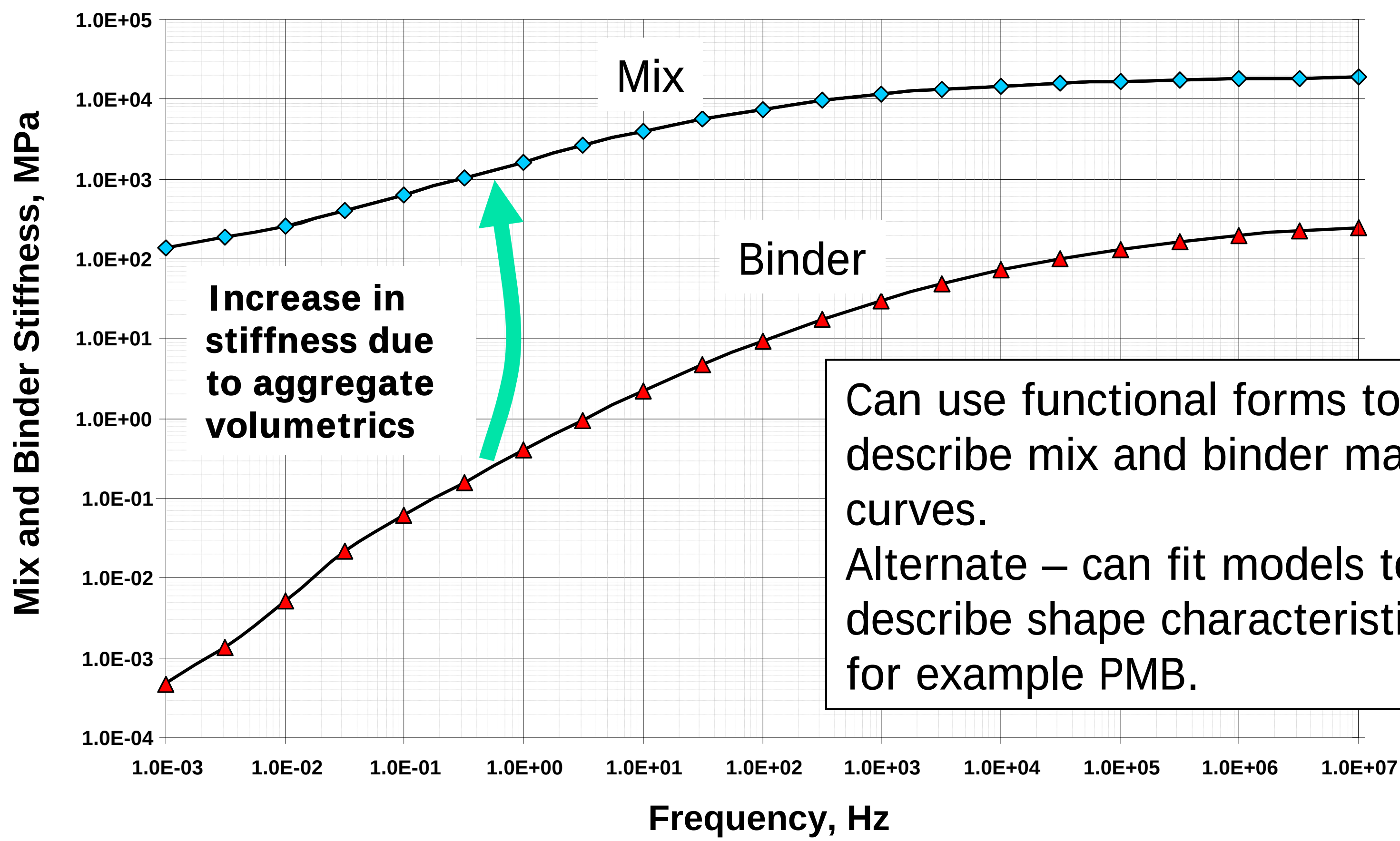
New concepts

- Relationship between slope of log E* (or G*) vs. ω and δ
- Generalized versus standard logistic functions
- Kaelble shift factor relationship
- Need for more frequencies
- Additional utility of data from E* master curve

How we have developed ideas

- Phase angle data can be deduced from stiffness vs. frequency relationship – we don’t need to measure
- Improvements to help with determinations
  - Testing – add a few more frequencies
  - Master curve functional – add a parameter to describe non-symmetrical shape of master curve
  - Shifting – use Kaelble modification to WLF

Mix vs. binder master curve



Can use functional forms to describe mix and binder master curves.
Alternate – can fit models to describe shape characteristic – for example PMB.

Mix to binder properties

- Things we need
  - Hirsch model
  - Relationship between phase and G*
- Others have shown that we can use Hirsch model to assess quality of RAP dispersion in HMA blends

Mix E* to binder G* - Hirsch

- Works well for large range of mixture stiffness values
- Previous slide is consistent with this information

Binder G* to binder δ

- Christensen-Anderson proposed relationship linking G* to δ
- Relationship is based on underlying relationship

$$\delta(\omega) = 90 \times \frac{d \log G^*}{d \log \omega}$$

Log-log relationship

- Fundamental relationship
- Applies to a wide variety of materials
- We have looked at with polymers, asphalt, mixes, etc. etc.
- CA →

$$G^*(\omega) = G_g[1+(\omega_c/\omega)^{(\log 2)/R}]^{-R/(\log 2)} \quad (1.22)$$

where

$G^*(\omega)$ = complex dynamic modulus, in Pa, at frequency ω, rad/s;
G_g = glassy modulus, typically 1 GPa;
ω_c = the crossover frequency, rad/s; and
R = the rheological index.

For the phase angle, δ, the following related equation applies:

$$\delta(\omega) = 90/[1+(\omega/\omega_o)^{(\log 2)/R}] \quad (1.23)$$

where

$\delta(\omega)$ = the phase angle, in degrees, at frequency ω, rad/s, and

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Binder

- CA equation
  - It can be shown that the log-log relationship is related to the phase angle

$$G^*(\omega) = G_0 \left[1 + (\lambda/\omega)^\beta\right]^{-1/\beta}$$

$$\delta(\omega) = 90 \left[1 + (\omega/\lambda)^\beta\right]^{-1}$$

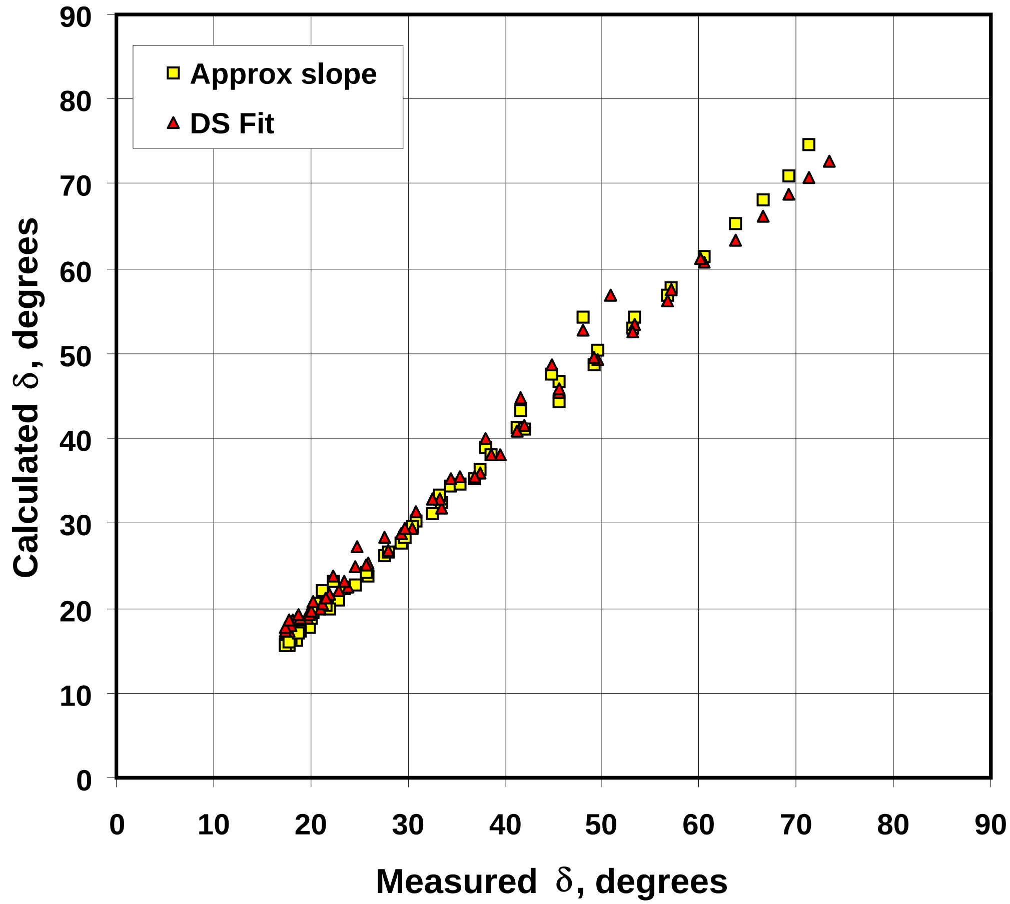
$$\frac{d \ln G^*}{d \ln \omega} = \{\frac{G_0}{\omega} \frac{(\lambda/\omega)^\beta}{[1 + (\lambda/\omega)^\beta]^{\frac{1}{\beta}+1}}\}\{\frac{\omega}{G_0}\left[1 + (\lambda/\omega)^\beta\right]^{1/\beta}\} =$$

$$\frac{(\lambda/\omega)^\beta}{[1 + (\lambda/\omega)^\beta]^{\frac{1}{\beta}+1}}\left[1 + (\lambda/\omega)^\beta\right]^{1/\beta} = \frac{(\lambda/\omega)^\beta}{1 + (\lambda/\omega)^\beta} = \frac{1}{(\omega/\lambda)^\beta + 1} = \left[1 + (\omega/\lambda)^\beta\right]^{-1}$$

Dickson and Witt (1974) and used in the development of the CA model.

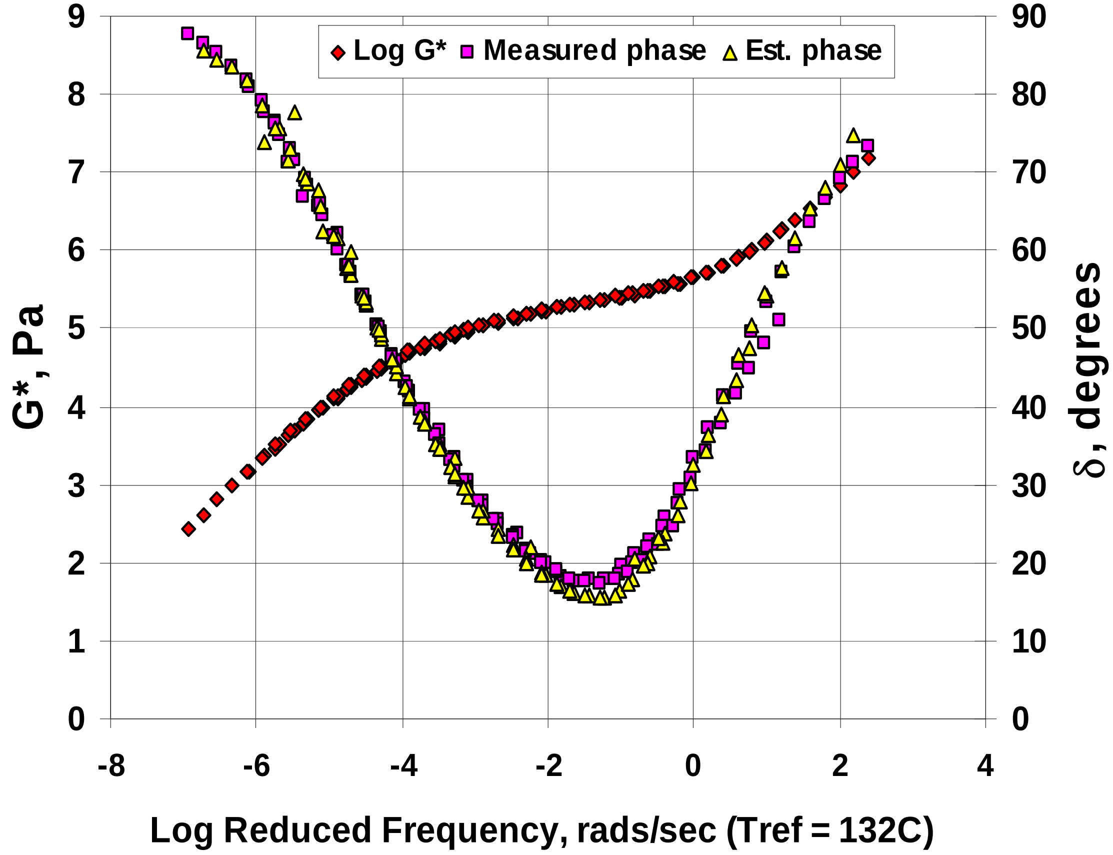
Polystyrene

- Very good fit with measured vs. calculated



Polystyrene

- Estimated phase angle fits real data very well from the log-log slope information



Phase angle

- Shown – for a wide variety of materials – that – δ=90(dlogG*/dlogω)
- Analysis is consistent with that produced by discrete spectra analysis of G* or G'G" (or E equivalents)
- Technique can help with analysis

Standard

$$\delta(\omega) = 90 \times \frac{d \log E^*}{d \log \omega} = -90\alpha\gamma \frac{e^{[\beta+\gamma(\log\omega)]}}{\left[1 + e^{\beta+\gamma(\log\omega)}\right]^2}$$

Generalized

$$\delta(\omega) = 90 \times \frac{d \log E^*}{d \log \omega} = -90\alpha\gamma \frac{e^{[\beta+\gamma(\log\omega)]}}{\left[1 + \lambda e^{\beta+\gamma(\log\omega)}\right]^{(1+1/\lambda)}}$$

RAP binder properties

1. Obtain mixture E*
2. Use E* data to back-calculate binder G* using Hirsch model
3. Estimate log-log slope of G* vs. ω plot
   a. Method 1 – fit CA model
   b. Method 2 – obtain approximate slope from alternate numerical method
4. Use G* and d with 2.2.13 and 2.2.14 to estimate binder viscosity
   a. Other methods could be used to estimate viscosity from G* data from analysis of frequency sweep data
5. Apply aging and MEPDG parameters to relationships obtained

Hirsch

- Hirsch model relates volumetrics and stiffness of binder to stiffness of mixture
- Can calculate for single points or isotherms

$$E^*_m = Pc\left[4{,}200{,}00\left(1-\frac{VMA}{100}\right)+3G^*_b\left(\frac{VFA\times VMA}{10{,}000}\right)\right]+\left(1-Pc\right)\left[\frac{1-\frac{VMA}{100}}{4{,}200{,}000}+\frac{VMA}{3\times VFA\times G^*_b}\right]^{-1}$$

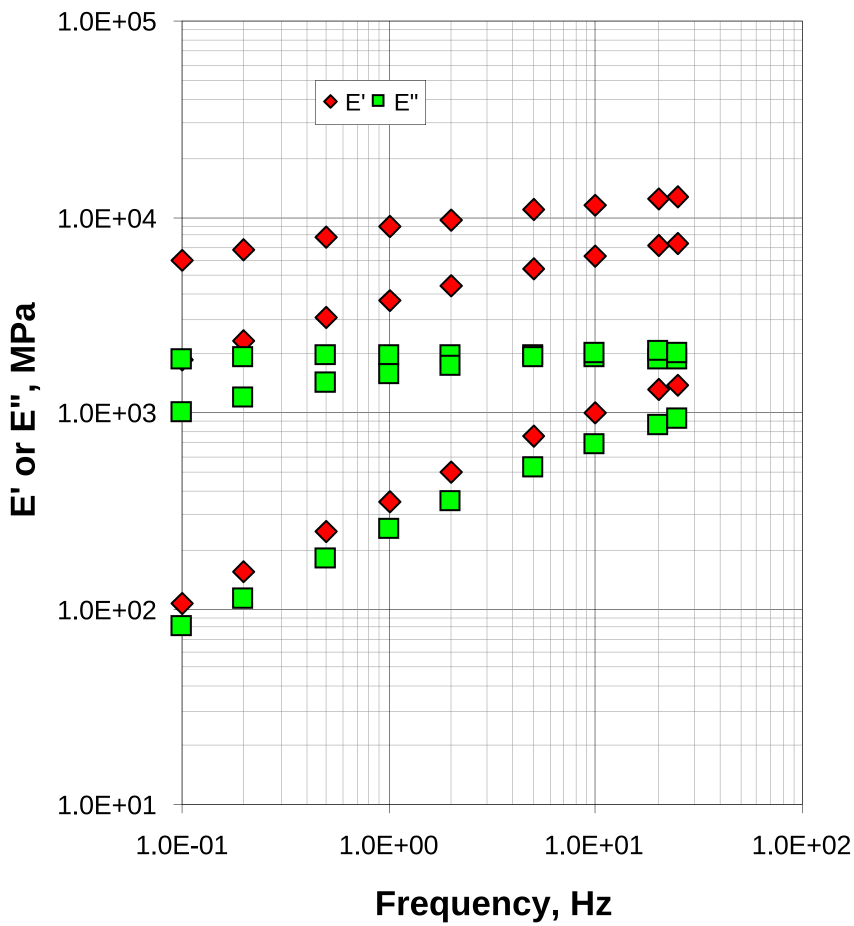
$$Pc=\frac{\left(20+\frac{VFA\times 3G^*_b}{VMA}\right)^{0.58}}{650+\left(\frac{VFA\times 3G^*_b}{VMA}\right)^{0.58}}$$

Issues and problems

- Various items in current scheme are problematic
  - Binder is used to dictate shift parameters
  - Symmetric sigmoid
- We would like to use better shifting techniques
  - Consequence – need more data points in isotherms to get better shifting
  - Modification to shift factor relationship

Data quality

- More recent testing on master curves for mixes enables more data points to be collected and with better data quality further assessment of models can be considered
- Number of test points/isotherm in present MEPDG scheme is limited resulting in numerical problems in some shifting schemes
- Need in many cases to assume model as part of shift development



Objective of better models

- Leads to better calculations
  - Spectra calculations and interconversions
  - Better definition of low stiffness and high stiffness properties are critical if considering pavement performance
  - Work looking at obtaining binder properties from mix data
  - Phase angle interrelationships
  - Considerable evidence that we should be using a non-symmetrical sigmoid function

Sigmoid

- Standard logistic

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

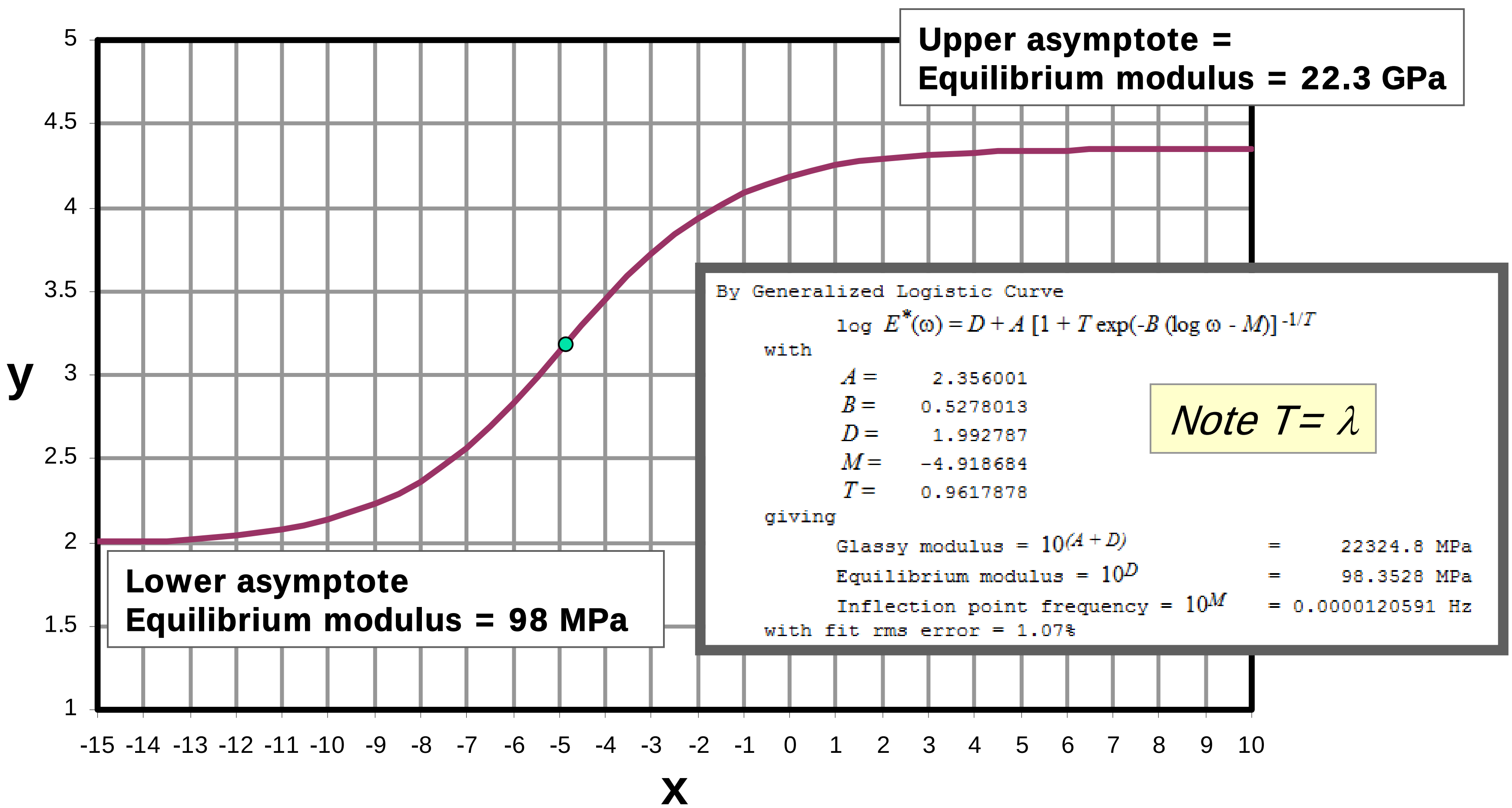
- Generalized logistic

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

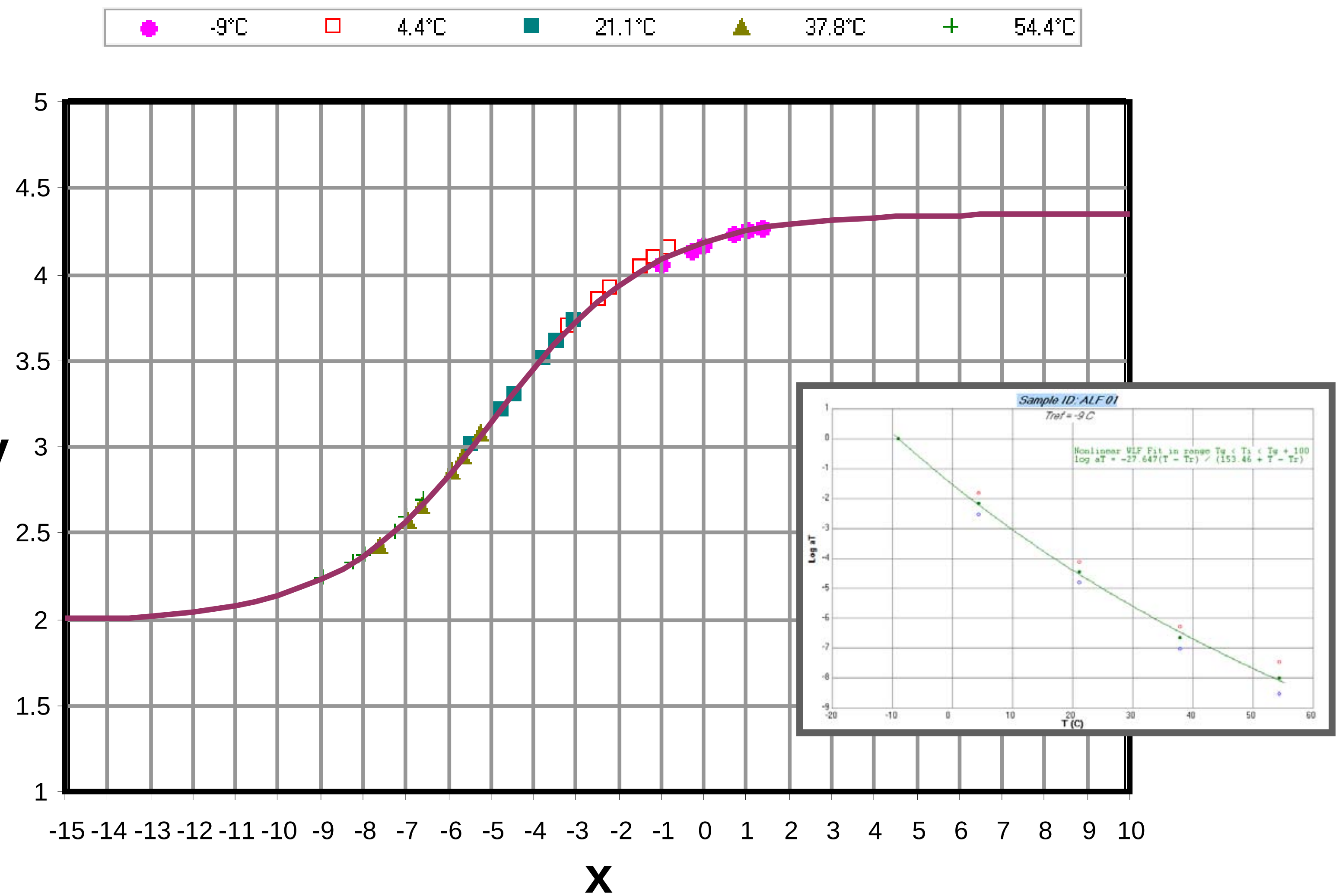
Why generalized logistic

- Allows non-symmetric sigmoid format consistent with asphalt material behavior
- Binder CA equation also based on non-symmetric behavior

Generalized logistic example



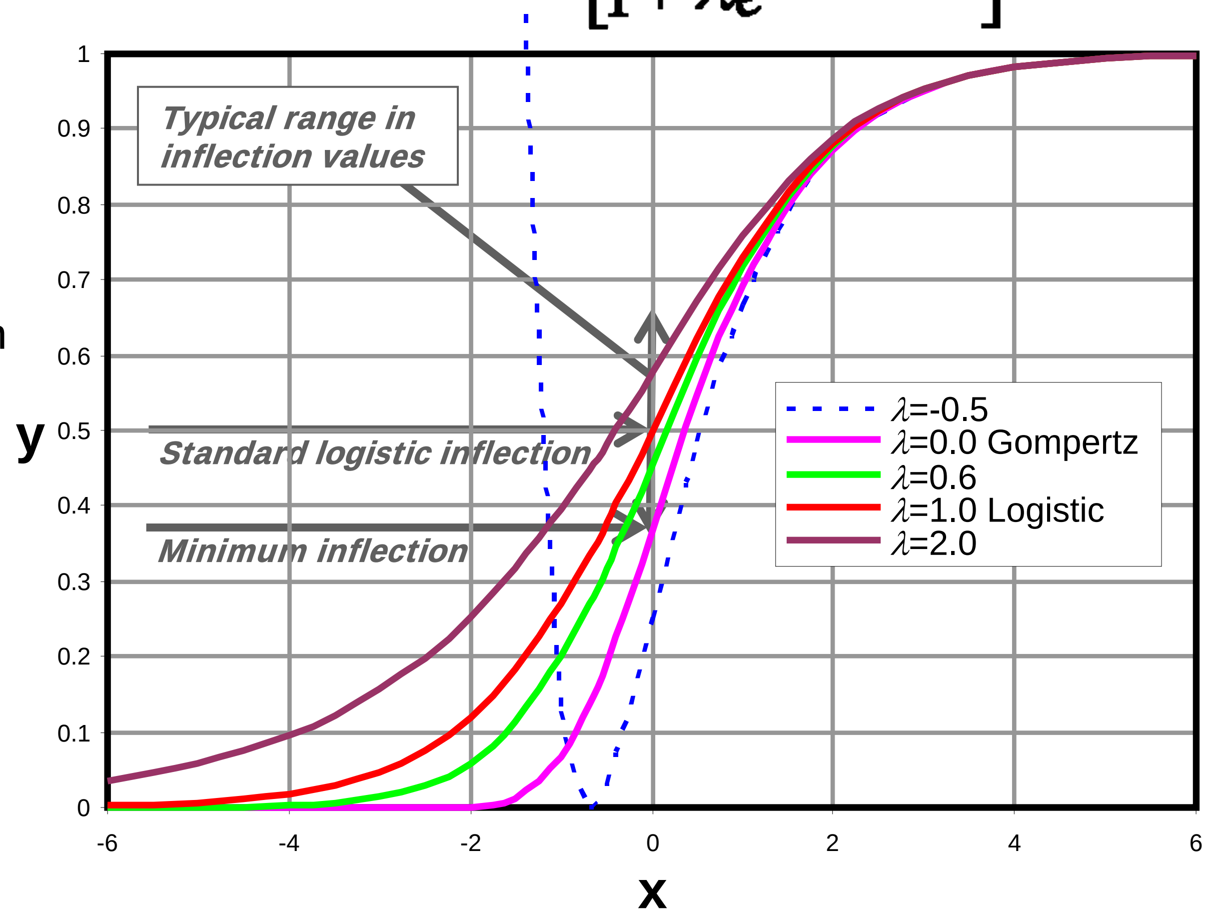
Generalized logistic example



Generalized logistic

- Generalized logistic curve (Richard's) allows use of non-symmetrical slopes
- Introduction of additional parameter λ
  - When λ = 1 equation becomes standard logistic
  - When λ tends to 0 – then equation becomes Gompertz
  - λ must be positive for analysis of mixtures since negative values will not have asymptote and produces unsatisfactory inflection in curve
  - Minimum value of inflection occurs at 1/e – or 36.8% of relative height

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



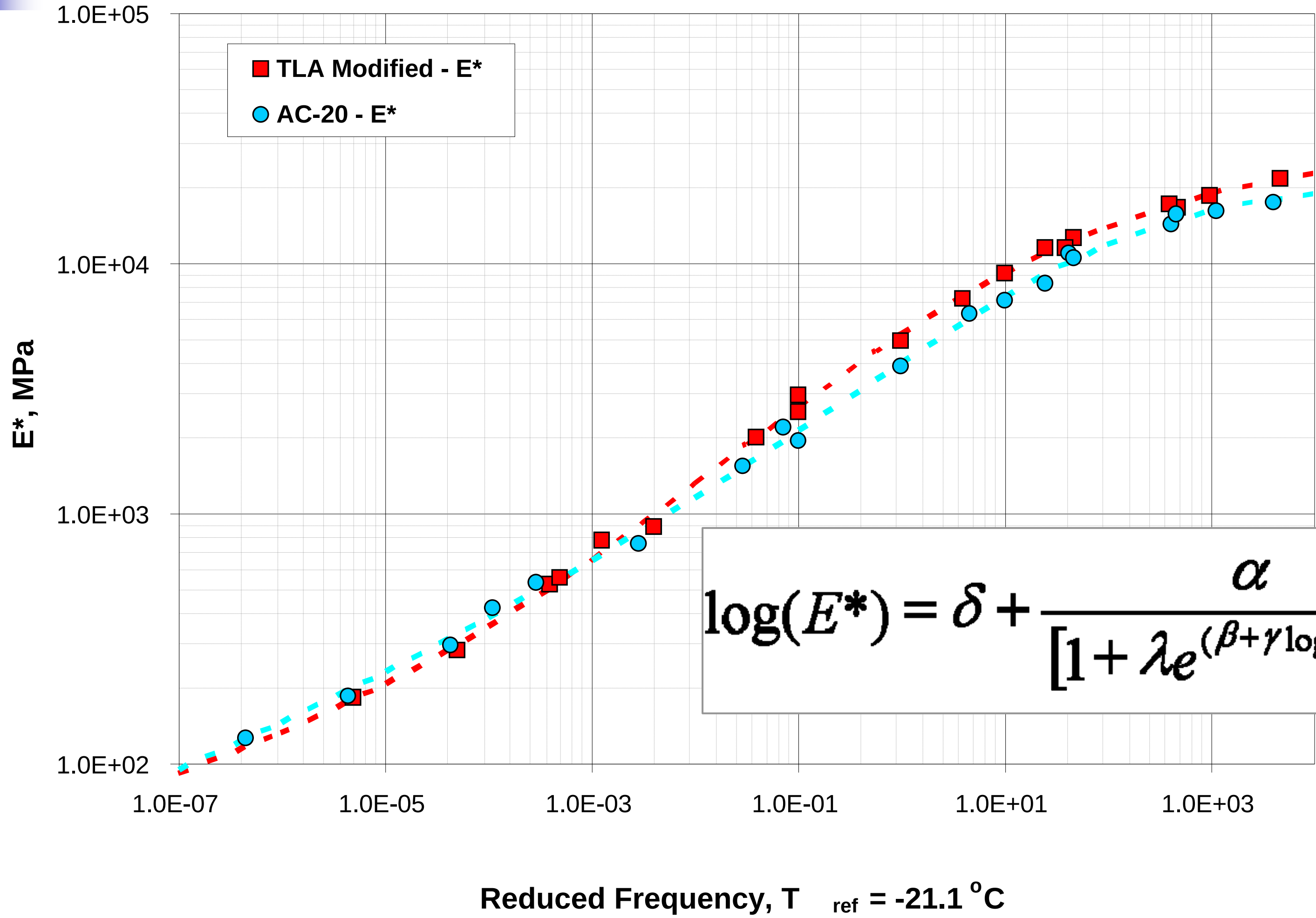
Kaelble shift factors

Kaelble shift factors

- Working with materials from MEPDG E* database – observed that shifting works best with Kaelble modification to WLF equation (*Arrhenius and WLF – do not work*)

$$\log a_T = -\frac{C_1(T - T_g)}{C_2 + |T - T_g|}$$

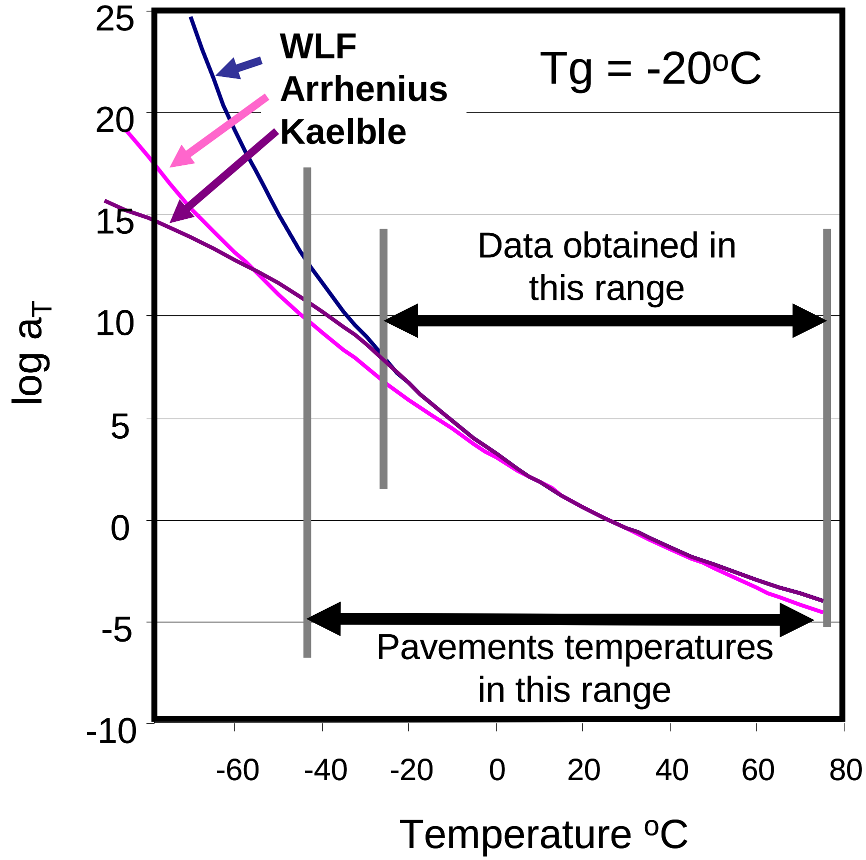
Data from MEPDG database



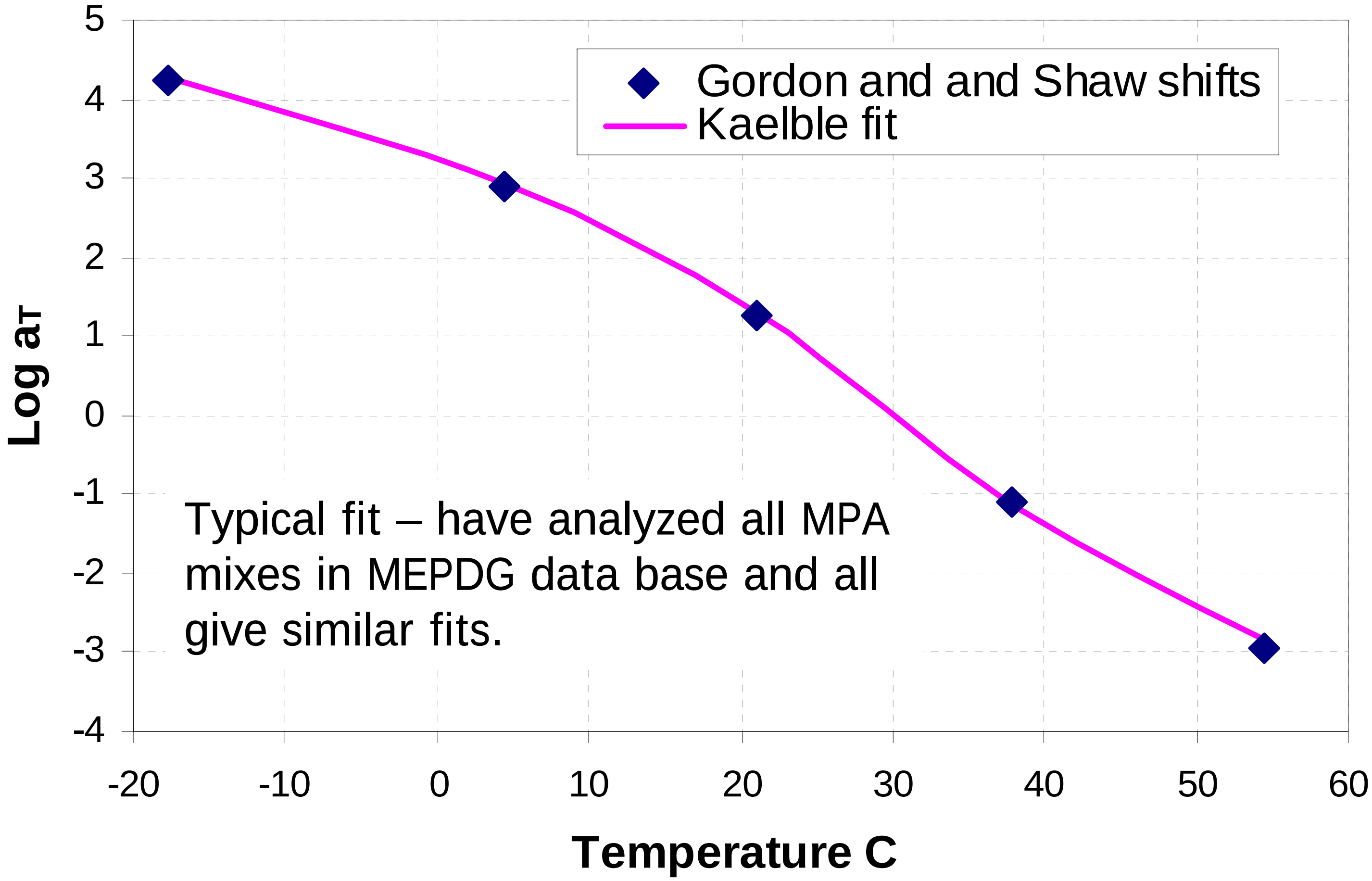
$$\log(E^*) = \delta + \frac{\alpha}{\left[1+\lambda e^{(\beta+\gamma\log\omega)}\right]^{1/\lambda}}$$

Kaelble shift factors

- WLF, Arrhenius, polynomial fits to shift factors are unstable as data is extrapolated to extreme conditions
- Kaelble provides a sigmoid shift factor relationship



Kaelble shift factors

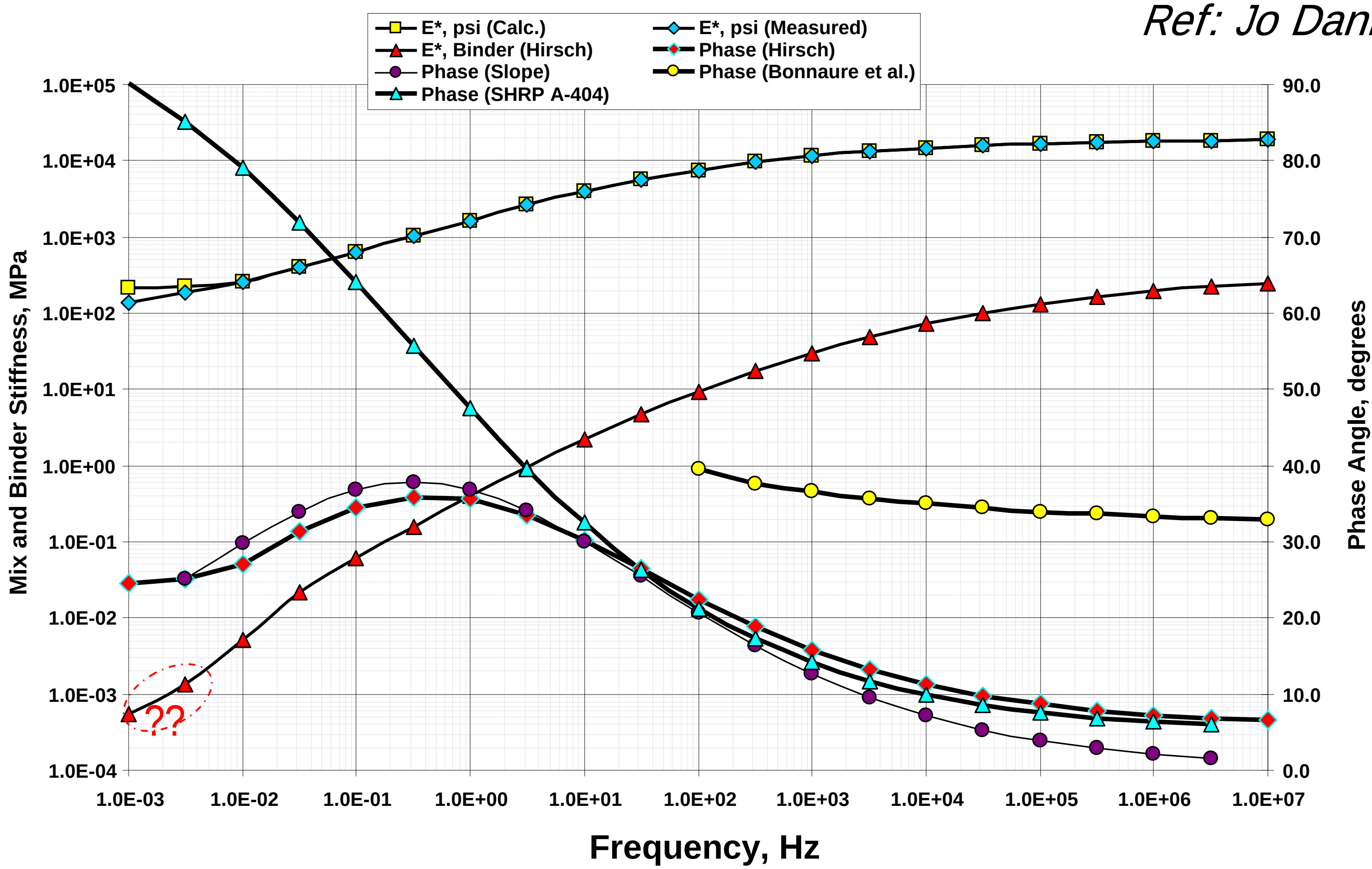


Needs

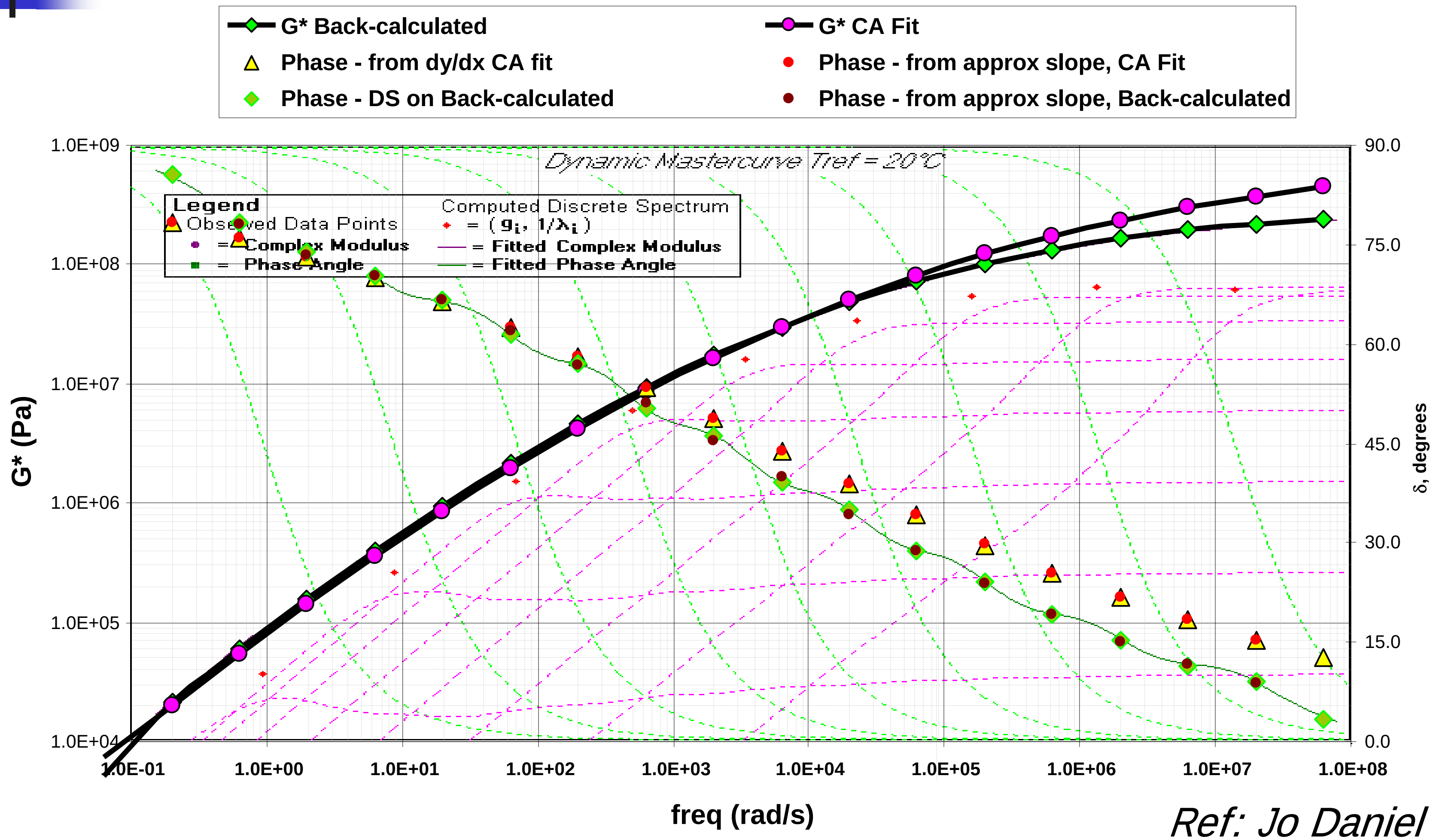
- Phase angle important in some MEPDG work – used to derive viscosity – can obtain from back-calculation of G_b* from mix data and then use log-log slope or *dy/dx* of CA model to obtain phase
- Can use method to assess data quality – often measurement of phase is poor
- Reduces need to always measure phase – can be easily deduced
- Can go back to old historical data and obtain phase information

Example RAP – mix to binder

Ref: Jo Daniel

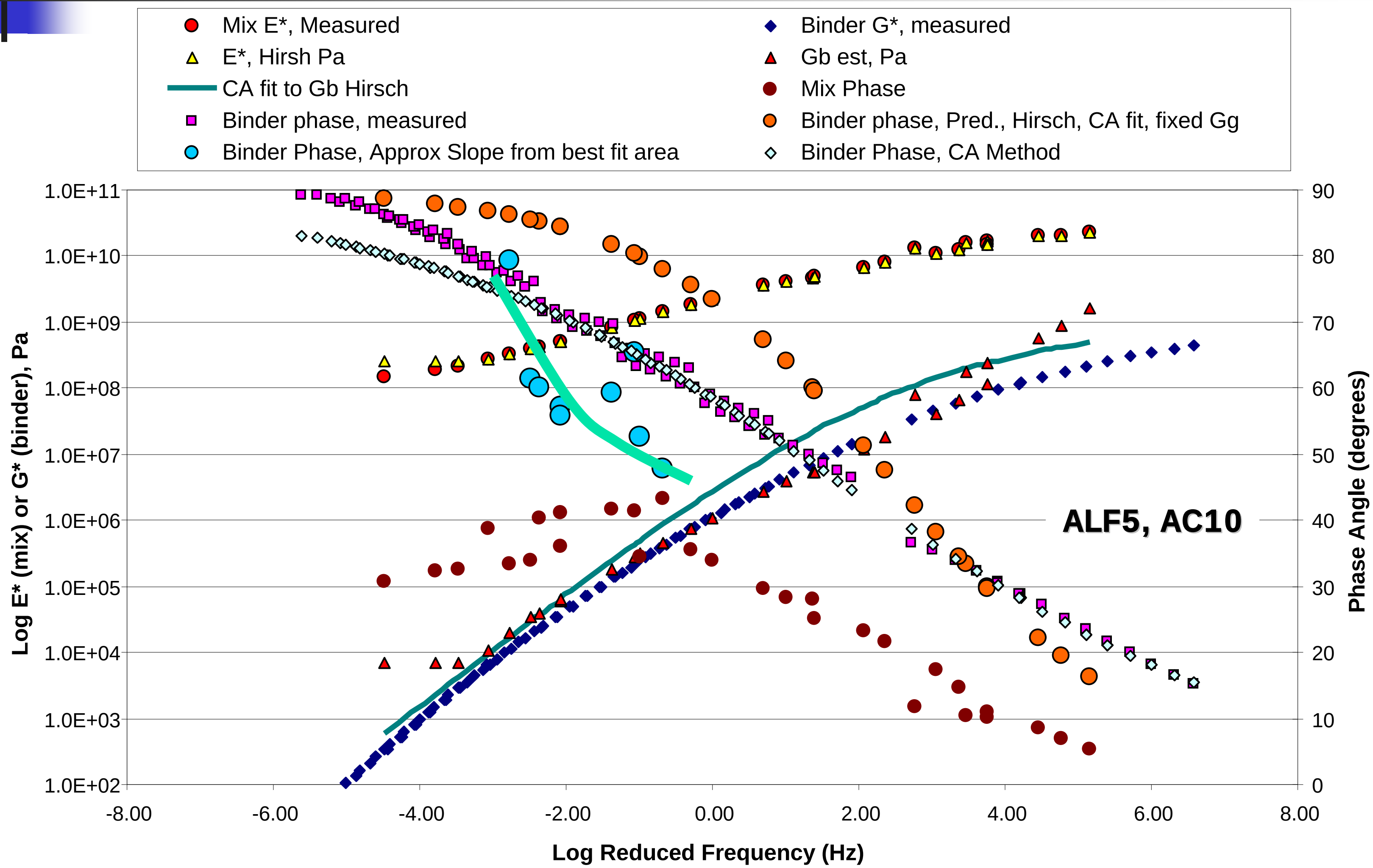


Example RAP – binder G* & δ



Ref: Jo Daniel

Problems with older data



Summary

- E* vs. ω mixture data provides significantly more information than currently assumed
  - Mixture phase angle
  - Binder G* and δ
  - Temperature shift factors
  - Can determine for individual isotherms if needed
- Recommendations
  - Increase test frequencies - does not significantly increase preparation/testing time
  - Use free shifting and generalized logistic sigmoid
  - Investigate relationships further, Hirsch, CA models etc.