Phase Angle Determination and Interrelationships within Bituminous Materials

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Phase angle

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

G or E**

Objectives

- To examine the development of phase angle relationships from stiffness data

Use

- Phase angle is difficult to measure
- Data exists which contains no phase angle information

History

- Various phase angle relationships exist for binder and mix materials

Binder

- Several methods exist
- Dobson (BP 1972)
- Dickerson and Witt
  - Developed relationship between G*, frequency and phase angle
  - Based on a log-log equation from analysis of "electric network"
- Christensen-Anderson
  - Proposed equation that relates phase to crossover frequency and rheological index

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

Mixes

- Bonnaure et al. (AAPT 1977)
  - Phase linked to binder stiffness and Vb
  - Limited for S_b > 5MPa

$$\phi_m = 16.36 \times V_b^{0.352} \exp\left[\frac{\log_{10} S_b - \log_{10} 5\times10^6}{\log_{10} S_b - \log_{10} 2\times10^9} \times 0.974 V_b^{-0.172}\right]$$

- SHRP A-404 report
  - Various models
  - Other similar relationships

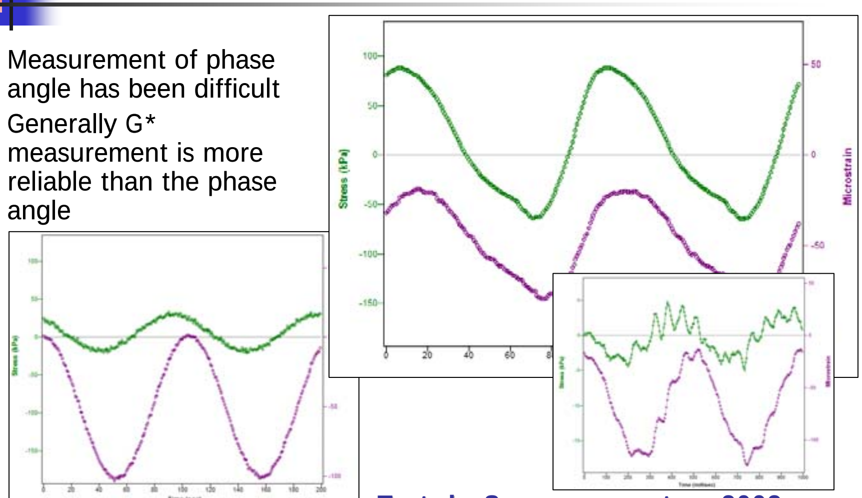
$$\phi_o = 260.096 - 17.172 \,\mathrm{Ln}(S_o)$$

- Hirsch (AAPT 2003)
  - Christensen, Pellinen and Bonaquist
  - Empirical relationship related to Hirsch parameters

$$\begin{cases} \phi_m = -21(\log Pc)^2 - 55\log Pc \\ Pc = \dfrac{\left(20 + \dfrac{VFA \times 3G_b^*}{VMA}\right)^{0.58}}{650 + \left(\dfrac{VFA \times 3G_b^*}{VMA}\right)^{0.58}} \end{cases}$$

Measurement of phase angle

- Measurement of phase angle has been difficult
- Generally G* measurement is more reliable than the phase angle



Tests by Superpave center - 2003

Starting point

- Poor historical data measurement
- Various equations to evaluate for mix and binder

Approach

- Consider from visco-elastic view point and develop understanding from different materials
- Start with binder – then develop for other materials including mixtures

Dickerson and Witt (1974)

- Proposed that the phase angle is related to logG* vs. logω slope
- Relationship had some residual δ at high stiffness
- Residual δ could be a result of measurement artifact rather than reality

Christensen Anderson (1991-92)

- 2 AAPT papers in 1991 and 1992
- Important to recognize that instrumentation and software now 20-years more advanced!
- Used log-log suggestion from Dickerson and Witt
- No residual δ at high stiffness, δ = 0 at E_{glassy}
- δ=90 at viscous asymptote

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.

Binder – logG* vs. logω

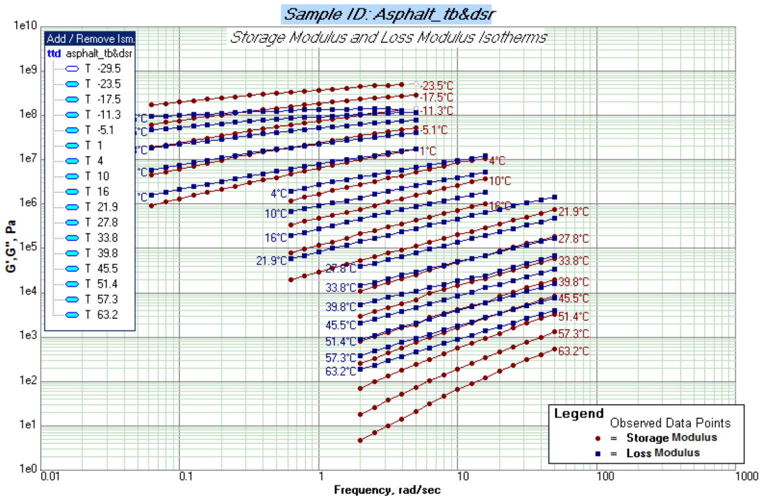
- Equation to note:

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

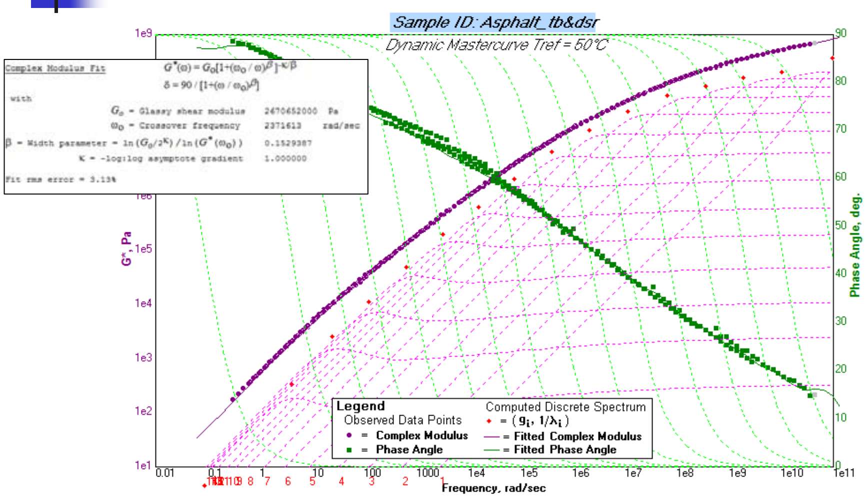
We will apply this concept to binders, mastics, mixtures, polymers etc. to evaluate how robust this technique is.

Note: Center part of relationship is CA model and will only work for binders/materials conforming to CA relationship.

Standard asphalt

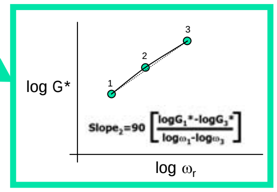


Standard asphalt



Standard asphalt

- Four methods used to obtain log-log gradient
  - 1 – slope – with polynomial – 3rd order
  - 2 – CA equation
  - 3 – DS fit
  - 4 – slope approx



G’=
```
=$AL$6*((AO11^2*$AM$6^2)/(1+(AO11^2*$AM$6^2)))+$AL$7*((AO11^2*$AM$7^2)/(1+(AO11^2*$AM$7^2)))+$AL$8*((AO11^2*$AM$8^2)/(1+(AO11^2*$AM$8^2)))+$AL$9*((AO11^2*$AM$9^2)/(
1+(AO11^2*$AM$9^2)))+$AL$10*((AO11^2*$AM$10^2)/(1+(AO11^2*$AM$10^2)))+$AL$11*((AO11^2*$AM$11^2)/(1+(AO11^2*$AM$11^2)))+$AL$12*((AO11^2*$AM$12^2)/(1+(AO11^2*$AM$12^
2)))+$AL$13*((AO11^2*$AM$13^2)/(1+(AO11^2*$AM$13^2)))+$AL$14*((AO11^2*$AM$14^2)/(1+(AO11^2*$AM$14^2)))+$AL$15*((AO11^2*$AM$15^2)/(1+(AO11^2*$AM$15^2)))+$AL$16*((
AO11^2*$AM$16^2)/(1+(AO11^2*$AM$16^2)))+$AL$17*((AO11^2*$AM$17^2)/(1+(AO11^2*$AM$17^2)))+$AL$18*((AO11^2*$AM$18^2)/(1+(AO11^2*$AM$18^2)))+$AL$19*((AO11^2*$AM$19^2)
/(1+(AO11^2*$AM$19^2)))+$AL$20*((AO11^2*$AM$20^2)/(1+(AO11^2*$AM$20^2)))+$AL$21*((AO11^2*$AM$21^2)/(1+(AO11^2*$AM$21^2)))
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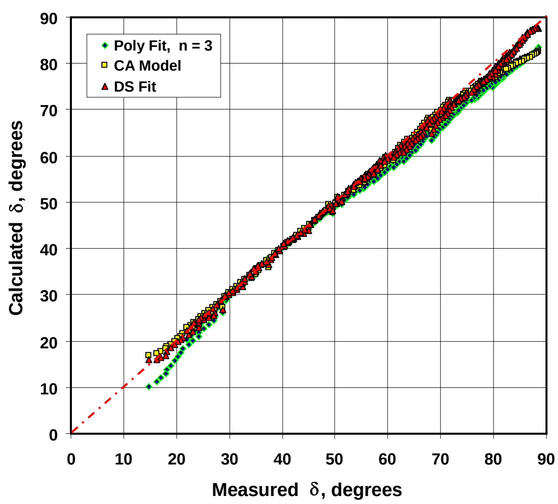
Standard asphalt

- All three methods produce a good fit of the data sets and determination of the phase lag
- r^2 >0.99 in all instances



Standard asphalt

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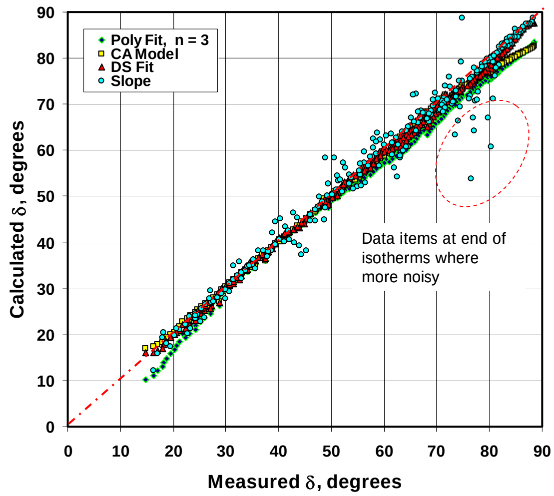
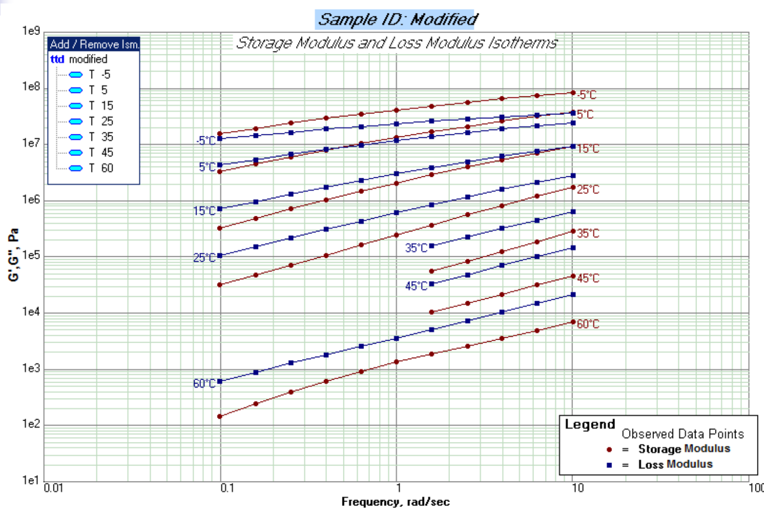
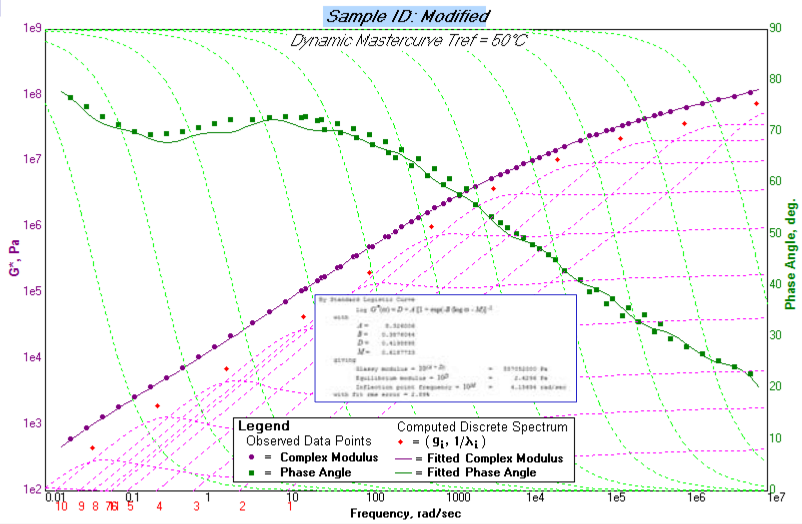


SBS modified resin

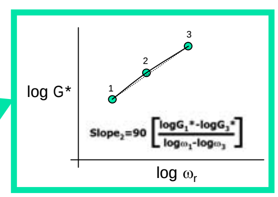


SBS modified resin



SBS modified resin

- Two methods used
  - 1 - slope – Poly=4
  - 2 - DS fit
  - 3 - Approx slope
  - 4 - Standard logistic
- CA equation would not be expected to fit

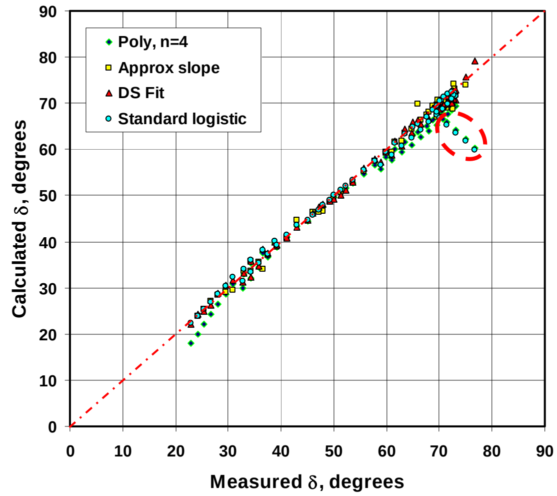


STANDARD LOGISTIC - ALTERNATE FORMAT

$$\log(E^*) = D + \frac{A}{1+e^{-B(\log\omega - M)}} \qquad \frac{d\log(E^*)}{d\log\omega} = AB + \frac{e^{-B(\omega-M)}}{\left[1+e^{-B(\log\omega-M)}\right]^2}$$

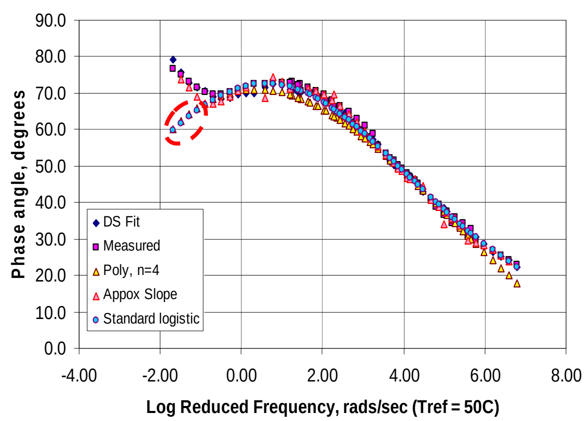
SBS modified resin

- Poly fit is poor fit at one end – maybe if increase order or use some other function would be better
- Standard logistic also has same issue
- Log-log from approximate slope gives same numbers as DS and measured

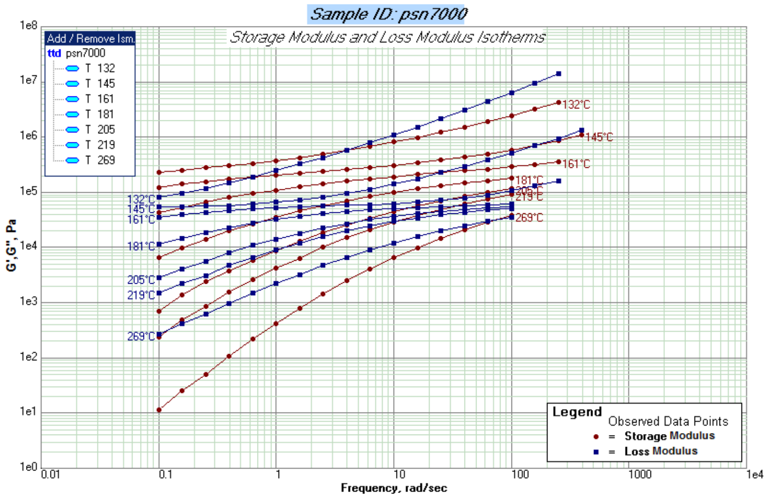


SBS modified resin

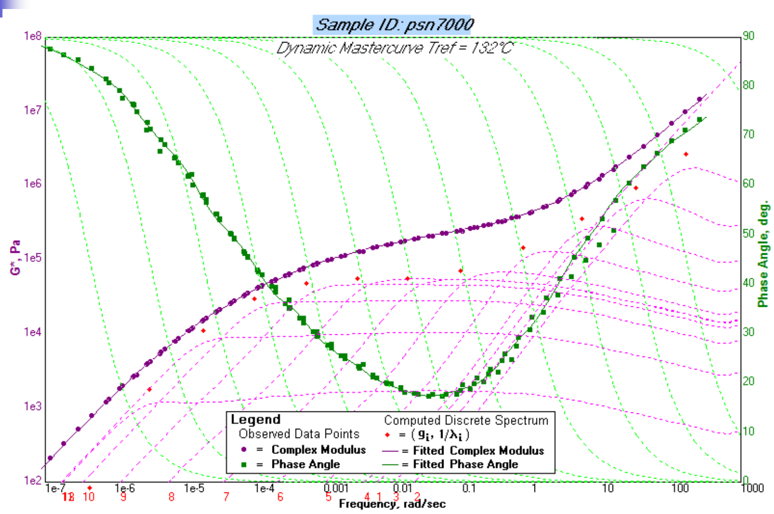
- The logistic function is not capable of predicting the turn up at low frequencies
- The polynomial fit gets this wrong
- Function form may consist of two CA models added! – more work in this area



Polystyrene



Polystyrene

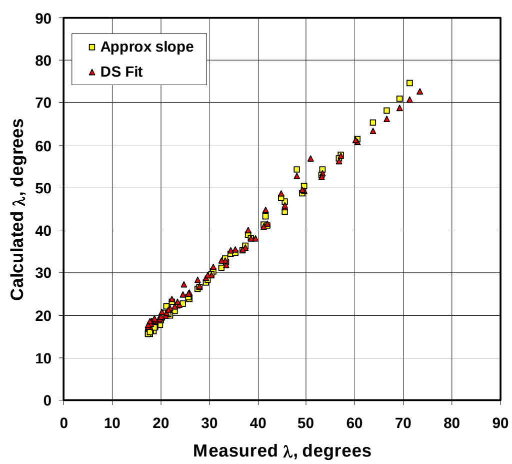


Polystyrene

- Two methods used
  - 1 - DS fit
  - 2 - Approx slope
- Equations (simple function forms) would not be expected to fit

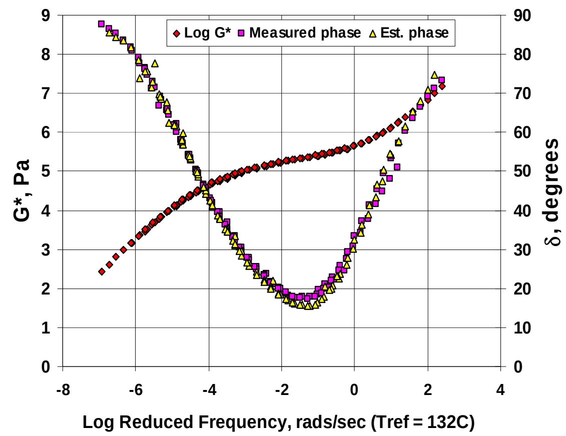
Polystyrene

- Very good fit with measured vs. calculated



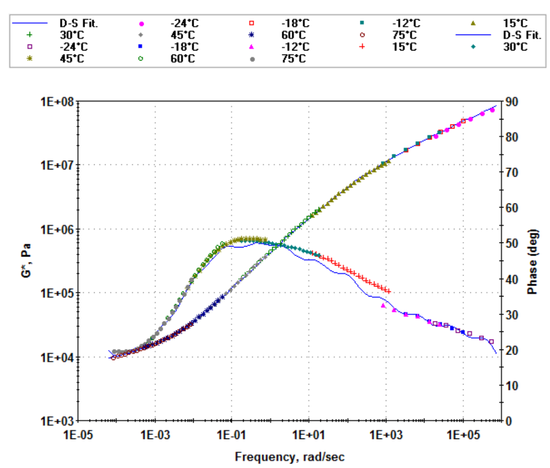
Polystyrene

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



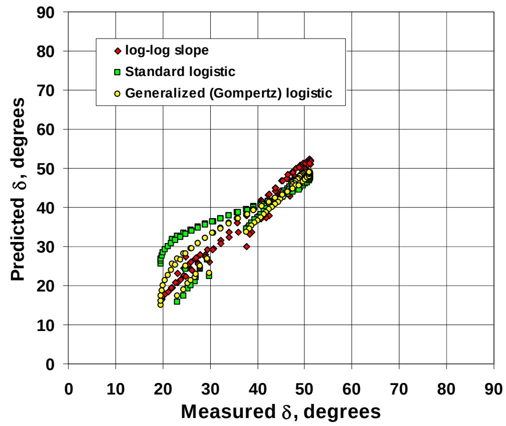
Roofing product

- Roofing material
  - 8.75 % Radial SBS Polyn
  - 61.25 % Vacuum Distille Asphalt
  - 30 % Calcium Carbonate Filler
- Master curve considered i range -24 to 75ºC – this range gives a good fit in linear visco-elastic region
- After 75ºC structure in material starts to change and material is not behavi in a thermo-rheologically simple manner



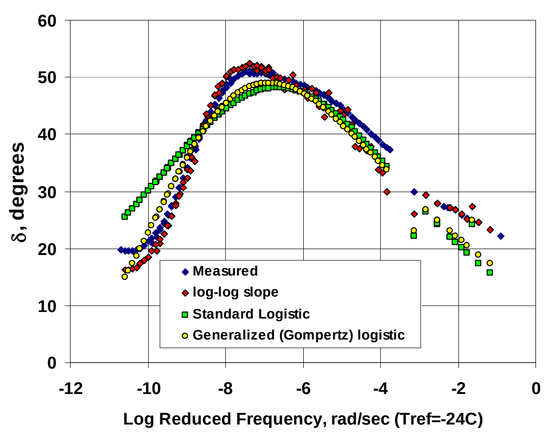
Roofing product

- Simple slope method shows validity
- Better fitting functions give better prediction



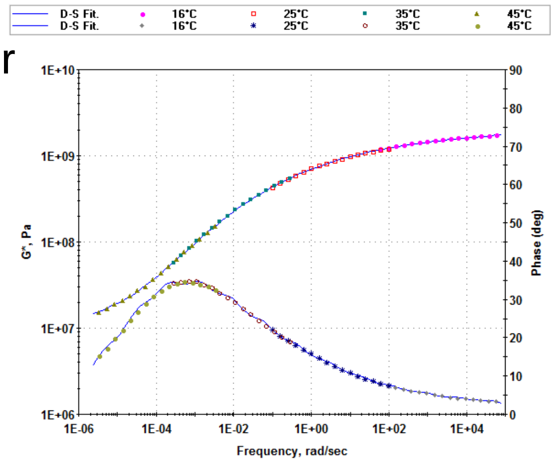
Roofing product

- Generalized logistic clearly provides a better prediction of phase response compared to standard logistic



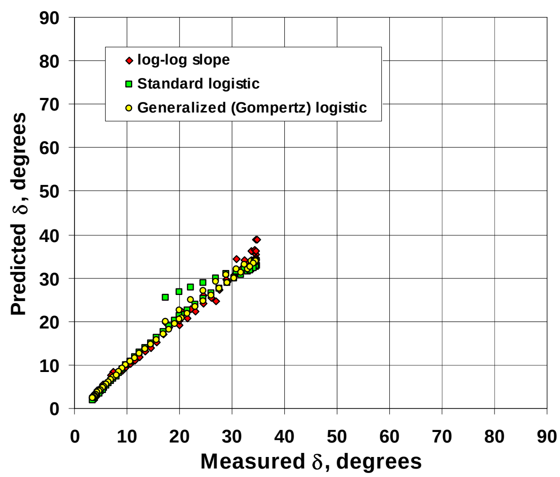
Adhesive product

- Master curve for a material used for fixing road markers



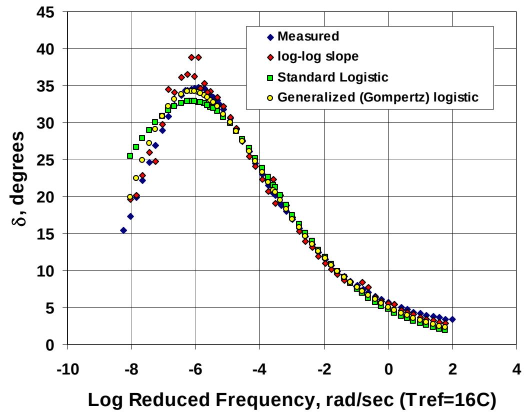
Adhesive product

- The better fit model produces a result close to that obtained from the slope approximation



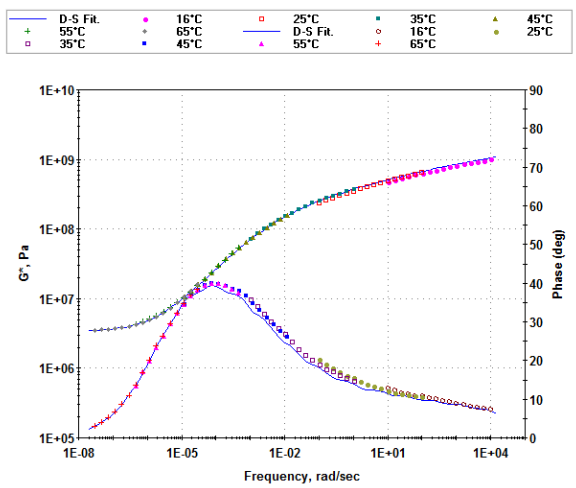
Adhesive product

- Generalized logistic – in this case the limiting Gompertz condition produces the best fit



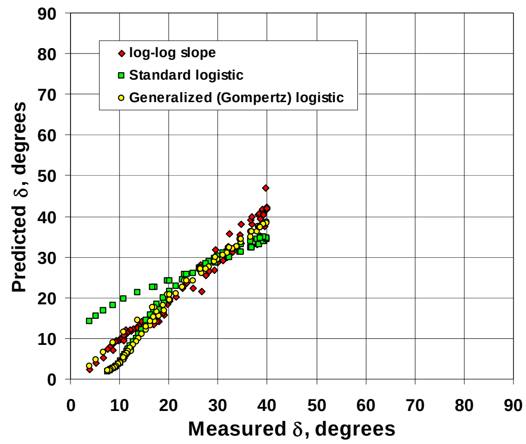
Thin surfacing on PCC

- Material mixed with aggregate and used as a thin surfacing material on concrete bridge decks



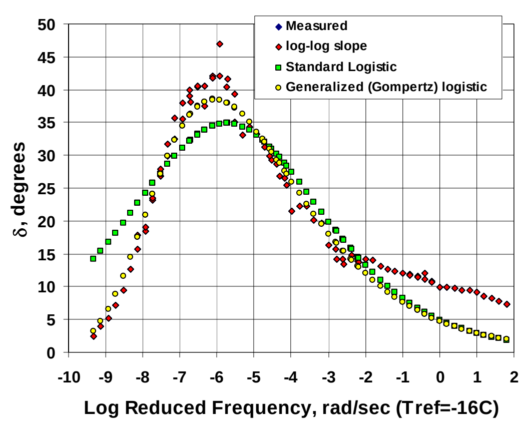
Thin surfacing on PCC

- log-log relationship produces phase angle
- Better fitting relationship produces better fit



Thin surfacing on PCC

- Standard logistic underestimates the peak phase angle response



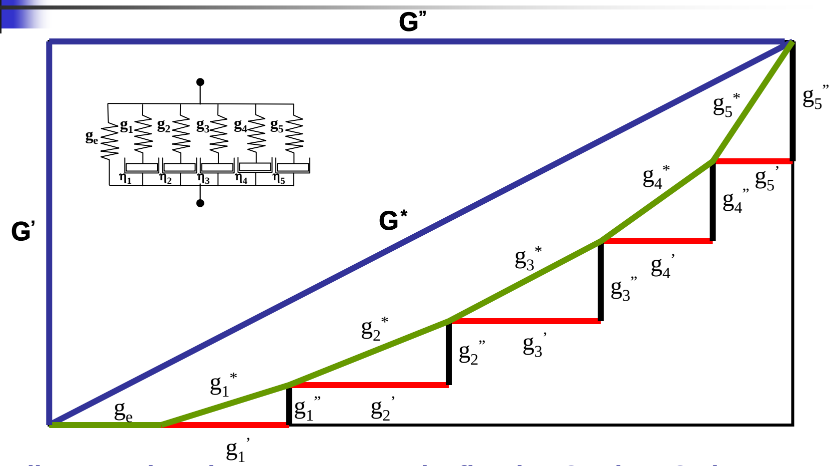
What we have

- Relationship holds well for large number of different materials investigated
  - Applies to polymers, mastics, mixtures, binders, etc, etc.
- When fits are poor, suspect
  - Poor phase angle measurement
  - Poor model format
- Very important to fit correct functional form model if you plan to use dy/dx to get slope

G* method

- If we have G* alone - or E* - we can determine phase angle via a fit of the discrete relaxation spectrum

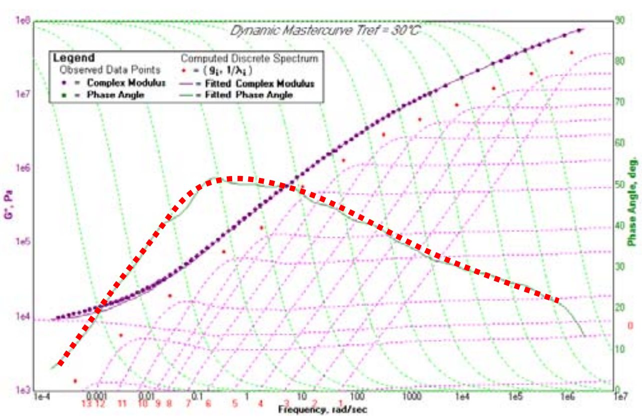
VE Solid representation



A discrete relaxation spectrum can be fitted to G* since G* is a vector sum of the G' and G" components.

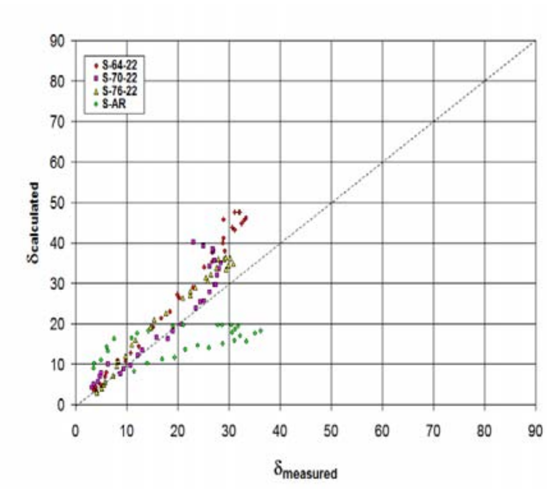
Example – G* only

- Material – Roofing product



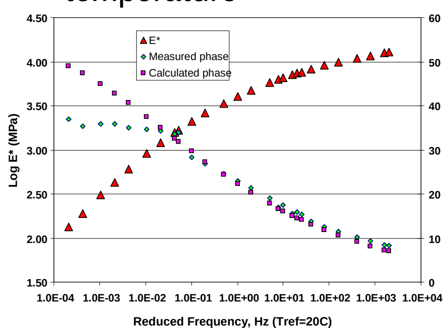
Asphalt mixtures (L1)

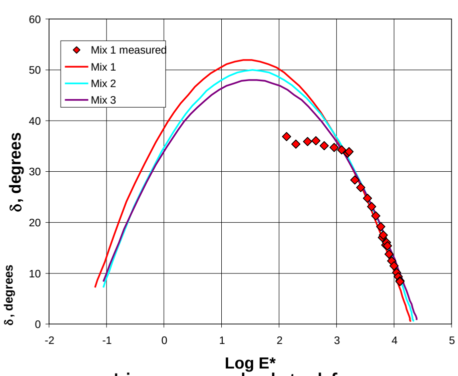
- Asphalt mixtures – CAIT NJ
- Fit is reasonable – but since MEPDG data format the slope interpolation is not so good
- Ideally would be better if more points per decade



Asphalt mixtures (L2)

- Data suggests possible problem with measured phase angle at highest temperature

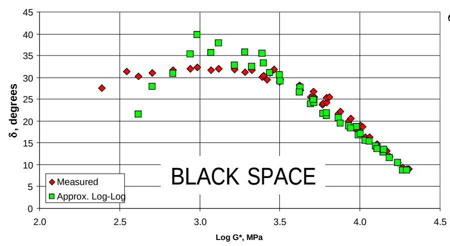


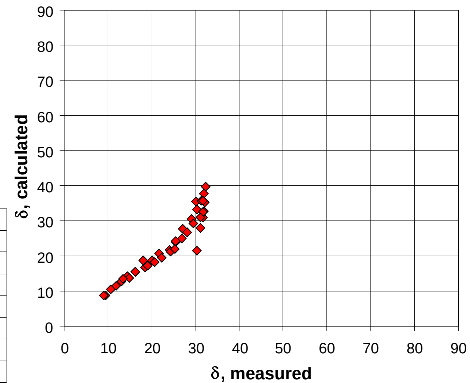


Lines are calculated from dy/dx of standard logistic sigmoid fit

Asphalt mixtures (L3)

- Highest temperature isotherm not quite in agreement with data from log-log





Asphalt mixes

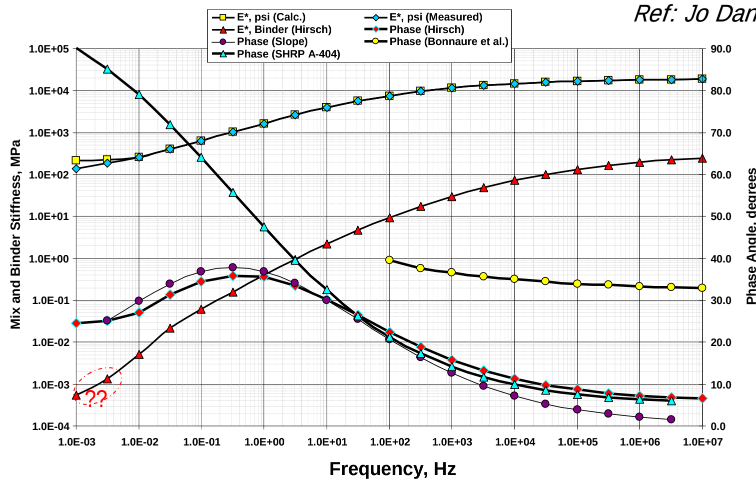
- Generally reasonable fits are obtained
- Looking at data sets – often problem at extremes – e.g. highest or lowest test temperatures and/or frequencies
- Issues still exist with equipment and testing procedures!

Needs

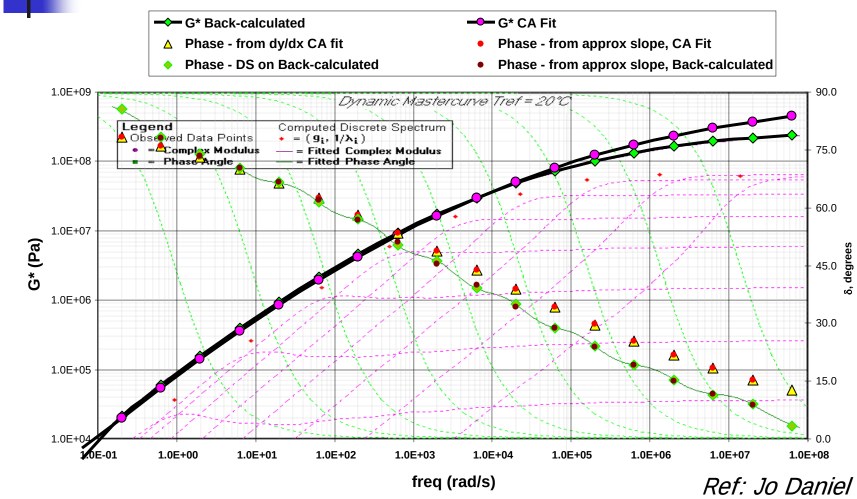
- Phase angle important in some MEPDG work – used to derive viscosity – can obtain from back-calculation of G_b* from mix data and then use log-log slope or *dy/dx* of CA model to obtain phase
- Can use method to assess data quality – often measurement of phase is poor
- Reduces need to always measure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

Summary

- 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"
- Technique can help with analysis