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The Rheological Parameter Jungle

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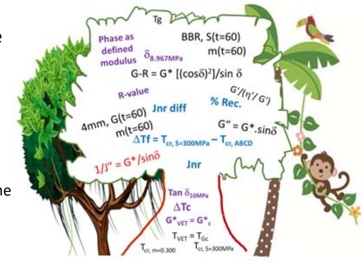
Little Rock, Arkansas

November 14th, 2023

The Asphalt Parameter Jungle

- Sometimes we don't see the wood because of the trees!
- A jungle or jumble of parameters!
- This talk will focus on the linear VE parameters
  - But we do recognize that some non-linear parameters are needed
    - Separate discussion



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Our industry choice ….

- Four physical characteristics of binders being considered that all define the shape of the master curve in the high stiffness region, these are:
  - R the R-value from the Christensen-Anderson model
  - ΔTc $T_S - T_m$ from BBR
  - Gc cross-over modulus
  - δ phase angle at a defined stiffness
- **Do we need all four – or do we adopt just one!**
- Some parameters however are not independent but are dependent on others
  - For example R is dependent on Gg and Gc
  - Other parameters can be dependent when extrapolated to or are calculated using a model fit
- Are we better using parameters that lack dependencies and we can measure?
- What about that point vs. shape parameter!! A thought on G-R concept!

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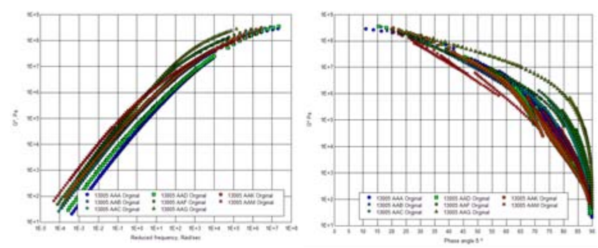
What are we trying to do with LVE measurements?



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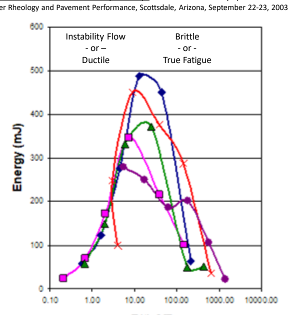
Toughness versus stiffness

Rowe, G.M. and Sharrock, M.J., "*The Direction Tension Test and the Behavior of Asphalt Binders at Low and Intermediate Temperatures,*" The 4th International symposium on Binder Rheology and Pavement Performance, Scottsdale, Arizona, September 22-23, 2003

- Toughness – the area under a stress-strain curve (in this case a DTT test) demonstrates that brittle to ductile fracture is in the stiffness range 1e6 to 1e9 Pa
  - Peak of energy around a stiffness of 10 to 50MPa
  - Note the range 1 MPa to 1000MPa as E(t) – this is in terms of a 1/3 of these values since E≈3G
- Different modified materials will show different heights/widths whereas all within a similar stiffness range



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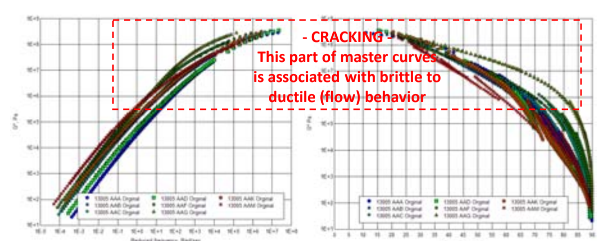

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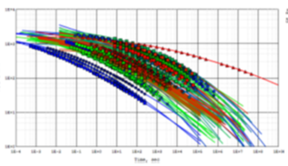
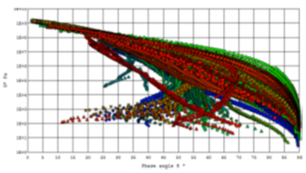
Review based upon extensive data set

- A large volume of data has been collected *over the years – and this presentation* makes use of that data set
- Data includes both modified and non-modified, RAP and recycled materials

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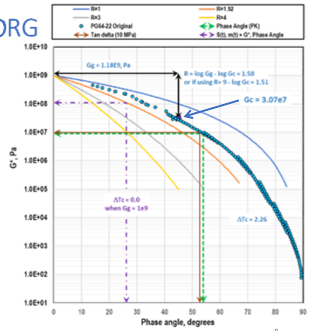
PG64-22 Shape of curve, ORG

- Shown are CA model lines with R-values from 1 to 4 - with the example shown the R around 1.51 to 1.58 depending on assumptions – considering the 4 choices!
  - Gc = 3.07e7 Pa
    - Should be expressed on log scale, 7.48
  - δ → Phase angle at 8.967 MPa = 53.96 °
    - Tan δ at 10 MPa = tan 52.65° = 1.31
  - R = 1.51 or 1.58 – depending on assumed Gg
    - 1.92 represents ΔTc = 0
    - Lower R = S controlled
    - Higher R = m controlled
  - ΔTc – For this orginal ΔTc = 2.211 (BBR+DSR) or 2.26 (BBR data)
- ALL Shape parameters define shape in high stiffness region



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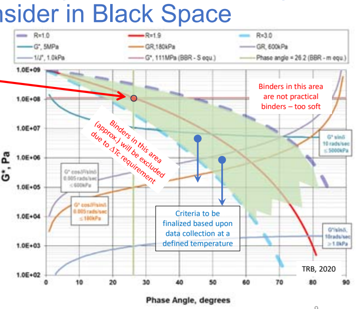
Cracking parameters and implementation, example of in South Africa – consider in Black Space

- Low temperature (PAV)
  - BBR parameters converted to G* = 111 MPa and phase angle, δ = 26.2°
  - **R** at **ΔTc = 0** is **1.92 (when Gg=1e9 Pa)**
- Durability cracking
  - ΔTc -5 limit on PAV
  - This limits R > ~3.0 (depends how R determined)
  - Excludes lower part of Black Space (higher part of Black Space – not practical binders)
- Combination of these parameters limit region in Black space that binders must fall into ***green area*** *– not considering PmB*
- Intermediate area
  - Need to be below G-R and orginal fatigue line – effectively controlled by **aging ratio – a bit more on this later!!!!!**
  - G* is typically about 7 MPa (R=2.2 when Gg=9 GPa, δ ≈ 44.5) for most practical binders at intermediate temperature when G*.sinδ = 5 MPa
  - Effectively controlled by aging limits on orginal to PAV (aging control also on orginal to PAV)
  - Note – tests at different frequencies – accounts in part for where on curve



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ΔTc

- Two methods being currently used in the industry
  - BBR and 4mm DSR (or other)
  - Data from the methods use different values of stiffness modulus and m-value
    - If we consider interconversion – then S(t) = 300 MPa would correspond to G* of approximately 111 MPa …. but we use a value … S(t) of 142 MPa
    - Differences exist in two methods – method with 4mm generally used for forensics, formulation and R&D
    - Some equipment issues with 4mm method
  - Method with BBR produces a temperature which is well defined and run in current equipment in specifications
- Does ΔTc capture the correct value
- Repeatability of measurement may be an issue that we need to consider
- ΔTc from 4mm work in BBR is different from that obtained from DSR
  - What is bias?
  - What effects of equipment type and specimen preparation?
- What about polymers and effects of these materials?


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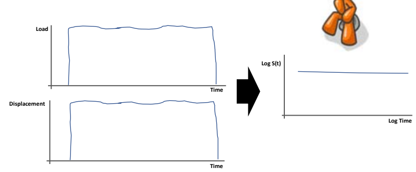
ΔTc – with high polymer contents in binder

- Think about loading a system such as this!



Material behaves as a elastic response – it is a strongly cross-linked polymer. Displacement is not time dependent as in a typical binder. When translated to S(t) versus time we have a very flat curve with m(t) close to zero. Very negative ΔTc – but note butadiene Tg ≈ -85°C

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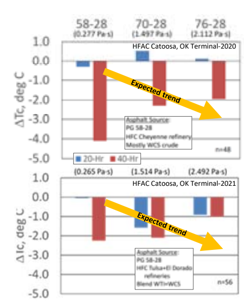
Trend confounded in some results

- Example presented at TRB 2022
  - Does aging confound the expected trend
  - What does the structure in the binder contribute to the degree of cross-linking and the expected ΔTc



Data from presentation by Robert McGennis "Gaps in the Binder Acceptance & Characterization – State and Contractors Perspective" 10 January 2022 Transportation Research Board, Annual Meeting, Washington, DC

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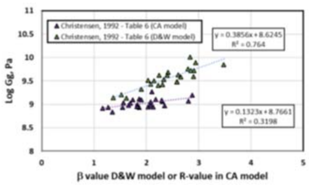
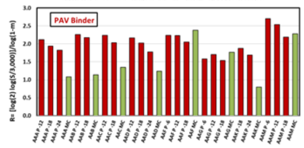
R-value

- R-value – recommended by NCHRP 9-59
  - ✓ Needs estimation of Gg
    - Gg not constant – would be a lot easier if it was!
    - DSR data – effectively defines Gc
      - We can measure Gc in a DSR … so why do we need R-value? Remember R=log Gg-log Gc
    - From BBR
      - Problem with this method is that the R-value then depends upon two extrapolations – remember that R = log Gg – log Gc, or equivalents in bending
      - If we consider R = 2, then Gc ≈ 10 MPa
        - o Lowest value measured in re-testing of SHRP core asphalts – was 44 MPa (>4x)
        - o R as computed from BBR is not a measured value but rather depends on extrapolation!





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R-value

- Adoption of different methods will give different values for the compute R value
  - ✓ Different results will be obtained if R is developed from BBR vs. DSR
  - ✓ Different values will be obtained from curve fitting depending upon assumptions made
    - Could use CA or CAM
    - Could use limiting values – 1e5 or 1e6 Pa
    - Recommendation from SHRP was to use a lower limit of 1e5 Pa
  - ✓ Value of glassy modulus is assumed as 1e9 Pa (shear), 3e9 Pa (bending)
    - Assumption is not correct – all materials are not the same!

AAPT – Anderson et al., 2011

$$R = \frac{(\log 2) * \log \frac{G^*(\omega)}{G_g}}{\log\left(1 - \frac{\delta(\omega)}{90}\right)}$$

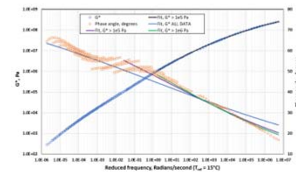
$G^*(\omega)$ = complex shear modulus at frequency ω (rad/s), Pa
G_g = glassy modulus, Pa (assumed to be 1E+09 Pa)
$\delta(\omega)$ = phase angle at frequency ω (rad/s), degrees (valid between 10 and 70°)

NCHRP 9-59, 2011

$$R = \log(2)\frac{\log(S/3{,}000)}{\log(1-m)}$$

S = BBR creep stiffness at 60 seconds (MPa), and
m = BBR m-value at 60 seconds.

Curve fitting



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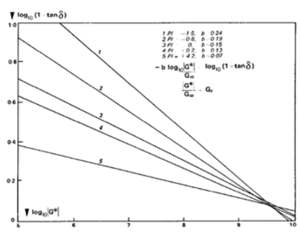
Dobson (1969) - 1+tanδ function

- Dobson used a function of 1+tanδ - to consider the variation in modulus
- This function tends to zero as the phase angle reduces
- Dobson noted a linear relationship between this function and the log of stiffness – in the high stiffness region
- Data suggested that binders with different PI values (penetration index) had differing values of Gg



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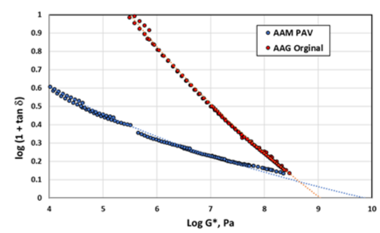
Dobson … what does this method show?

- Comparison shows two very different binders from SHRP core asphalts
- Dobson's method seems to be reasonable and consistent with other data
  - Note – this graph has not fitted any model to the data



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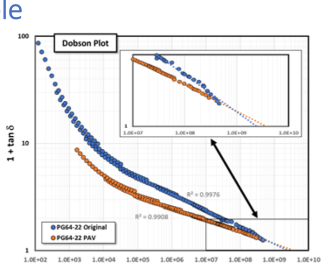
Gg and PG64-22 example

- An easy way to exam Gg variability is to construct a plot in the manner proposed by Dobson
  - When [1 + tan δ] = 1, then δ = 0 and we have an estimation of the Glassy Modulus, Gg
  - In this example we can clearly see that the DSR+BBR data is suggesting different values of Gg
    - Note – log scale!
  - No model here – just draw a straight line through the data! I have put a straight line through the data > 1e5 Pa.
- My conclusion from this – Gg is not constant as defined by current testing knowledge/methods!



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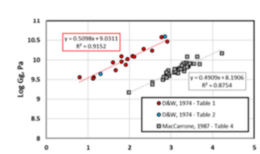
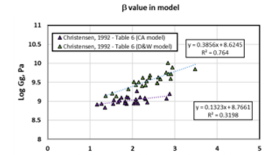
Variation of Gg in literature

- Analysis by Dickerson and Witt, MacCarrone and Christensen all showed a dependency of Gg on the shape of the master curve
- After reviewing … conclude that ..
  - No unique value of Gg exists
  - Magnitude of value depends upon model chosen – hyperbola model compared to the exponential shape of the CA model





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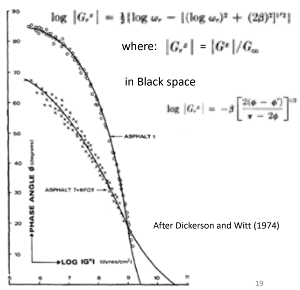
Dickerson and Witt (hyperbola model)

- Analysis considered by several authors
- Key to values obtained is shape of adopted model
  - Also different researchers made some different assumptions in analysis
  - Vertical shift applied in one case
    - Other analysis assumptions/methods not disclosed
  - Note β term in this model describes flatness of curve in similar manner to R-value



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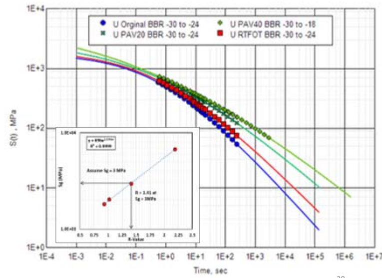
Model fit to BBR data

- Example of PmB tested in 4/2023
  - 4 aging conditions – all at a reference temperature of -24C
  - As the material ages the curves get flatter and the fit of the CA model extrapolates to higher value of Sg



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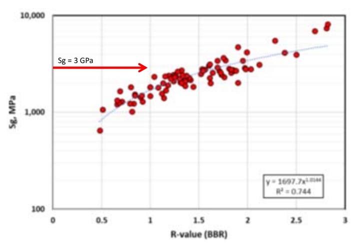
Sg calculated from BBR data set versus R

- In this case a model fit was used to estimate R and Sg
- Values are not consistent with constant 3GPa
  - As materials age generally R values increase and Sg increase



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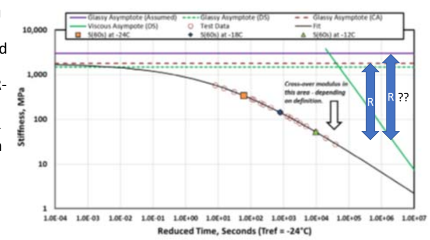
BBR example – why we get different numbers

- Depending where you are on the curve and which isotherm is used use of the equation produces a different R-value
- If a model fit is used – clearly R is different in this case depending upon the assumption used



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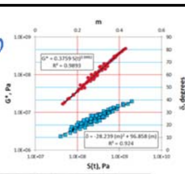
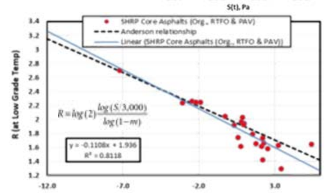
Using isotherm corresponding to grade temperature

- Best relationship with ΔTc is obtained if we use a stiffness isotherm at the S(t) grade temperature
  - But note as stiffness tends to be closer to a constant value – then the calculation of R depends more significantly on m-value
    - m-value is analogous to phase angle
    - So – if this is better – then why not just use the phase angle!

$$R = log(2)\frac{log(S/3{,}000)}{log(1-m)}$$





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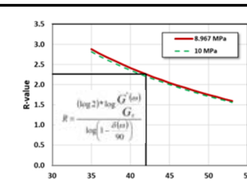
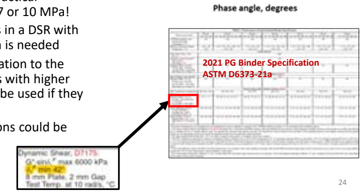
Phase angle

- δ at 8.967 MPa, effectively defines the shape of the master curve
  - ✓ If we assume a Gg of 1e9 Pa – the phase angle can be related directly to the R-value or Gc
  - ✓ The Tan δ value proposed at 10 MPa defines essentially the same point (for all practical purposes) …. can we either do 8.967 or 10 MPa!
  - ✓ We can easily measure these values in a DSR with existing methods – no extrapolation is needed
  - ✓ If we consider R-value - the modification to the fatigue requirements allows binders with higher loss modulus (5000 to 6000 kPa) to be used if they have a R-value less than 2.26!
  - ✓ Concept used in existing specifications could be extended





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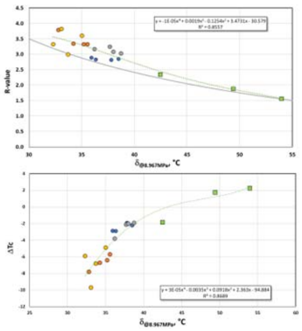
δ_{PK}

- Now adopted by ASSHTO for fatigue specification in addition to G*.sinδ
- Orginal specification effectively controls R-value
- Adoption of δ_{PK} allows binders with lower R-values to have higher stiffness
  - Consistent with orginal approach
- δ_{PK} approach is an effective control on R-value
- R-value is strongly linked to ΔTc
  - Both SHAPE parameters – one in time/frequency domain and other in temperature domain
  - **Can we specify/control δ_{PK} instead of ΔTc?**
  - **Do we need both?**



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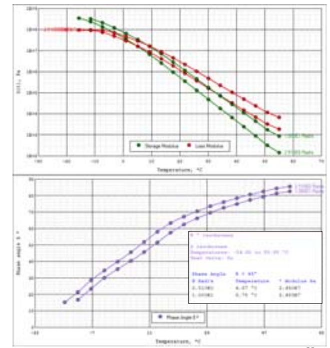
Gc or G^*_{VET}

- The cross over modulus
  - ✓ G' = G", δ = 45°
  - ✓ Defines the stiffness
  - ✓ log Gc = log Gg – R
  - ✓ If Gg assumed as 1e9 Pa – then ....
    - log Gc = 9 – R
  - ✓ If R = 2 then Gc will be about 10 MPa
    - Can be easily measured in DSR
    - If expressed as <u>log scale</u> – then repeatability similar to phase
      - *<u>Error in parameters that we consider on a log basis should be considered on a log scale!</u>*



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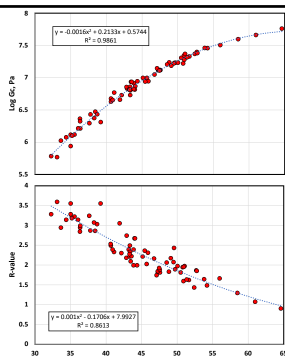
ΔTc, R, Gc or δ

- 4 parameters – we have proposals in different research and implementation to include multiple methods
  - R-value and ΔTc both proposed in different NCHRP work
  - δ implement, in part, in AASHTO M320/332 methods
    - Easy to obtain from existing methods for G*.sinδ
  - Gc and δ are best measures – but current implementation efforts around ΔTc and R-value



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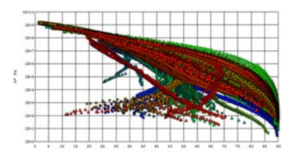
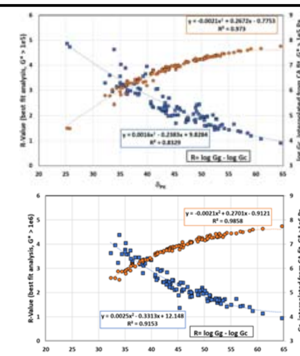
Limiting values

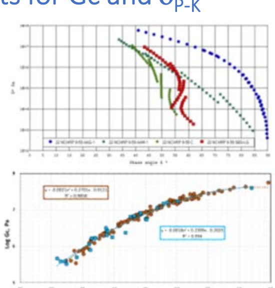
- 1e6Pa works better than 1e5Pa
  - If we use CA as a smoothing function to calculate the parameters such as Gc, R, δ_{PK}



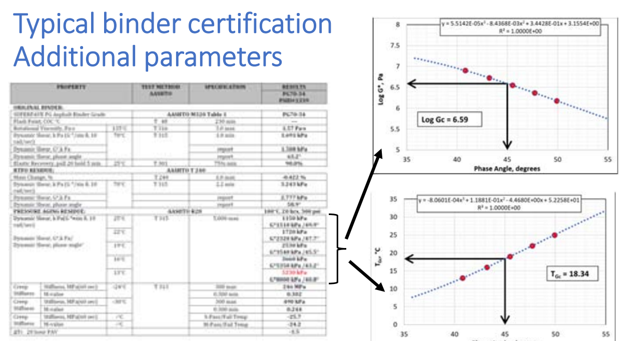


How about other data sets for Gc and δ_{P-K}

- This is an example of using the data published by NCHRP 9-59 to calculate δ_{PK} and log Gc
  - Despite some questionable data – the trends are very good
    - 4-exmples shown in Black Space
    - Full data set compared in 2nd graphic
  - This data exists in many research studies but has not been fully explored or analyzed
- Very easy to obtain Gc and δ without sophisticated analysis
  - These are the only two of the four that can be obtained by direct measurement



Typical binder certification Additional parameters



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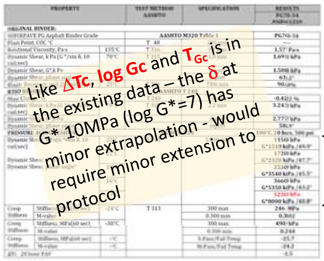
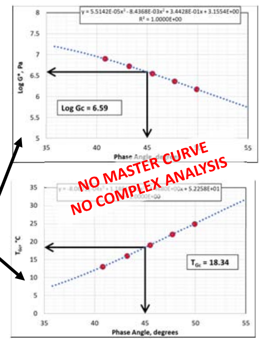
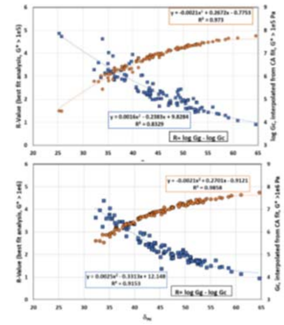




δ vs. R vs. Gc vs. ΔTc

- Our extended analysis is suggesting that δ is the best method with **log Gc** a very close second!
  - Interesting that this concept was suggested about 30+ years back by French workers!



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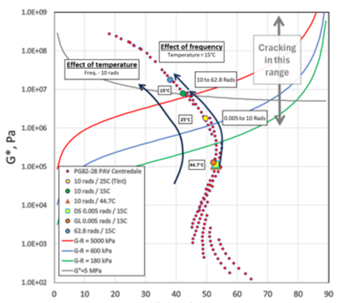
Consideration of fatigue and block cracking with point parameter

- Different point parameter analysis to consider different types of cracking
- Fatigue criteria using a higher frequency
  - May need to go to a higher frequency to better capture durability
    - 10 Hz proposed by NCHRP 9-59 workers
    - 10 rads / 15°C being used by Rowe et al. in proposed specifications
    - 0.005 rads / 15°C original from Glover
      - Or 44.7°C and 10 rads



Conclusions

- The use of δ or log Gc rather than the rheological index (R-value) and delta Tc (ΔTc) and could provide a better tool for specification development since these parameter appear to have greater accuracy/precision and are within a range that measurements can generally be conducted by rheometers
  - Both these alternate parameters can be easily measured in the same equipment used to define G*.sinδ, the existing fatigue parameter since this is within the range of the expected values
  - The same test could also be used to determine the G-R parameter at the same time
    - Recommend higher frequency to be in correct stiffness range

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Questions, Comments ?!