Binder Rheology 101 – Relaxation Spectra

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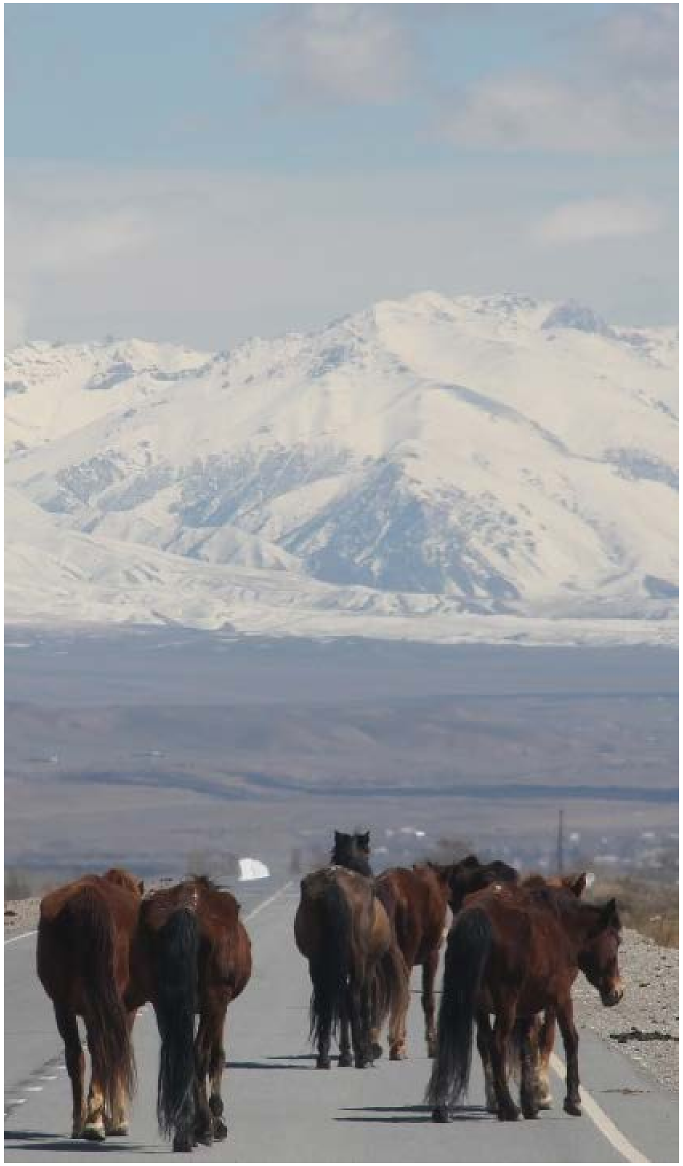
Binder ETG Meeting, April 2014

Overview

- What is relaxation spectra
- Historical perspective
- What it means
  - Other simplifications
  - Field correlations
  - Black space

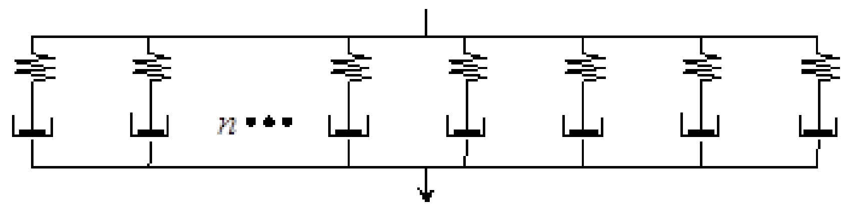


What is relaxation spectra

- Discrete
  - Model the asphalt by a series of springs and dashpots

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

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



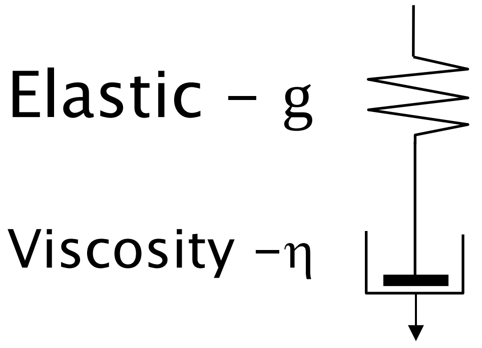
Relaxation Spectra Model

- Continuous
  - A infinite series of springs and dashpots

Objective – to define stiffness and how material relaxes stresses

Simple visco-elastic model

Maxwell Element



<u>Consider</u>
Spring constant, stiffness, g
Relaxation time, viscosity/stiffness,
$\lambda = \eta/g$

<u>STATIC LOAD</u>

$$G(t) = ge^{-t/\lambda}$$

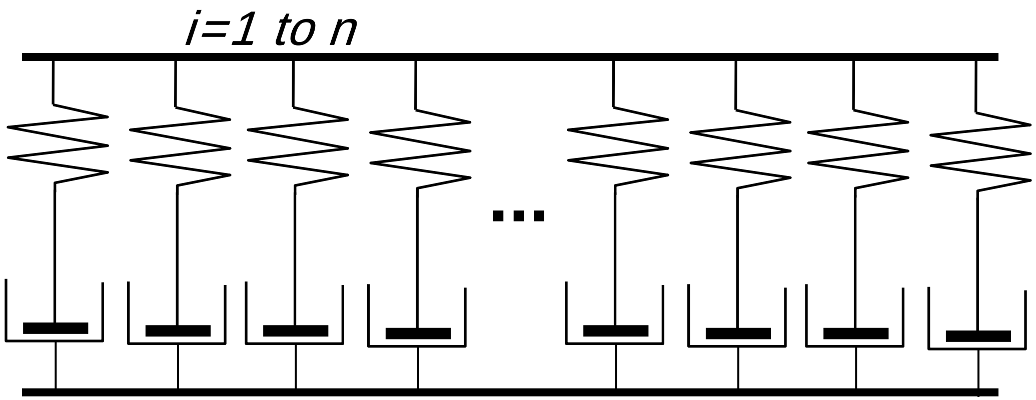
<u>DYNAMIC LOAD</u>

$$G'(\omega) = g\,\frac{\omega^2\lambda^2}{1+\omega^2\lambda^2}$$

$$G''(\omega) = g\,\frac{\omega\lambda}{1+\omega^2\lambda^2}$$

Simple visco-elastic liquid model

Generalized Maxwell Model



Consider

Spring constant, stiffness, g_i

Relaxation time, viscosity/stiffness, $\lambda_i = \eta_i / g_i$

$$G(t) = \sum_{i=1}^{n} g_i e^{-t/\lambda_i}$$

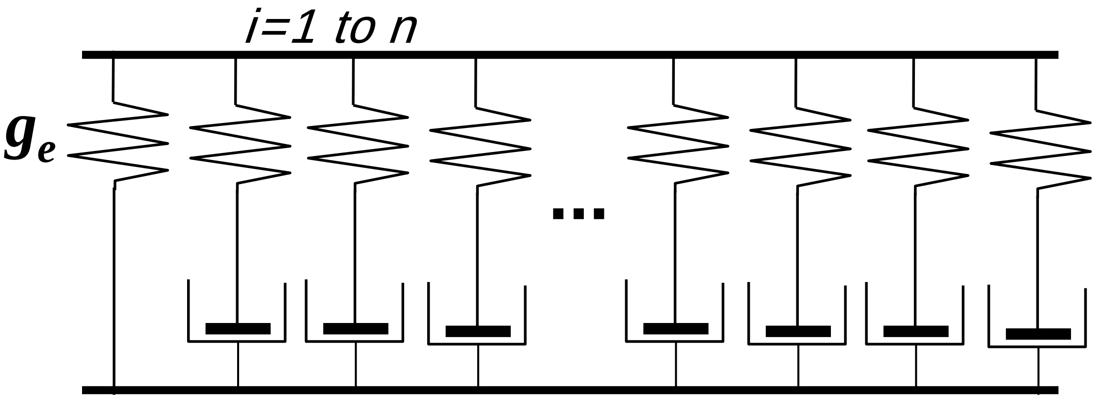
$$G'(\omega) = \sum_{i=1}^{n} g_i \frac{\omega^2 \lambda_i^{\,2}}{1+\omega^2 \lambda_i^{\,2}}$$

$$G''(\omega) = \sum_{i=1}^{n} g_i \frac{\omega \lambda_i}{1+\omega^2 \lambda_i^{\,2}}$$

EQUATIONS FOR
VISCO-ELASTIC LIQUID

Simple visco-elastic solid model

Generalized Maxwell Model



$$G(t) = g_e + \sum_{i=1}^{n} g_i e^{-t/\lambda_i}$$

$$G'(\omega) = g_e + \sum_{i=1}^{n} g_i \frac{\omega^2 \lambda_i^2}{1+\omega^2 \lambda_i^2}$$

$$G''(\omega) = \sum_{i=1}^{n} g_i \frac{\omega \lambda_i}{1+\omega^2 \lambda_i^2}$$

Consider

Spring constant, stiffness, g_i

Relaxation time, viscosity/stiffness, $\lambda_i = \eta_i / g_i$

EQUATIONS FOR VISCO-ELASTIC SOLID

From discrete to continuous spectra

- Discrete

$$G'(\omega) = G_e + \sum_{i=1}^{n} g_i(\omega\lambda_i)^2/(1+(\omega\lambda_i)^2)$$

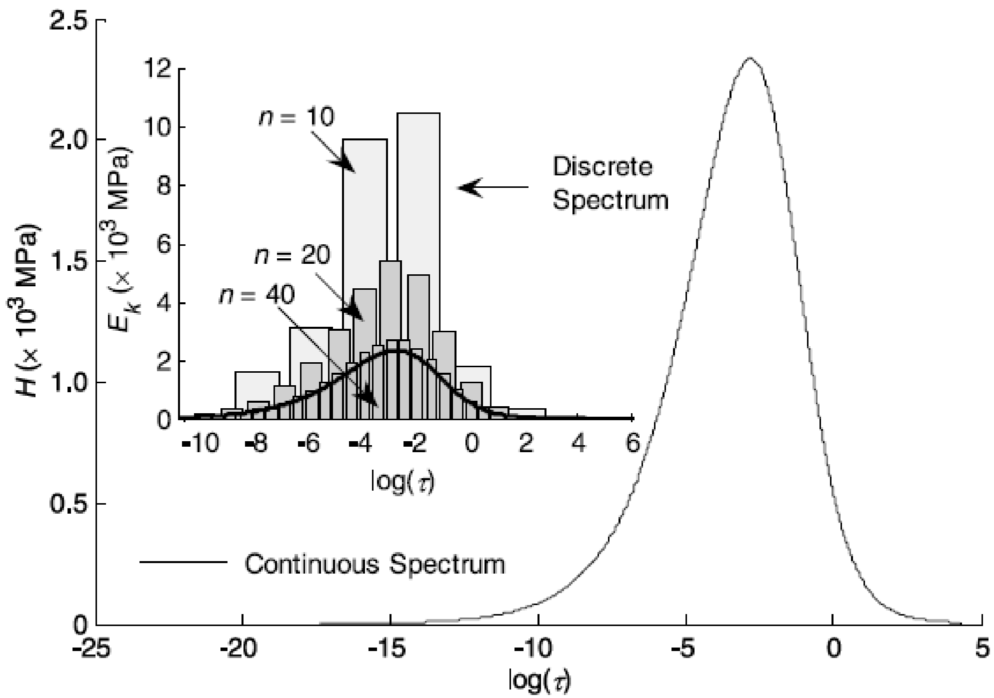
  - Keep adding … infinite Maxwell elements …. goes to

$$G'(\omega) = G_e + \int_{-\infty}^{+\infty} H(\omega\tau)^2/\left(1+(\omega\tau)^2\right) d\ln\tau$$

  - Becomes complex mathematically at this stage

Can't use discrete to define shape!

- Continuous relaxation spectrum H(τ) from the storage modulus master curve (inset) and the continuous spectrum as limiting case of the discrete spectrum with different numbers of Maxwell elements (n)
- Will need continuous to obtain a measure of the shape – or – a parameter that captures shape



Graph taken from 2011 – Continuous relaxation and retardation spectrum method for viscoelastic characterization of asphalt concrete
Sudip Bhattacharjee, Aravind Krishna Swamy, Jo S. Daniel

What now !!!???

- Let’s explore some ideas!

Historical perspective

- Many authors have defined
  - 1969 – R. Jongepier and B. Kuilman (AAPT)
  - 1972 – G.R. Dobson (IP)
  - 1974 – E.J. Dickerson and H.P. Witt (SoR)
- Use and correlations
  - 1988 – I. Ishai, B. Brule, J.C. Vaniscote and G. Ramond (AAPT)
  - 1990 – F. Moutier, G. Ramond, C. Such and J. Bonnot (SHRP Conference – London)
  - Others ….

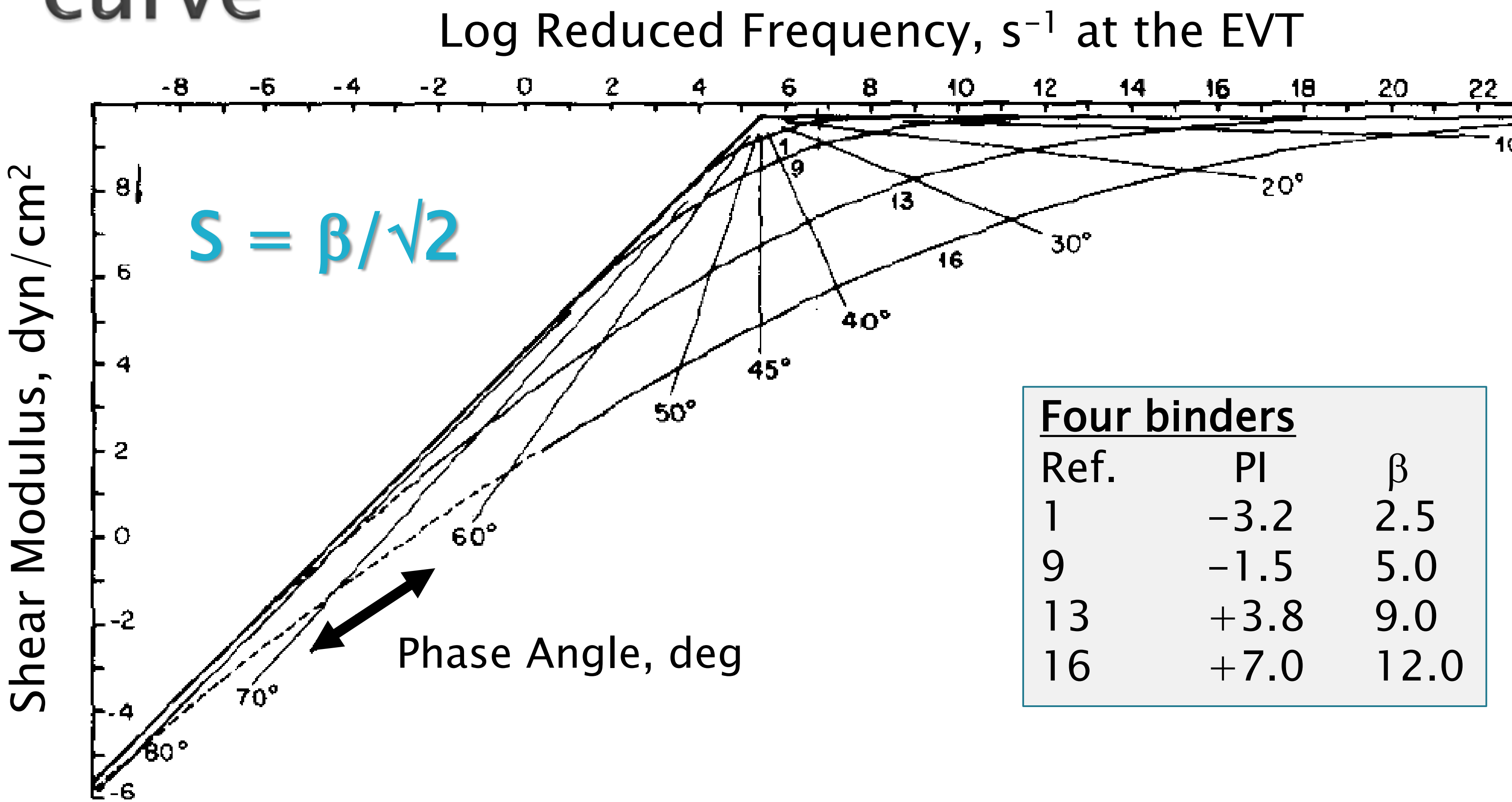
Jongepier and Kuilman

- Approach used by French workers
- Method presented in AAPT in 1969

- Method defined “S” – standard deviation of relaxation spectra

- $S = \beta/\sqrt{2}$

β Used to define shape of master curve



$S = \beta/\sqrt{2}$

Four binders

Ref.	PI	β
1	−3.2	2.5
9	−1.5	5.0
13	+3.8	9.0
16	+7.0	12.0

β is → *R. Jongepier and B. Kuilman, "Characteristics of the Rheology of Bitumens, Association of Asphalt Paving Technologists, Volume 38, 1969.*
Note – different authors use different definitions.

Dobson – 1972

- Based on empirical observations:
  - Log-log slope of complex modulus versus frequency is a function of loss tangent and relaxation spectrum
  - Explicit relationship between loss tangent and complex modulus
  - Results in a “universal mastercurve”

$$\log \omega_r = \log G_r - \frac{1}{b}\left[\log(1 - G_r^{\,b}) + \frac{20.5 - G_r^{\,-b}}{230.3}\right]$$

  - Impractical because gives frequency as function of modulus instead of modulus as function of frequency

Dickinson and Witt – 1974

- Represented mastercurve as a hyperbola

$$\log\left|G_r^*\right| = 0.5\left\{\log\omega_r - \left[(\log\omega_r)^2 + (2\beta)^2\right]^{0.5}\right\}$$

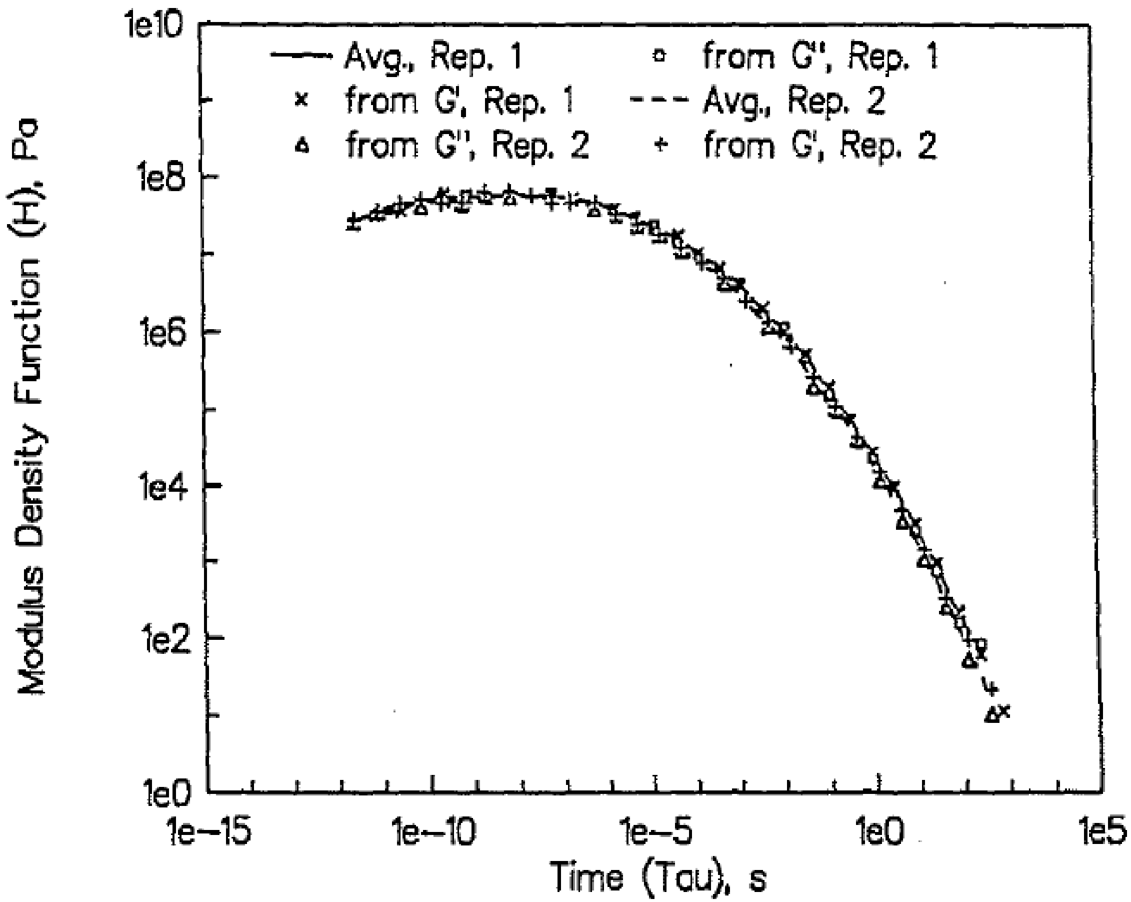
$$G_r^*(\omega) = G^*(\omega)/G_g$$

$$\omega_r = \omega\eta_o a(T)/G_g$$

- Coefficients are obtained by iteration
  - Not user friendly

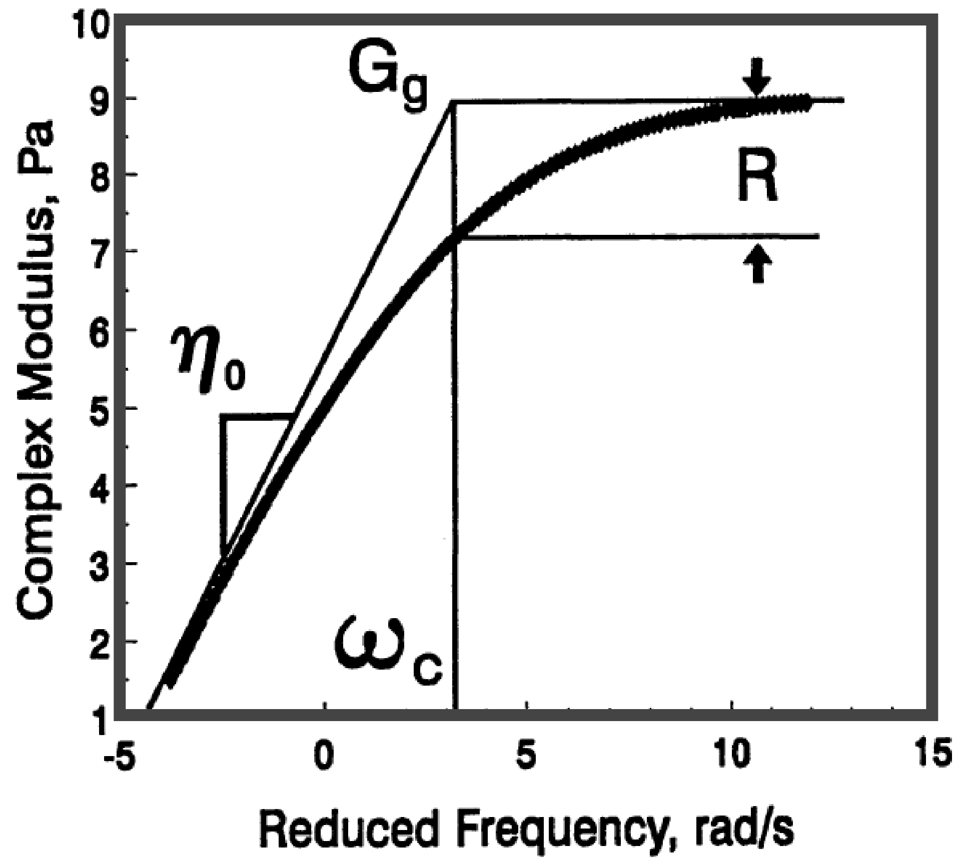
Don Christensen (1992)

- Looked at shape of relaxation spectra to influence model development
- Noted that shape of spectra was not Gaussian but best defined by a skewed logistic function
  - Led to CA model



CA model – 1993

- Relates $G^*(\omega)$ to G_g, ω_c and R
- Three parameter model to describe $G^*(\omega)$
  - Glassy modulus, G_g
  - Location parameter, ω_c
  - Shape parameter, R
- Parameters have intuitive meaning
- Model may be extended to phase angle and creep compliance



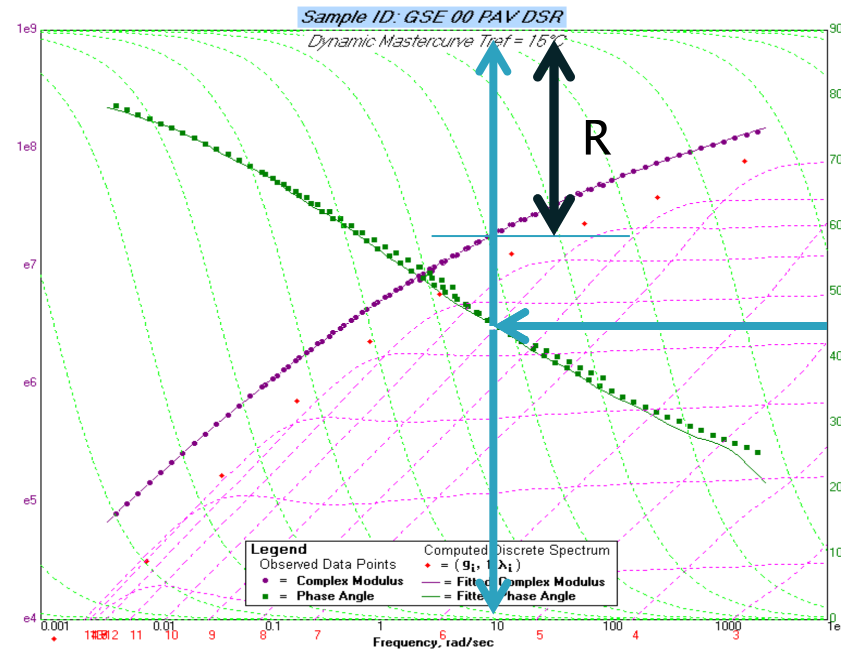
R-value

- Easy to compute from single data points

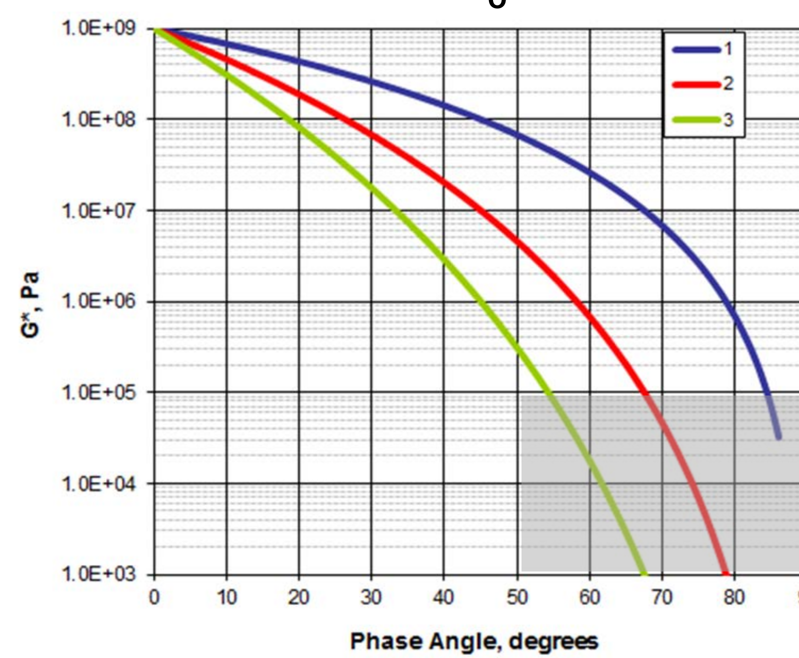
$$R = \frac{(log2) \times log\left(\frac{G*(\omega)}{G_g}\right)}{log\left(1 - \frac{\delta(\omega)}{90}\right)}$$

- Place in Black space linked to R
- All interrelated via VE- time temperature functions

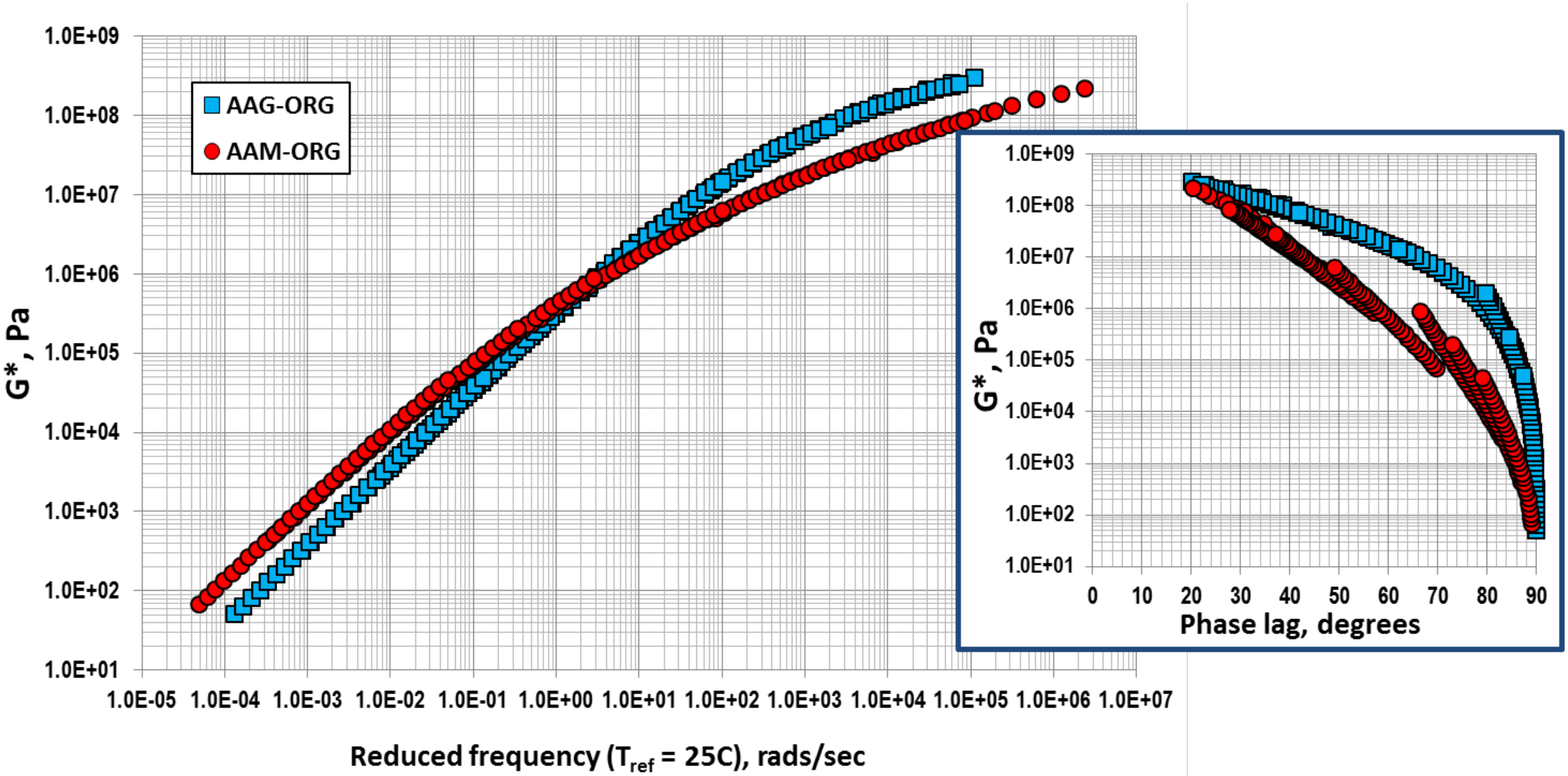
  ….. and
- Cross-over frequency, VET, G-R or other parameters such as d =45 all related to R-value
- Field performance shows cracking is related to R



ω_o

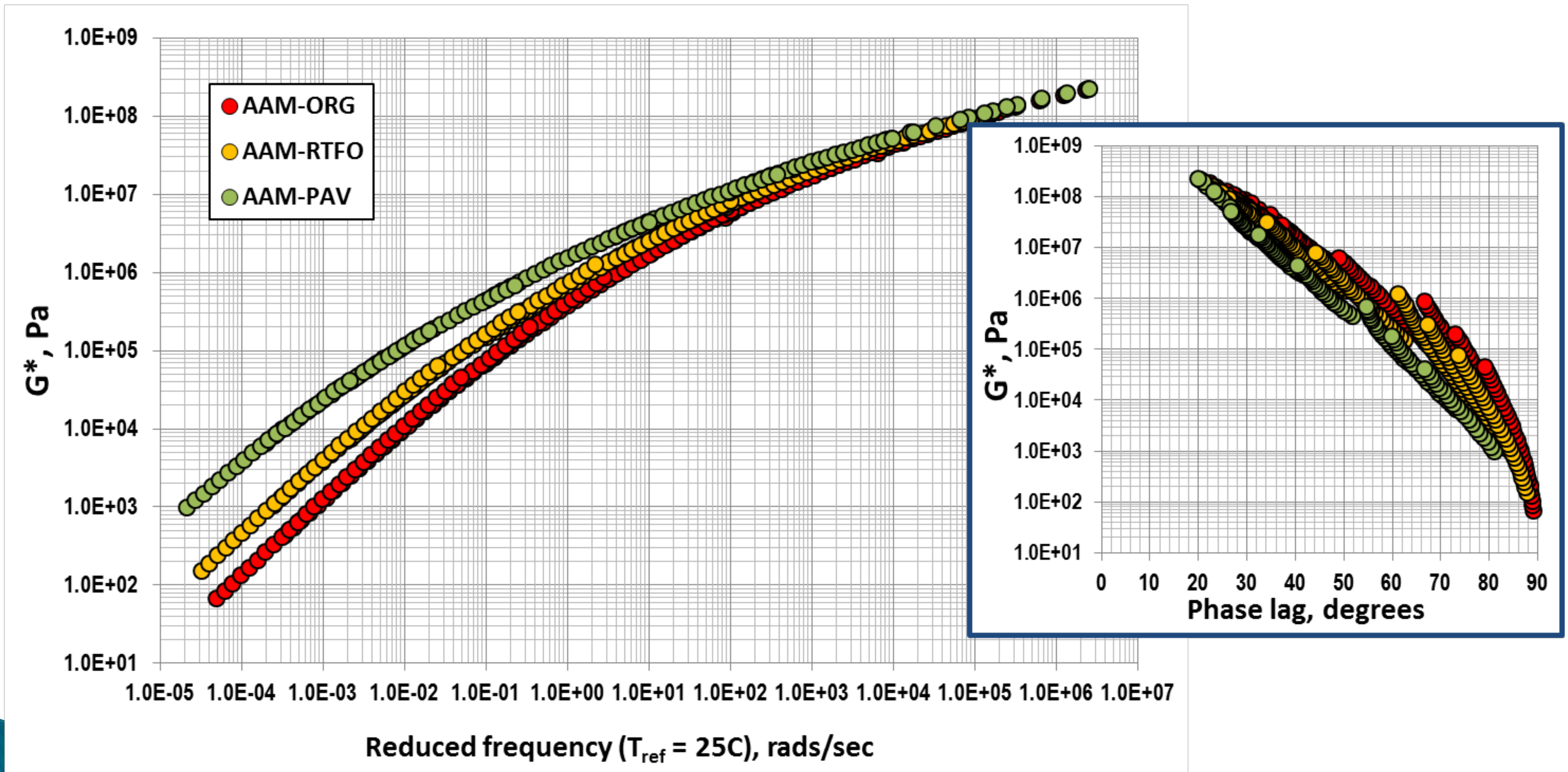


Different rheological types

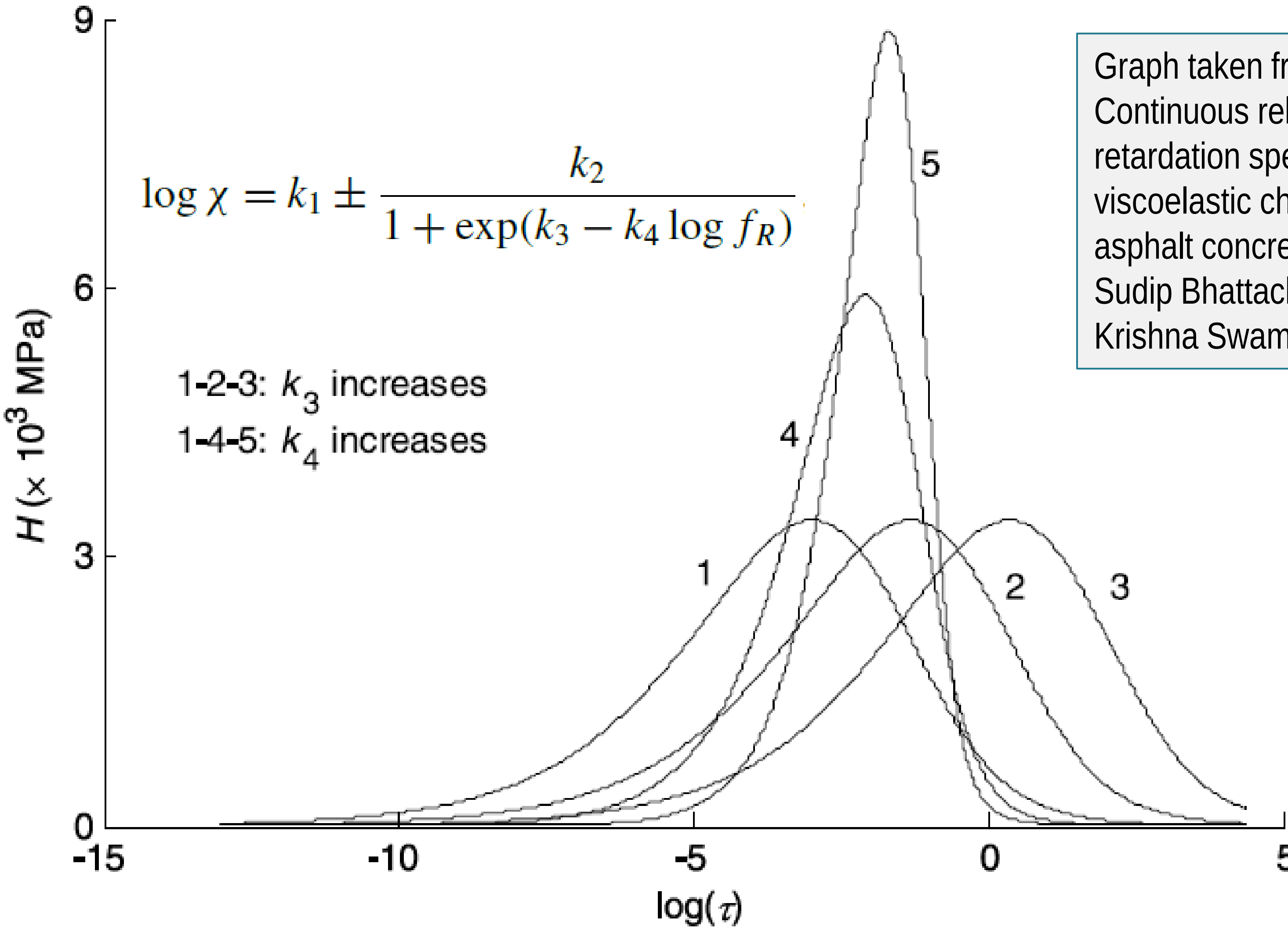


Changes with aging

- R value increases
- Cross over modulus reduces
- Cross over frequency reduces



Position and shape dependency



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Specification concepts

- R Value – was in an early draft!
- Temperature susceptibility parameter – SHRP Straw-man spec.

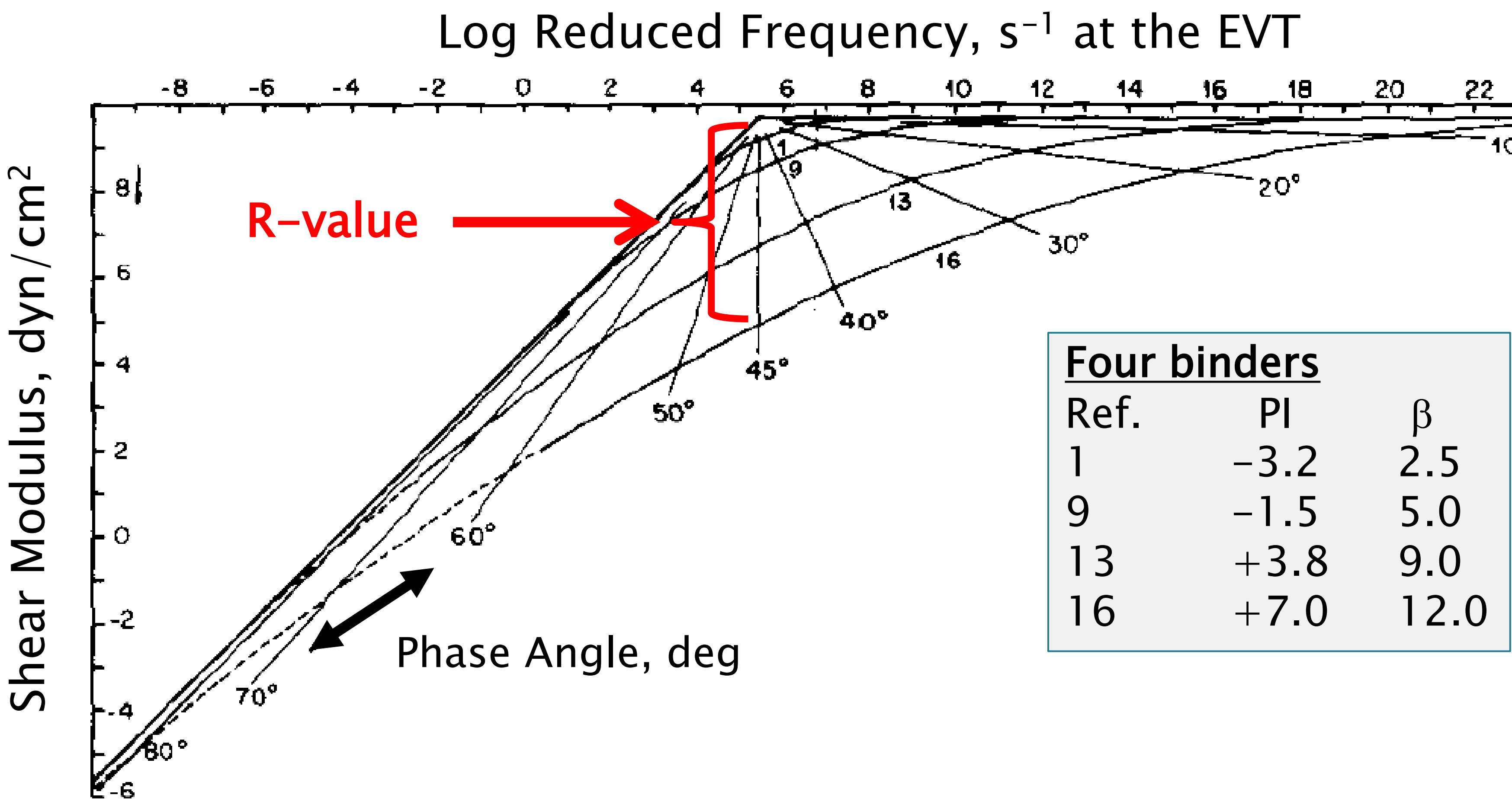
- Phase angle – French

- VET parameters – G^*_{VET} and T_{VET} – UK

- G-R parameter – in Black Space

- How do the relate to relaxation spectra???
  - Importance of R-value and understanding performance in Black Space

β versus R



Four binders

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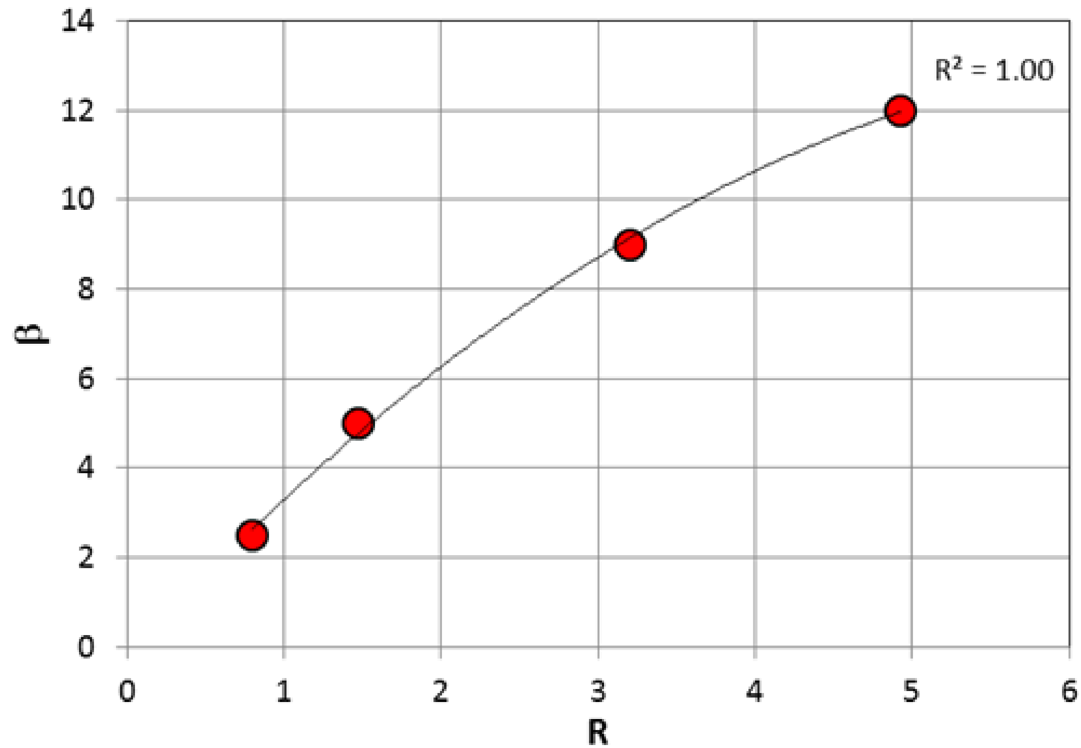
Note – different authors use different definitions.

β and R

- β and R have a correlation which has a r^2 of 1.00 with this data
  - This is expected!
- Both β and R are defining the shape of the relaxation spectra
  - Different assumptions!



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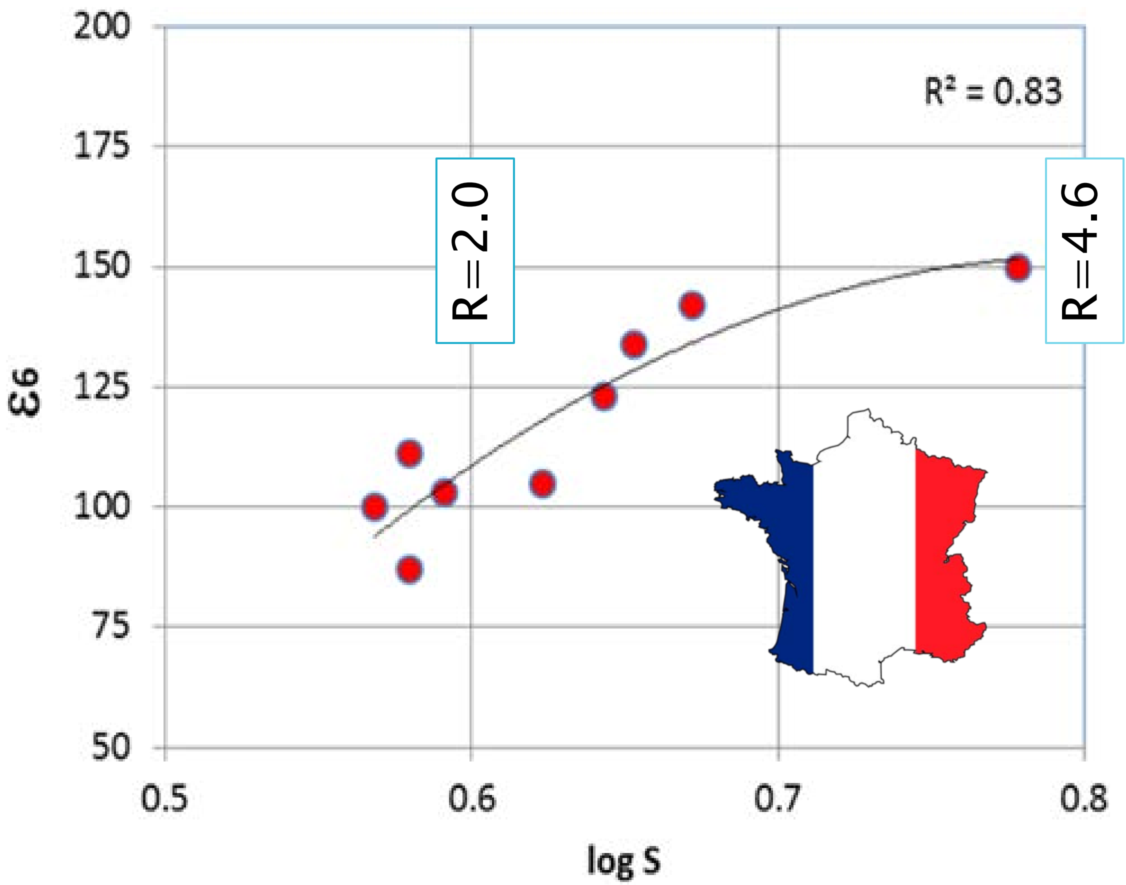
Relaxation spectra and fatigue (1988 – 1990)

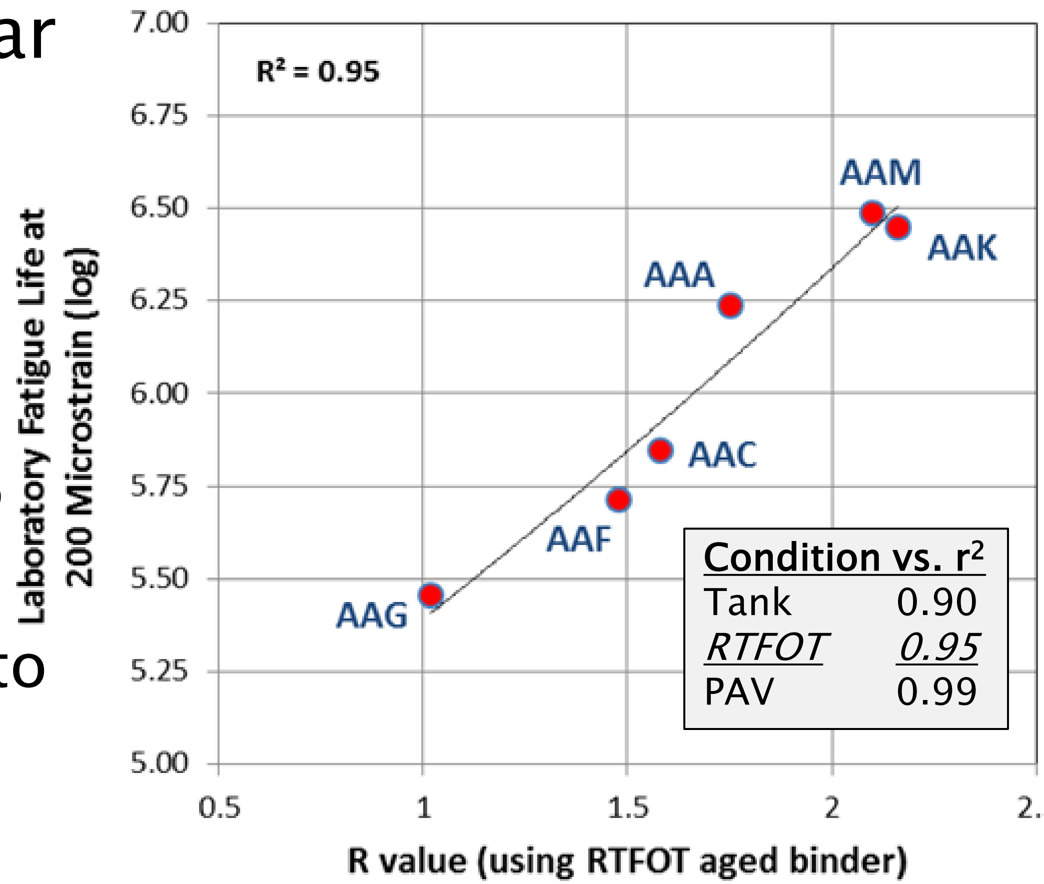
- Data presented shows that strain level required to give a fatigue life of 1,000,000 load applications is highly correlated to the S (standard deviation of relaxation spectra)
  - Note – S is based upon β
  - β has 1.00 correlation with R
- Consequently – horizontal axis could be replaced by R



Data from: F. Moutier, G. Ramond, C. Such and J. Bonnot (1990)

SHRP Validation data on mixes vs. R value computed from new AI data set on SHRP Core asphalts

- Binders have similar stiffness values
- R value computed using different assumptions to those originally developed in SHRP
  - G_g allowed to vary
  - C1 and C2 allowed to vary
  - Rouse density correction applied



Ref for mix data: *J.A. Deacon, A.A. Tayebali, G.M. Rowe and C.L. Monismith, "Validation of SHRP A-003A Flexural Beam Fatigue Test," Engineering Properties of Asphalt Mixtures and the Relationship to Performance, ASTM STP 1265, Gerald A. Huber and Dale S. Decker, Eds., American Society for Testing and Materials, Philadelphia, 1994.*

Trend with fatigue

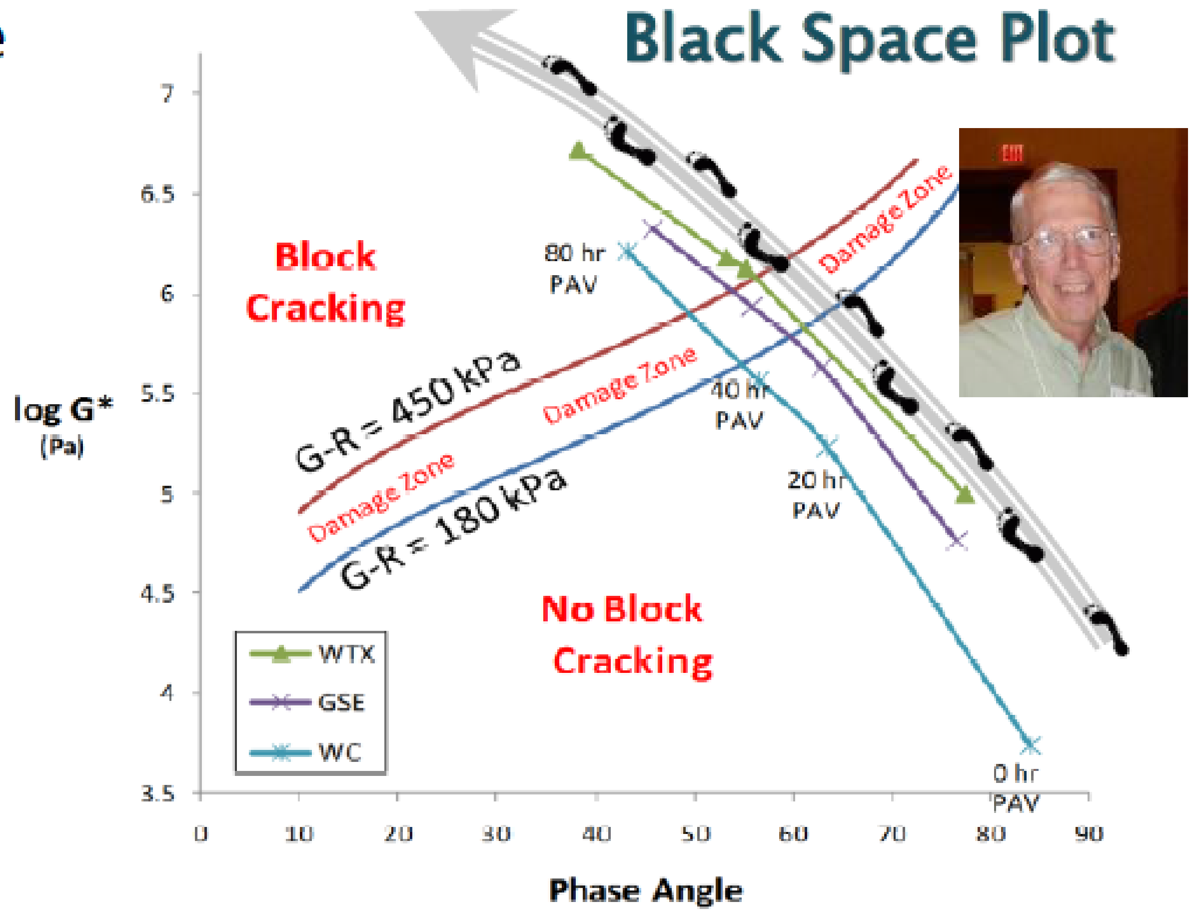
- Controlled strain fatigue test
- Higher R for same stiffness results in lower G″
- Fits with current concept of load associated cracking being related to G*.sinδ

Other concepts

- Durability issues
  - Position in Black Space – G-R Parameter dependent on R
  - Δ Tc – is based on low temperature cracking – R value dependent
- Low temperature cracking
  - Change from S controlled to m controlled based on R-value
- VET – UK use a Visco-elastic transition temperature and modulus at this point
  - G* VET Related to R
- $G^*_c = G_g - R$

G–R concept

- Important – since as the rheology changes the asphalt binder propensity to crack increases
- Hardening results in binder embrittlement–fracture at a lower strain "*march to death*" for an asphalt binder

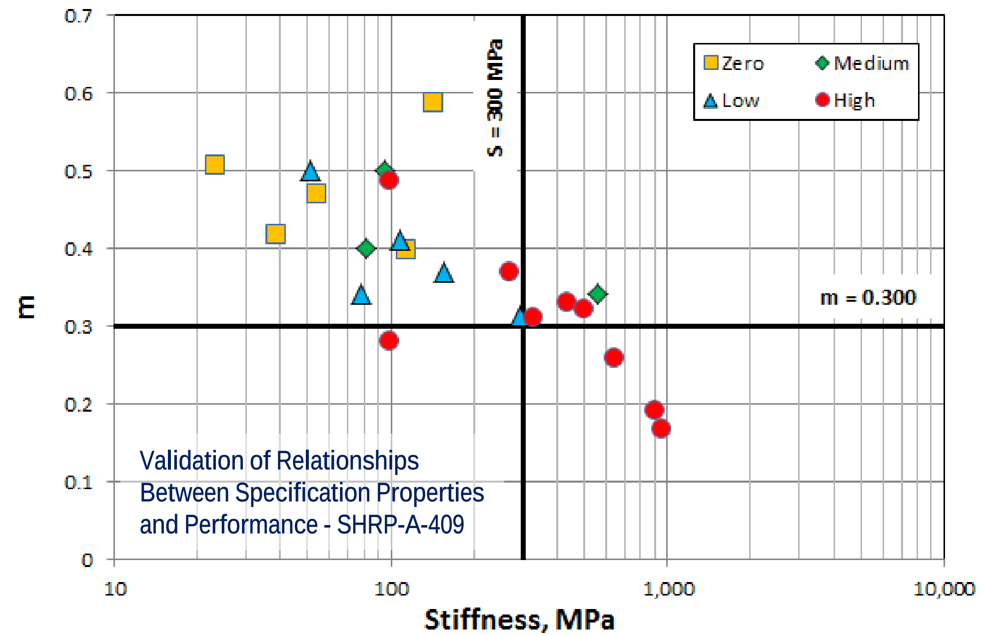


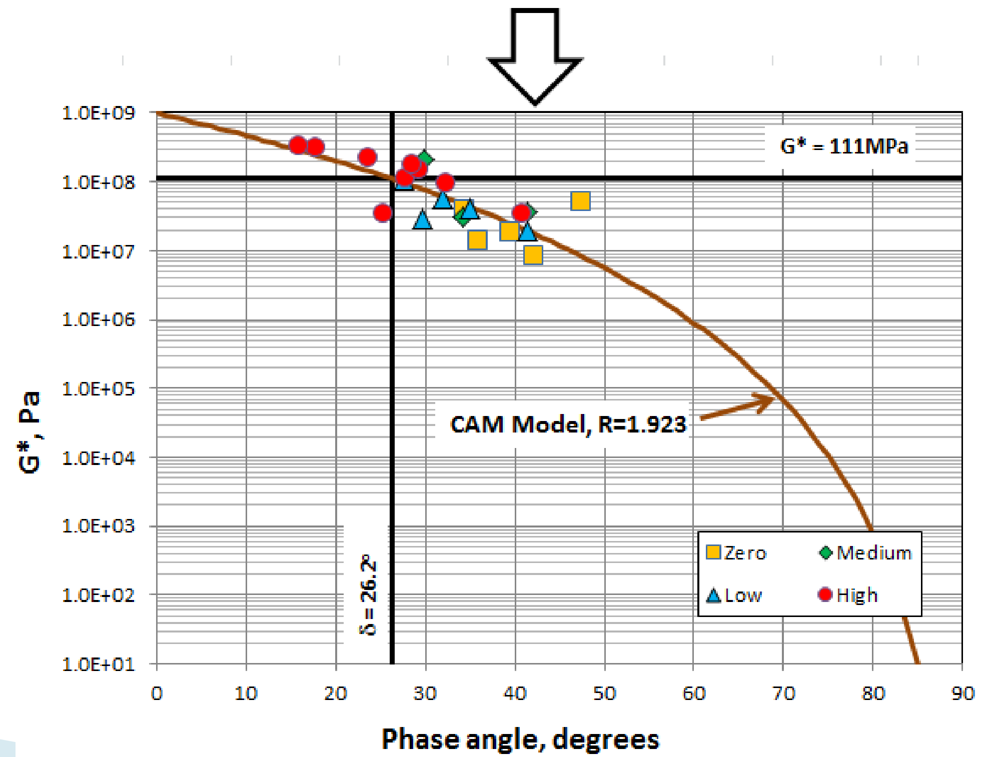
G-R concept

- Applied to distress at Newark Airport – non-load associated
- RAP durability study – Netherlands
- HyRap mixes in USA
  - Concept seems to account for non-load associated cracking/durability cracking
  - Captures same – ranking as ΔT_c – easy test to run in DSR at intermediate temperatures (stiffness)
  - Driven by relaxation properties

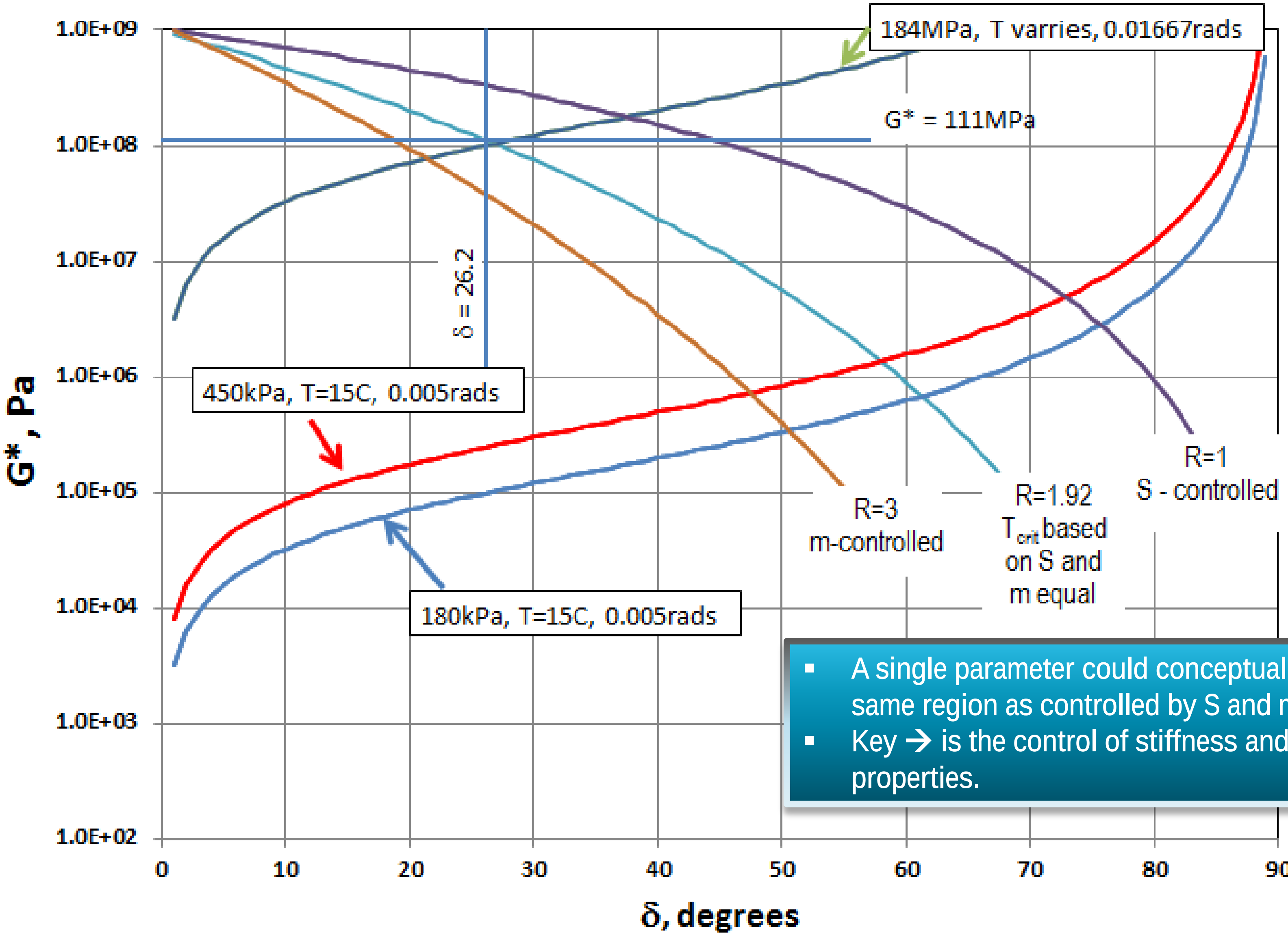
Thermal Cracking

- BBR parameters can be substituted with G* and δ 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 ≈1.92





Extending the G-R concept – to cold temperature cracking

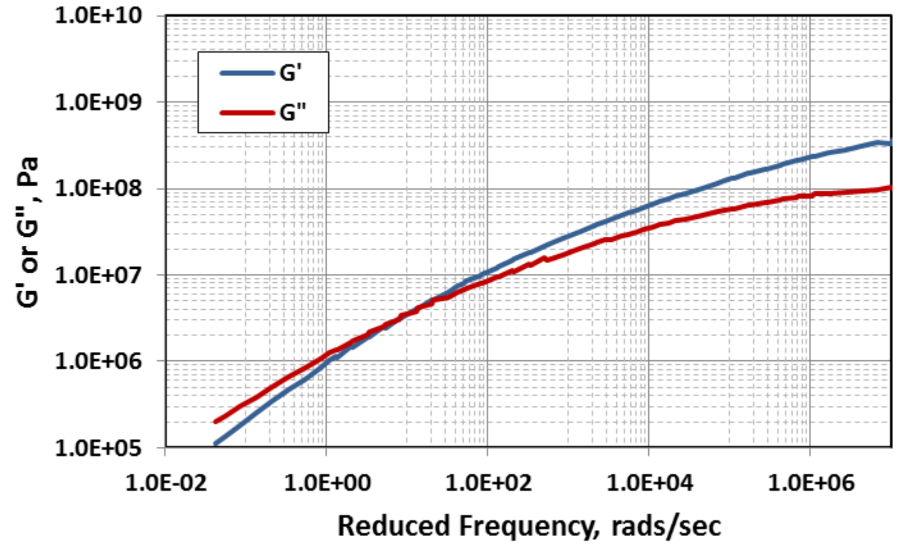


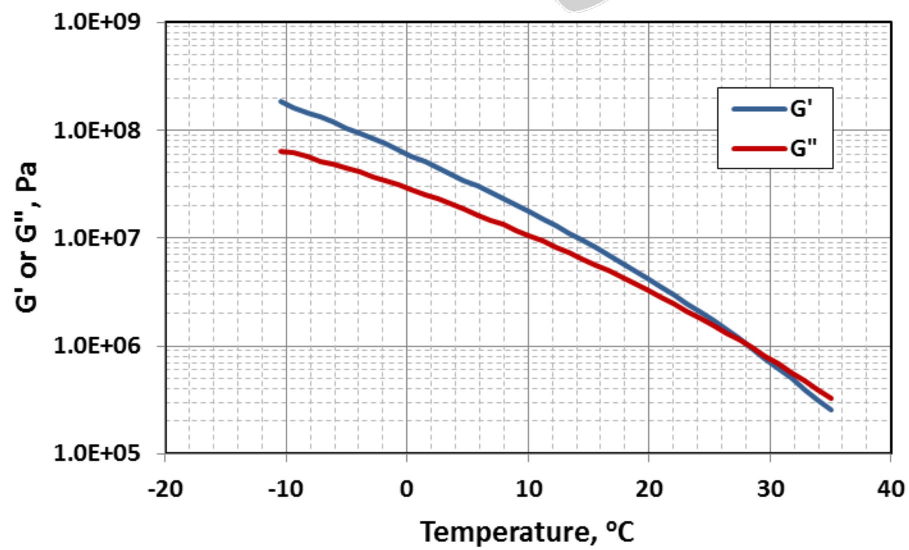
- A single parameter could conceptually define the same region as controlled by S and m.
- Key → is the control of stiffness and relaxation properties.

VET concept

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 $\delta = 45°$ 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 → via understanding of interrelationships …





CA and VET

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

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

$$G^*{}_{VET} = G_g \cdot 2^{\left({}^{-1}/_{\beta}\right)}$$

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

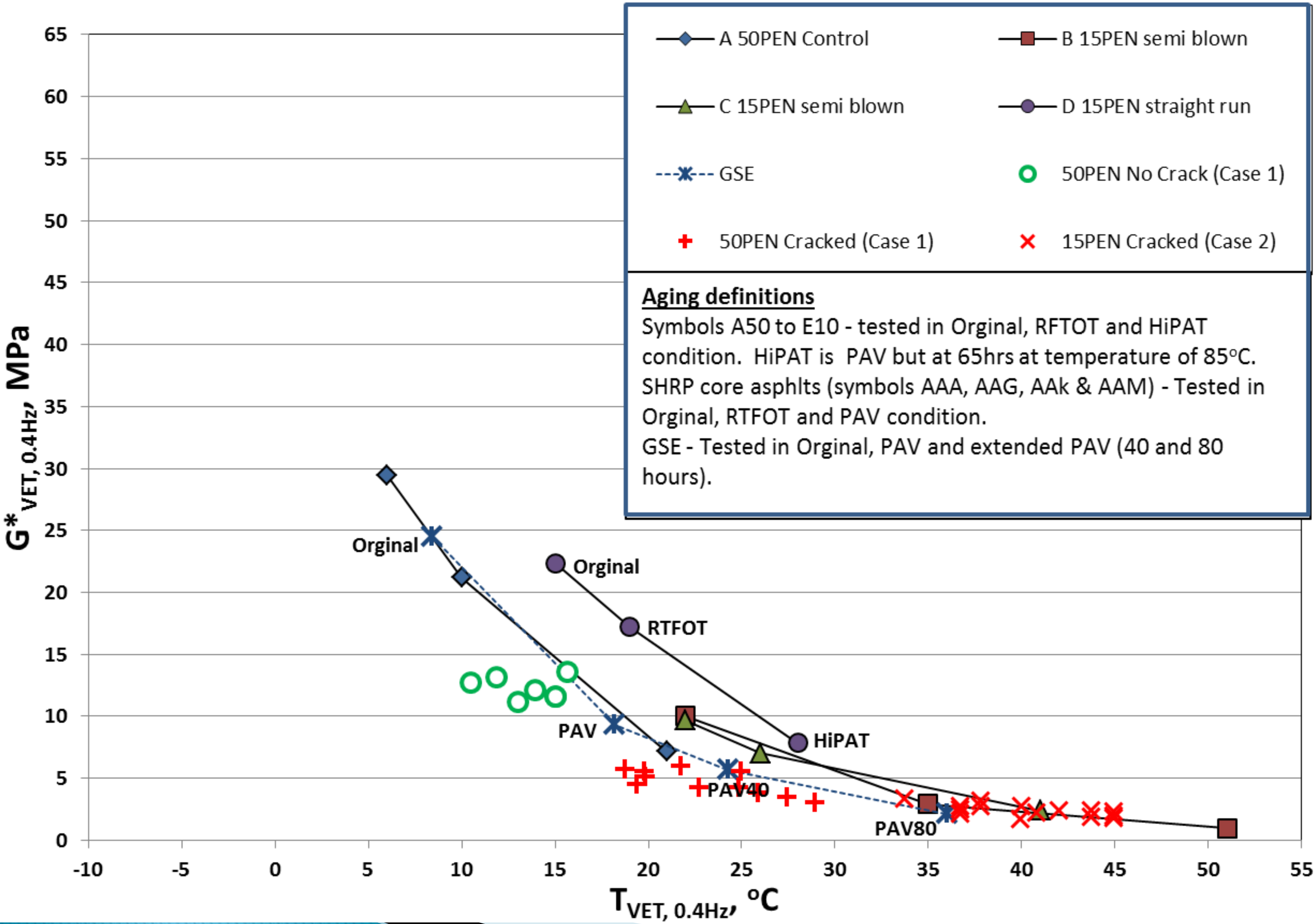
$$\log a_T = -C_1\left(\frac{T - T_d}{C_2 + |T - T_d|} - \frac{T_r - T_d}{C_2 + |T_r - T_d|}\right)$$

$R = \log 2/(\beta)$

$$G^*{}_{VET} = 10^{(9-R)}$$

When $G_g = 1e9$

UK data



A 50PEN Control
B 15PEN semi blown
C 15PEN semi blown
D 15PEN straight run
GSE
50PEN No Crack (Case 1)
50PEN Cracked (Case 1)
15PEN Cracked (Case 2)
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).
Orginal
Orginal
RTFOT
HiPAT
PAV
PAV40
PAV80
G*VET, 0.4Hz, MPa
TVET, 0.4Hz, °C
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-10
-5
0
5
10
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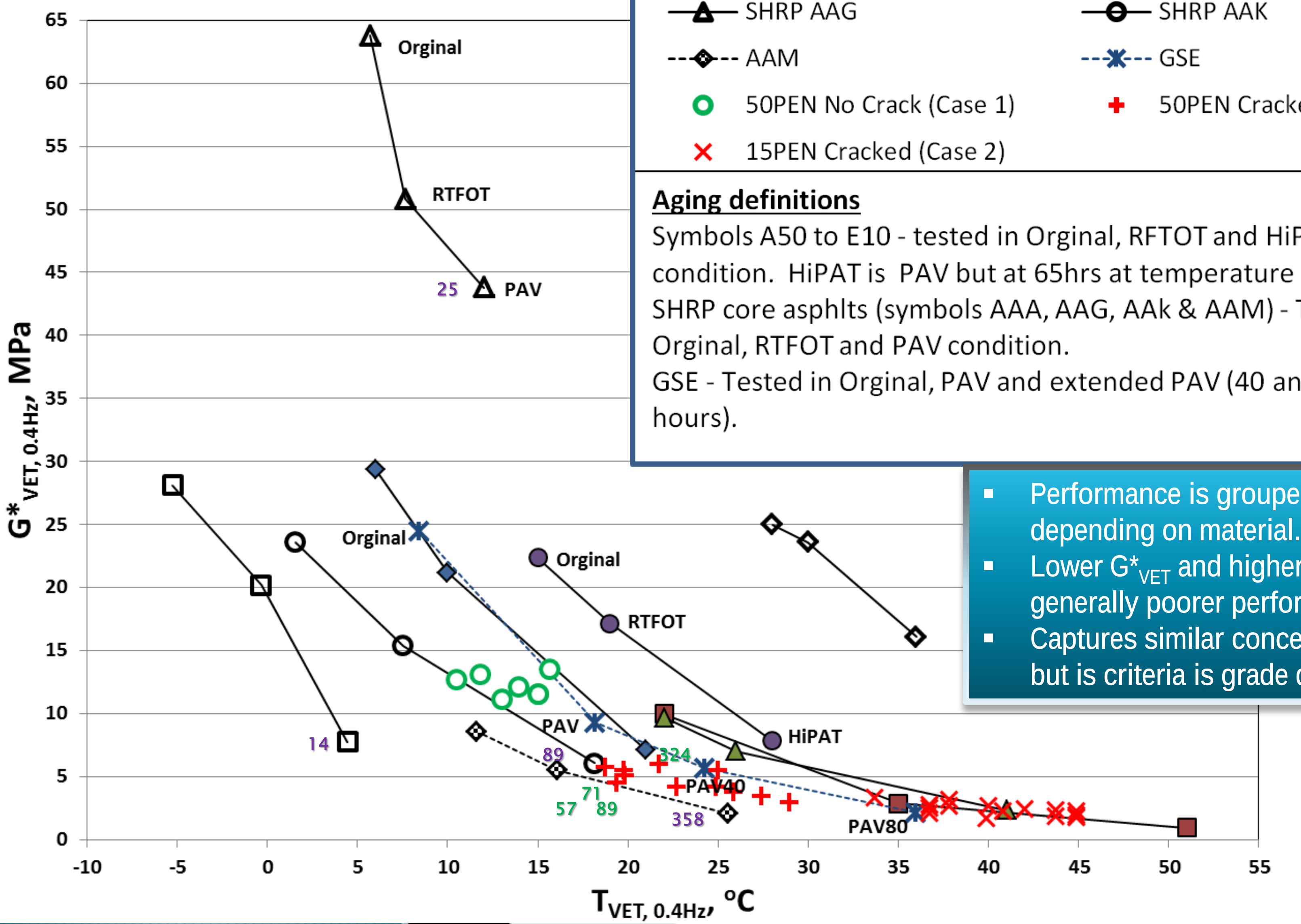
25
30
35
40
45
50
55

VET data



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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!

VET, ΔT_C and G-R concept

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

Others

- Note $G^*_c = G^*_{VET}$
- French approach of using phase angle at specified frequency – also captures R

Closing thoughts

- No need for complex math – R effectively describes shape/relaxation – without need for complex math
- Load associated and non-load associated distress – may not be ranked in same manner
    - Need to review SHRP fatigue validation
    - Extend maybe to other test sites, NCAT, MnROAD, others
    - Data mining!

Relaxation and stiffness properties are key to understanding cracking

Thank you for listening.

Questions?
Comments?