Binder Specifications with a Focus on Cracking

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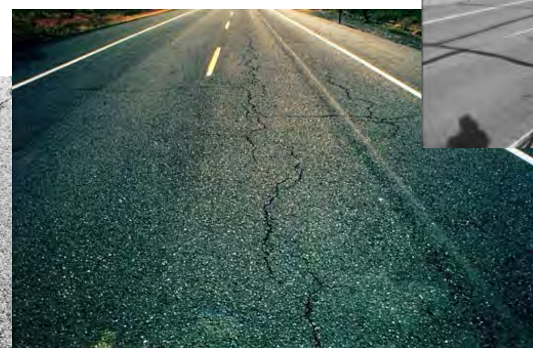
Objectives

- To consider binder specification requirements and how specification parameters help us to understanding cracking performance

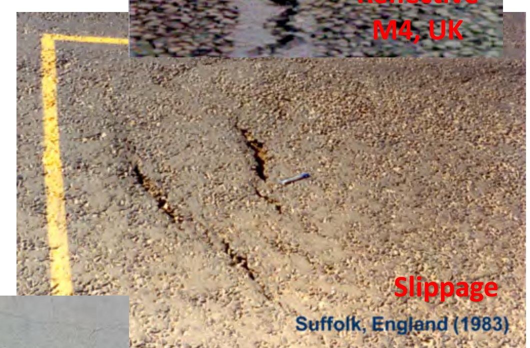
Cracking

- Cracking is a phenomena that occurs at higher stiffness
  - Use stiffness as surrogate for temperature for understanding comparable performance
    - Can then use a temperature range for a test based on this understanding
  - Conventional binders (unmodified) all have similar performance window based upon stiffness
  - Toughness peaks in mid stiffness region
    - Close to Visco-elastic transition temperature (VET) – or Cross-over frequency temperature, Cross-over modulus, G_c, tan $\delta = 1$ and binder stiffness 10 to 50 MPa
  - Temperature for cracking (durability) window covers stiffness range 1MPa to approx. 500 MPa
  - Need to define differences that polymers offer with regard to performance
    - Need a ultimate property performance test
  - Some aspects associated with cold temperature behavior still need more research

Linkage of cause and effects – aging and cracking



Which are best binder test parameters – G*.sinδ, ΔTc, G-R, DENT, LAST, etc.?



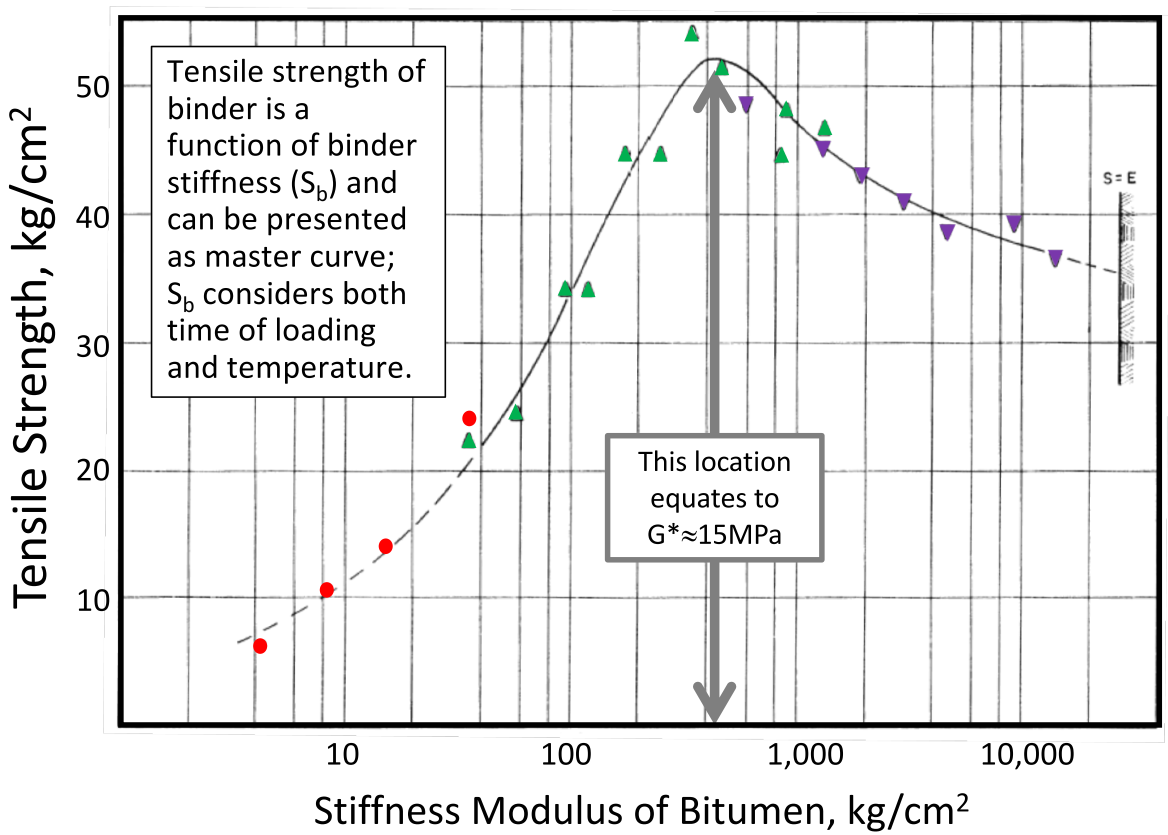
Strength versus temperature

- Historical Perspective
- Wide variety of research where strength is normalized with respect to temperature
  - Huekelom (AAPT 1966) essential reading
  - Ferry, Viscoelastic Properties of Polymers, 3rd Edition
  - Strategic Research Program DTT Test, SHRP A-369 (1994)
  - Polymers in non-asphalt literature, extensive literature
  - Etc.

Binder strength master curve

Hukelom, AAPT, vol 35, p 358, "Observations on the rheology and fracture of bitumens and asphalt mixtures"

- The concept that for conventional asphalt binders a tensile strength/strain master curve exists is well know for past **50 years**
- Holds true for many types of tests



Ferry's Book (T. Smith data)

- Similar results for polymers
- Example:
  - Styrene-butadiene rubber
  - Tensile strain
  - Data is shifted to a reduced strain rate that captures both time and temperature

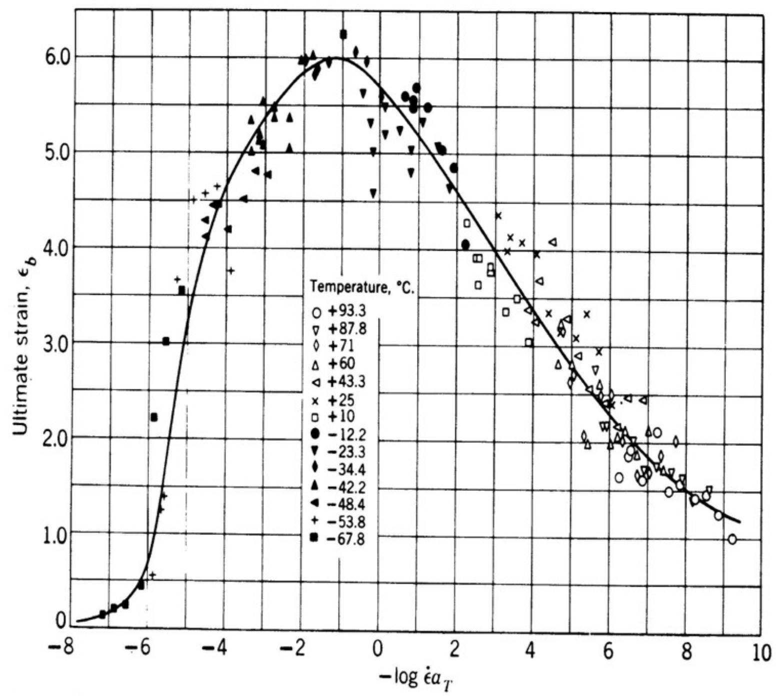


FIG. 19-3. Tensile strain at break plotted against logarithm of strain rate (in sec^{-1}) reduced to 263°K for a cross-linked styrene-butadiene rubber at 14 temperatures as indicated (Smith.[106])

Ferry's Book (T. Smith data)

- Styrene-butadiene rubber
- Tensile strength
  - Data is shifted to a reduced strain rate that captures both time and temperature

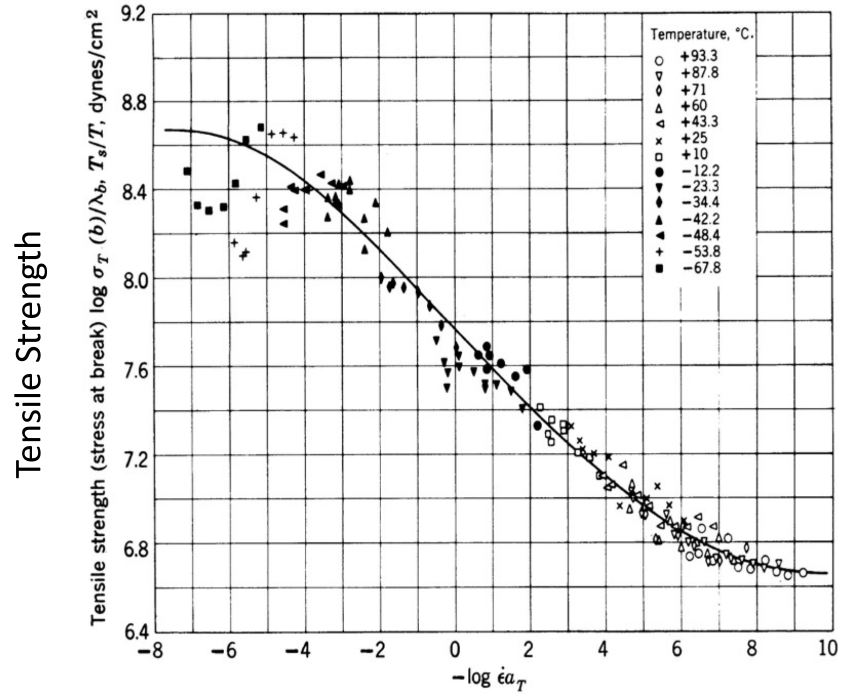


FIG. 19-4. Tensile strength in force per unit initial cross-section area, $\sigma_T(b)/\lambda_b$, plotted against logarithm of strain rate, both reduced to T_s = 263°K for the material of Fig. 19-3 at the same 14 temperatures. (Smith.[106])

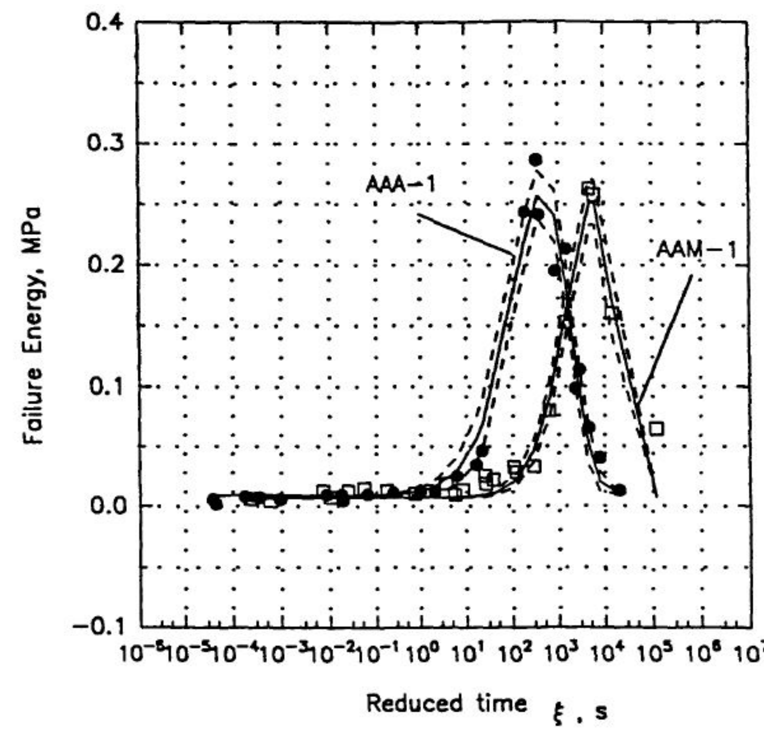
Log_{10} reduced strain rate

SHRP A-369, Anderson et. al (1994)

- Failure master curves of stress, strain and energy for conventional binders
- Functional form for energy

$$F(\xi) = A + \beta 1[(Z)^{(\beta 4-1)}][\exp(-(Z)^{\beta 4})]$$

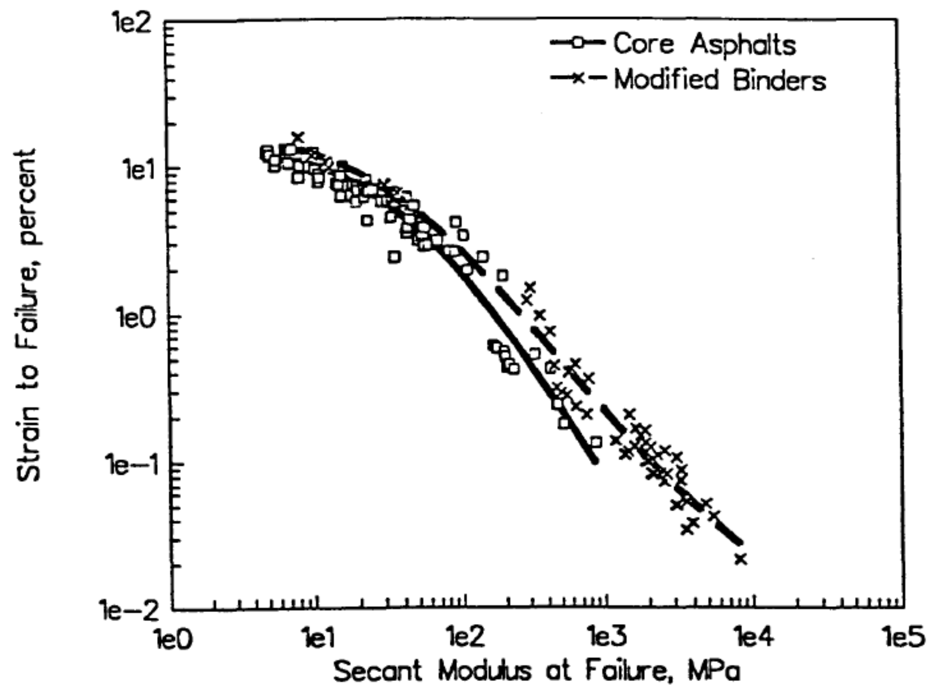
$F(\xi)$ = failure strain or failure energy
A = constant
β_1 = magnitude parameter
Z = $(\log(\xi) - \beta_2)/\beta_3$
β_2 = location parameter
= $0.5392\beta_3$ for failure strain master curve
= $0.5011\beta_3$ for failure energy master curve
β_3 = scale parameter
β_4 = shape parameter, fixed (constant) at 10
$\log(\xi)$ = common log of reduced time, $\xi = t/a(T)$
$a(T)$ = shift factor obtained from rheological measurements



Note – reduced time – not adjusted to stiffness

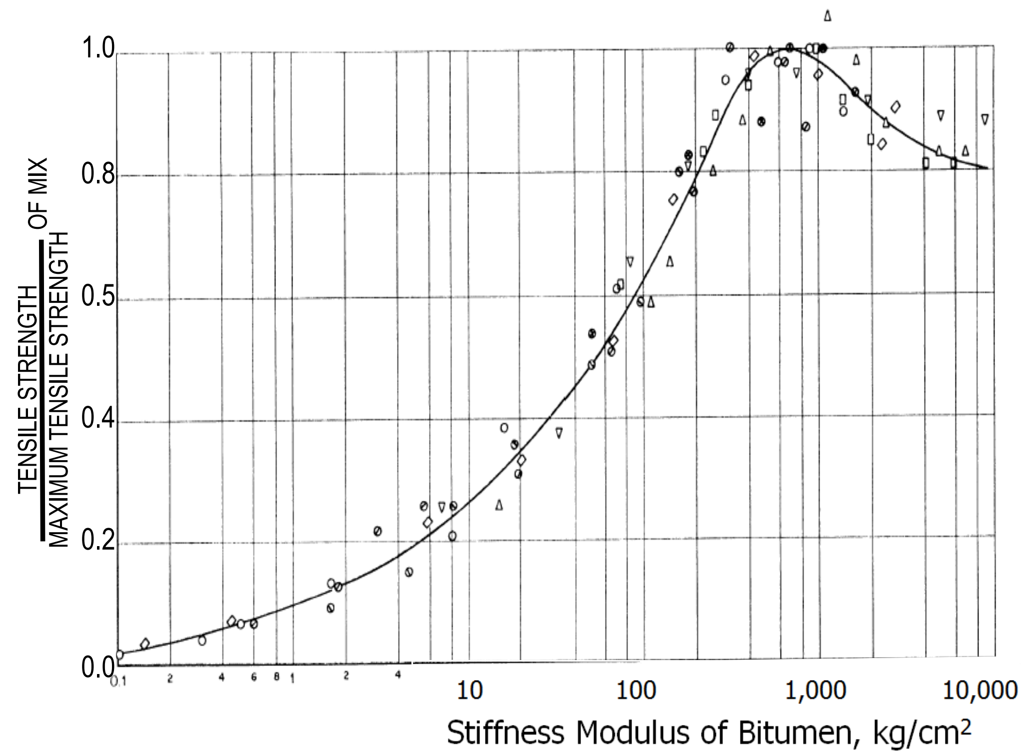
SHRP Project A002 – Failure strain master curve

- Similar data from the SHRP project demonstrated the same effect
- This curve is strain at failure in DTT test
- Binder stiffness expressed as secant modulus



What about mix properties

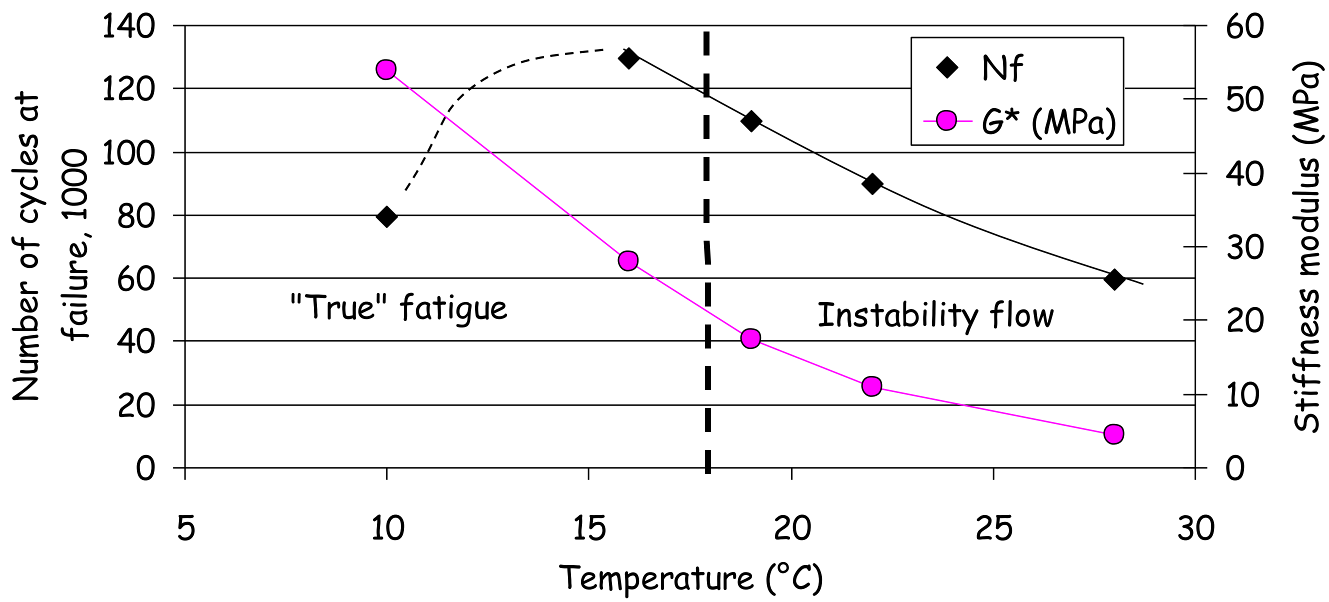
- We know binder and mixture properties are related
- Items to consider
  - Binder rheology on mix rheology
  - Effect of mix aging versus binder aging
  - What mix parameters should we be considering
  - How we capture mix parameters
    - Important to consider loading time and temperature – fracture properties of mix depend upon the stiffness of the binder!



Stiffness vs. strength

- Stiffness important to describe strength, strain and properties at break
  - Could use other parameters that include effect of time and temperature
    - Stiffness is conceptually easy to understand since we use it as a specification parameter
  - Could use S(t), G*, E(t), etc.
- Properties are both a function of loading rate and temperature!
  - Applies to range of visco-elastic materials, bitumen, asphalt mixes, rubber, SBS, others, etc.
    - All practical materials going into HMA!

“Fatigue” vs. Temperature and Stiffness (G*)



Anderson, Marasteanu, Planche, Martin and Gauthier - Evaluation of Fatigue Criteria for Asphalt Binders – TRB 2001

Stiffness range where transition from "instability flow" to "fatigue"

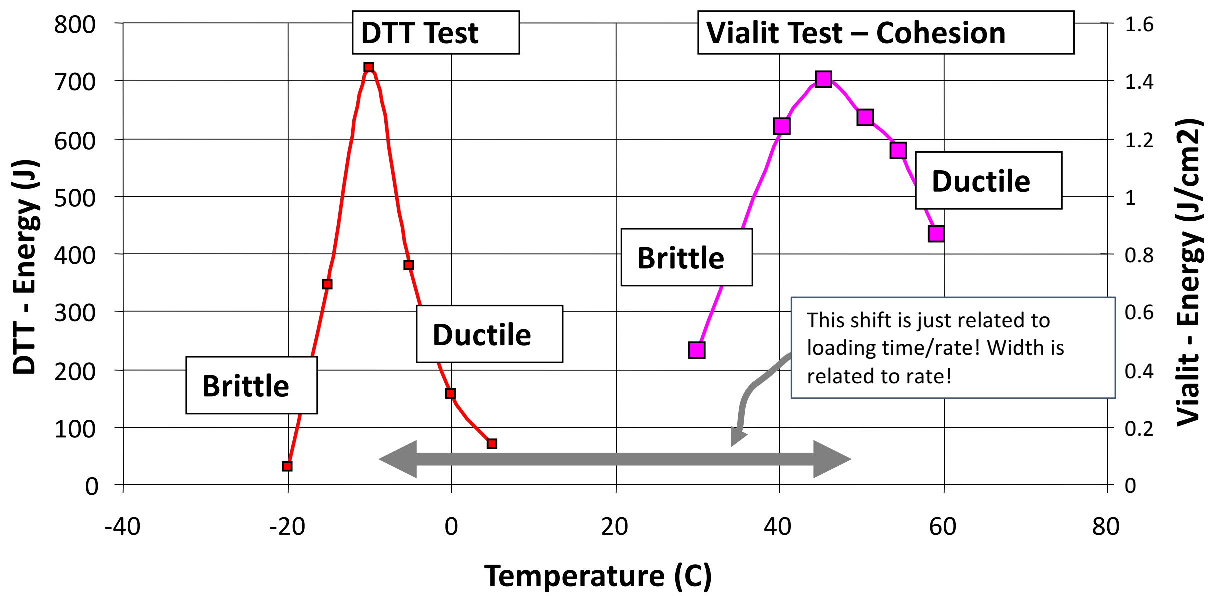
- Range in stiffness where fatigue cracking and instability flow dominate – G* = 9 to 28 MPa

Binder	Fatigue cracking	Instability flow
Unmodified	28 to 55 MPa	5 to 18 MPa
SB crosslinked	15 to 45 MPa	5 to 10 MPa
EVA modified	13 to 45 MPa	5 to 9 MPa

Other data sources

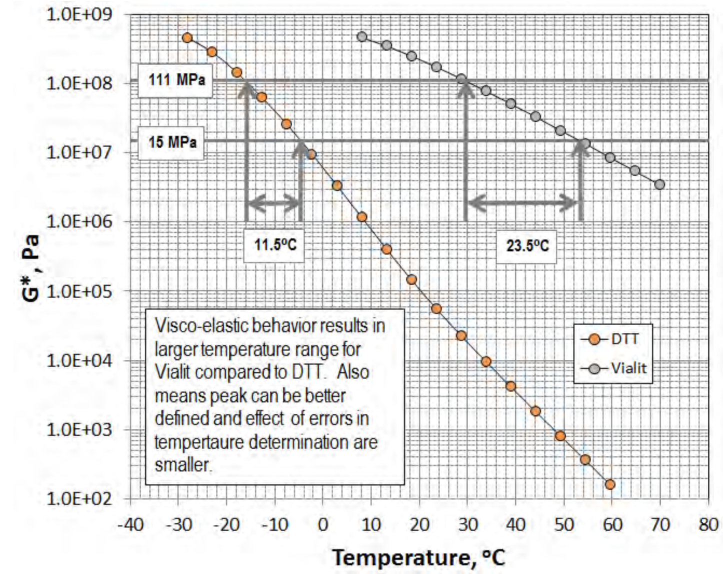
- Many other data sources will show this type of behavior since it is descriptive of physical behavior – for example DTT versus Cohesion tests

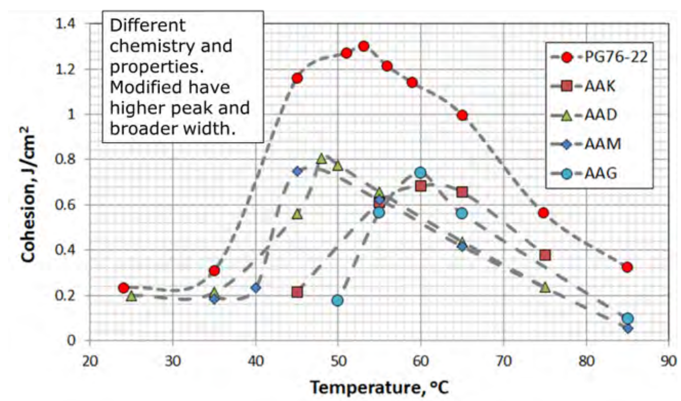
Stiffness effect – explains these brittle to ductile transitions.



Understanding the cohesion

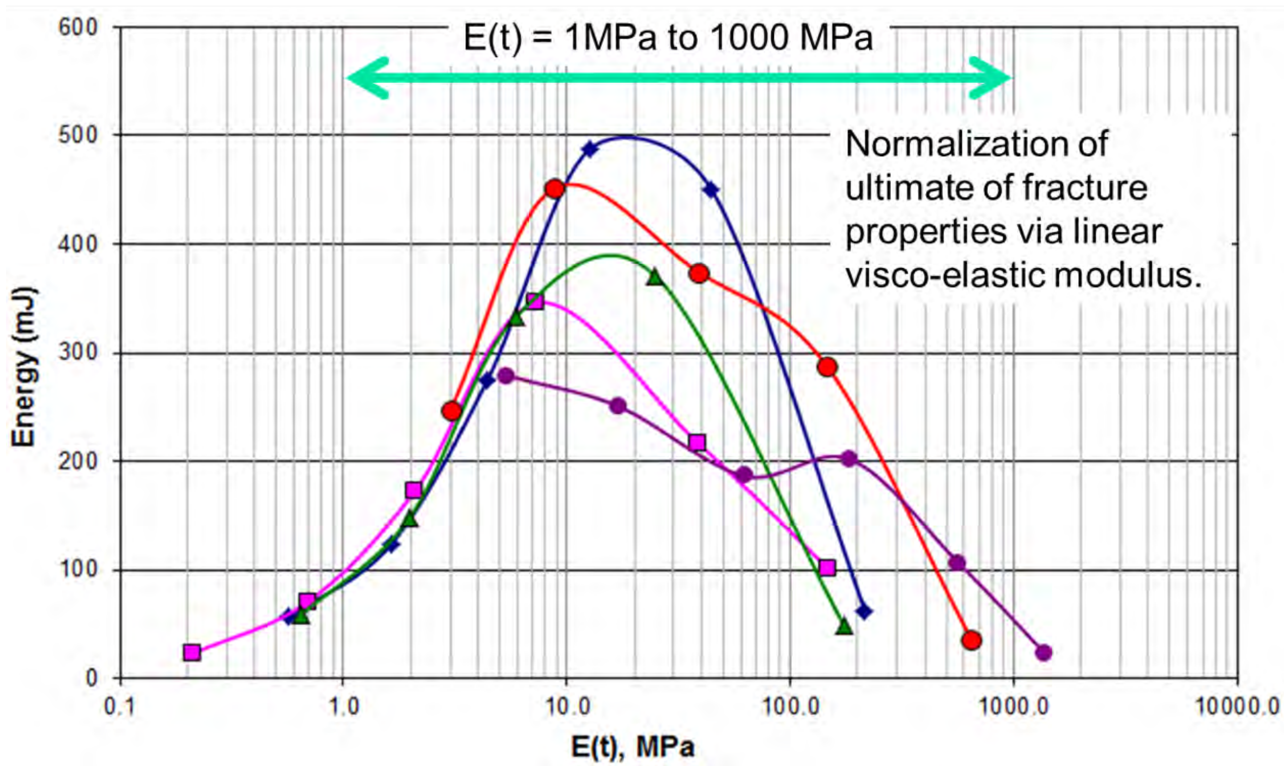
- Position and width of curve in an ultimate property test depends upon three factors
  - Rheology
  - Loading rate
  - Strength
- Uses cohesion range and height to qualify differences in PmB modified binders in some specifications





Range from viscous to flow type behavior

- DTT tests on various materials
- Range is similar for modified and unmodified materials
- Range is similar – but peak heights are different for modified materials



Black space

- Originates in electrical engineering and adapted for asphalt technology
- Traditionally shown a plot of G* versus δ
  - Better to consider as measure of stiffness vs. relaxation
- Examples in asphalt engineering
  - Used since early 1970's
  - Mid 1990 – S vs. m (parameters from Bending Beam Rheometer)
  - Extensively used in Europe
  - G* and δ in recent USA studies linked to Glover-Rowe concept

Dickerson and Witt (1974)

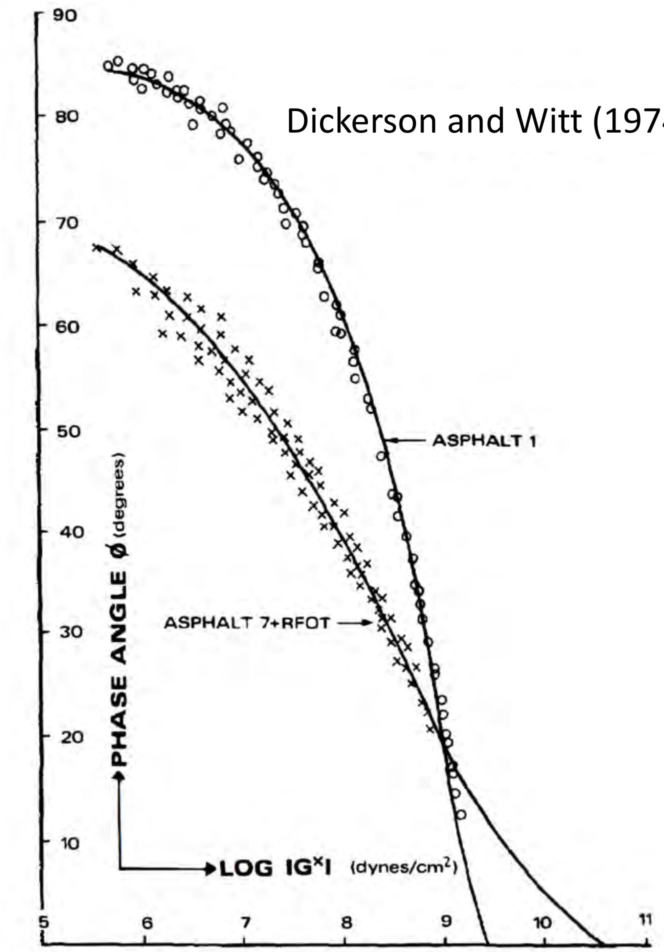
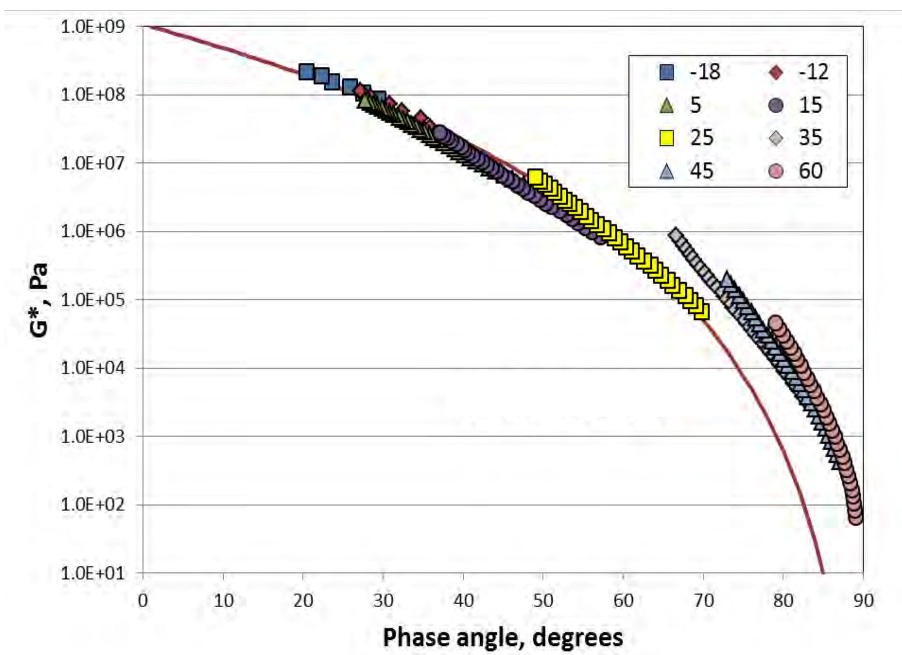


Fig. 4. Hyperbola model—Black's representation of the complex plane (asphalts 1 and 7 RFOT).

1 dyne/cm² = 0.1 Pa

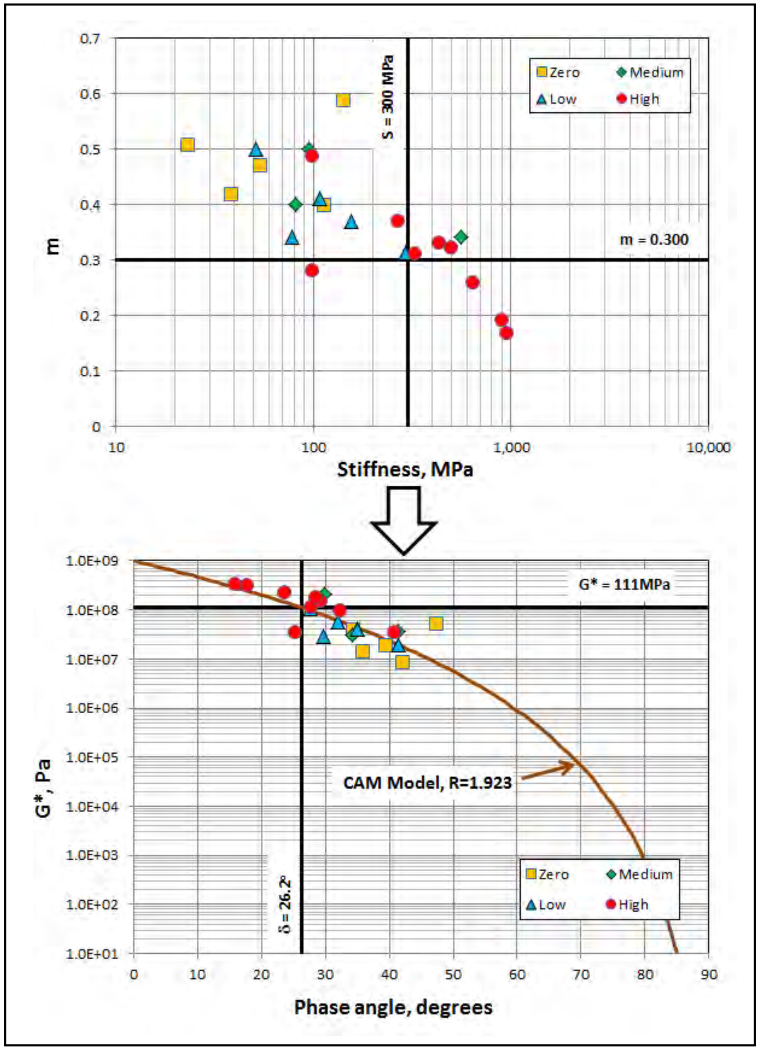
Black space

- Typical example for asphalt binder – works well within certain well defined limits
- We can then plot on this type of graph our specification functions
- CA model defines rheology in region of 10^5 to 10^9 Pascals to a good accuracy
  - From this possible to calculate G-R, G_c, ΔT_c and other parameters



Black space BBR

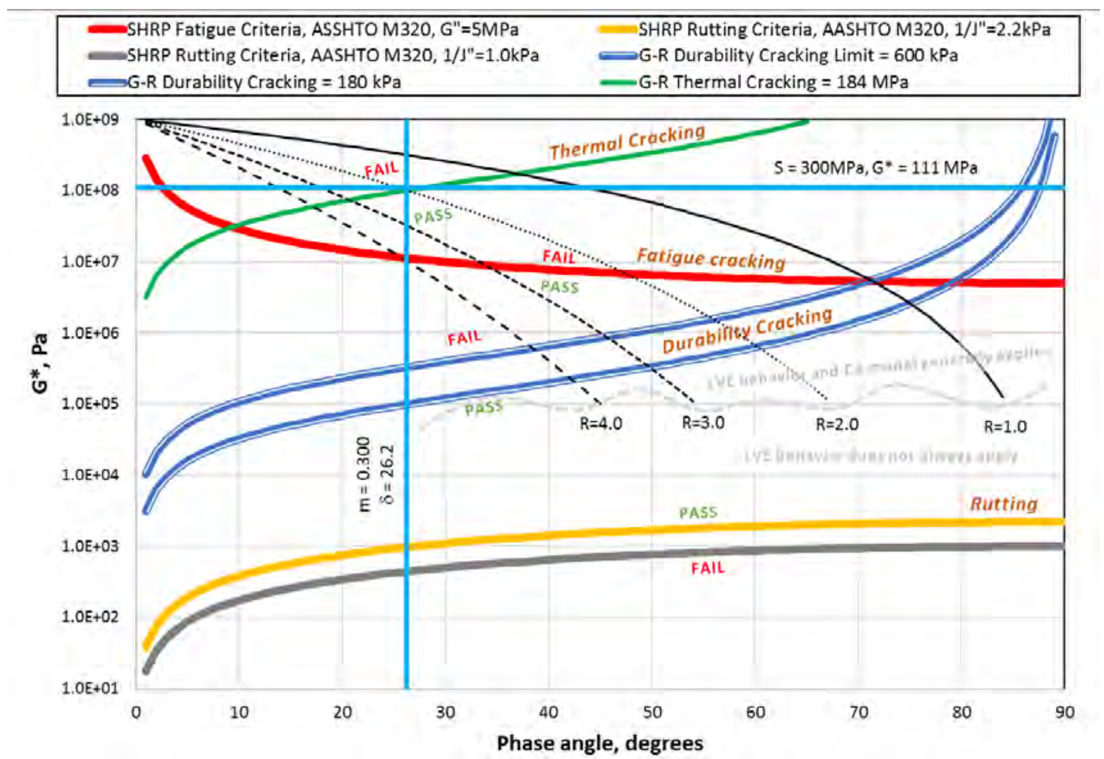
- Black space concept applies equally to data from BBR
  - Need to capture stiffness and relaxation properties
  - S(t) is related to G*
  - m(t) is related to δ
- Example shown is for BBR validation done during SHRP (top right) compared to the same data shown via an interconversion to G* and δ using approximation relationships



(CTAA, Rowe, 2014)

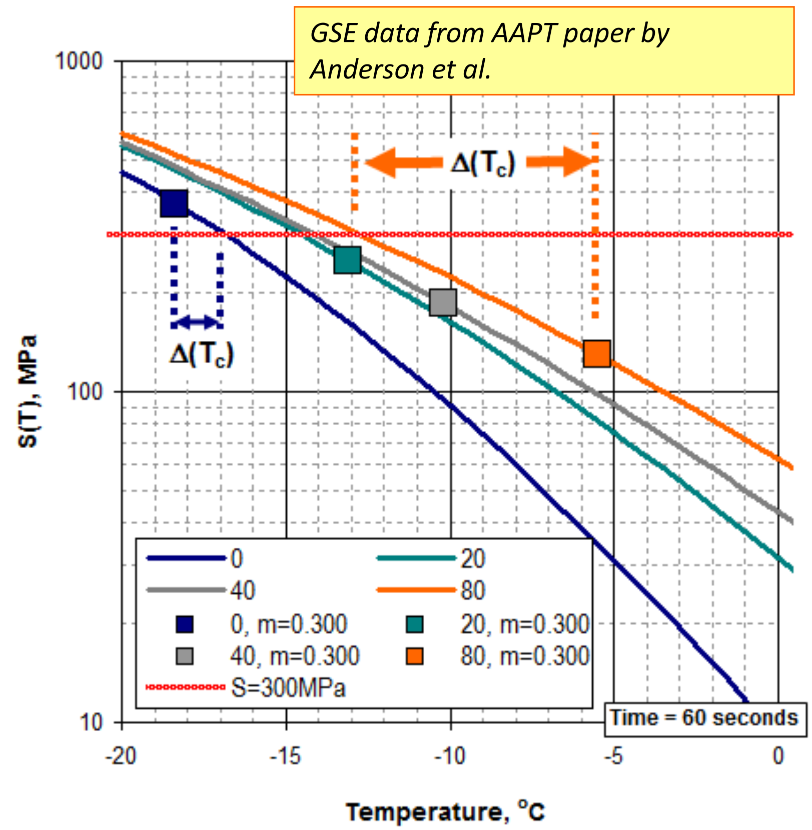
Limits in binder testing for Black space

- The graph shows limits for specification parameters in use today, and some alternates, all expressed in a Black space for asphalt binder
  - Current specifications
    - G*.sinδ – 10rads/sec, fatigue cracking
    - G*/sinδ – 10rads/sec, deformation/rutting
  - Alternate considerations
    - Durability and thermal cracking
      - G*.(sinδ)2/cosδ
  - Different limits, rates and temperatures apply
  - Deformation outside area covered by linear visco-elastic binder properties



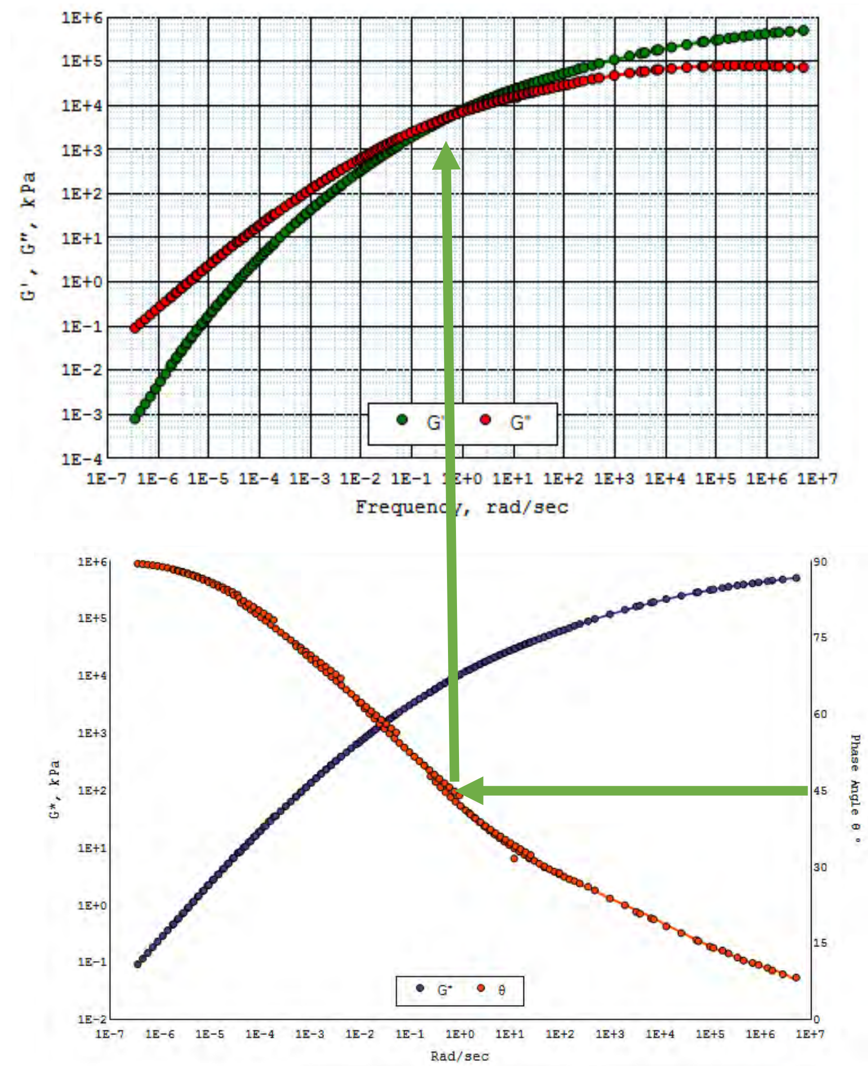
What is ΔT_c ?

- $T_{S(60s)}$ -$T_{m(60s)}$
- ΔT_c defines the slope of the stiffness curve in the temperature domain
- Unit is ^oC
- Is a shape parameter in the higher stiffness region – related to temperature susceptibility and the rheological index



What is G_c?

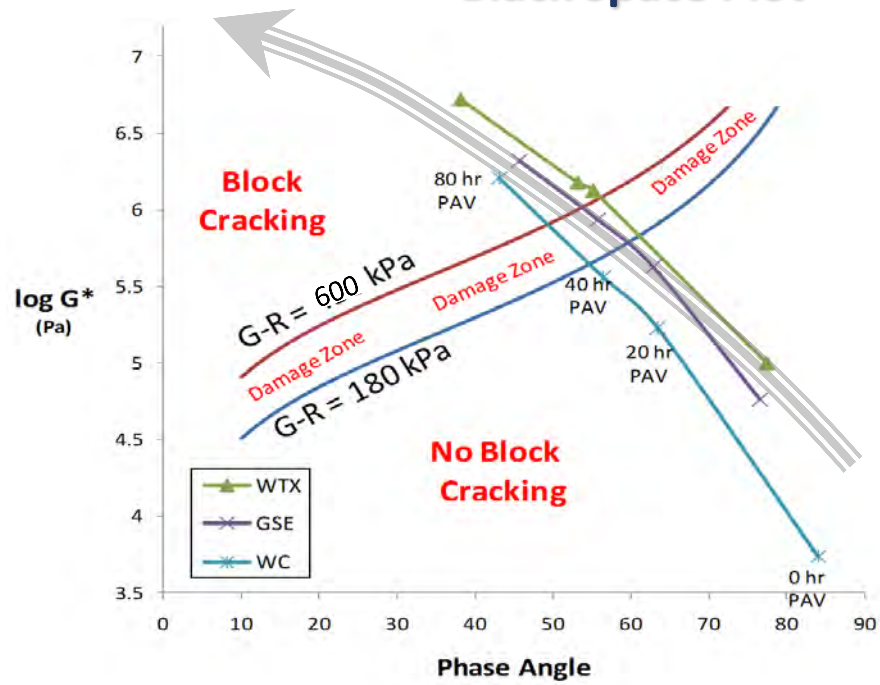
- G_c is the cross-over modulus
- Is the modulus of the binder when the phase angle is 45°
- Is the modulus when $G^*.\cos\delta = G^*.\sin\delta$ (or $G' = G''$)
- Is related to the R value in the CA model
- Also called G^*_{VET}



What is Glover-Rowe (G-R) parameter ?

- G-R = $G^*.(\cos \delta)^2/\sin \delta$
  - Defined at 15°C and 0.005 rads/sec
- This defines a point within a Black space plot of G* vs. phase angle
- Is a point property in a similar manner to S, m, $G^*.\sin\delta$, $G^*/\sin\delta$, J_{nr}, etc.

Black Space Plot



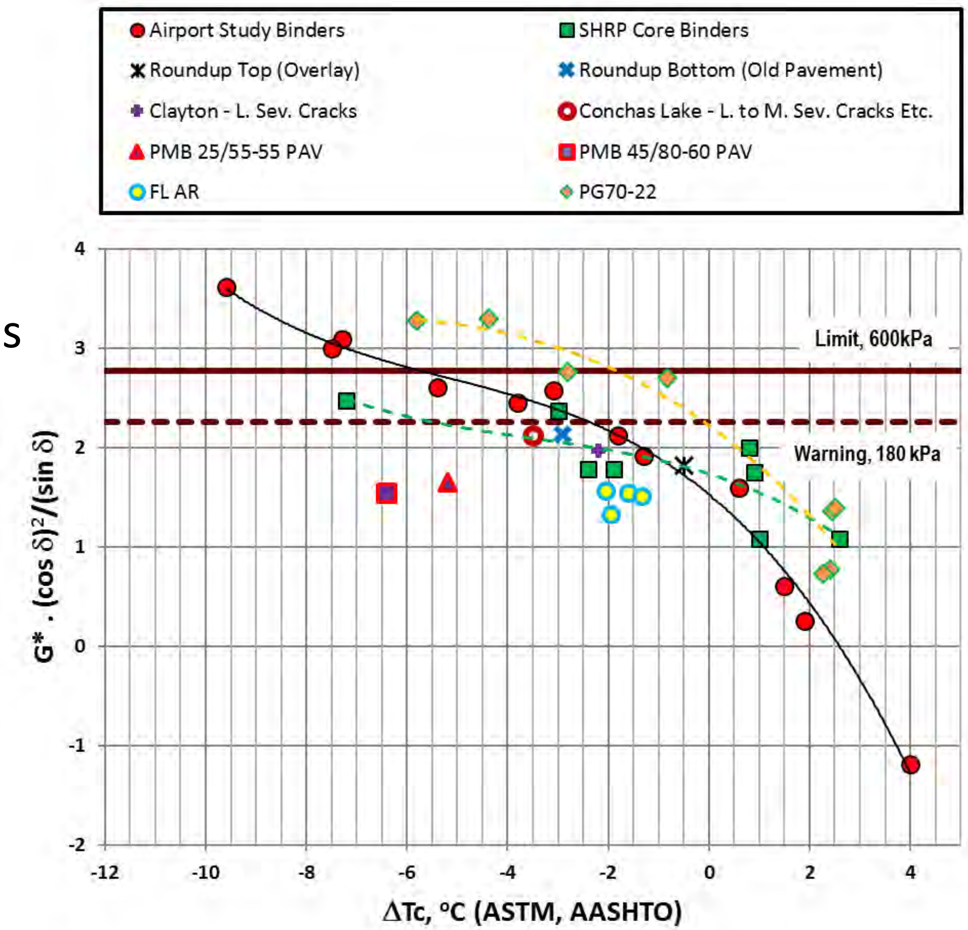
Point vs. shape

- Need to consider what is defined as a point property versus a parameter that defines a shape of the master curve or part of the master curve

Point versus shape

- Will not necessarily correlate since they are defining different parameters
- Initial relationship shown for ΔT_c versus G-R does not apply to many materials
  - Which is a more reliable indicator of performance?
  - In our existing specifications we have not used a shape parameter without a point parameter!

Point	Shape
Rheology S, m, G*.sinδ, G*/sinδ, J_{nr} *Empirical* Pen, R&B SP, Frass	*Rheology* R, WLF/Arrhenius, ΔT_c, A+VTS, etc. *Empirical* PI, PVN, etc.



How do we use all of this …..

- Helps us to interpret data, test condition, loading configurations, etc.
- Need to assess existing and new methods in rational manner
- Time-temperature dependency can be determined from simplified testing
- Time-temperature is uniformly valid for rheology and ultimate properties

A couple of thoughts on analysis

- We have more data in data sets than we use
  - R-value captured in all SHRP data
    - Many ways we can estimate
- Extrapolation vs. interpolation
- Specification parameters – property driven – will they be the same in different climates?
- Rate of loading effects….
  - Consideration of stiffness helps us to understand tests
- We don't test our binders in a "non-thermo dynamic equilibrium" condition
  - Do we need longer conditioning times as proposed in Canada
- What is the correct aging condition?
  - Work ongoing on this aspect!

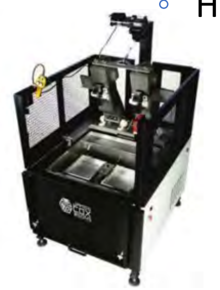
The mix matters!

- Paved 2 hours apart! LHS → OK, RHS → durability cracking

Photo: GM Rowe - 2008/12/08, paved 2001 – 7 years old

… many tests being considered for the mixture!

- Hamburg



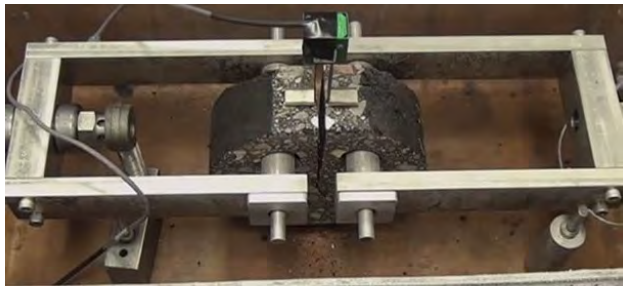
- SATS

- Bending beam fatigue test

- Tensile tests
  - Use of beam, direct or indirect tension

- Fracture tests

Texas Overlay Tester



Direct compact tension test

Semi-circular bend test

… and finally ---

- Don’t forget the crew with the paver, rollers, etc…
    - A good binder – will not substitute for good site practice

Summary

- In the development of tests and concepts for cracking we should consider
  - That cracking is within region of binder stiffness than can be characterized by LVE – brittle to ductile (instability flow) transition
  - Stiffness can be used as a normalizing parameter to assess quality of products
  - A “ultimate property” master curve exists for our materials
  - For a given material – a pass fail criteria can be developed in a Black space plot
    - This failure criteria may vary with modifiers or may need some adjustment
  - Important to consider what are point vs. shape parameters in specifications
  - **Durability cracking/environmental stress cracking**
    - **$\Delta T_c \geq -5^oC$**
    - **G-R ≤ 600 kPa**


Thankyou for listening
Comments/Questions??