Strength from Stiffness
(Ultimate Properties Must Be Considered Relative To Stiffness)

David A. Anderson, PhD, PE
Professor Emeritus, Penn State

Geoffrey M. Rowe, PhD, PE
Abatech

FHWA Asphalt Binder ETG
Oklahoma City, OK
September 15-16, 2015

Ultimate Properties – What Are They?

- ☐ Property that can be used to characterize or rank a material at the time of rupture
  - ✓ Attempt to rank material according to their propensity to rupture when loaded
  - ✓ Loading may be caused by applied stress, strain
  - ✓ Mechanically or thermally induced
- ☐ Wide range from “fundamental” to empirical
  - ✓ Used in research as well as “index” properties for specification use
- ☐ Review of literature shows all obey time-temperature superposition

Ultimate Property Tests – Some Examples

- ❑ Strength
  - ✓ Not fundamental property
  - ✓ Value depends upon specimen size and configuration
  - ✓ Easy to measure
- ❑ Fracture Properties
  - ✓ Properties independent of specimen size and configuration
  - ✓ Difficult to measure – require viscoelastic characterization
- ❑ Energy to Failure – Cohesive energy to fracture
  - ✓ Not fundamental property
  - ✓ Value depends upon size and configuration
  - ✓ Easy to measure

Theme of Today’s Presentation

- ❑ Ultimate properties depend upon test temperature and rate of loading
  - ✓ For specification purposes an ultimate property must be determined at the use temperature
  - ✓ Specifying and ultimate property a single temperature for all binder grades will give misleading results
- ❑ Ultimate properties obey time-temperature equivalency
  - ✓ Linear viscoelastic time-temperature shift functions also define time-temperature dependency of ultimate properties

Stiffness - Linear visco-elastic parameters

- ❑ Linear visco elastic parameters – test conditions
  - ✓ Measurements at small strain areas
  - ✓ BBR, DSR measurements
  - ✓ Used to generate numerical time-temperature algorithm and material dependent parameters

Note: Literature for a wide range of materials shows that both linear, non-linear, and empirical index properties obey time-temperature superposition

Ultimate Properties – Test Parameters

- What is an ultimate property?
  - Stress/strain at break
  - Energy
  - Fracture property
  - Etc.
- Objective of today’s presentation ……………………
  - To illustrate how rheology can be used as a descriptive tool for ultimate properties
  - The demonstrate that an understanding of rheology is necessary to properly interpret and use ultimate properties
  - 3 major items to be considered

Issue 1: 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
  - ✓ Mixtures, FENIX test, Constr. and Bldg. Materials, (2012), pp 372-380.

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

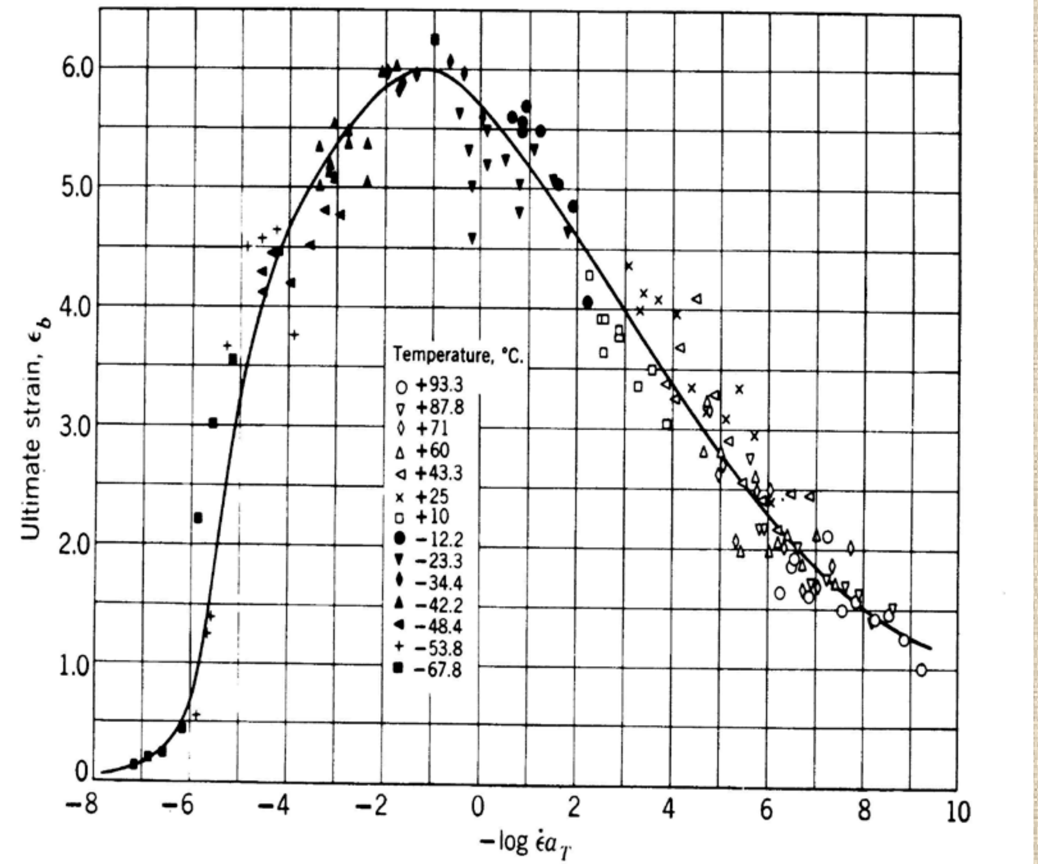
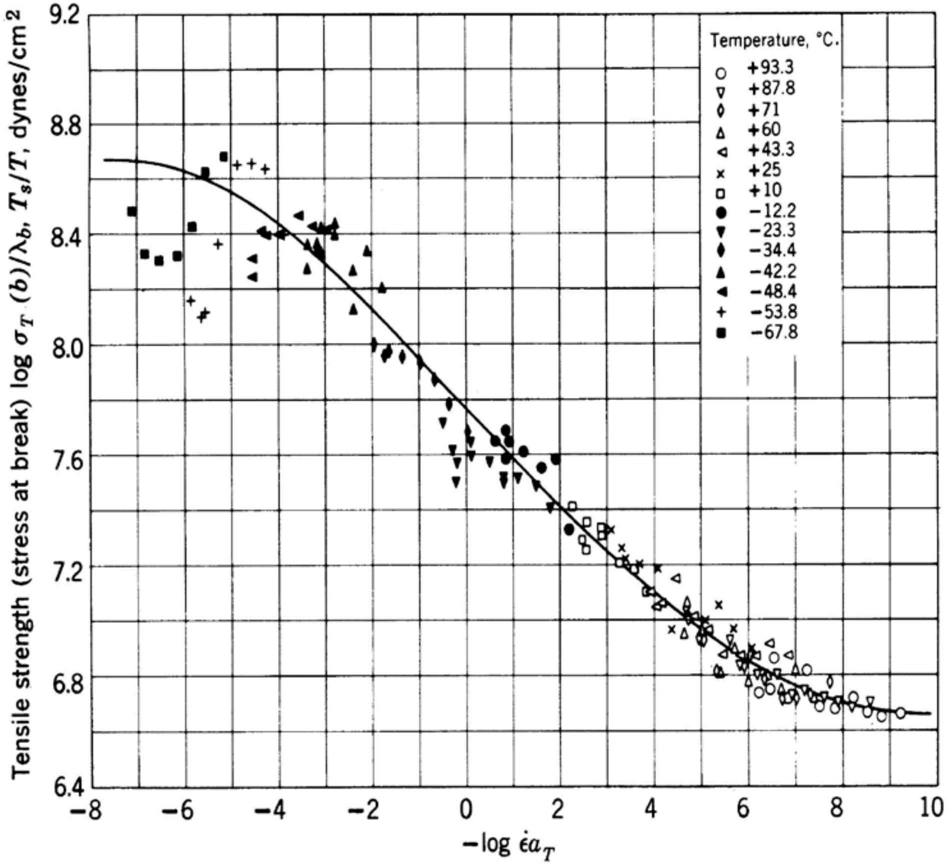


FIG. 19–3. Tensile strain at break plotted against logarithm of strain rate (in sec^{-1}) reduced to 263°K for a cross-linked styrene-butadiene rubber at 14 temperatures as indicated (Smith.[106])

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



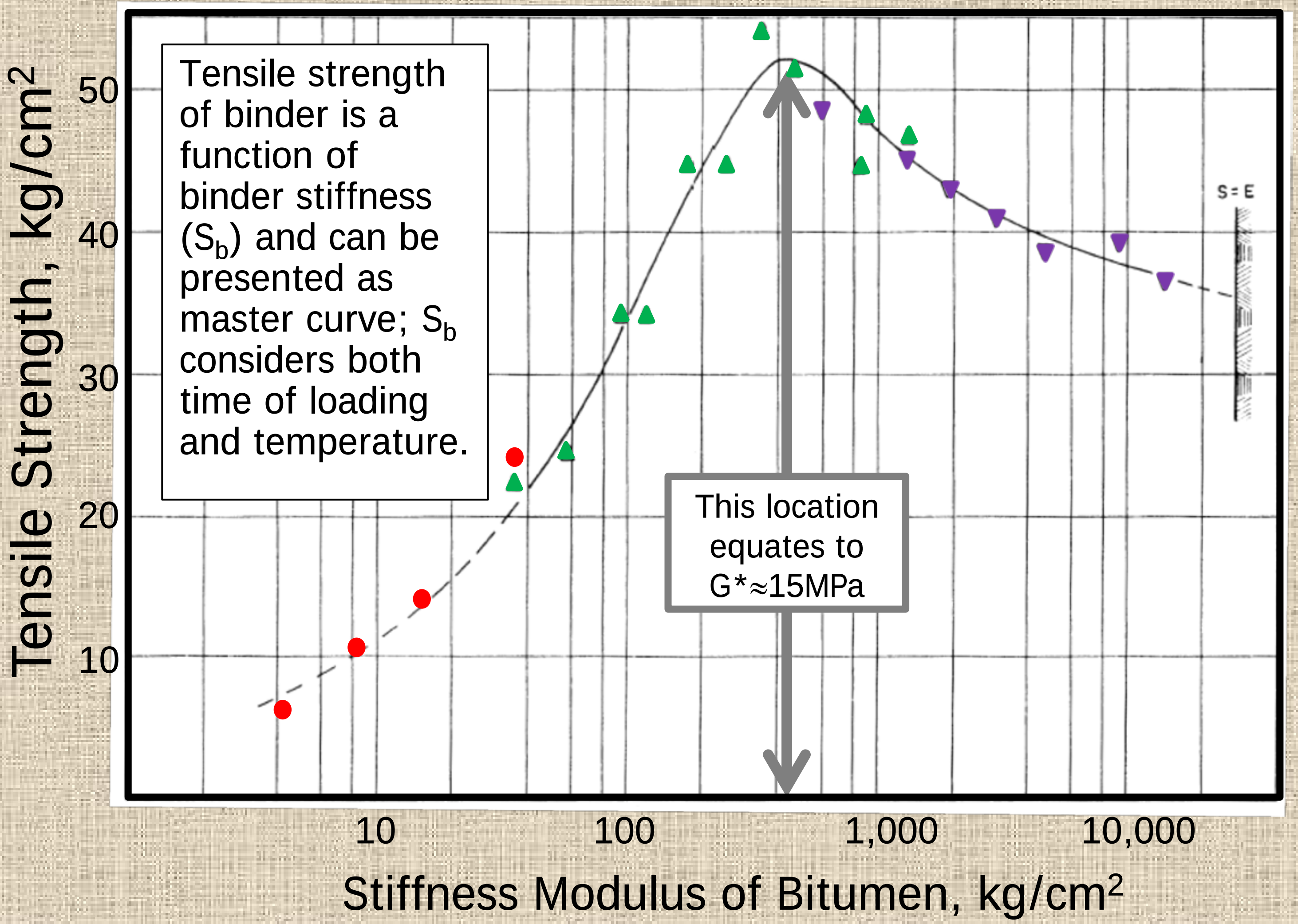
Tensile Strength

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$_{10}$ strain rate

Heukelom (1966)

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

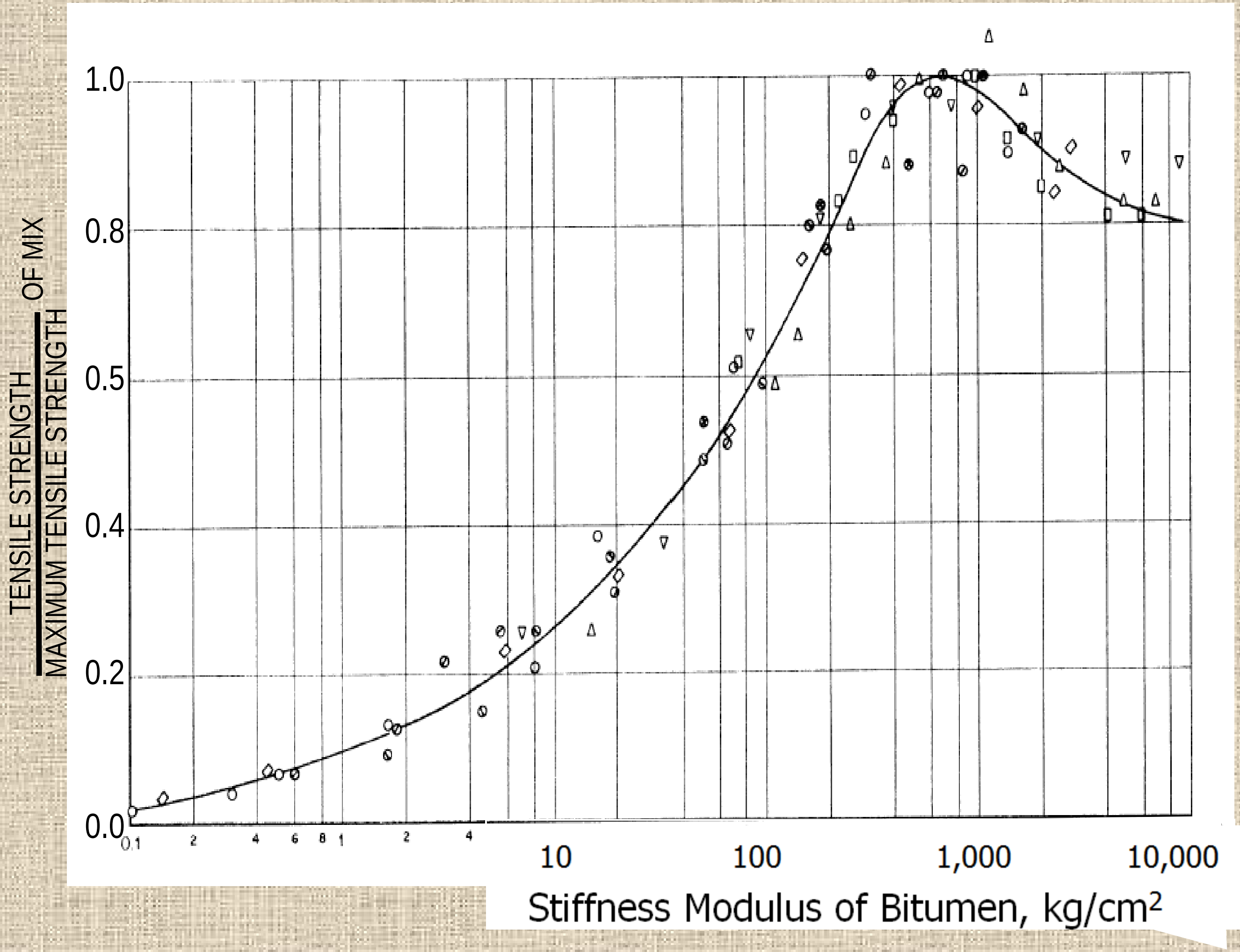


Tensile strength of binder is a function of binder stiffness (S_b) and can be presented as master curve; S_b considers both time of loading and temperature.

This location equates to G*≈15MPa

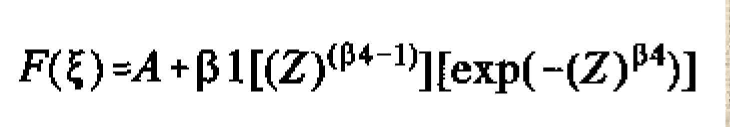
Heukelom (1966)

- Extended testing to mixtures with same result
- Done for 8-mix types

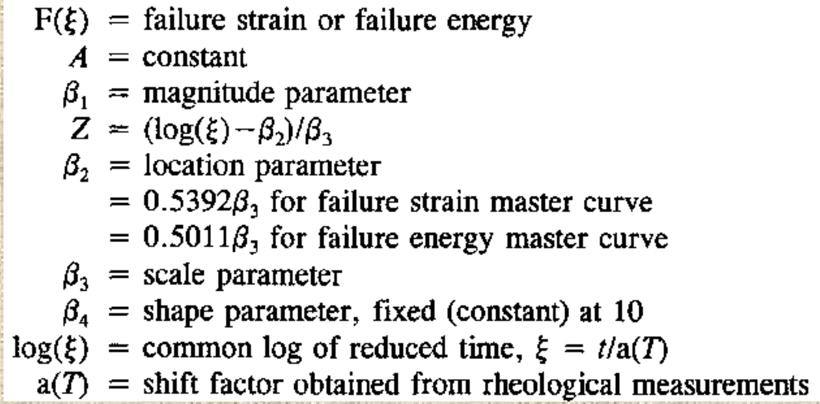


SHRP A-369, Anderson et. al (1994)

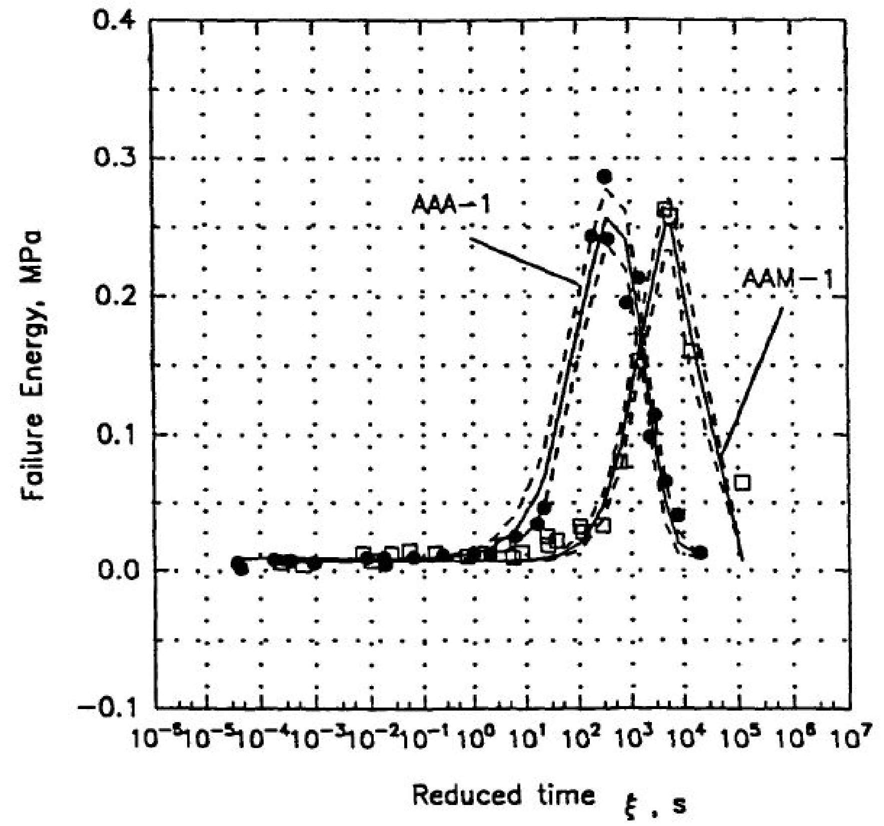
- Failure master curves of stress, strain and energy for conventional binders
- Functional form for energy



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



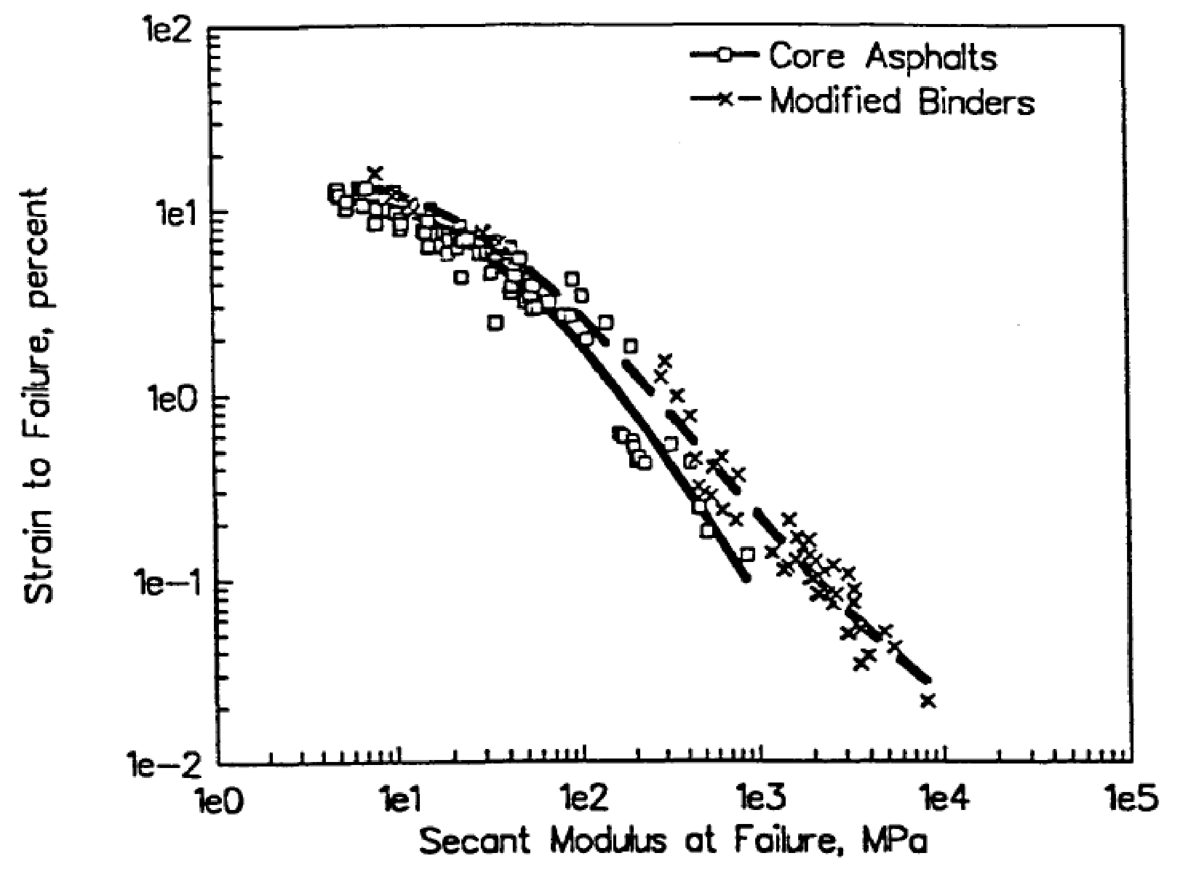
$F(\xi)$ = failure strain or failure energy
A = constant
β_1 = magnitude parameter
Z = $(\log(\xi)-\beta_2)/\beta_3$
β_2 = location parameter
= $0.5392\beta_3$ for failure strain master curve
= $0.5011\beta_3$ for failure energy master curve
β_3 = scale parameter
β_4 = shape parameter, fixed (constant) 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 A-369, Anderson et. al (1994)

- Also looked at SECANT modulus at failure from DTT test
- Secant modulus can be considered as a “binder stiffness”
- Produces single curve for all binders tested during SHRP 2A Project



Summary - Item 1

- ☐ 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!

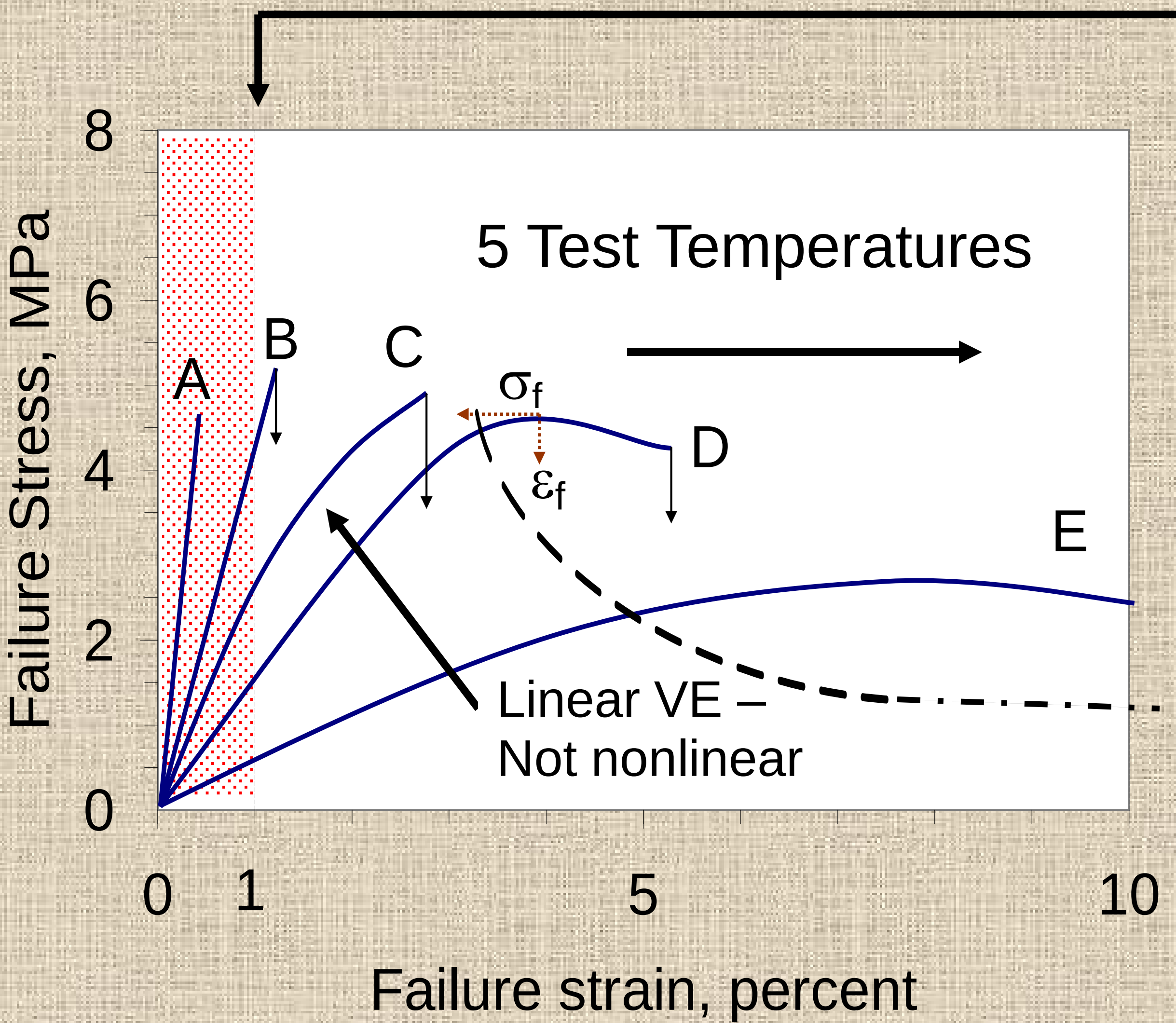
Item 2 - Brittle to instability flow (ductile)

- Fatigue and fracture will exhibit a brittle to instability flow (ductile) transition!

Item 2

- Stiffness can be used to define the transition between “ductile” and “brittle” failure
  - ✓ Not a single stiffness value bit range
  - ✓ Perhaps better said between brittle and brittle-ductile behavior
- Failure mechanism changes as pass through transition
  - ✓ “True” fatigue behavior with crack propagation in traditional sense occurs below this transition
  - ✓ Crack formation by viscous flow above transition
- Definition of brittle and definition via yield stress associated presence controversial at least!

Typical Stress-Strain Curves

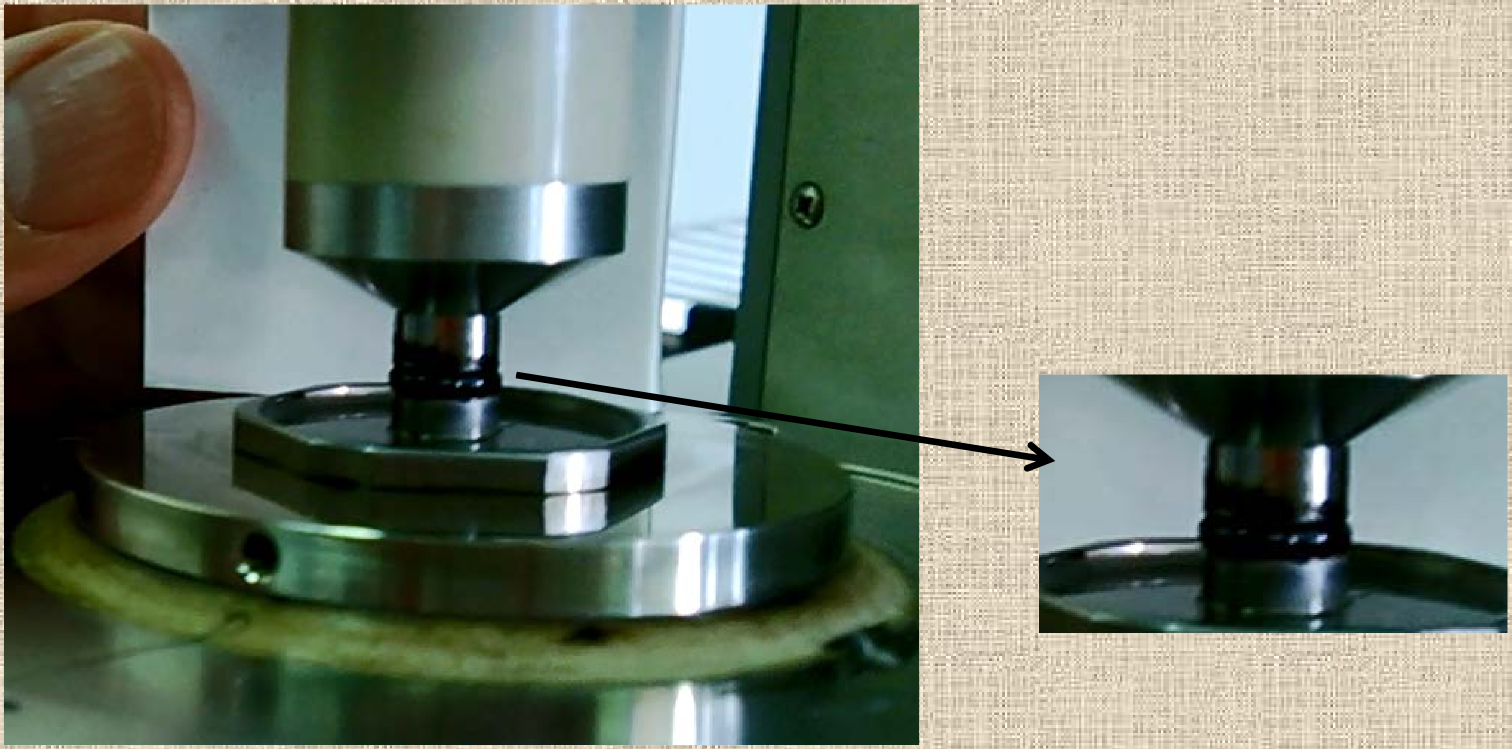


At test conditions used in DTT approximately equal to 300 MPa in BBR at 60s

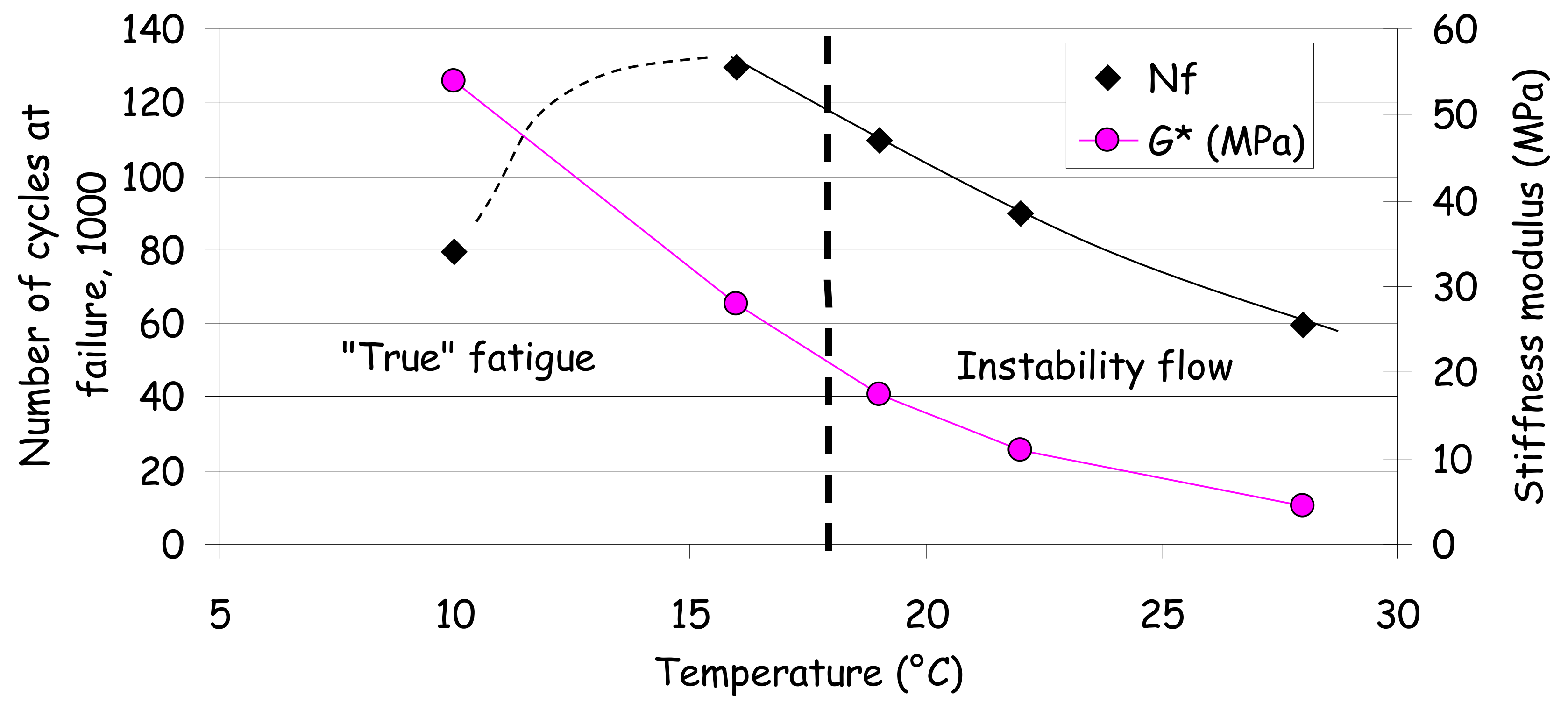
Linear VE limit

Observations from DSR “Fatigue” Test

- Evolution of failure in LAS test
- Observe flow above room temperature



“Fatigue” vs. Temperature



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

Stiffness range where instability flow dominates

- Range in stiffness where fatigue cracking and instability flow dominate

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

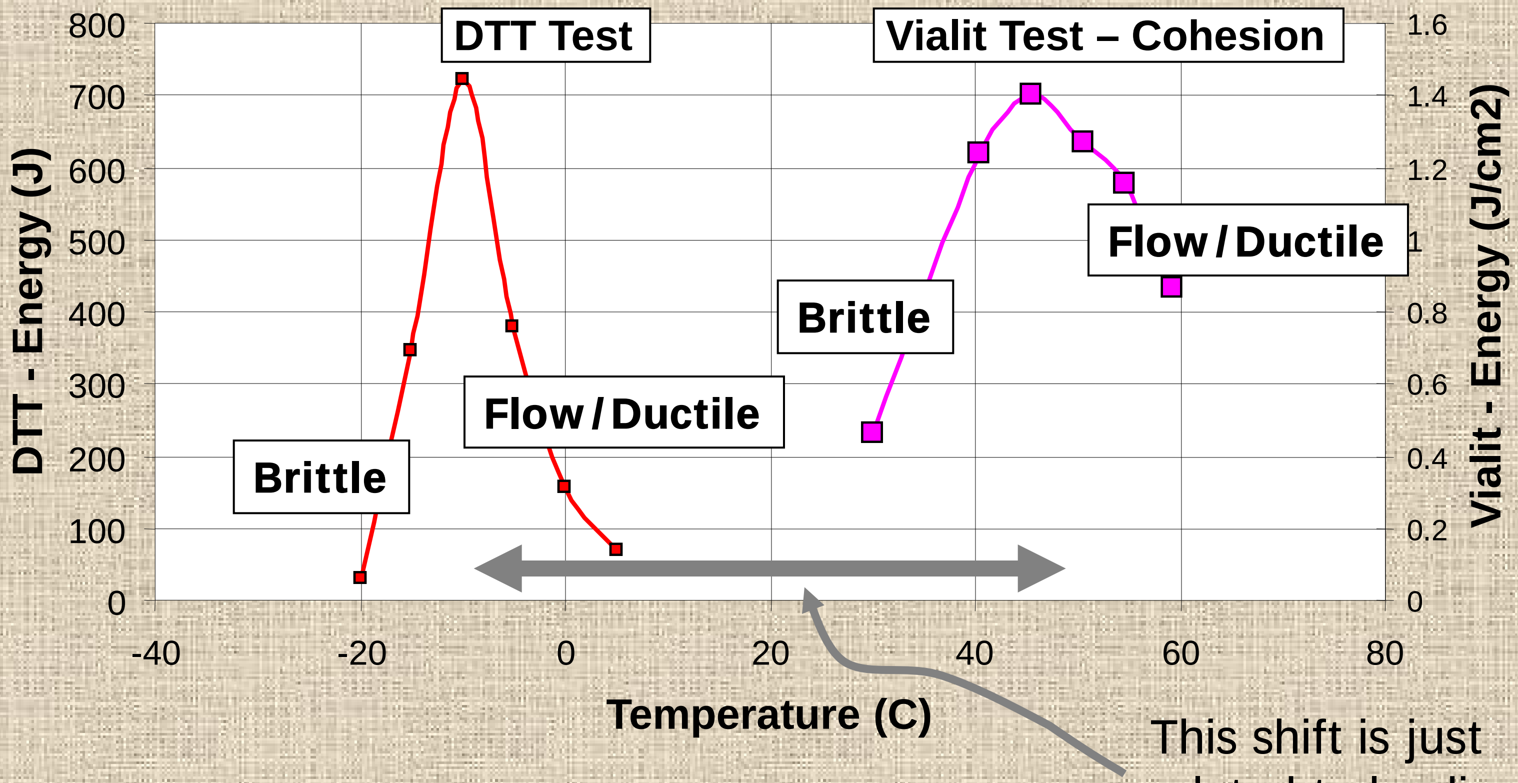
- Note that values are in same range as presented above for strength
  - ✓ Stiffness normalizes the effect of temperature and loading rate

Item 3

- Importance of loading speed on temperature window
- Temperature window depends upon speed of loading
  - ✓ Example demonstrated with Vialit Cohesion Test

Example of a cohesion fracture test

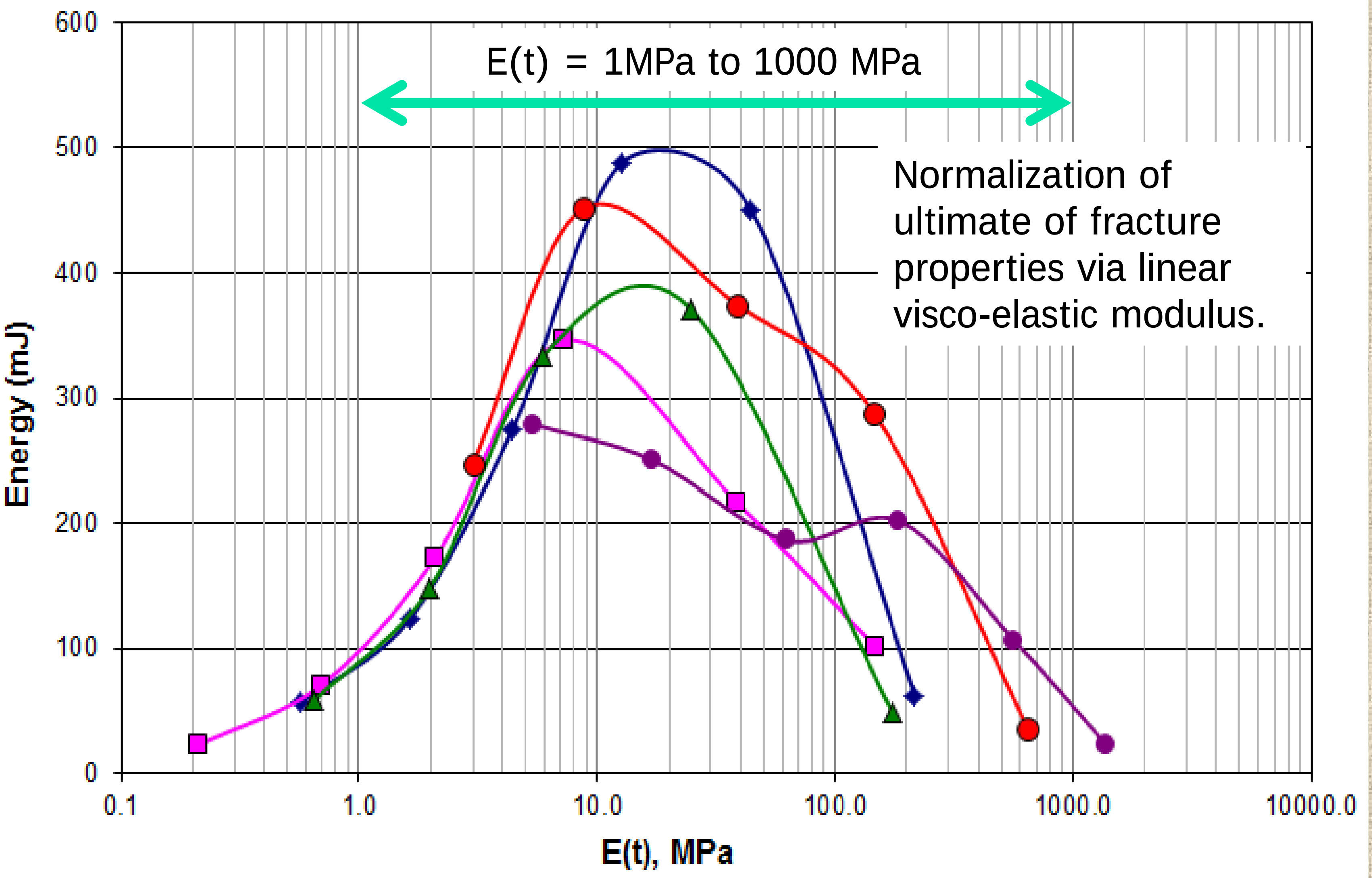
Fracture properties and temperature



This shift is just related to loading time/rate! Width is related to rate!

Really a stiffness effect – needed to explain these brittle to ductile transitions.

Energy plots for DTT data
– Energy to failure vs. Modulus



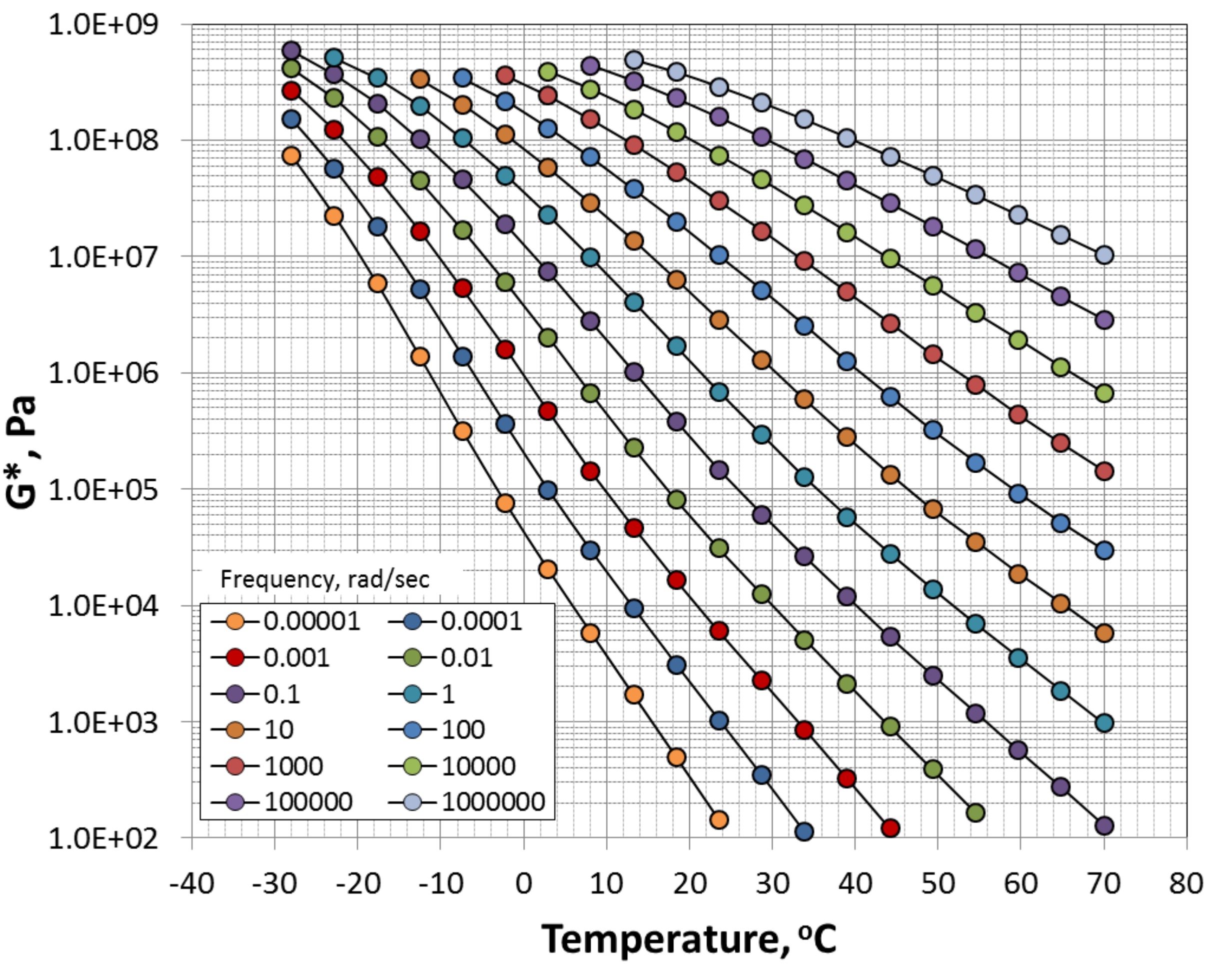
Normalization of ultimate of fracture properties via linear visco-elastic modulus.

Range of stiffness needed

- ❑ If using E(t) – previously observed flow/ductile to brittle range covered from about 1MPa to 1000 MPa
- ❑ Note G*≈ E(t)/3
  - ✓ 300 kPa to 300 MPa – 3.0x10^9 to 3x10^8 Pa
- ❑ CA model fit works well in limited range 10^5 to 10^9 Pa
  - ✓ This range covers stiffness range above where we would describe fracture behavior
  - ✓ We use the CA model to generate isochronal plot for stiffness in this range

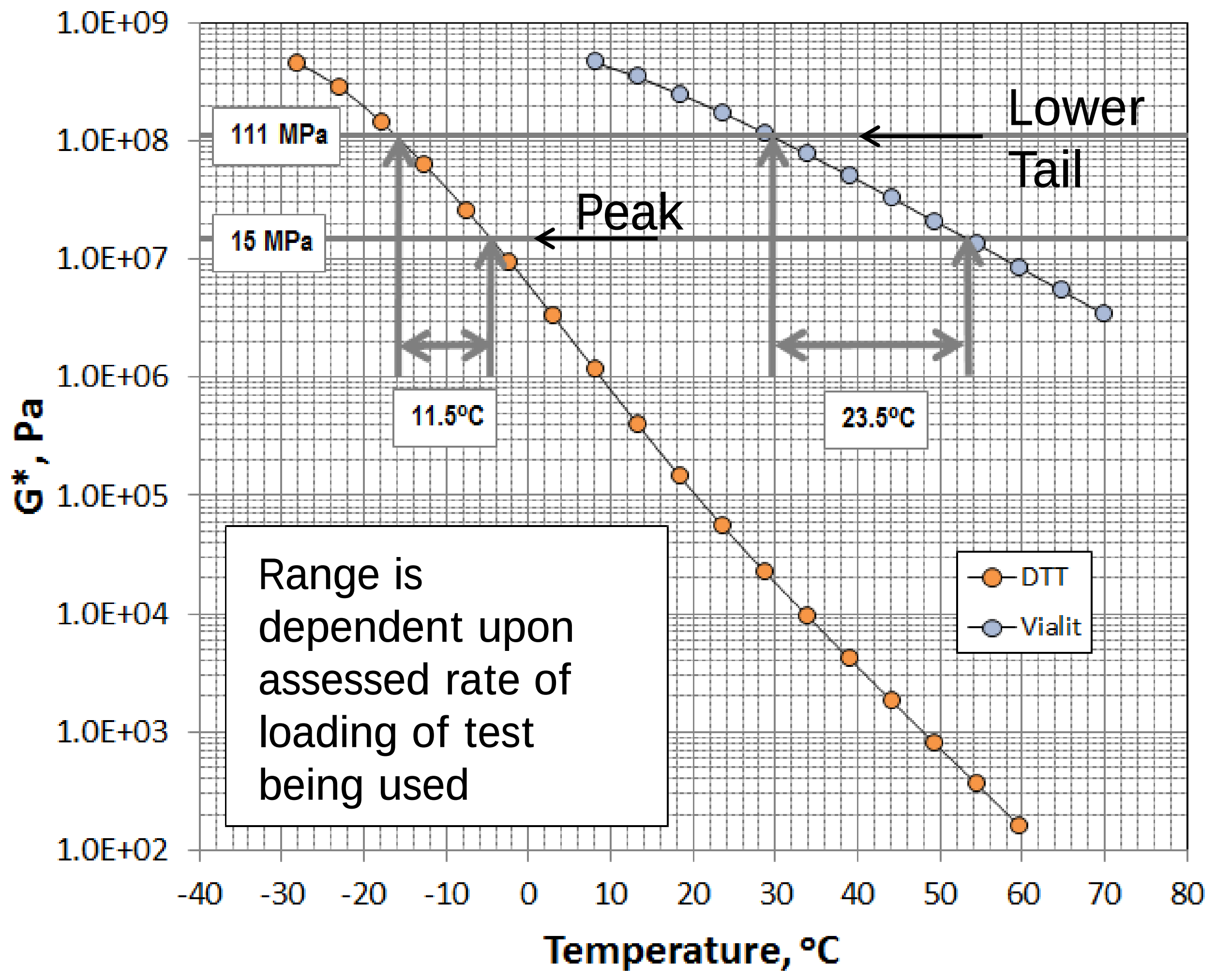
Rate of loading effects

- Rate of loading effects range of results that will be obtained in temperature domain if properties are dependent upon stiffness as shown earlier.
- Rate of any fracture test is key to understanding behavior.



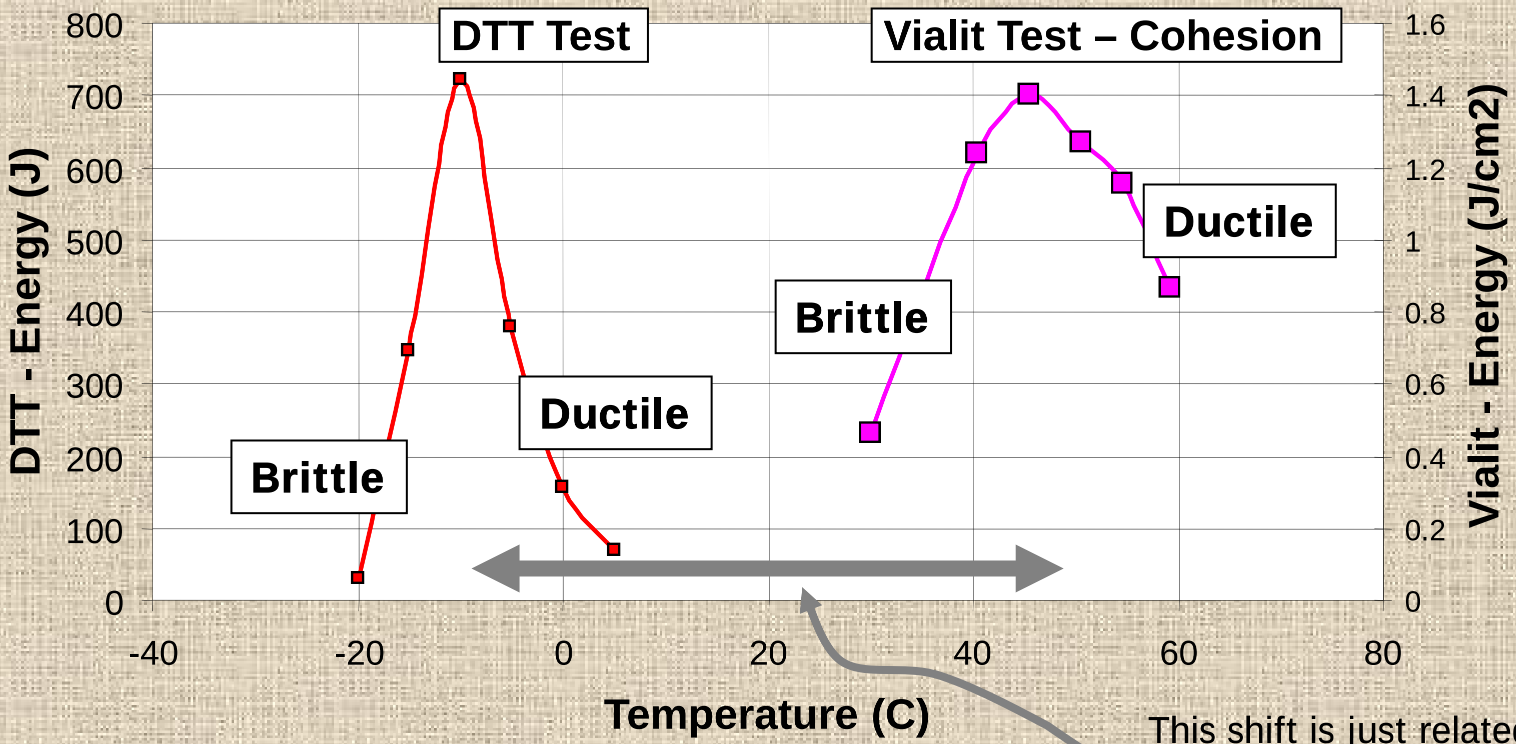
Loading rate versus temperature range, assessed from DSR data

- The loading rate in Vialet and DTT can be used to generate isochronal plot for each test
- A fast rate will give a shorter temperature range since



Range is dependent upon assessed rate of loading of test being used

Fracture properties and temperature

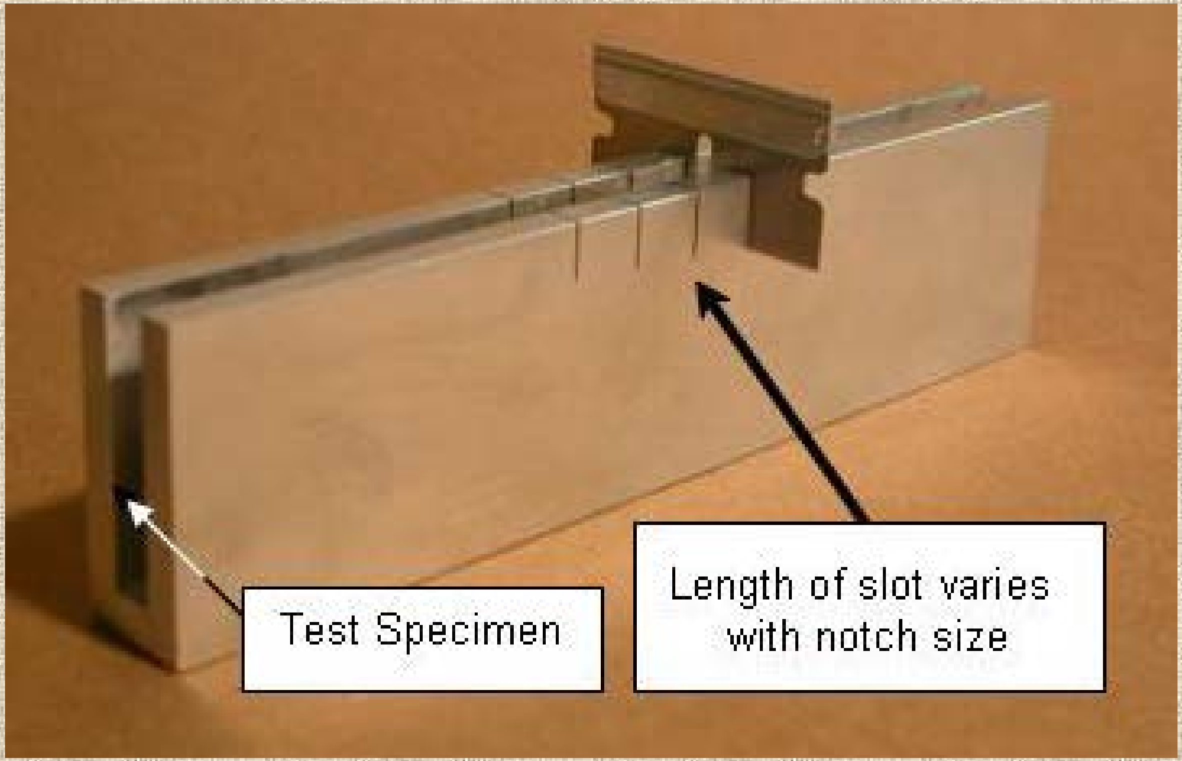


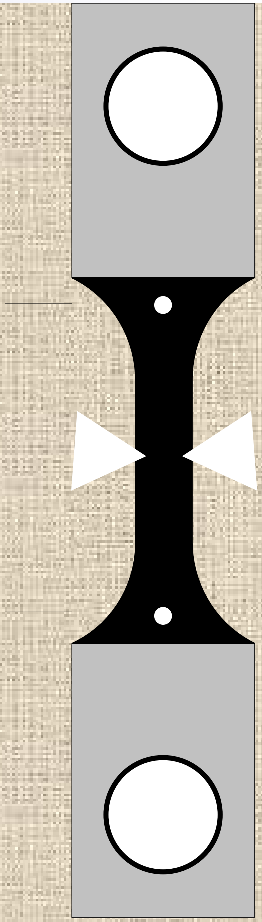
This shift is just related to loading time/rate! Width is related to rate!

Really a stiffness effect – needed to explain these brittle to ductile transitions.

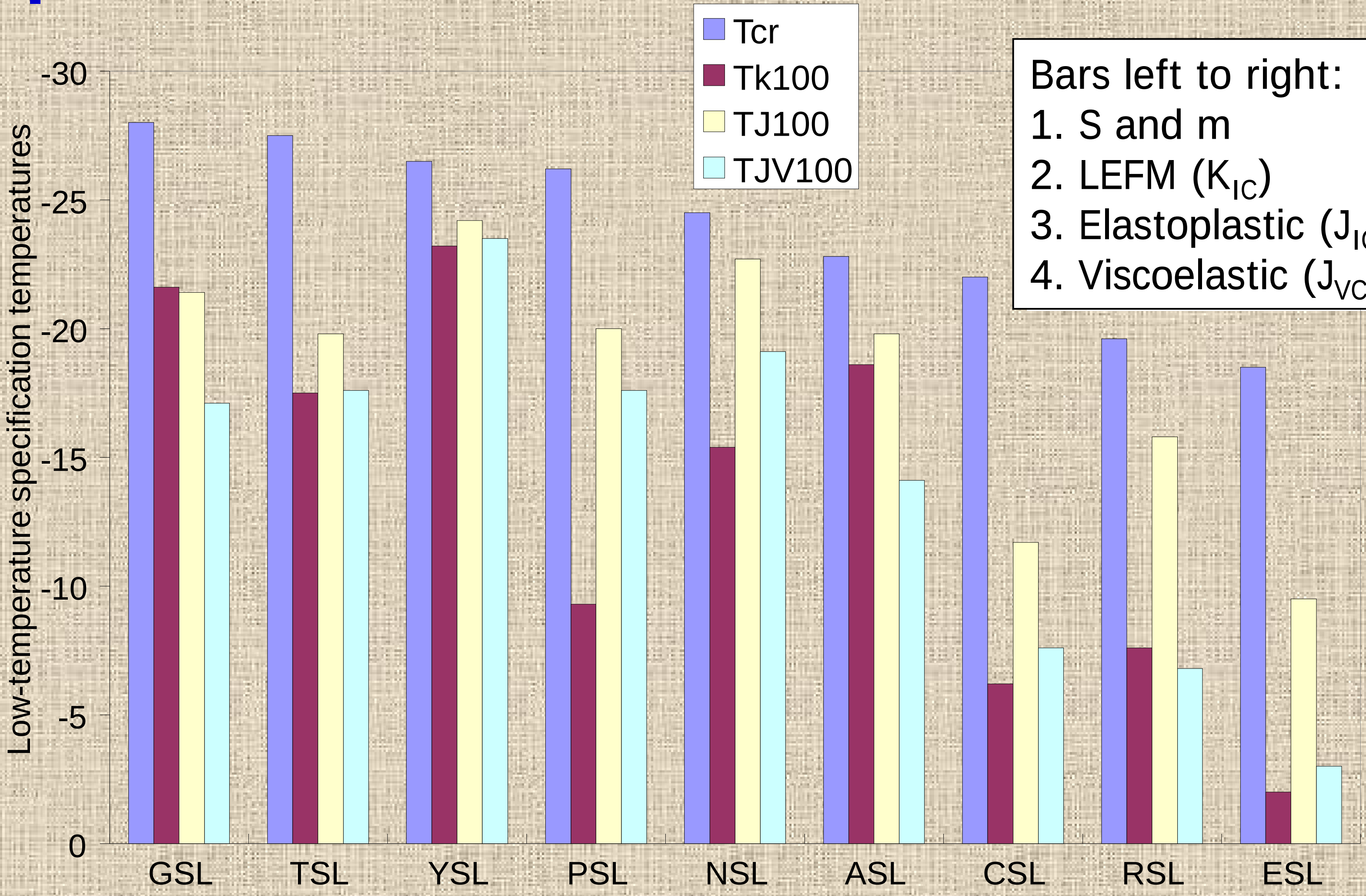
Fracture Properties from Double Notched Test in Tension

Evaluation of Elastic, Plastic, and VE Fracture Mechanics Parameters





Ranking depends on methodology
Ranking at equi-toughness

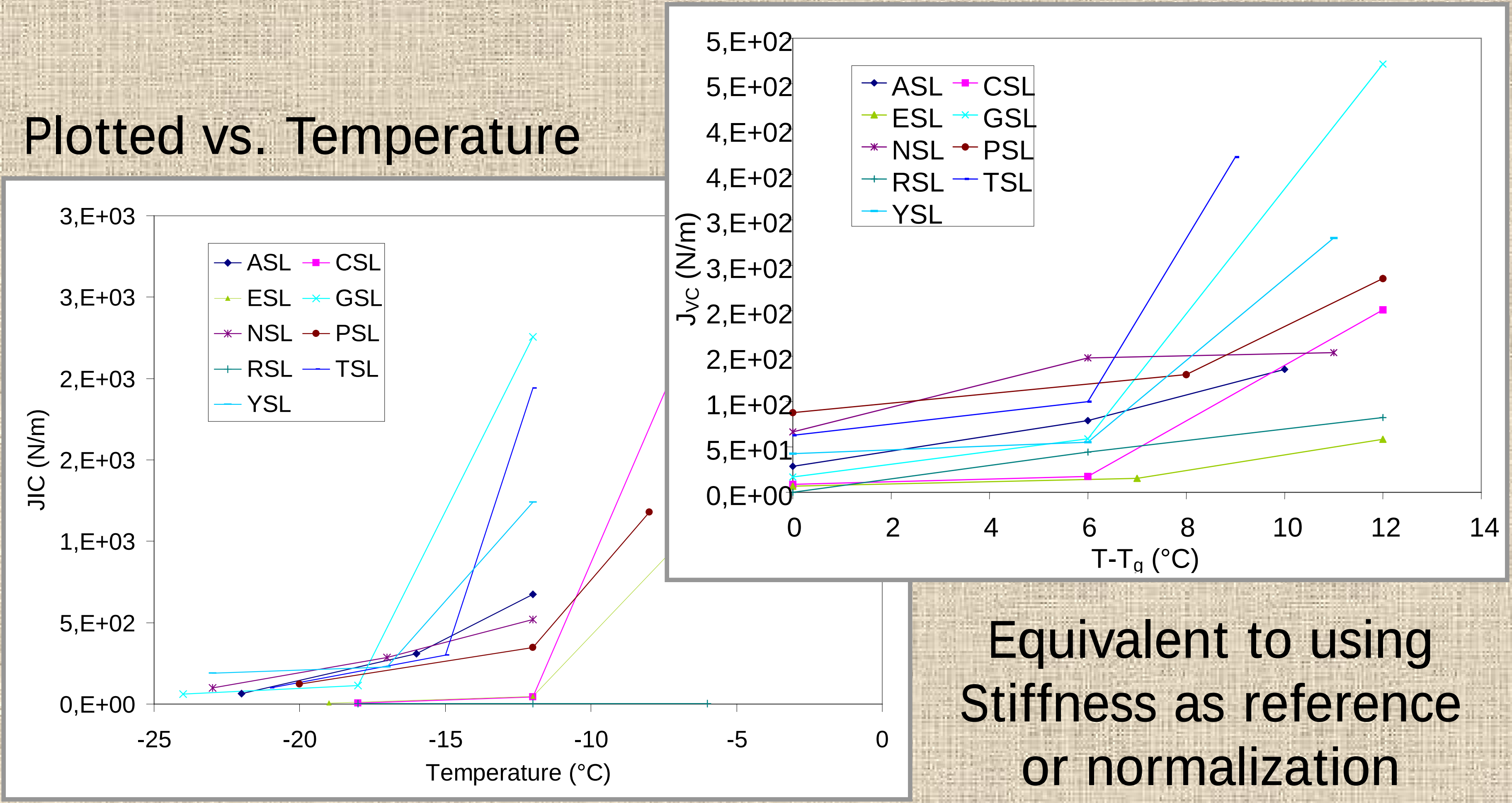


Bars left to right:
1. S and m
2. LEFM (K_{IC})
3. Elastoplastic (J_{IC})
4. Viscoelastic (J_{VC})

Use of T_g as reference temperature when analyzing fracture mechanics parameters

Plotted vs T - Tg

Plotted vs. Temperature



Equivalent to using Stiffness as reference or normalization temperature!

Item 3

- Temperature window – of interest depends on the rate of loading

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 – beyond scope of today's presentation – rheology 101 for March 2016?
  - ✓ Time-temperature algorithm is uniformly valid for rheology and ultimate properties

Item 3 – Importance of rheological behavior when evaluating ultimate properties

- ❑ Rheological type
  - ✓ Linear visco-elastic behavior relates to ultimate properties whether they be fatigue, “cracking” strength, or whatever the property of interest may be
  - ✓ Can use this in analysis
  - ✓ Can use this in testing for reasonableness
- ❑ When comparing ultimate properties need to do comparison at equi-stiffness temperature
  - ✓ Corollary: In specification test must obtain parameters service temperature at rate consistent with service

Items 1 to 3

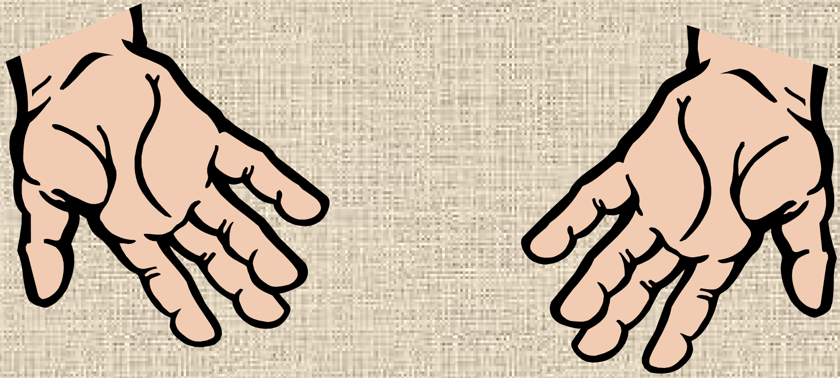
- Require that we determine stiffness characteristics accurately for range that effects cracking
- Model stiffness master curve with BBR, DSR and CA fit with Kaelble
  - ✓ Possible from standard data that is collected
- Food for thought……
  - ✓ When writing a specification specify ultimate properties at temperature and loading rate consistent with service

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

Summary

1. Stiffness – G*, E(t) is a vital element in specification-interpretation of ultimate properties
    1. When conducting research carefully consider the relationship between loading rate-temperature-stiffness
    2. Ultimate binder property at single temperature-loading rate is a poor candidate for predicting performance
2. A transition between brittle and flow-type behavior occurs at approximately 10-30 MPa
3. The rheological type is of key importance to understand ultimate properties/performance
4. Consequences:
    1. Data collection – only use G* >1 x 10^5 MPa in model fits
        - ✓ Sufficient to describing brittle to ductile fracture, etc.
    1. Capture data in range of stiffness to cover transitions!
    2. Linear VE time-temperature dependency of binder also relates to cracking of mixes – thermal, fatigue, durability, etc.
        - ✓ Dependent upon shape and position of master curve stiffness and relaxation properties



GOODBYE!

Geoff sends his best wishes to everyone!