Evaluation of Aspects of E* Test Using HMA Specimens with Varying Void Contents

Dr. Geoffrey Rowe - Abatech Inc.
Mr. Salman Hakimzadeh - University of KY
Mr. Phillip Blankenship – The Asphalt Institute
Dr. Kamyar Mahboub – University of KY

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Objectives of paper

- Consider and compare different analysis techniques for construction of the master curve
- Measure and analyze the effect of permanent strain on samples that have been tested using the SPT modulus test

Study formed part of project being conducted for Kentucky Transportation Cabinet (with support from FHWA) to assess the effect of differing levels of compaction on a typical mixture performance.

Overview

- Experimental
- Analysis
- Observations
- Recommendations
- Conclusion

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Experimental - Mix design

- Used a standard KY mix design
  - 25% Limestone #8's
  - 26% limestone sand (unwashed), 14% limestone sand (washed)
  - 15 percent natural sand (rounded)
  - Asphalt binder (PG 64-22)

Specimen and test setup

- Specimen production from gyratory specimens by cutting and coring
- Temperature condition
- Tested in IPC SPT tester

Experimental - Compaction levels

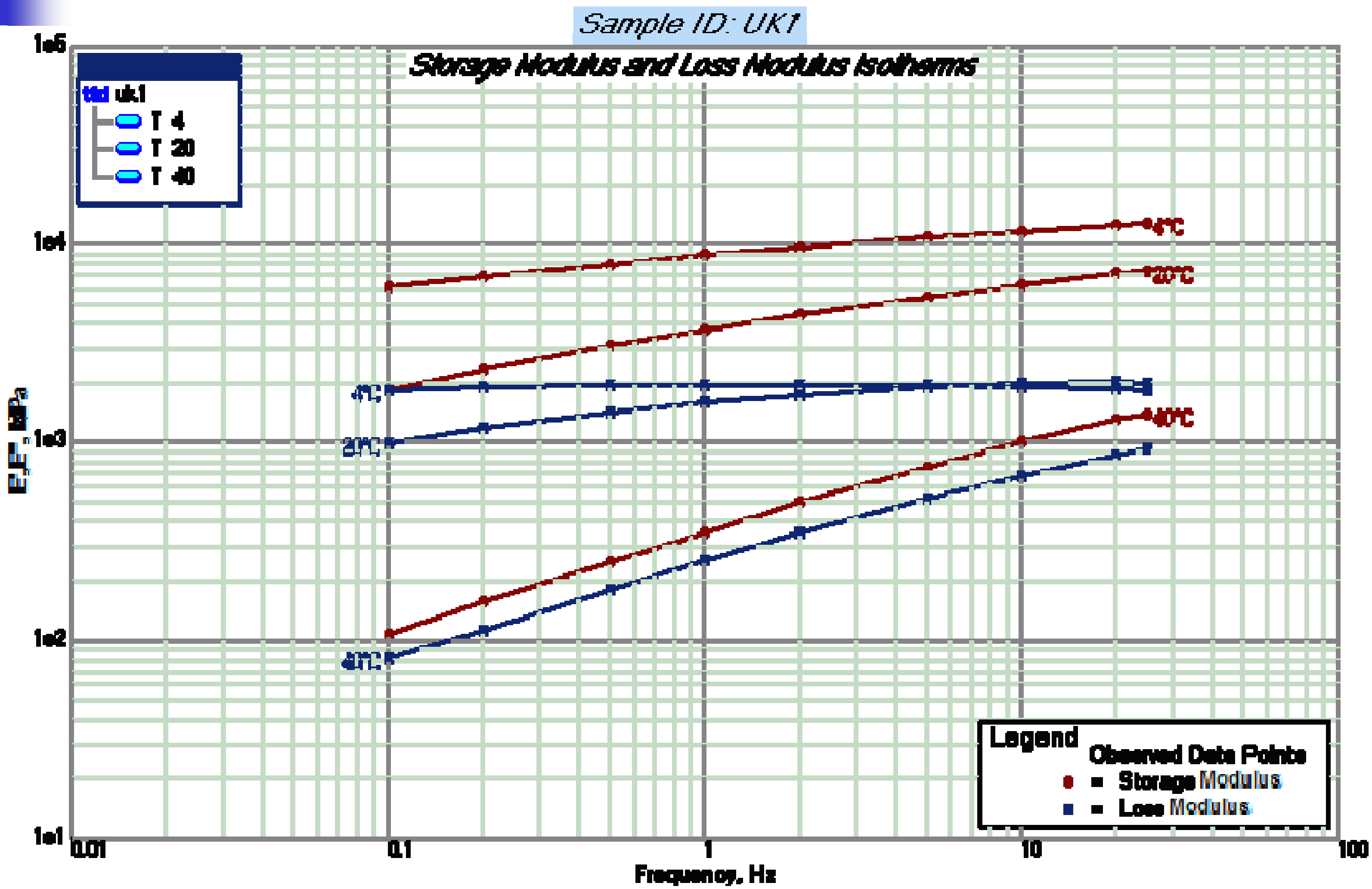
- Compacted in Superpave Gyratory Compactor to give different volumetrics

Series Ref.	Air Voids, %	VMA, %	VFA, %
1	11.3	21.1	46.3
2	9.8	19.8	50.2
3	8.4	18.5	54.6
4	7.1	17.4	58.8
5	5.5	15.9	65.4
6	3.8	14.5	73.4
7	2.3	13.1	82.1

Testing

- |E*| tests AASHTO TP 62-03
- 7 series → (14 specimens – 2 at each void content)
- 3 temperatures (4, 20 and 40°C)
- 9 frequencies (25, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1 Hz)
- |E*| and δ for each test condition

Typical data – expressed as E' and E"



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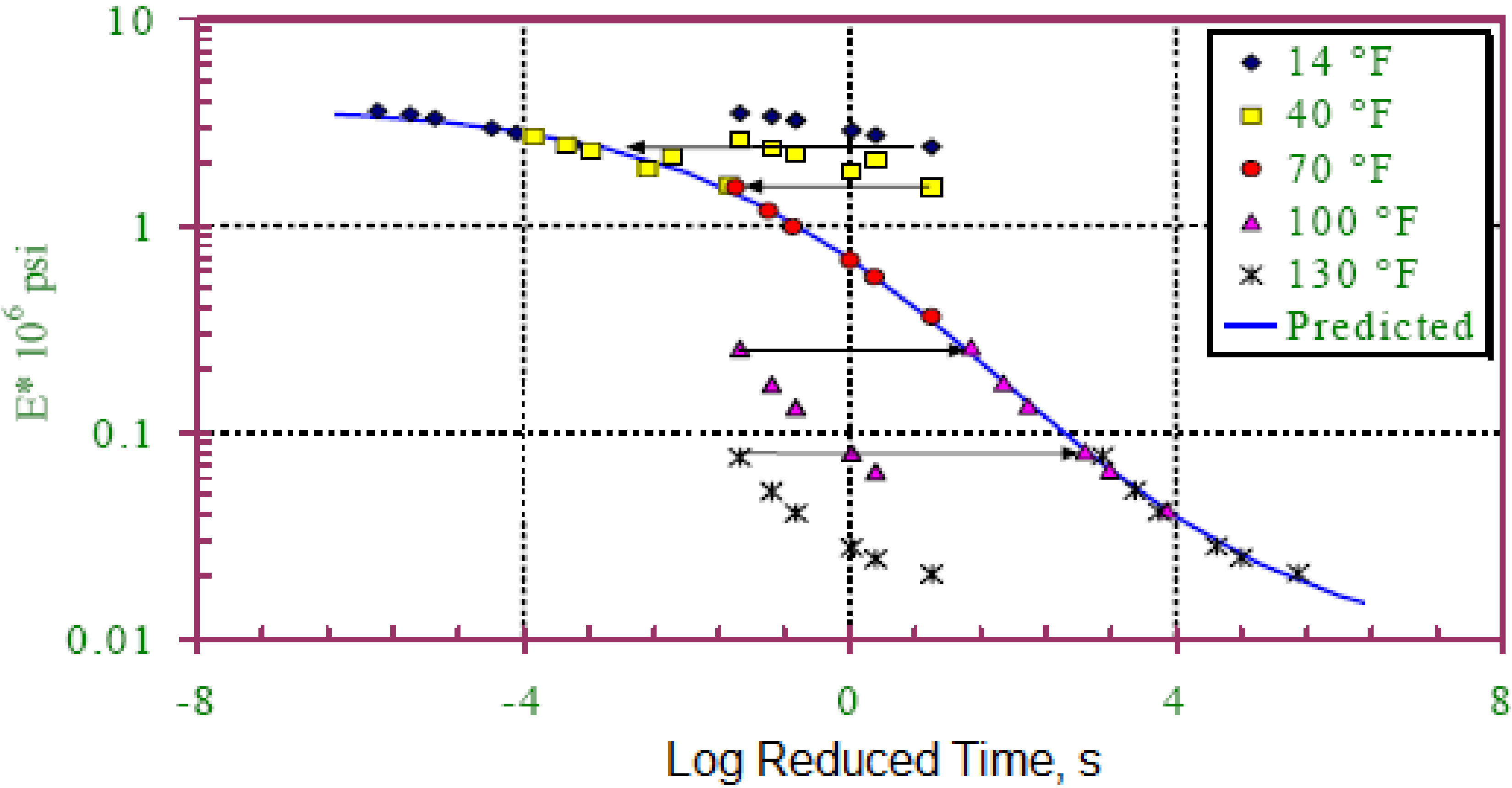
Analysis - to produce E* master curve in MEPDG format



E* format

MEPDG referenced as Witczak's (symmetrical or standard logistic) Sigmoid

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log\omega)}}$$

Alternate sigmoid - Richards' (non-symmetrical or generalized logistic) Sigmoid

$$\log|E^*| = \delta + \frac{\alpha}{\left[1+\lambda e^{\beta+\gamma(\log\omega)}\right]^{1/\lambda}}$$

δ *Lower asymptote, limit for |E*| at long loading times and high temperatures*

α *Describes upper asymptote, (δ+α) gives limit for |E*| at short loading times and low temperatures*

β,γ, λ Describes the shape of the sigmoid

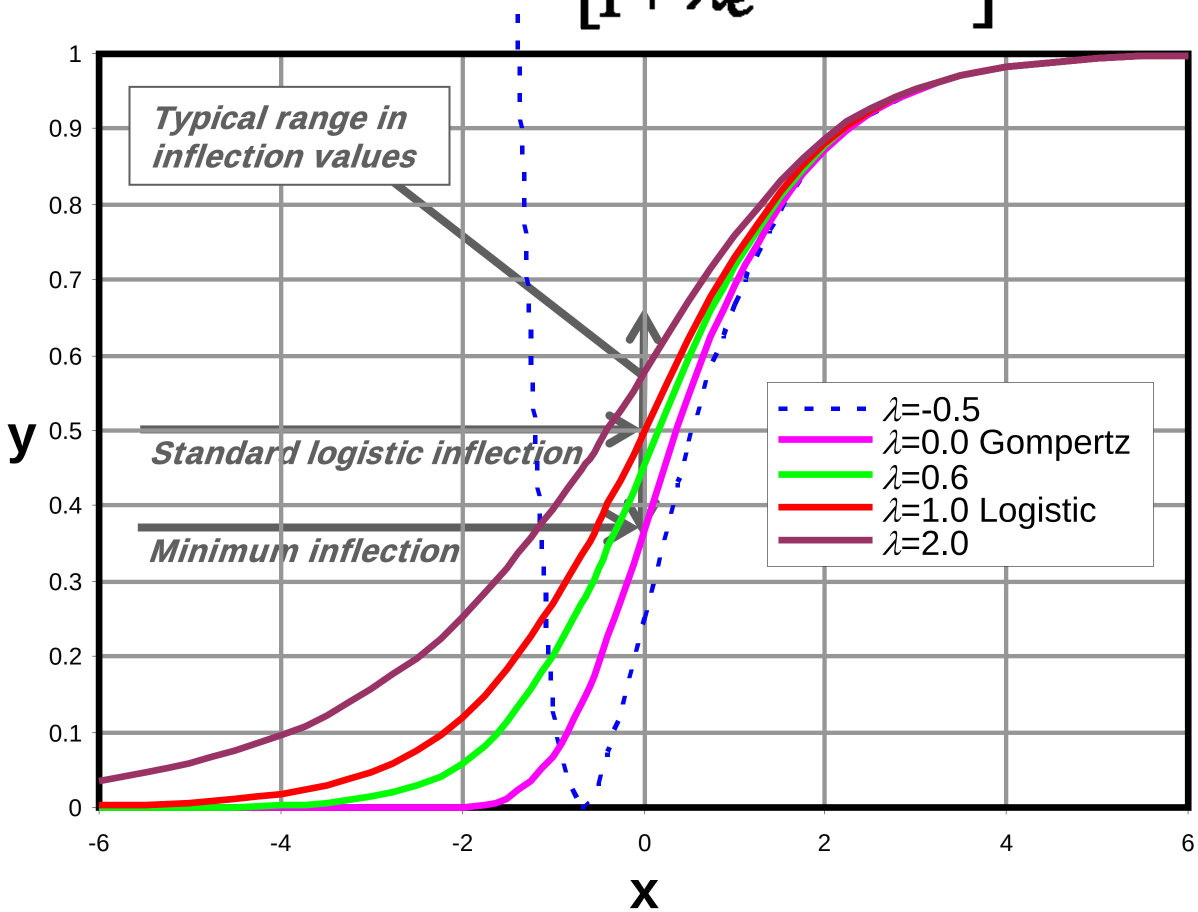
Analysis methods

- Excel-Solver analysis using solver to obtain master curve fits using the Witczak sigmoid function.
- RHEA™ produced an analysis with discrete spectra to obtain glassy and equilibrium modulus values and other contributing parameters to the relaxation and retardation spectra.
- RHEA - further used to determine fits to both Witczak's (standard logistic curve) and the Richard's sigmoid (generalized logistic curve) functions.

Why Generalized logistic

$$\log(E^*) = \delta + \frac{\alpha}{[1+\lambda e^{(\beta+\gamma \log \omega)}]^{1/\lambda}}$$

- Generalized logistic curve (Richard's) allows use of non-symmetrical slopes
- Introduction of additional parameter λ
  - When λ = 1 equation becomes standard logistic
  - When λ tends to 0 – then equation becomes Gompertz
  - λ must be positive for analysis of mixtures since negative values will not have asymptote and produces unsatisfactory inflection in curve
  - Minimum value of inflection occurs at 1/e – or 36.8% of relative height



Glassy and equilibrium

- Glassy and equilibrium modulus are considered as the asymptotes that are obtained from the various model fits with the glassy modulus corresponding to the higher asymptote and the equilibrium corresponding to the lower asymptote

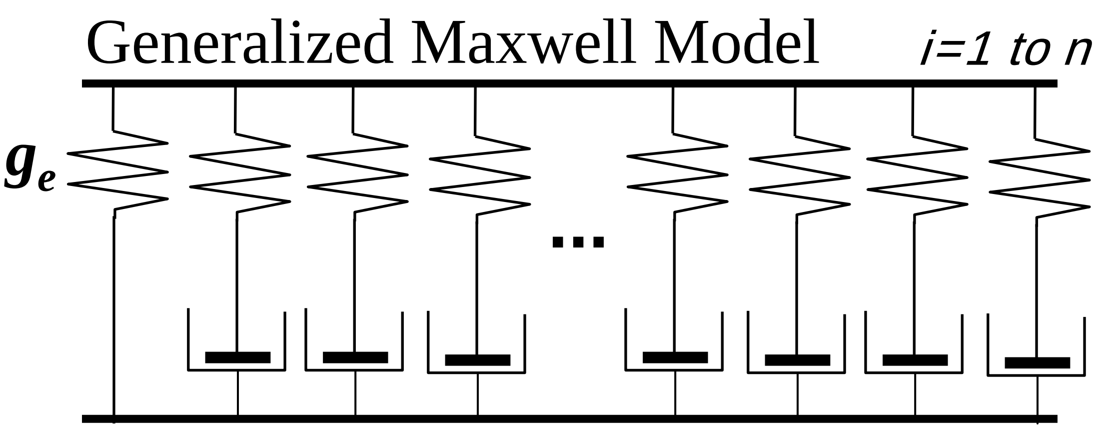
$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log \omega)}}$$

equilibrium modulus

$\alpha + \delta =$ glassy modulus

Glassy and equilibrium

- Glassy and equilibrium modulus also computed for visco-elastic solid fit of discrete spectra to data set



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

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

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

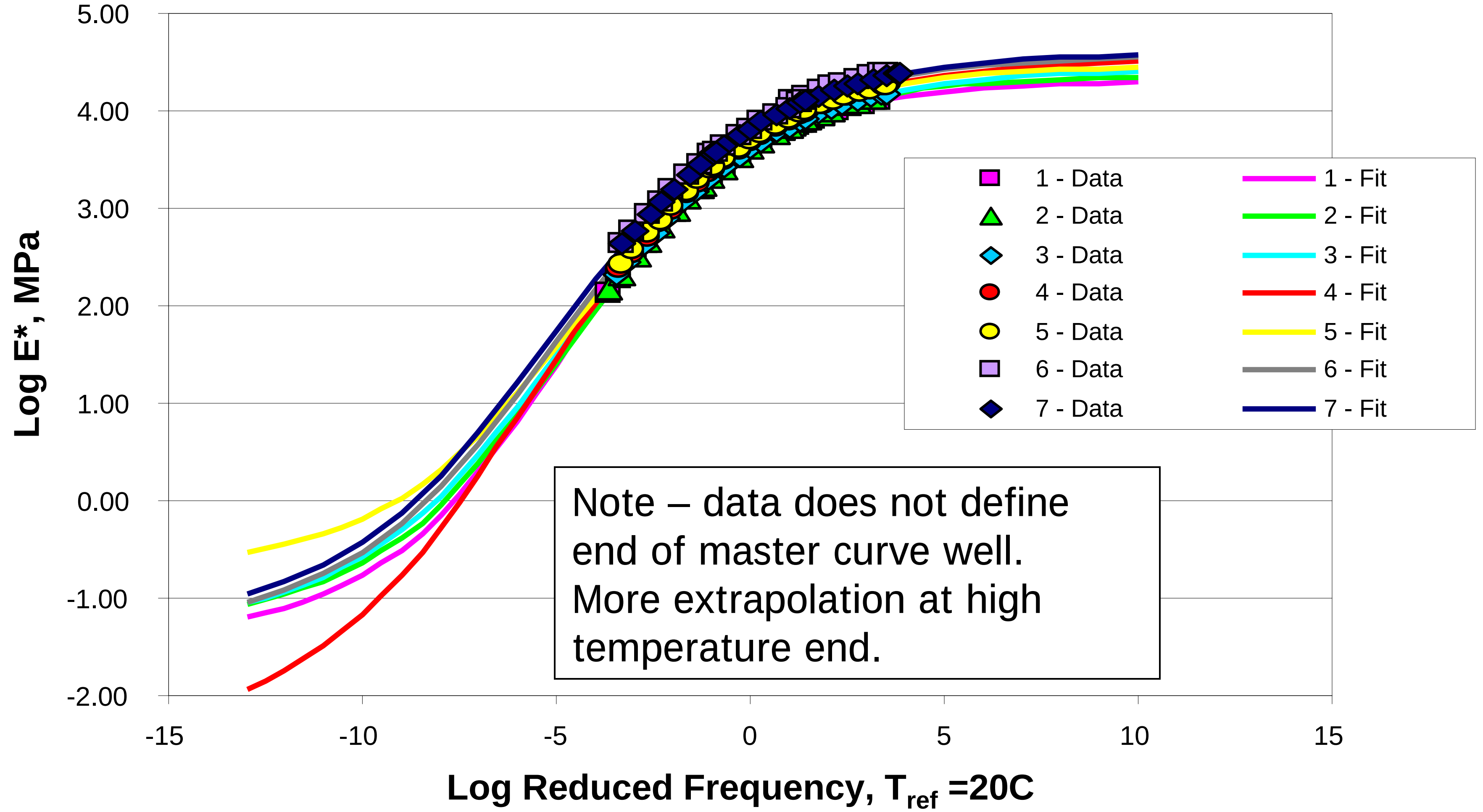
Consider

Spring constant, stiffness, g_i

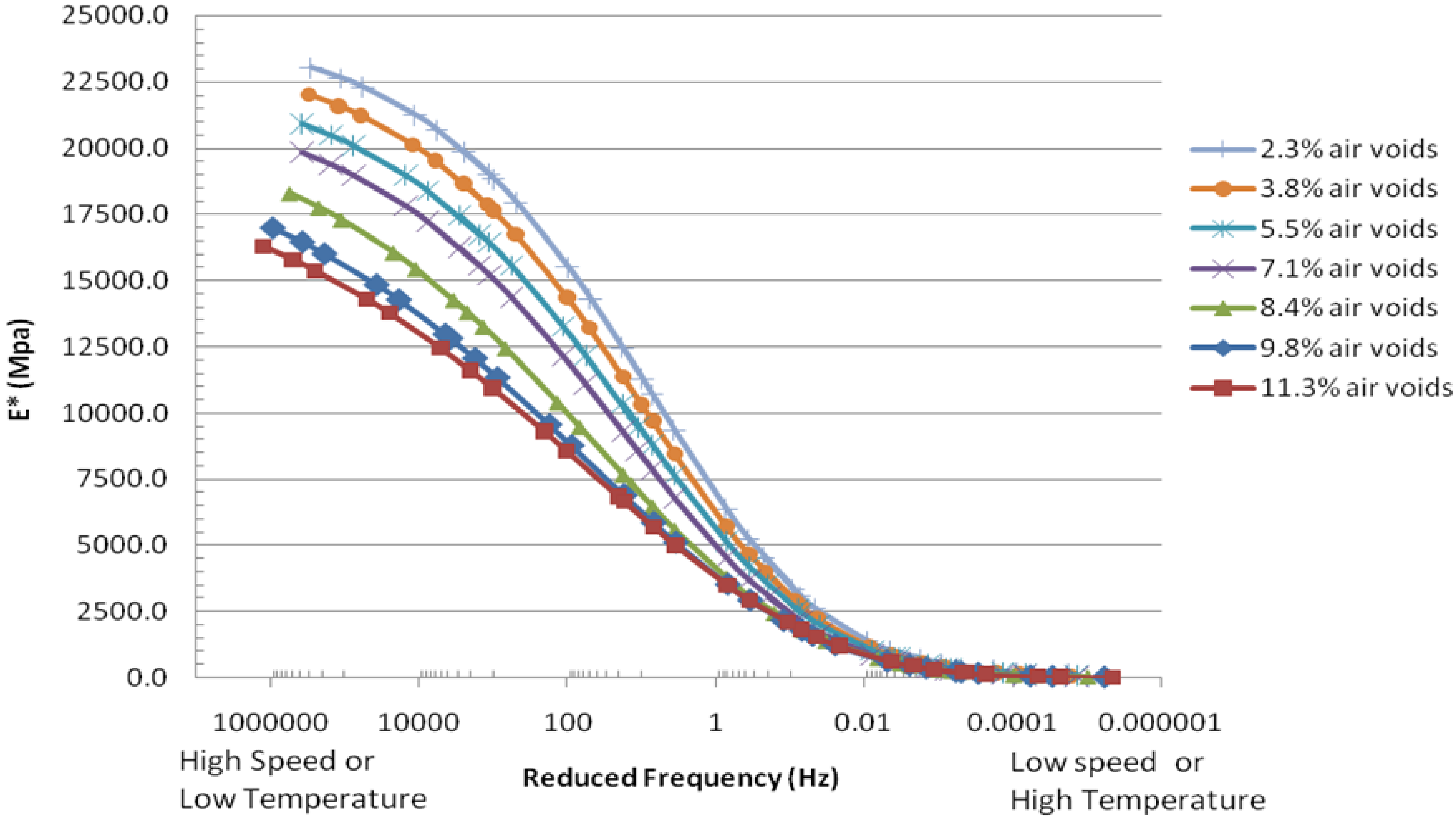
Relaxation time, viscosity/stiffness, $\lambda_i = \eta_i / g_i$

EQUATIONS FOR
VISCO-ELASTIC SOLID

Excel-Solver

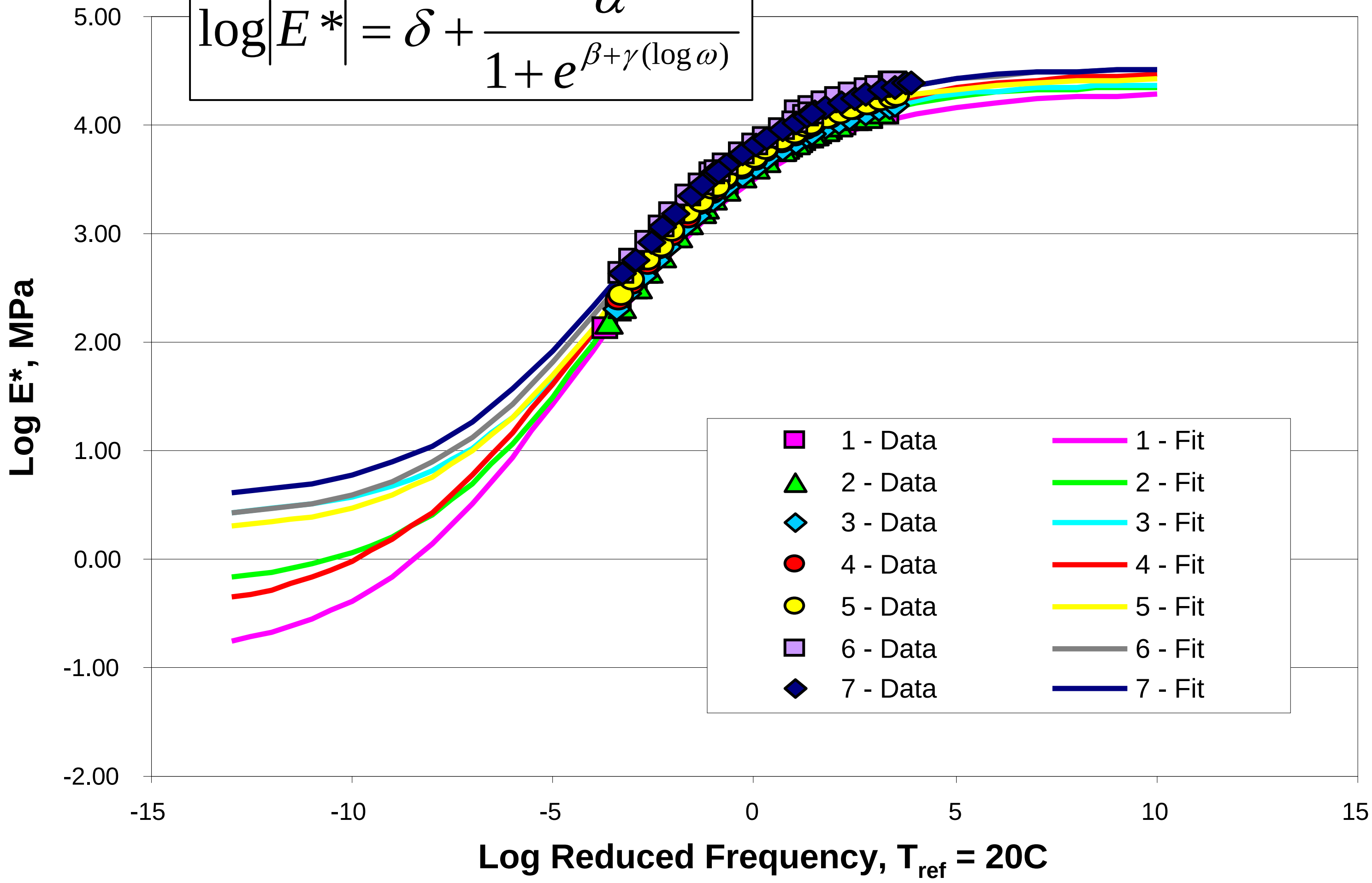


Excel-Solver

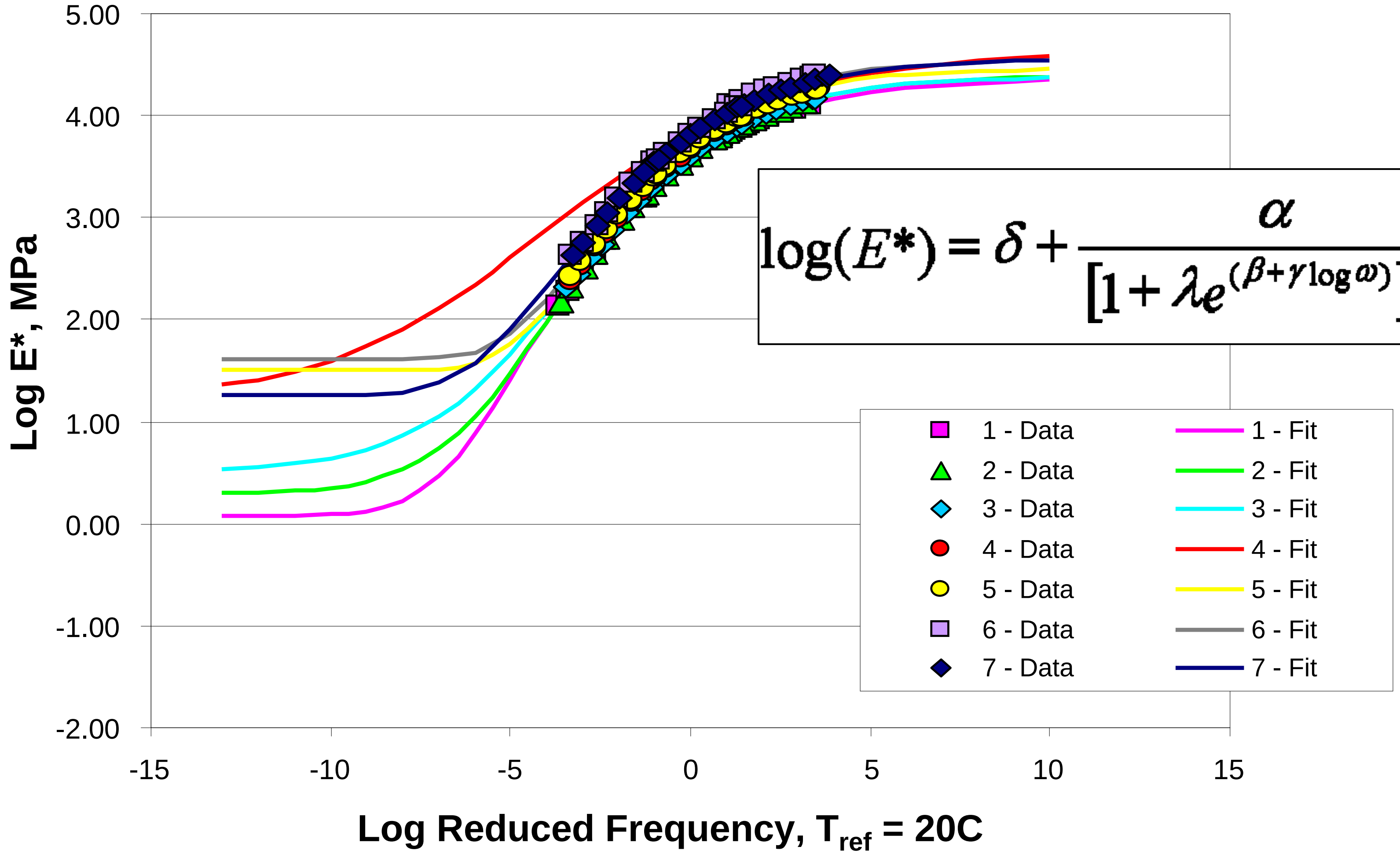


RHEA - standard logistic

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log\omega)}}$$



RHEA - generalized logistic



$$\log(E^*) = \delta + \frac{\alpha}{\left[1 + \lambda e^{(\beta + \gamma \log \omega)}\right]^{1/\lambda}}$$

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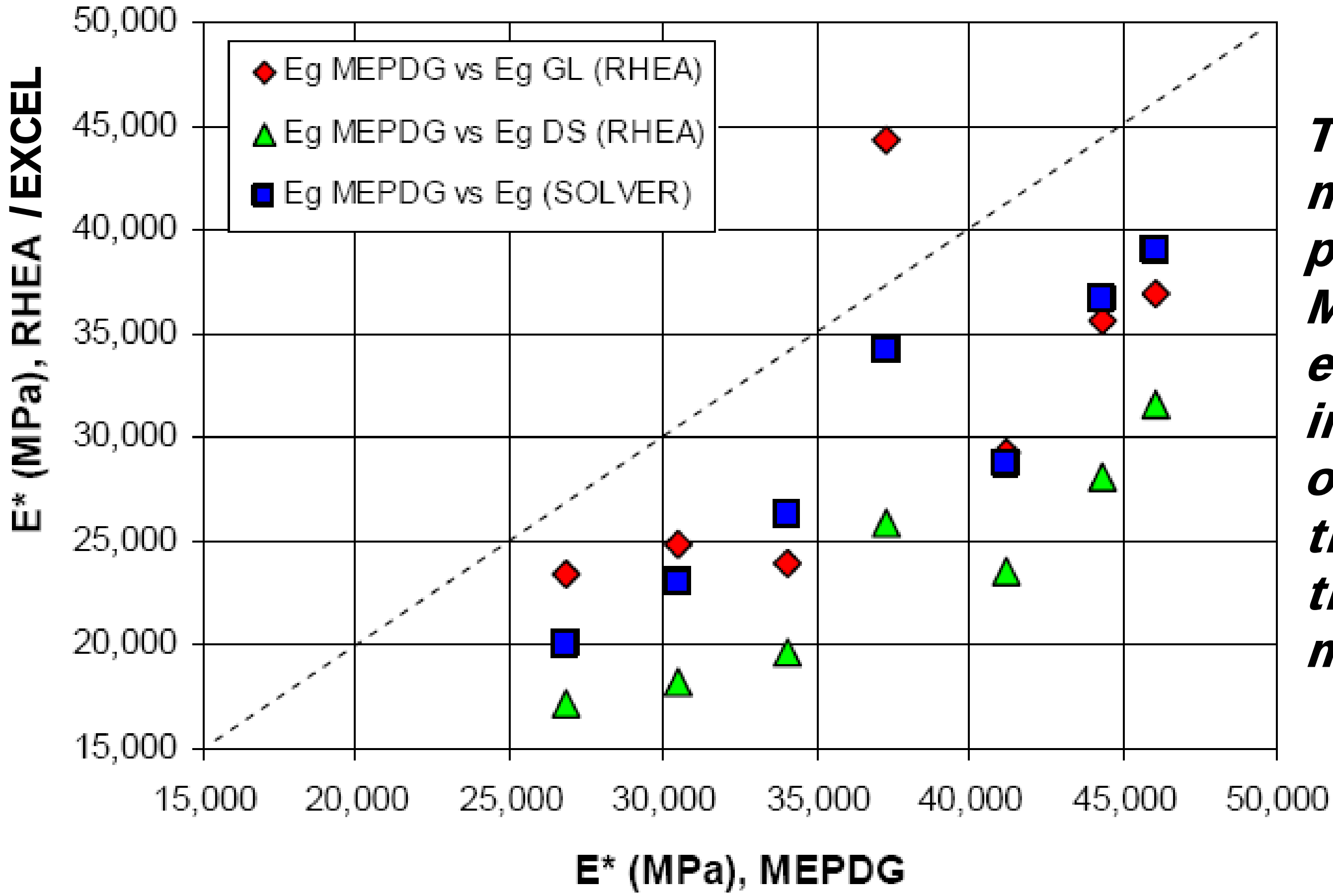
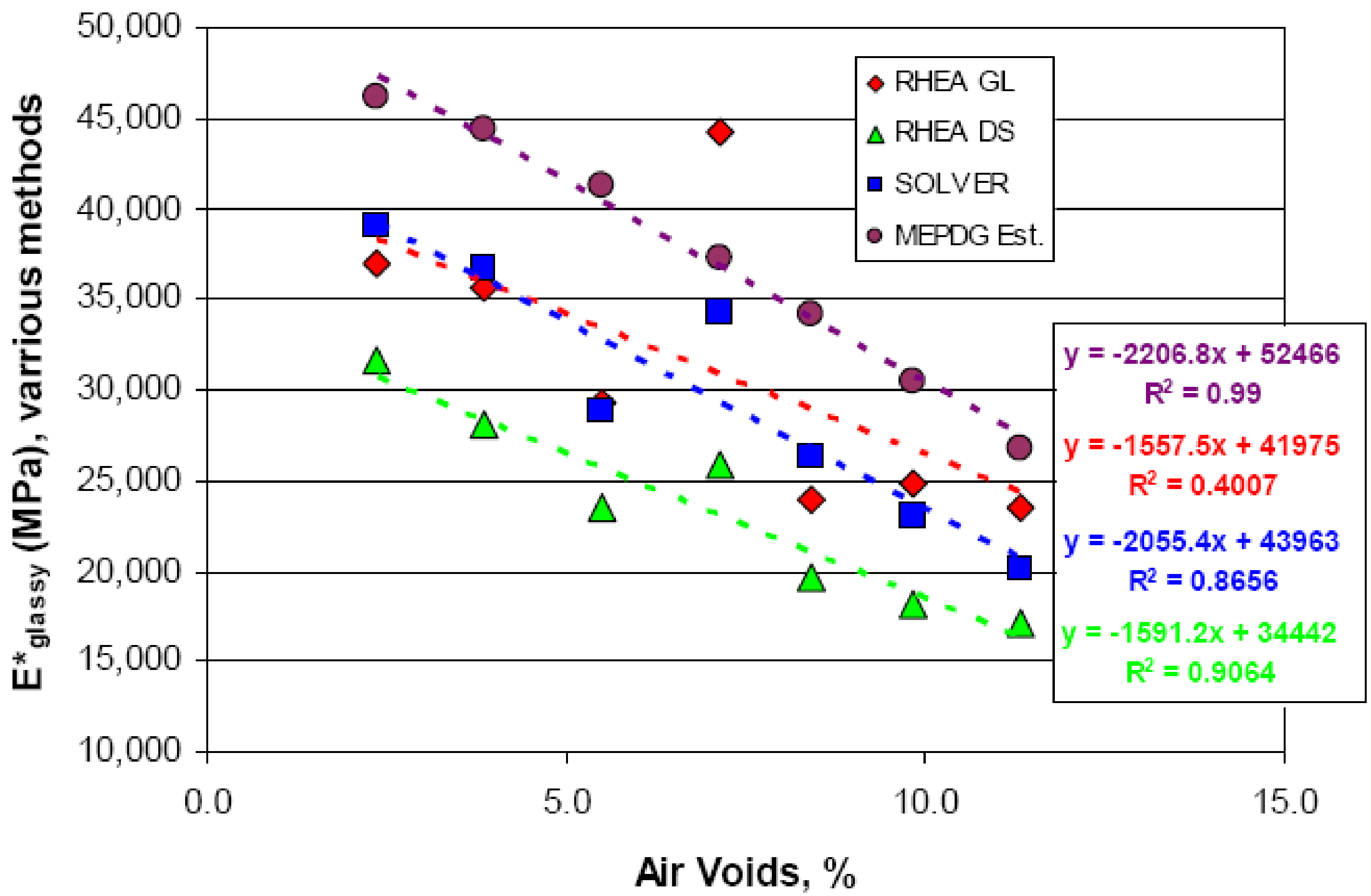
E* (glassy) (MEPDG) vs. other methods

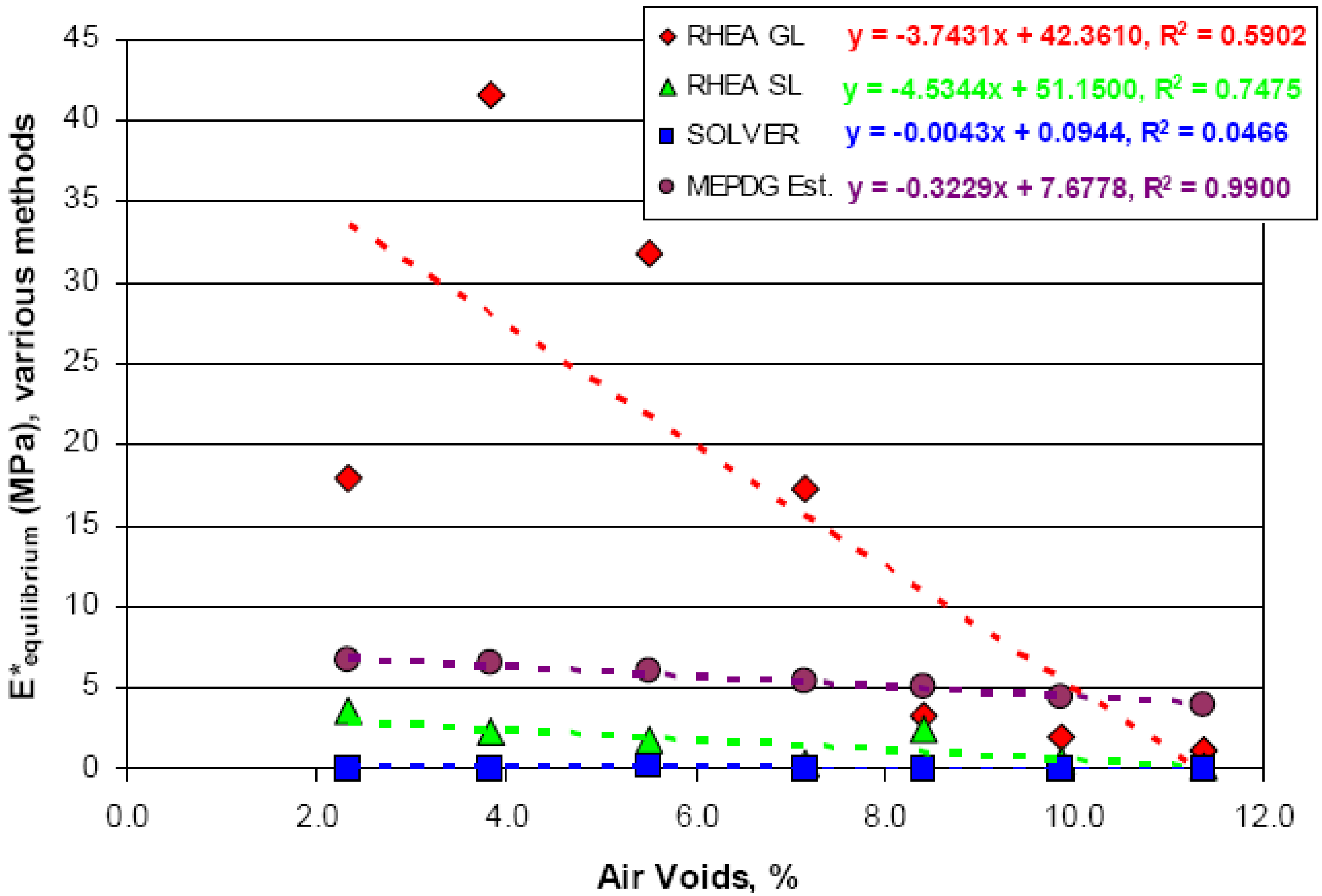


The glassy modulus predicted by the MEPDG predictive equation results in a higher value of modulus than that obtained by the other methods.

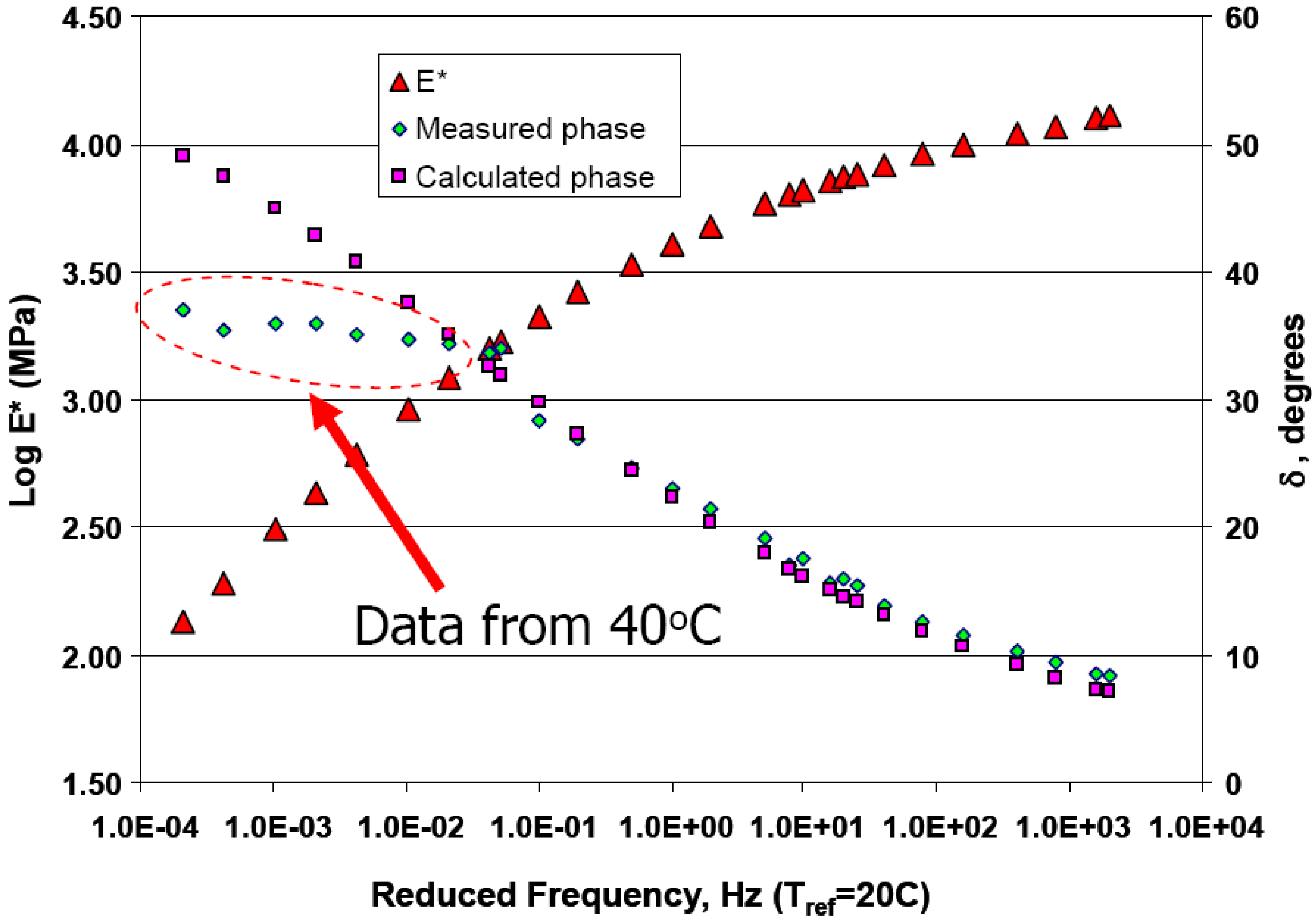
E* (glassy) vs. air voids



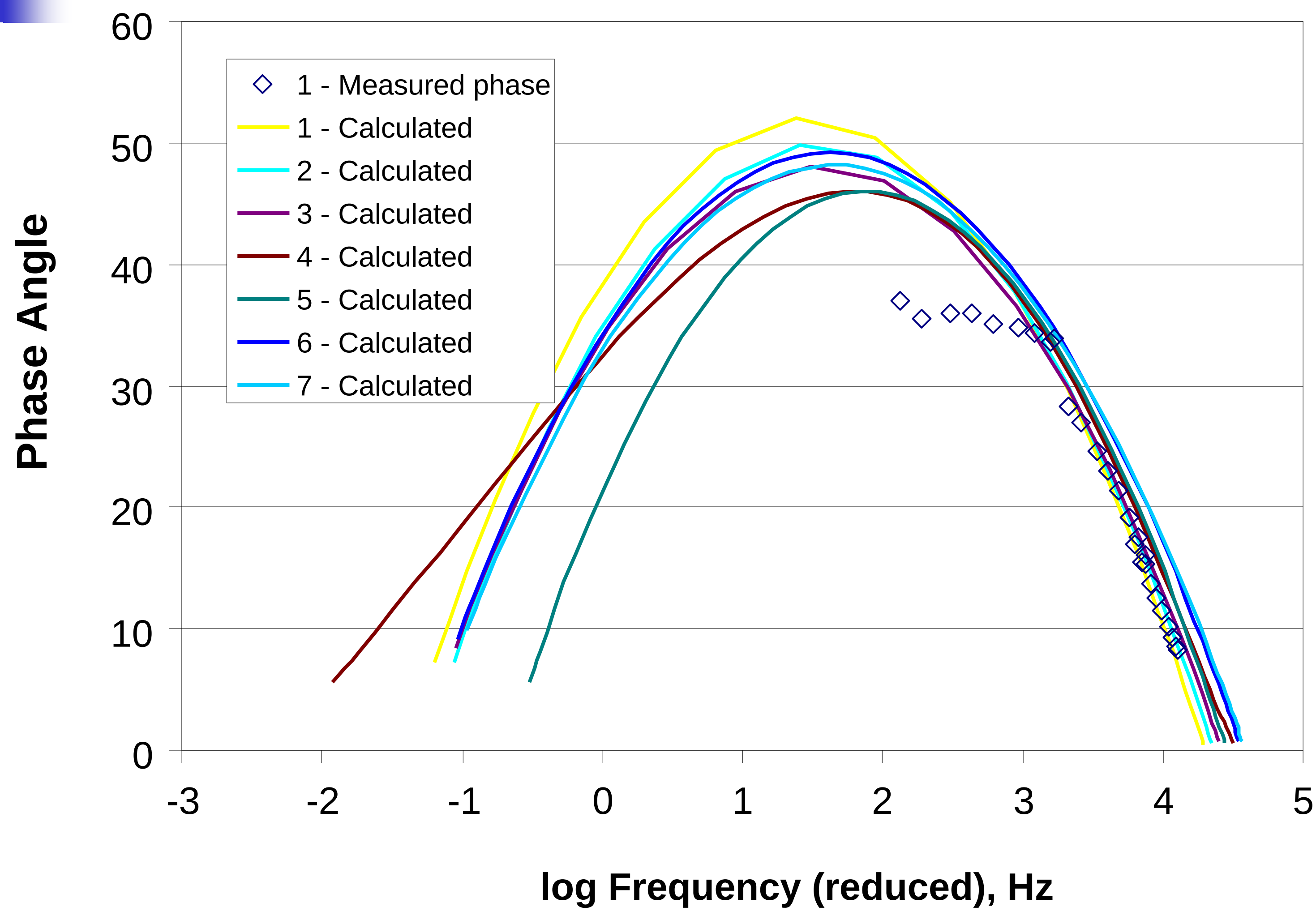
E* (equilibrium) vs. air voids



E* and δ with frequency



Phase angle for all void levels



Phase angle calculation

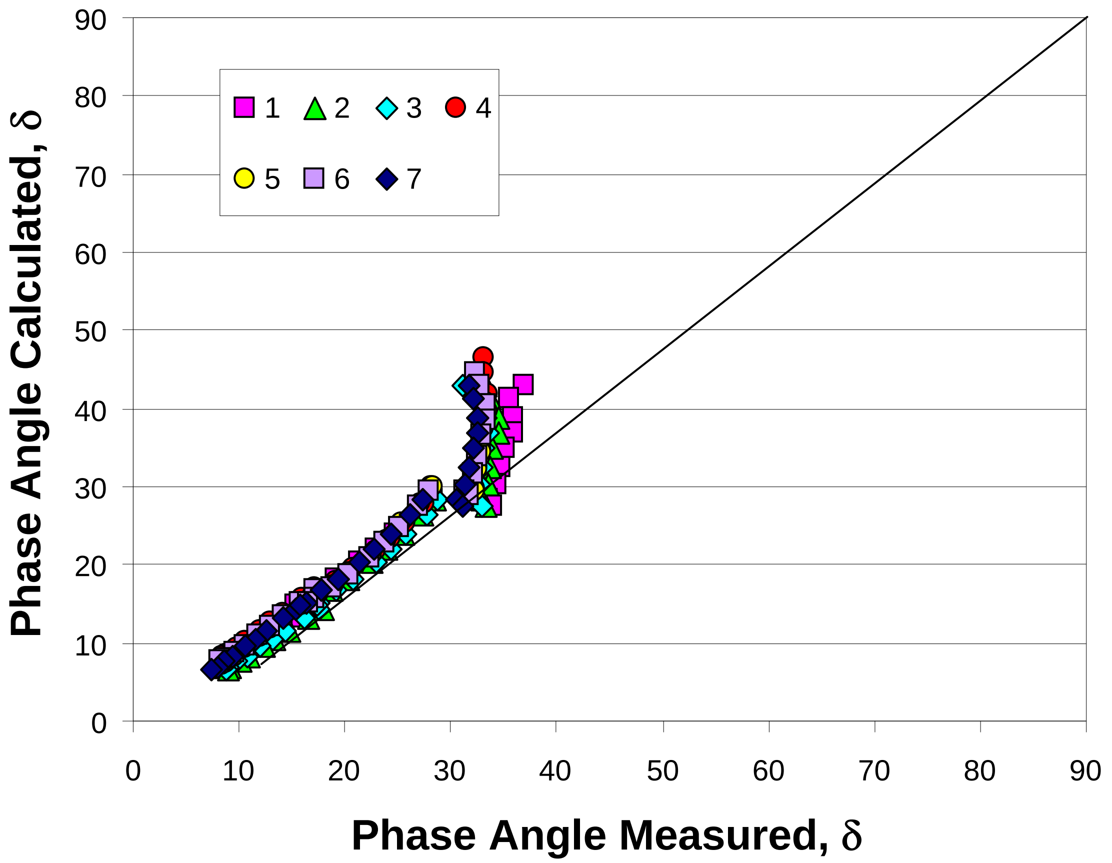
- Shown – for a wide variety of materials – that – $\delta = 90(d\log E^{*}/d\log\omega)$ *{or G*}*

Standard logistic function $$\log\left|E^{*}\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log\omega)}}$$

$$\delta(\omega) = 90 \times \frac{d\log E^{*}}{d\log\omega} = -90\alpha\gamma\frac{e^{[\beta+\gamma(\log\omega)]}}{\left[1+e^{\beta+\gamma(\log\omega)}\right]^{2}}$$

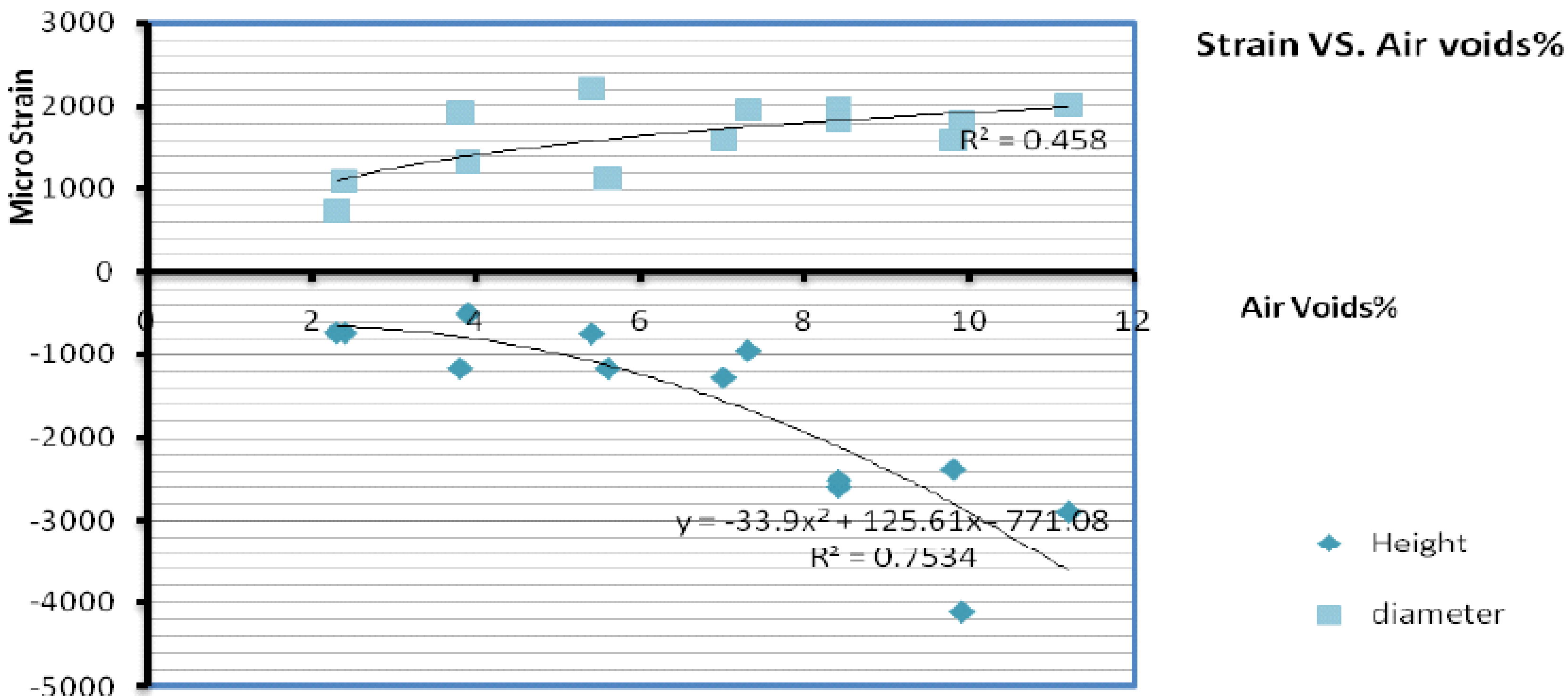
Phase angle for all void levels

- All data sets show deviation at highest temperature

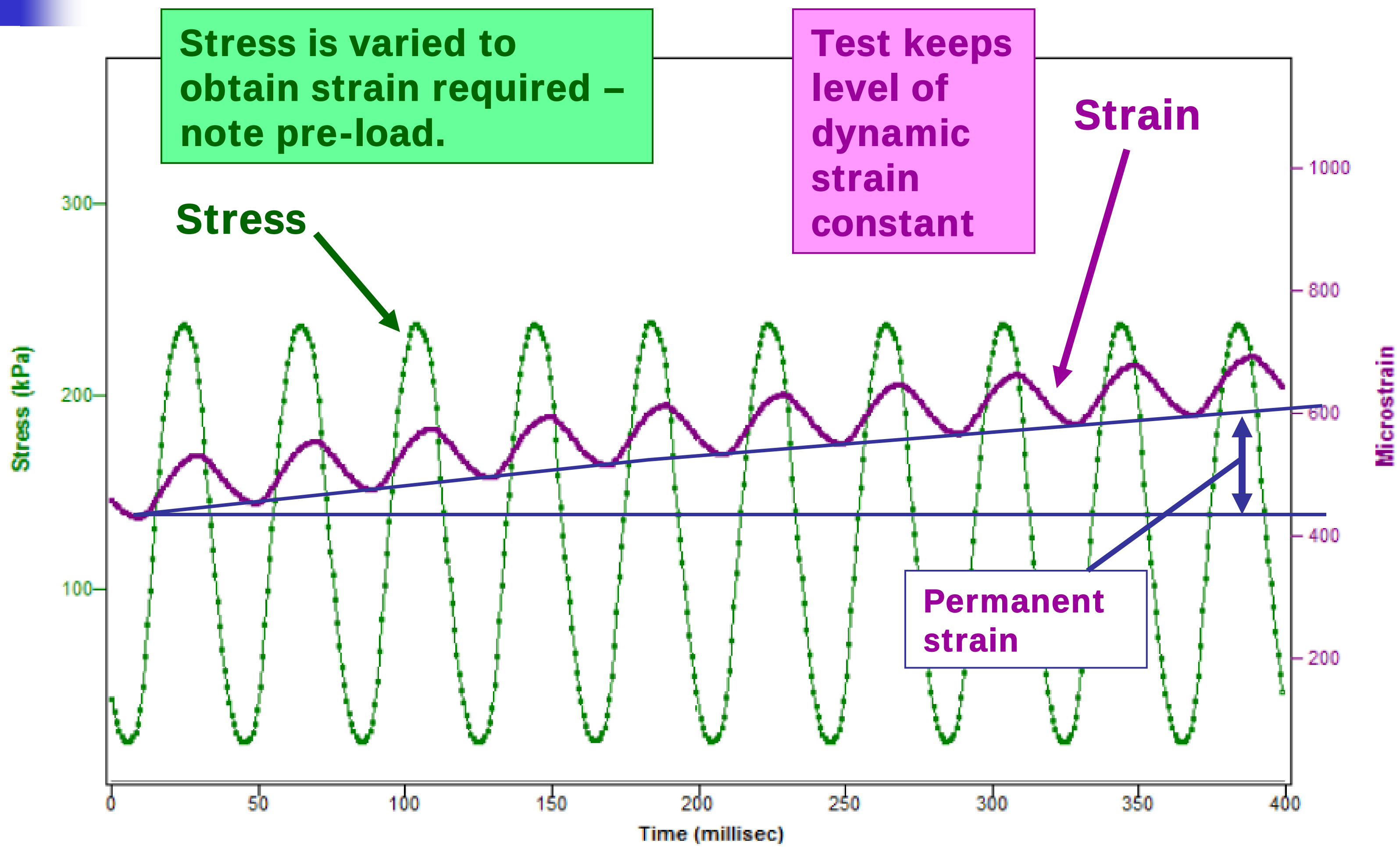


Change is specimen dimensions

- The change in specimen dimensions most likely has some effect on the data
  - The difference in air voids before and after the tests are small
  - The difference between replicates (and retests) is small

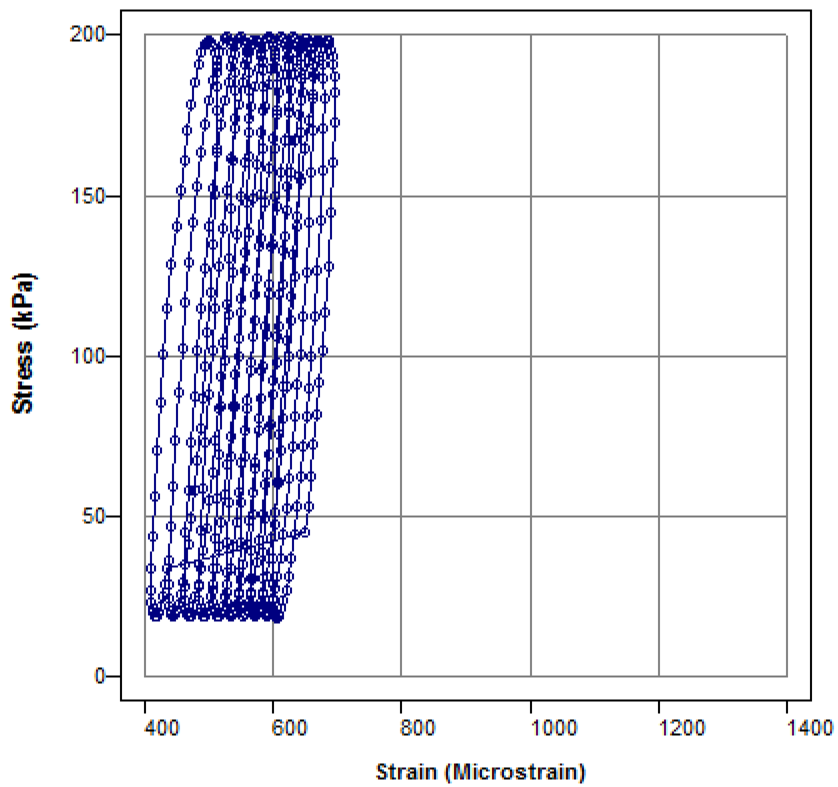


Response to haversine loading



25Hz

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM



UK3B_84.CSV

Temperature 40.0 °C

25 Hz, Cycles N/A

Dissipated Energy

86.05

(J / m^3, = Pa)

20Hz

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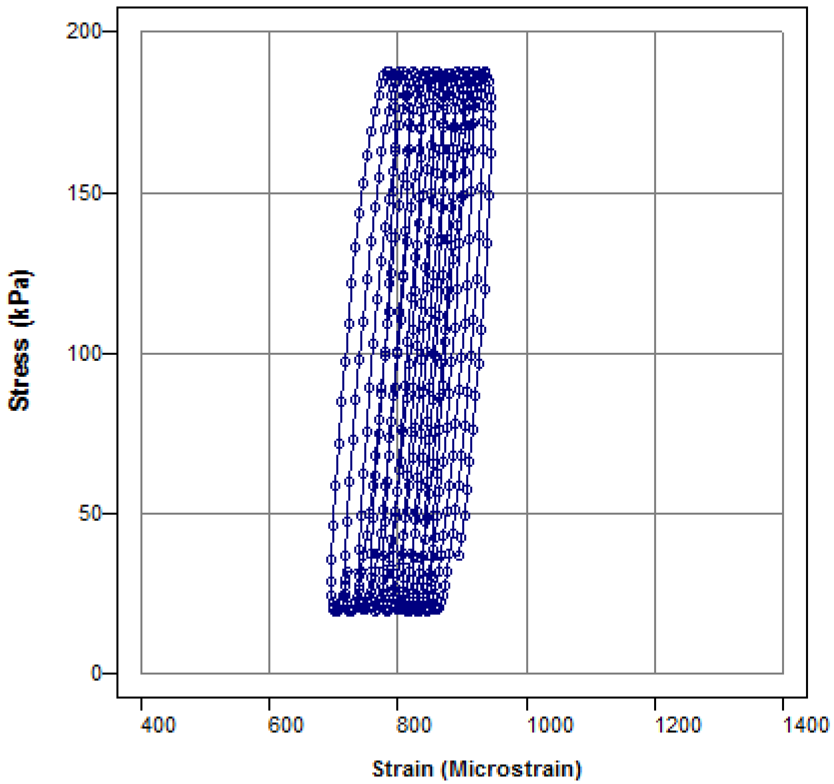

UK3B_84.CSV

Temperature 40.0 °C

20 Hz, Cycles N/A

Dissipated Energy

76.51

(J / m^3, = Pa)

10Hz

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
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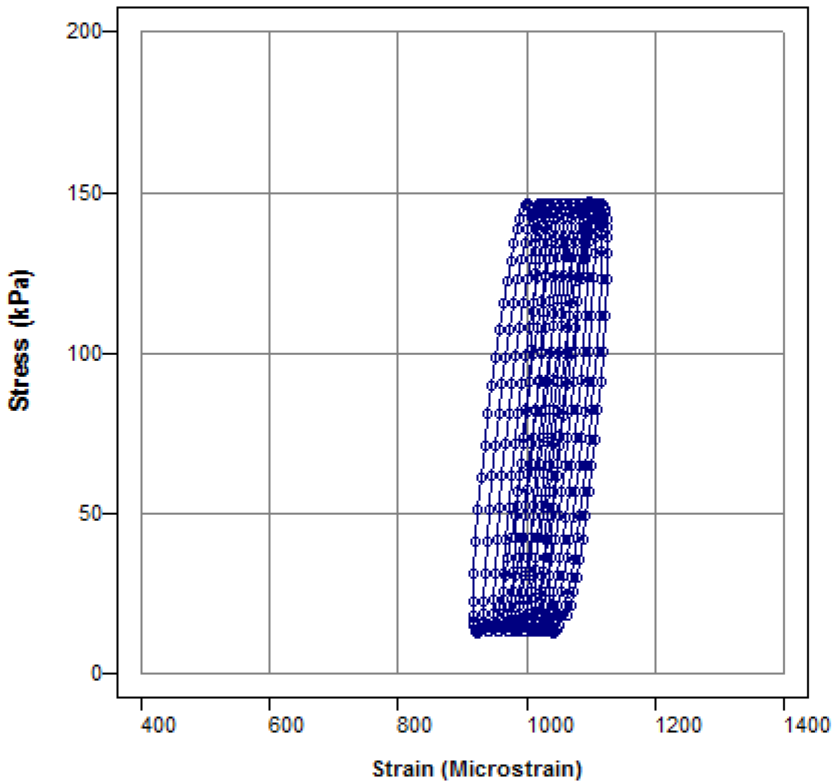


UK3B_84.CSV

Temperature 40.0 °C

10 Hz, Cycles N/A

Dissipated Energy

60.67

(J / m^3, = Pa)

5Hz

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM

UK3B_84.CSV

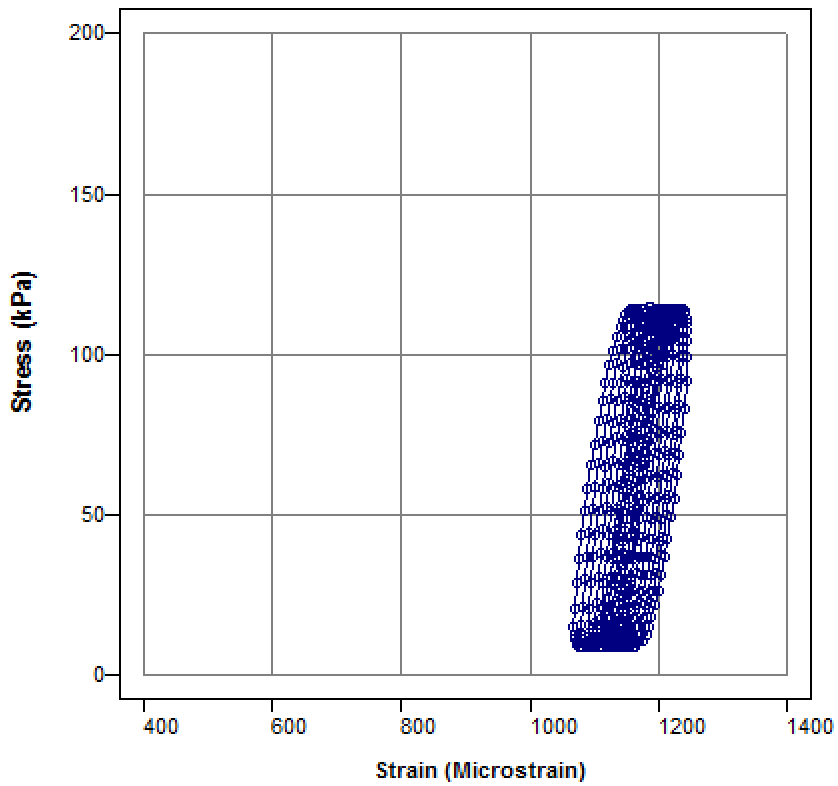
Temperature 40.0 °C

5 Hz, Cycles N/A

Dissipated Energy

46.45

(J / m^3, = Pa)



2Hz

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM

UK3B_84.CSV

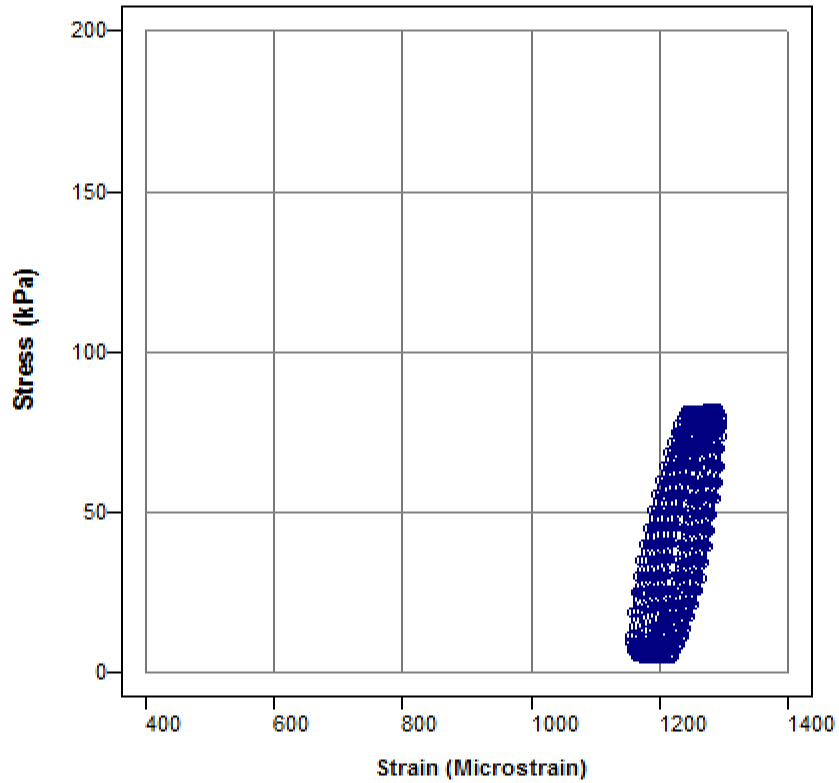
Temperature 40.0 °C

2 Hz, Cycles N/A

Dissipated Energy

34.12

(J / m^3, = Pa)



1Hz – no creep

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
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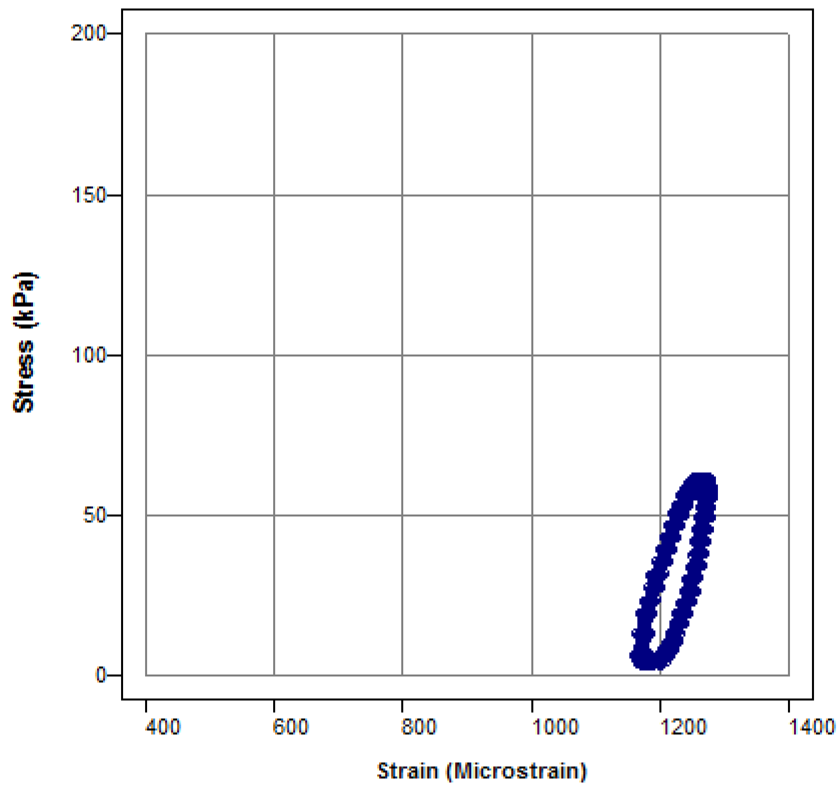


UK3B_84.CSV

Temperature 40.0 °C

1 Hz, Cycles N/A

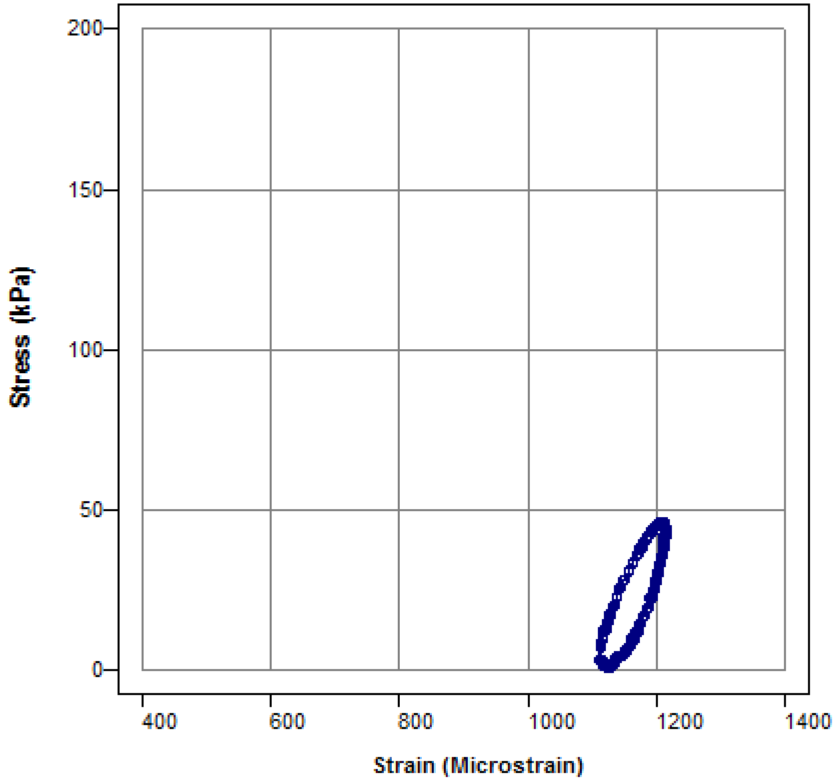
Dissipated Energy

26.35

(J / m^3, = Pa)

0.5 Hz – strain lower, no creep

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM



UK3B_84.CSV

Temperature 40.0 °C

0.5 Hz, Cycles N/A

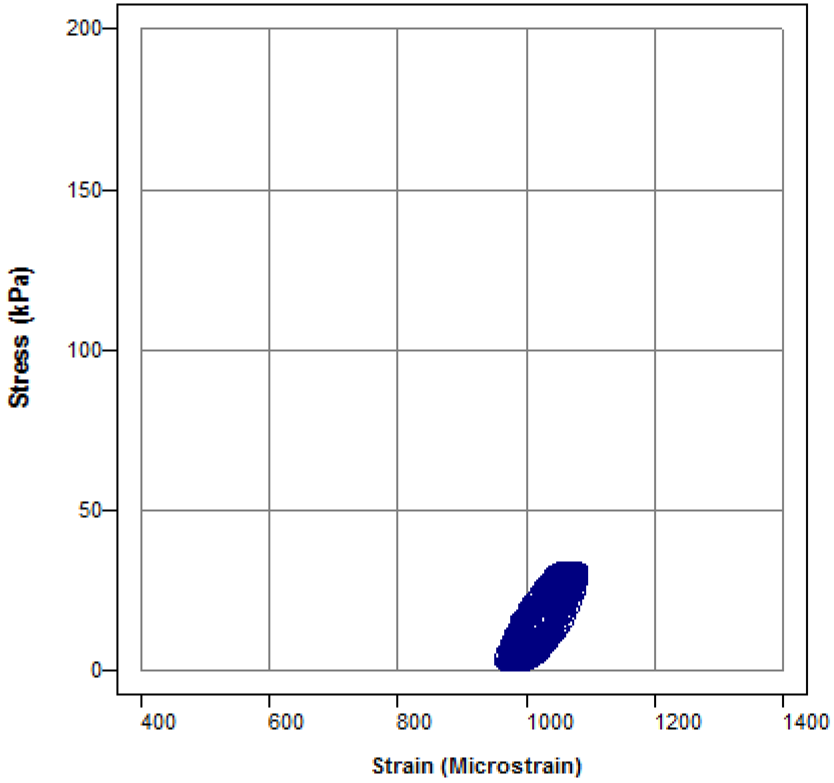
Dissipated Energy

18.75

(J / m^3, = Pa)

0.2Hz – strain lower, creep

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM



UK3B_84.CSV

Temperature 40.0 °C

0.2 Hz, Cycles N/A

Dissipated Energy

11.42

(J / m^3, = Pa)

0.1Hz – strain lower, creep

Project UK Density Operator Phil Blankenship Target test temperature 40.0 Average dynamic strain range from 75 to 125 micro-strain Specimen UK 3b
Test date and time Wed, May 21, 2008, 2:53 PM

UK3B_84.CSV

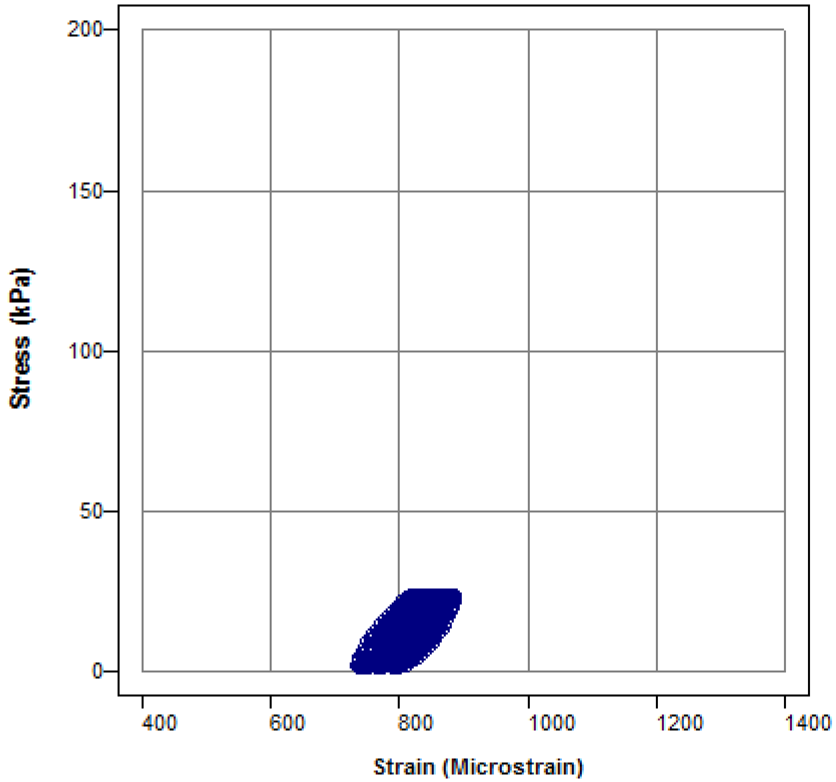
Temperature 40.0 °C

0.1 Hz, Cycles N/A

Dissipated Energy

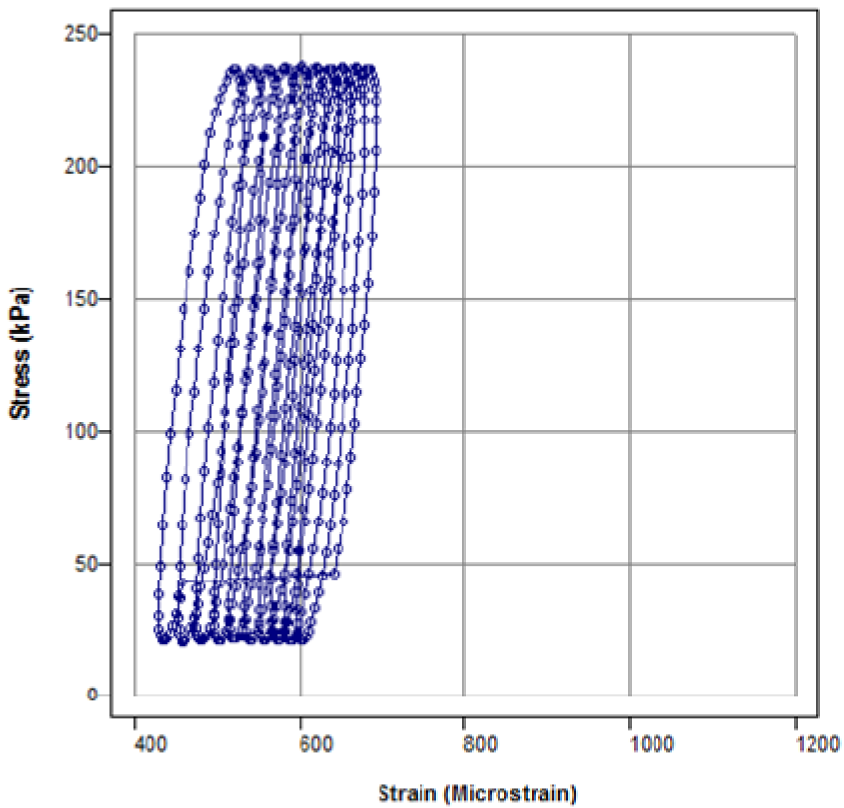
7.73

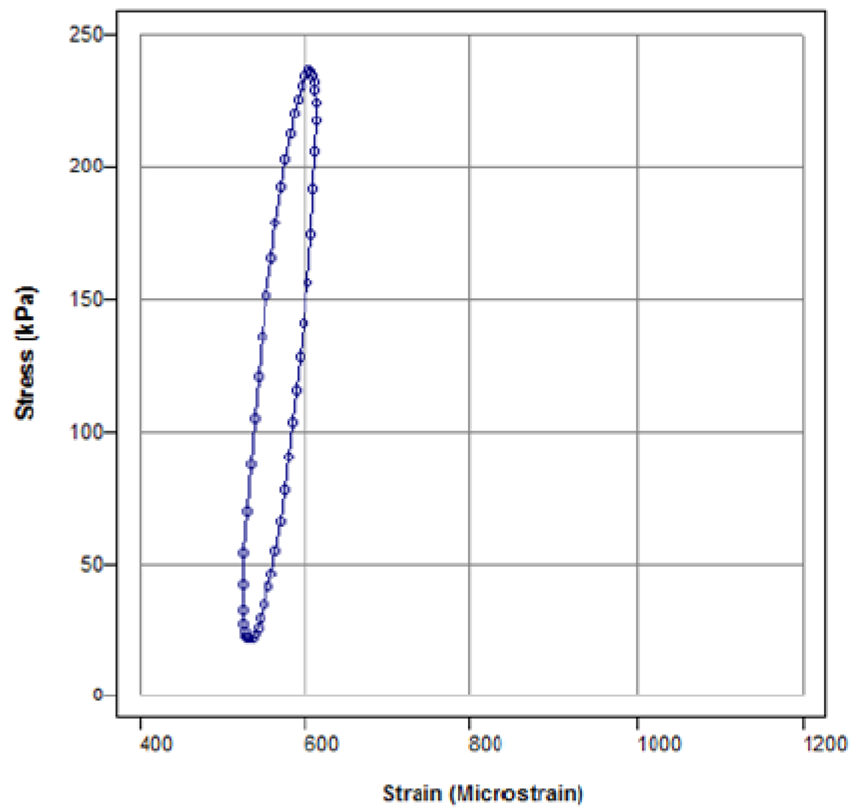
(J / m^3, = Pa)



Hysteresis

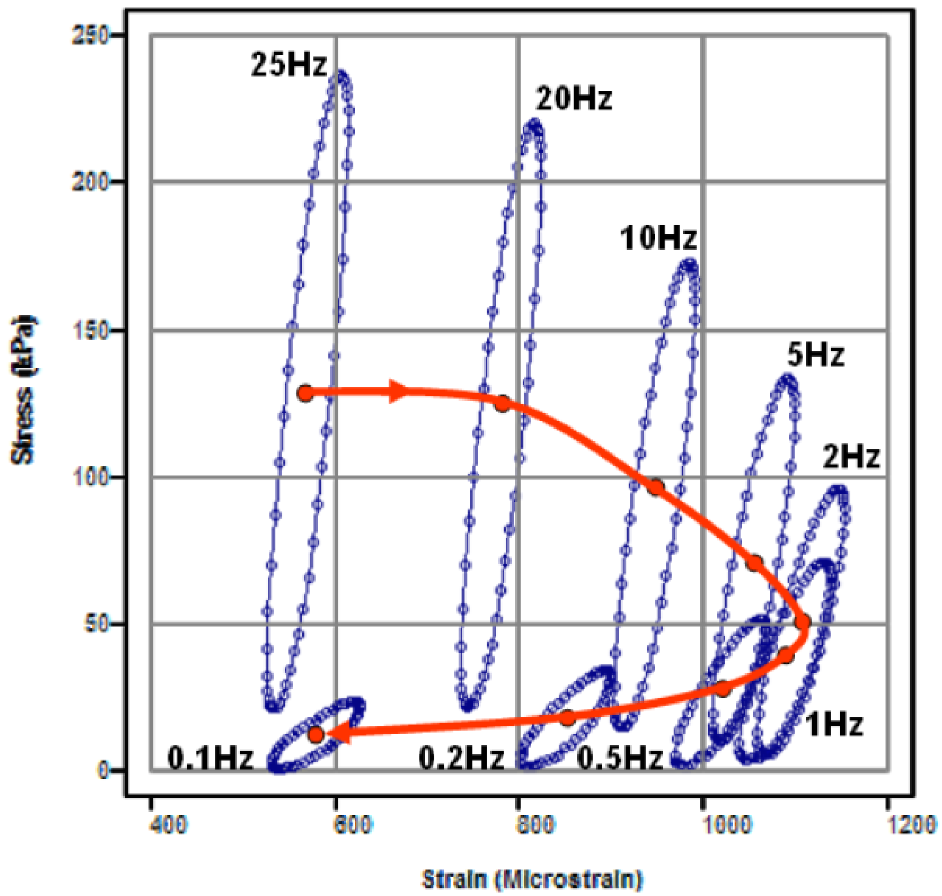
- Hysteresis and average loop, 25 Hz





Evolution of hysteresis

- The test moves from the high frequency to low – as per the direction of the red line
- The strain changes by over 1000 microstrain – the equipment appears to reset and the strain reduces
- The reduction is strain is an artifact of the software and is not really occurring
  - Really the specimen is deforming more in the axial direction



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Test frequencies

- Adding some additional test frequencies to the isotherms will improve the stability of shifting
- This is important if we wish to assess suitability of different functional forms
- Does not extend significantly the testing time

Additional study/analysis

- Need to determine effect of permanent strain of E* mastercurve
- What is effect of plastic strain occurring
- How to quantify a “reset” that occurs in current software
- Probably best not to use specimens for flow testing

Use of phase angle

- Can use phase angle predictive relationship to assist with assessment of quality of data
  - If is does not agree – then look for issues with testing
- Always inspect quality of data sets by careful examination of wave forms

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Conclusions -1 of 2

- The values of equilibrium and glassy modulus are significantly affected by the selected analysis method as well as by the volumetric properties of the mixture.
- The MEPDG prediction procedure significantly over-predicts the glassy asymptote.
- The phase analysis data obtained from the high temperature testing did not coincide with the expected relationship for this parameter. It is highly likely that large permanent strain is significantly affecting this parameter.

Conclusions -2 of 2

- Retests of materials properties at 20^{o}C before and after the full frequency sweep data gave very similar results.
- The permanent strain occurring in any given specimen appears to be significantly affected by the volumetrics. Additional work is required to deduce if this is truly a volumetric effect or a stiffness effect.

Thank you for your attention

This presentation will be posted on

www.abatech.com

Questions / Discussion?