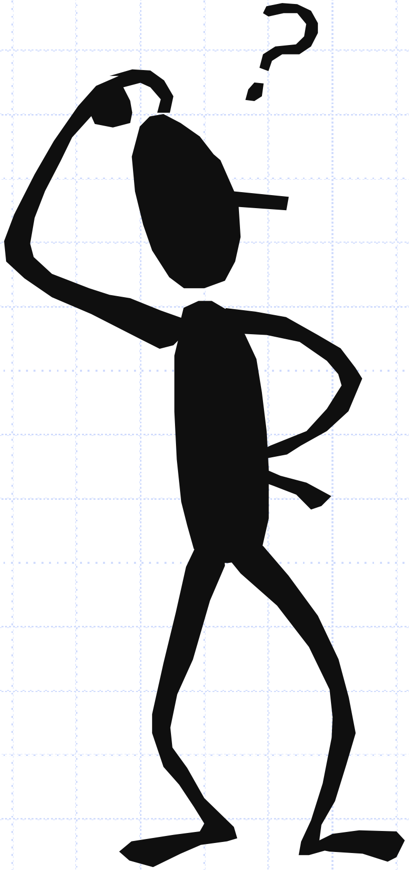
Simple Performance Test Procedure

NCAUPG Technicians’ Workshop

January 2006

“Simple Performance Test”



- What is it???

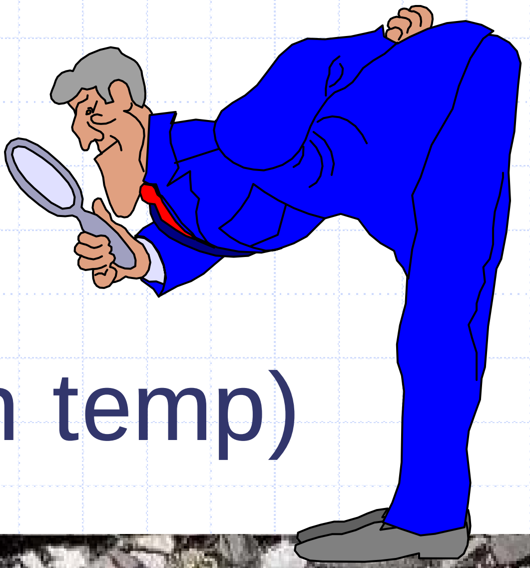
Definition

- “A test method(s) that *accurately* and *reliably* measures a mixture response characteristic or parameter that is *highly correlated to the occurrence of pavement distress* (e.g., cracking and rutting) over a diverse range of traffic and climatic conditions.)

NCHRP 465, Witczak et al.

SPT - What Is It?

- Test(s) that indicates how mix will perform
  - Rutting
  - Cracking
- Emphasis on rutting (high temp)



Performance Test(s)

- Missing piece of Superpave system
  - Binder specifications in place
  - Mix design system in place
  - *Need a performance test to evaluate mix design and new materials*

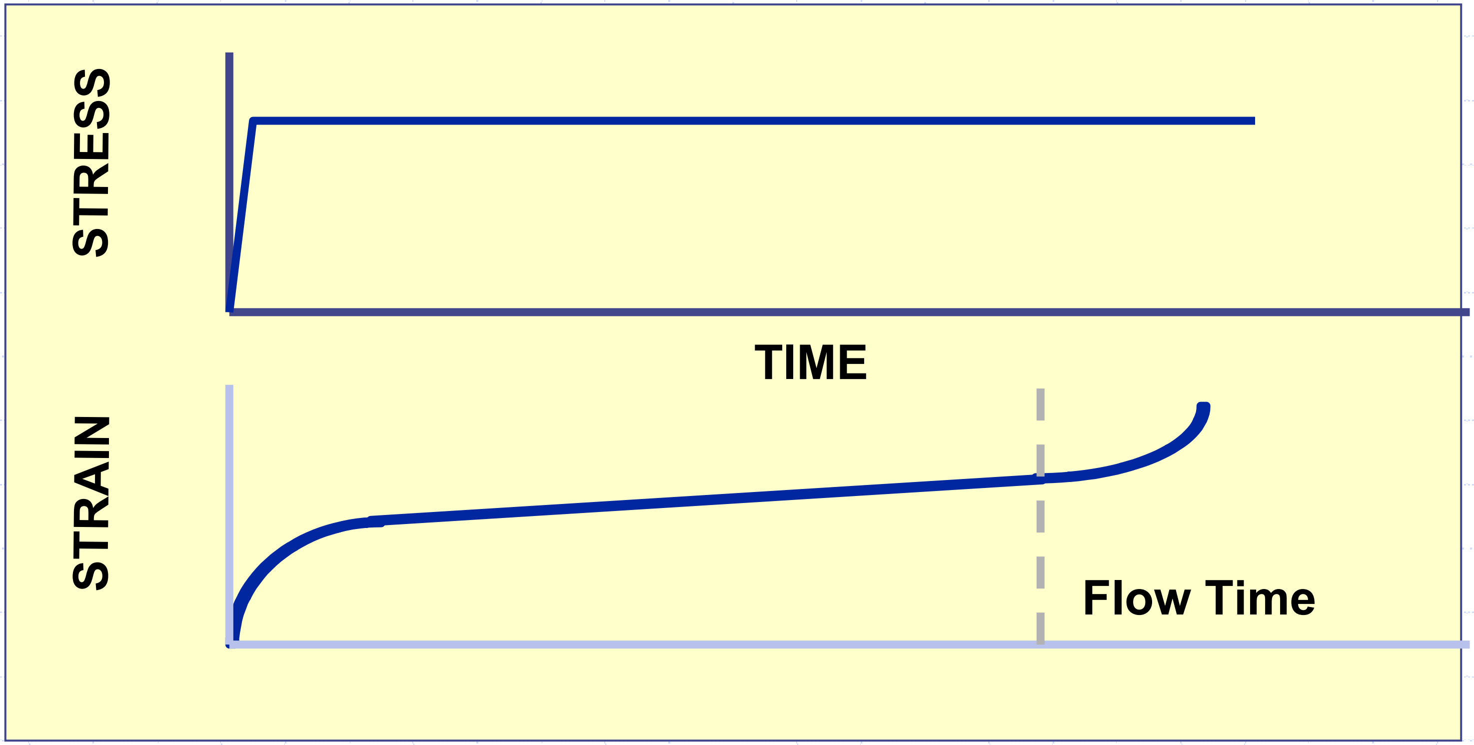
Superpave Performance Tests

- The future of HMA mix design and structural design
- Major national research efforts
  - NCHRP 9-19 Models
  - NCHRP 1-37a Pavement Design Guide
  - NCHRP 9-29 Equipment Development

Superpave Performance Tests

- Rutting
  - Dynamic Modulus (|E*|)
  - Flow Time (from static creep)
  - Flow Number (from repeated load triaxial)
- Fatigue
  - Dynamic Modulus
- Low Temperature Cracking
  - Indirect Tensile Test (AASHTO T322)

Creep Flow Time, FT

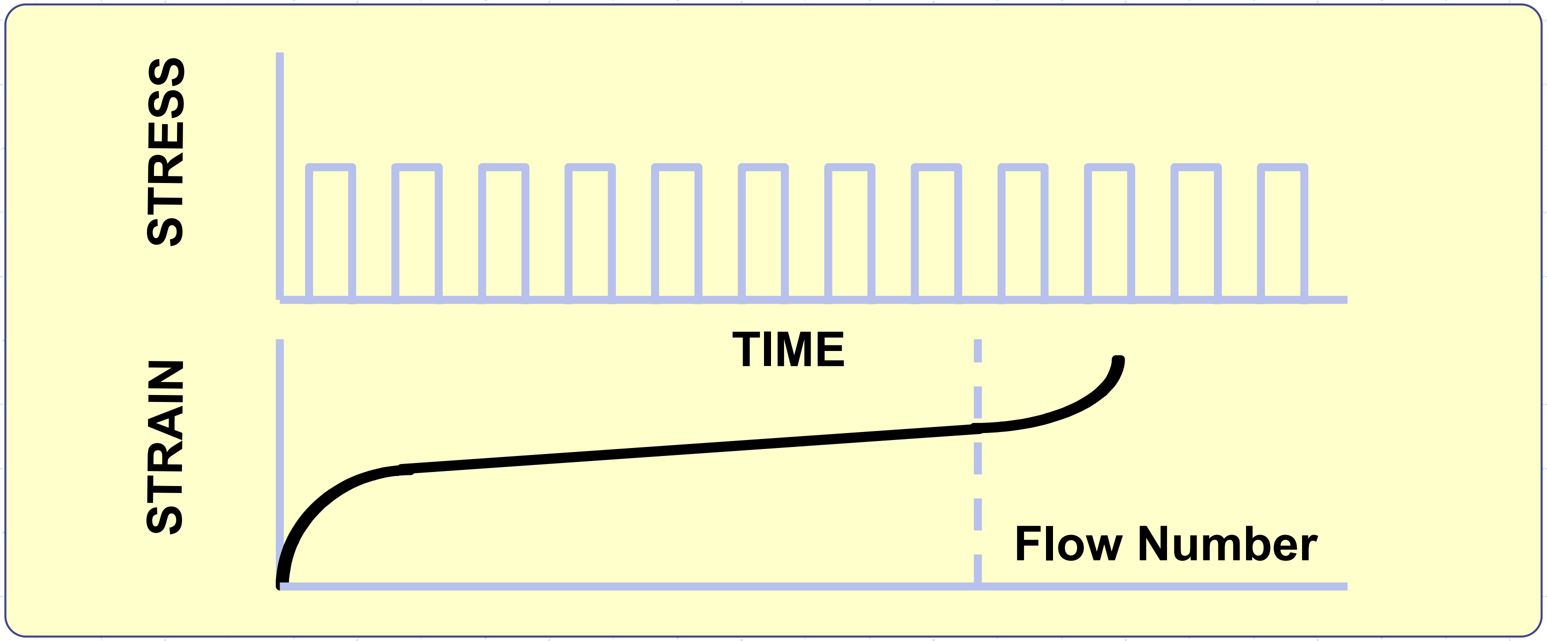


Rutting - Min FT at High Temp

Flow Time

- Simple equipment
- Simplest Test
- Minimal training

Repeated Load Permanent Deformation Test, FN

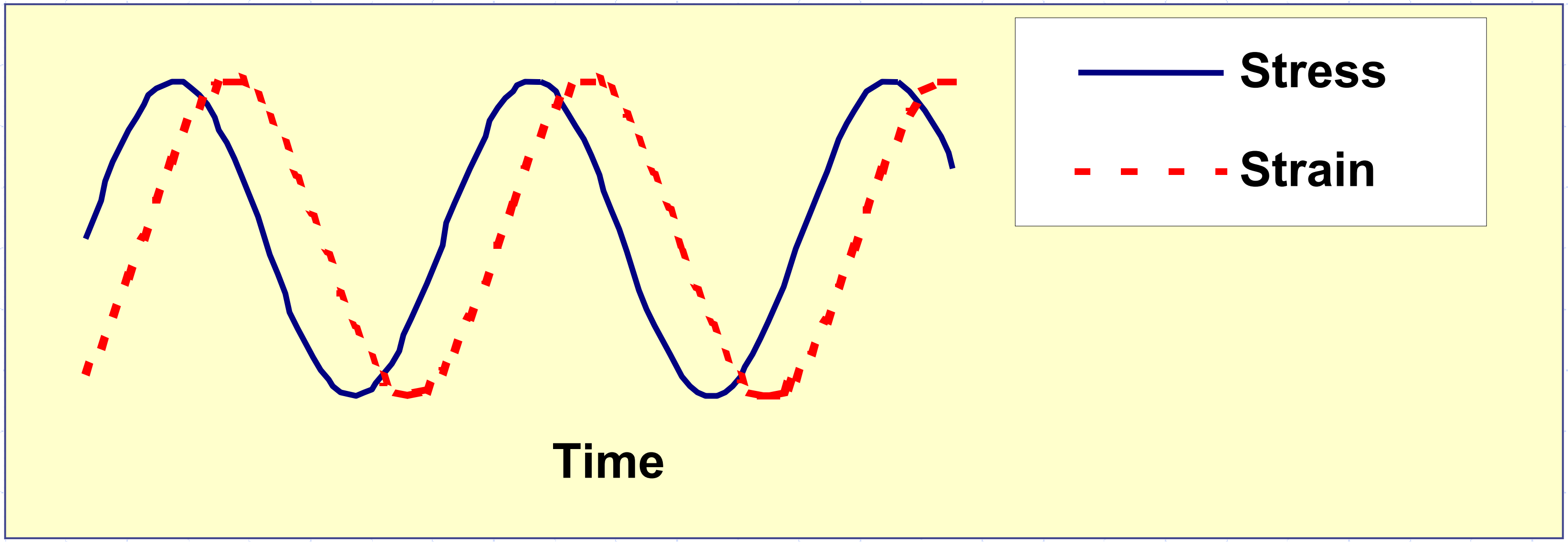


Rutting - Min FN at High Temp

Flow Number

- Repeated load may be best simulation of actual loading
- Needs work before use as specification tool (NCHRP 9-29, 2003)
  - That work is in progress

Complex Modulus, /E*/



Rutting - Min |E*| at High Temp

Fatigue Cracking - Max |E*| at Intermediate

Focus on |E*|

- Dynamic modulus is leading candidate
  - Can be used for both rutting and fatigue
  - Same test equipment and protocol at different temperatures
  - Can also be used for pavement design in the Mechanistic-Empirical Pavement Design Guide

Review

- Definitions of Modulus, etc.
- Significance of Dynamic Modulus
  - Uses
- Dynamic Modulus Test
- Examples of Data
- Data Quality Checks
- The Future

Terminology

- Modulus
- Complex
- Dynamic
- Phase Angle

Terminology

- Stress = the load applied to something divided by the area to which it is applied.
  - Think of it as pressure
  - Symbol - τ (tau)
  - Units – load per unit area (psi, kN/m^2)
  - 1 kN/m^2 = 1 kPa, 1 M Pa = 1000 kPa
  - 1 kPa = 0.145 psi, 600 kPa = 87 psi

Terminology

- Strain = change in length (deformation) divided by original length.
  - Symbol – **ϵ** (sigma)
  - Units – length over length, unitless
  - How much does something stretch or deform under load?
  - Rate of strain – how fast something deforms

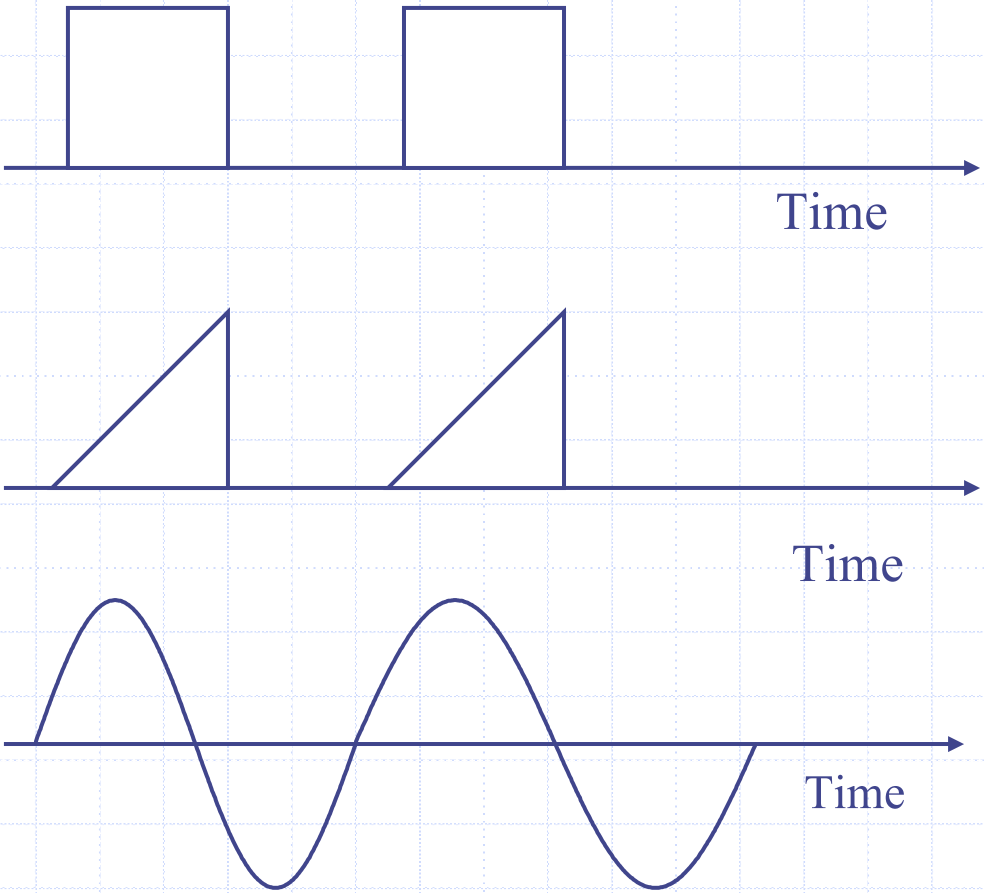
A Little More Terminology

- Modulus – stress divided by strain.
  - Units – same as stress, load per unit area
  - Many different moduli are used in engineering: E, M_r, G*, |E*|
  - How much stress does it take to produce a unit of strain?
  - Related to stiffness or strength.

Cyclic Loading

- Cyclic loading means load is applied and removed repeatedly.
- This type of loading can help us understand how a material behaves.
  - Think of traffic loading on pavement.

Cyclic Loading Examples

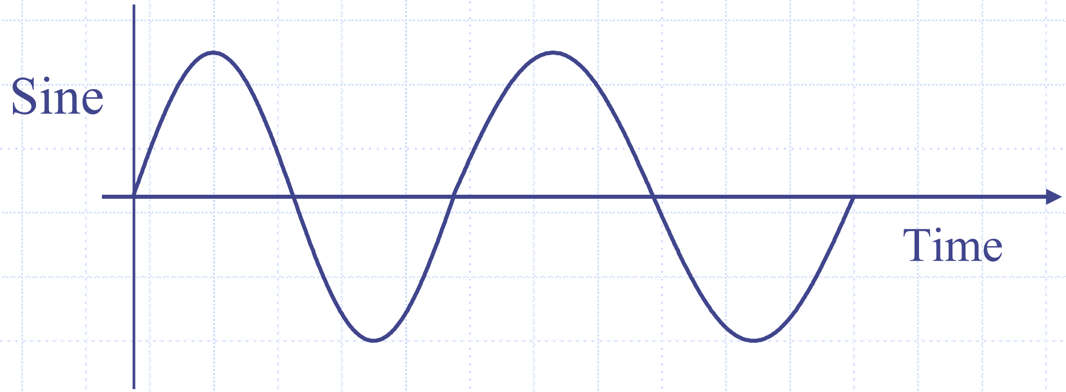


Definitions

- Cycle = one complete load application
- Period = time it takes to complete one cycle (units of time)
- Frequency = one (1) divided by the period of the cycle (inverse) – expressed as cycles per second
  - 1.0 Hertz (Hz) = 1.0 cycle per second

Sine Wave

- A special type of cycle where the x axis is time and the y axis is the sine of the angle.

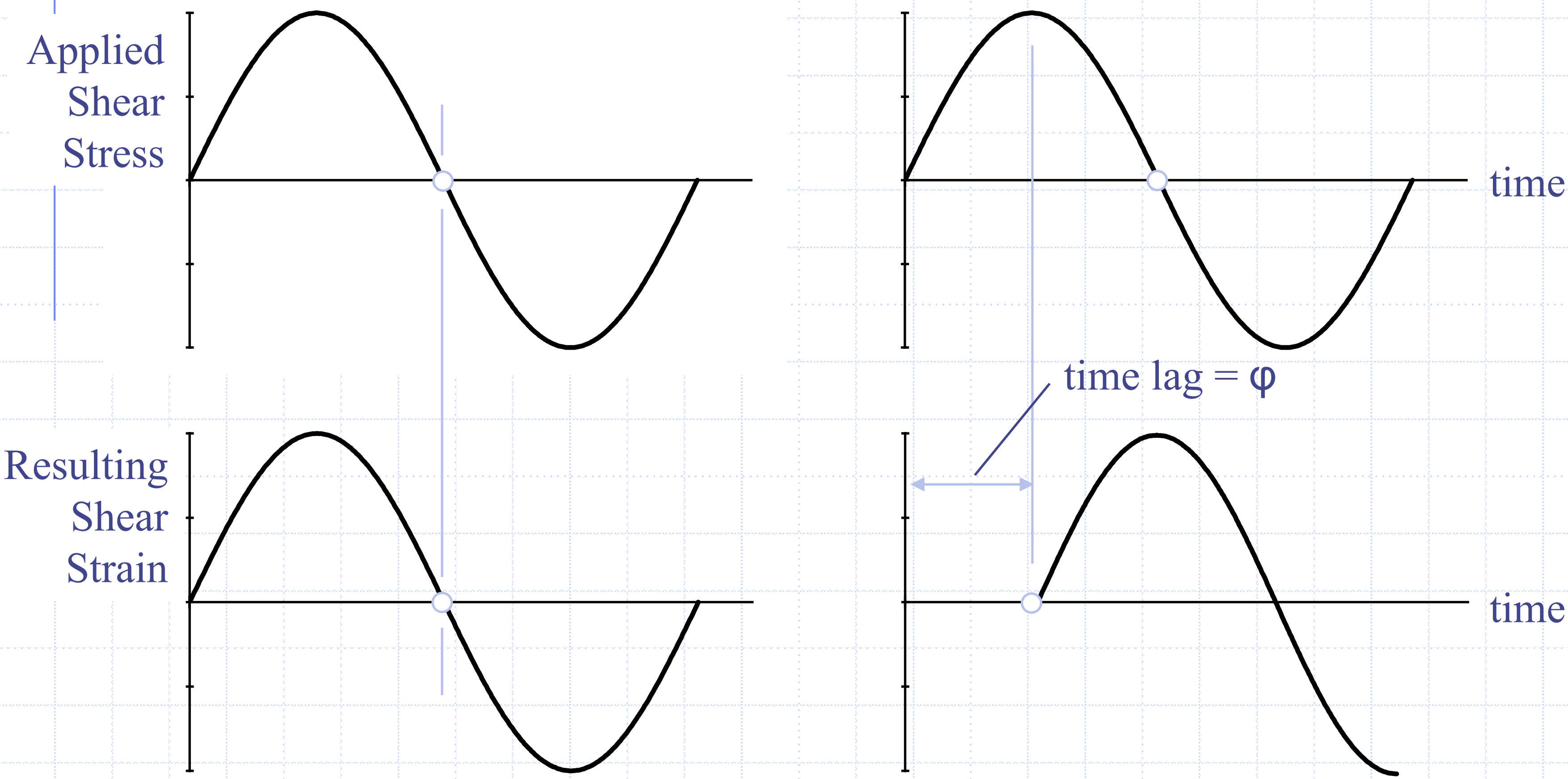


Material Response

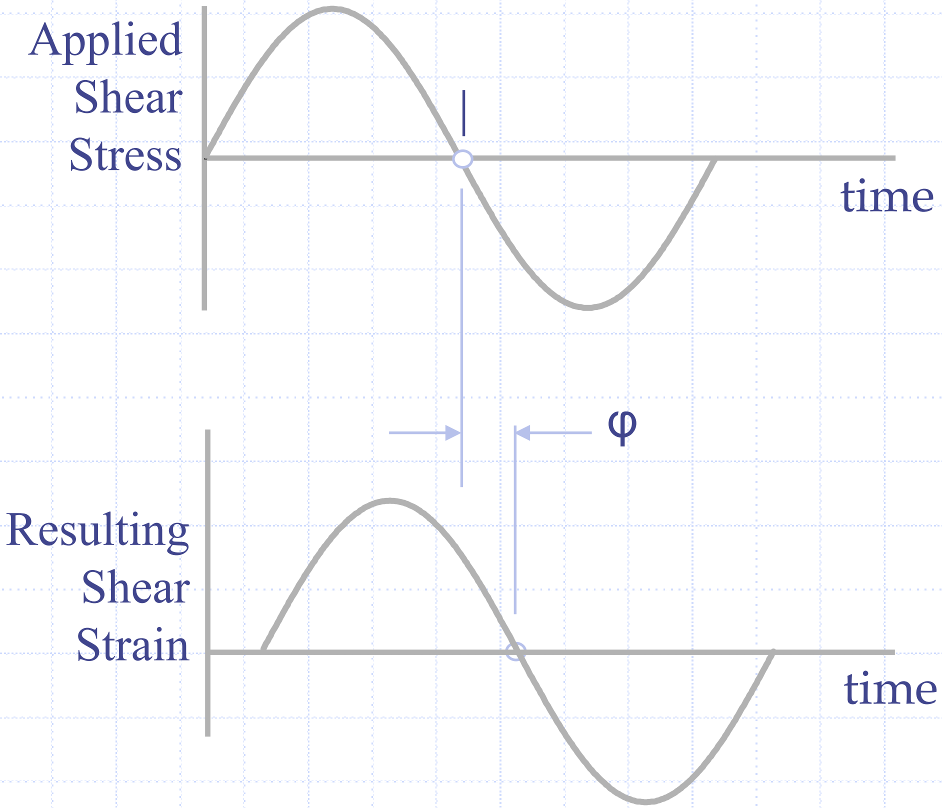
- Strain can be recovered on unloading
  - If recovered immediately, material is fully *elastic*
  - If recovered, but only gradually, material is *viscoelastic*
- If strain is not recovered on unloading
  - If strain is immediately, but not completely, recovered, material is *elastoplastic*
  - If strain is gradually, but not completely, recovered, material is *viscoplastic*.

Elastic: φ = 0 deg

Viscous: φ = 90 deg



Viscoelastic: 0 < φ < 90 º



$$|E^*| = \frac{\sigma_o}{\varepsilon_o}$$

φ = time lag

Look Familiar?

- Analogous to G^* and δ for binder
- Compressive rather than shear loading, but similar in concept

Complex and Dynamic Modulus

- Since the peak stress and peak strain do not occur at the same time (viscoelastic), the modulus is termed "complex"

- The absolute value of the complex modulus is called the dynamic modulus

Is it New?

- Dynamic modulus testing has been around for a long time.
- First ASTM protocol was written in 1979.
- Used in Asphalt Institute MS11 for Design of Airfield Pavements

Significance

- “Stiffness,” as indicated by dynamic modulus, can be related to permanent deformation resistance (loss modulus, E’) and fatigue resistance (storage modulus, E”)

Significance

- Dynamic Modulus is sensitive to elastic and viscous behavior of the mixture
- Correlated to permanent deformation and rutting
  - Zhou and Scullion correlated |E*| with rutting on 20 Texas SPS sections
  - Powell did not find correlation with NCAT Track rutting, but observed rutting was very low

Uses

- Estimate rutting resistance – at high temperatures or long loading times (low frequency)
- Estimate fatigue resistance – at lower temperatures or short loading times (high frequency)
- Used in MEPDG for design of flexible pavements
- Compare rutting and fatigue resistance of various mixtures

Triple Whammy!

- Can gather information for all of these things with one test protocol
- Flow time, flow number are still options
- Flow number needs work before using as specification test*
- Neither offers so much in one package.

* NCHRP Report 513. Work in progress.

NCHRP 513

- 9-29, *Simple Performance Tester for Superpave Mix Design: First-Article Development and Evaluation*
- Recommended some refinements to protocols from 9-19
  - Some to make specification reflect capabilities of first-article, commercial device(s), others to simplify/unify procedures, etc.

Dynamic Modulus Testing

Equipment

Procedure

Data

Triaxial Testing Equipment

Method of Test

- Stress-controlled test
- Sinusoidal axial compressive load is applied to cylindrical specimen.
- Resulting axial strain response is measured.
- Applied stress and measured strain used to calculate modulus.

Variables

- Temperature
- Frequency
- Confinement
  - Confining pressure recommended with gap or open-graded mixtures

Protocol (per 513)

Apply axial compressive load at

- given temperature
- over a range of loading frequencies

- Calculate |E*| at each frequency.

Temperature Control

- Environmental chamber to provide temperature range of 20 to 60°C (68 to 140°F)
- Control to ±0.5°C (1°F)

Test Temperature

- Test temperature will be defined in a Standard Practice (to be developed)
- 9-19 recommendations were to test at a T_{eff} for permanent deformation (25-60°C) and a T_{eff} for fatigue (4-20°C) based on climate (Ayesha will show some examples later)

Frequencies

- 513 recommends minimum of five frequencies between 0.1 and 25 Hz
  - User selects with guidance from Standard Practice (to be developed)
  - Ten conditioning cycles and ten testing cycles at each frequency.
  - 50 data points captured per cycle during testing cycles
  - Stress adjusted during conditioning cycles to keep average dynamic strain between 75 to 125 microstrains

Sample Size and Preparation

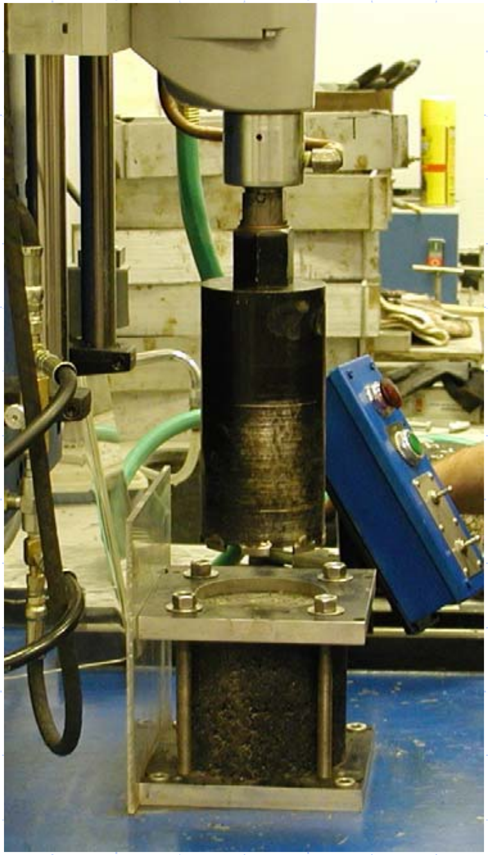
- Test specimen 100 mm in diameter, 150 mm high
- Compact 150 mm diameter specimen about 165 mm high then core and saw
- Automated system has been developed

Disadvantage

- Specimen Size
  - 1:1.5 D/H Ratio required to ensure fundamental properties
  - 100 mm diameter by 150 mm high
  - Smooth parallel ends (Sawed)
- Sawed and Cored From Over-Height Gyratory Specimens
  - Not all SGC's can produce specimens
- 9-29 automated fabrication system

Cored Specimen

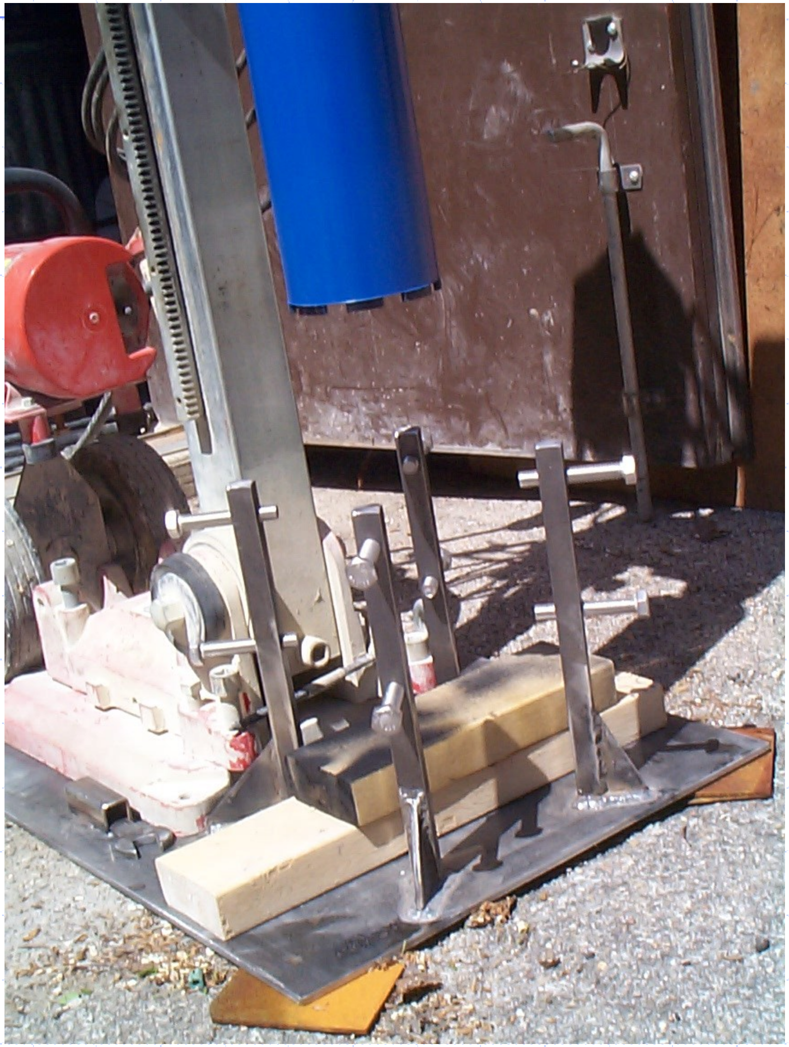
Coring Jig – Asphalt Institute



Coring Jig

4.25” nominal diameter bit

Coring Jig



Finished specimen

9-29 Instrumentation LVDT's

Regional Effort

- Funded by FHWA
- Five Superpave mixes, one Marshall mix
  - Iowa, Kansas, Michigan, Missouri, Minnesota (SP and M)
  - Also have 2 SMAs (Indiana and Missouri)
  - 2 mixes from Wisconsin (58-28 and 70-28)

Objectives

- First look at candidate tests and how typical regional mixes will perform
- Extend to open graded and SMA mixes
- Compare SPT to SST
- Feedback to FHWA on practical testing issues

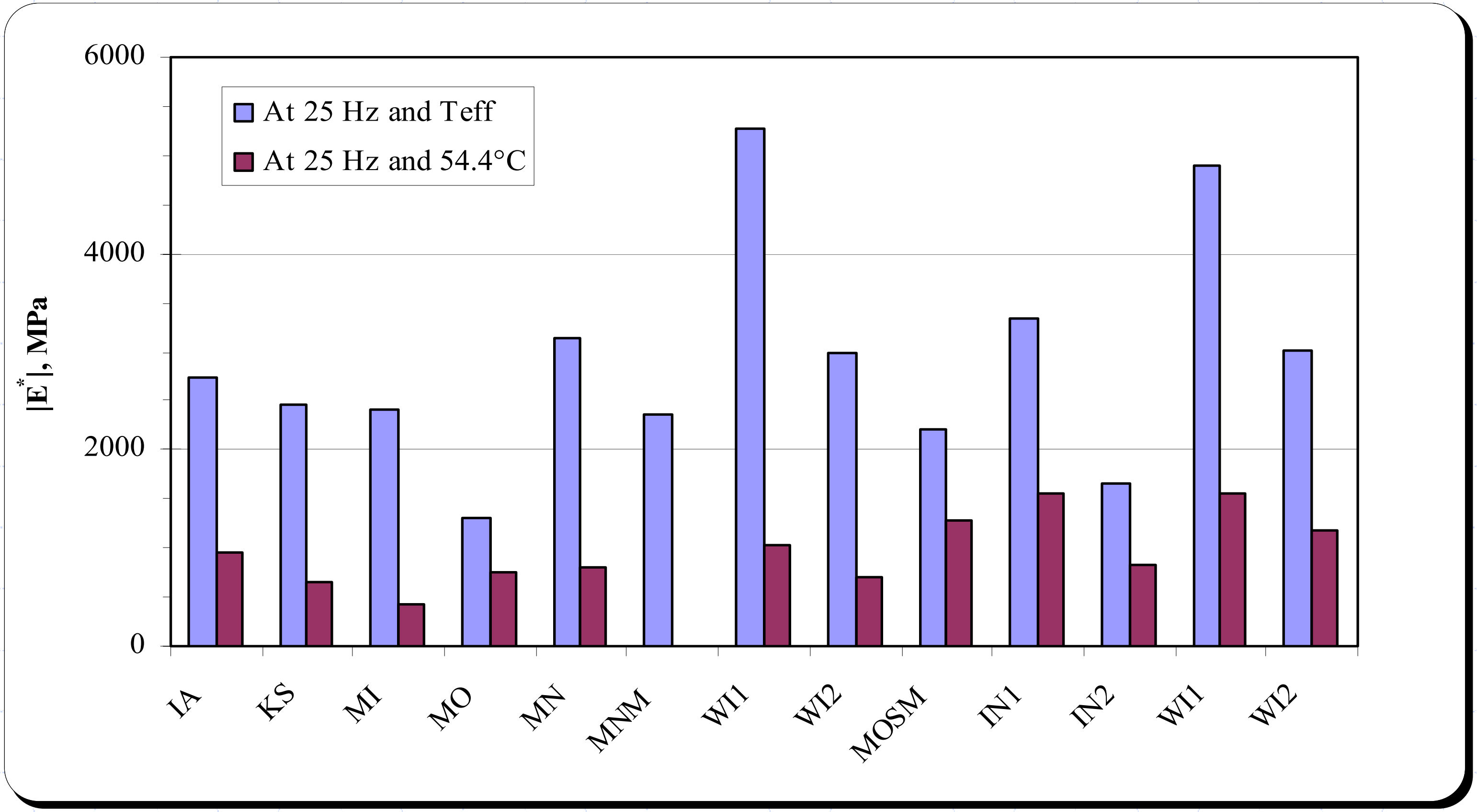
Mix Types/Sizes

Indiana	9.5 SMA, 12.5 SMA
Iowa	12.5
Kansas	9.5
Michigan	9.5
Minnesota (M)	¾" minus
Minnesota (RAP – S)	12.5 Fine
Missouri	12.5 Coarse, 12.5 SMA
Wisconsin	12.5 Fine

Effective Temperatures

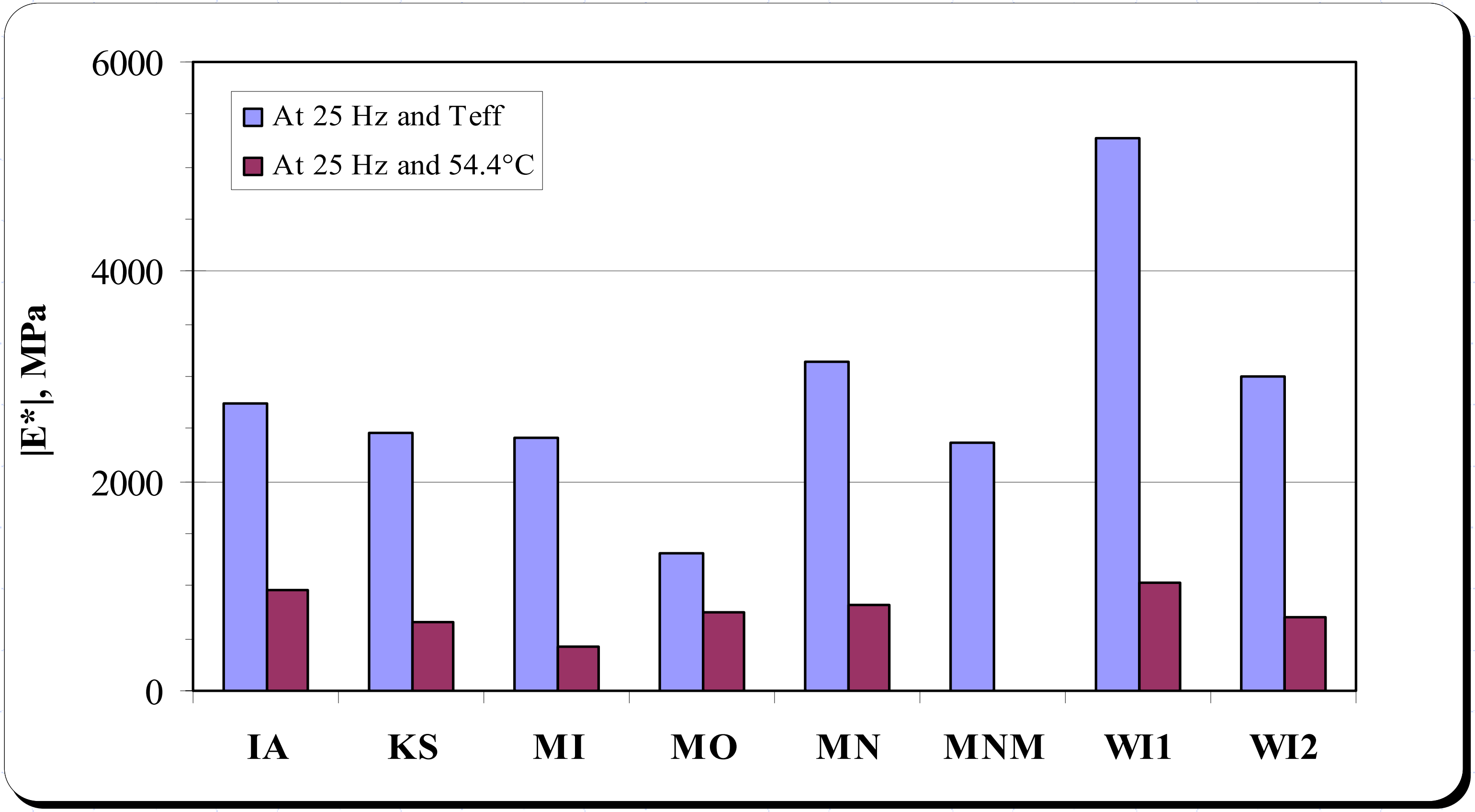
Indiana Iowa	38.4, 39.6 39.1°C	PG70-28 PG64-22
Kansas	40.4°C	PG64-22
Michigan	34.2°C	PG58-28
Minnesota	36.9°C	PG64-28 (M) PG64-22 (S)
Missouri	41.1°C 41.8°C	PG70-22 (SMA) PG76-22
Wisconsin	34.0°C	PG70-28 PG58-28

Dynamic Modulus, |E*| @ 25 Hz

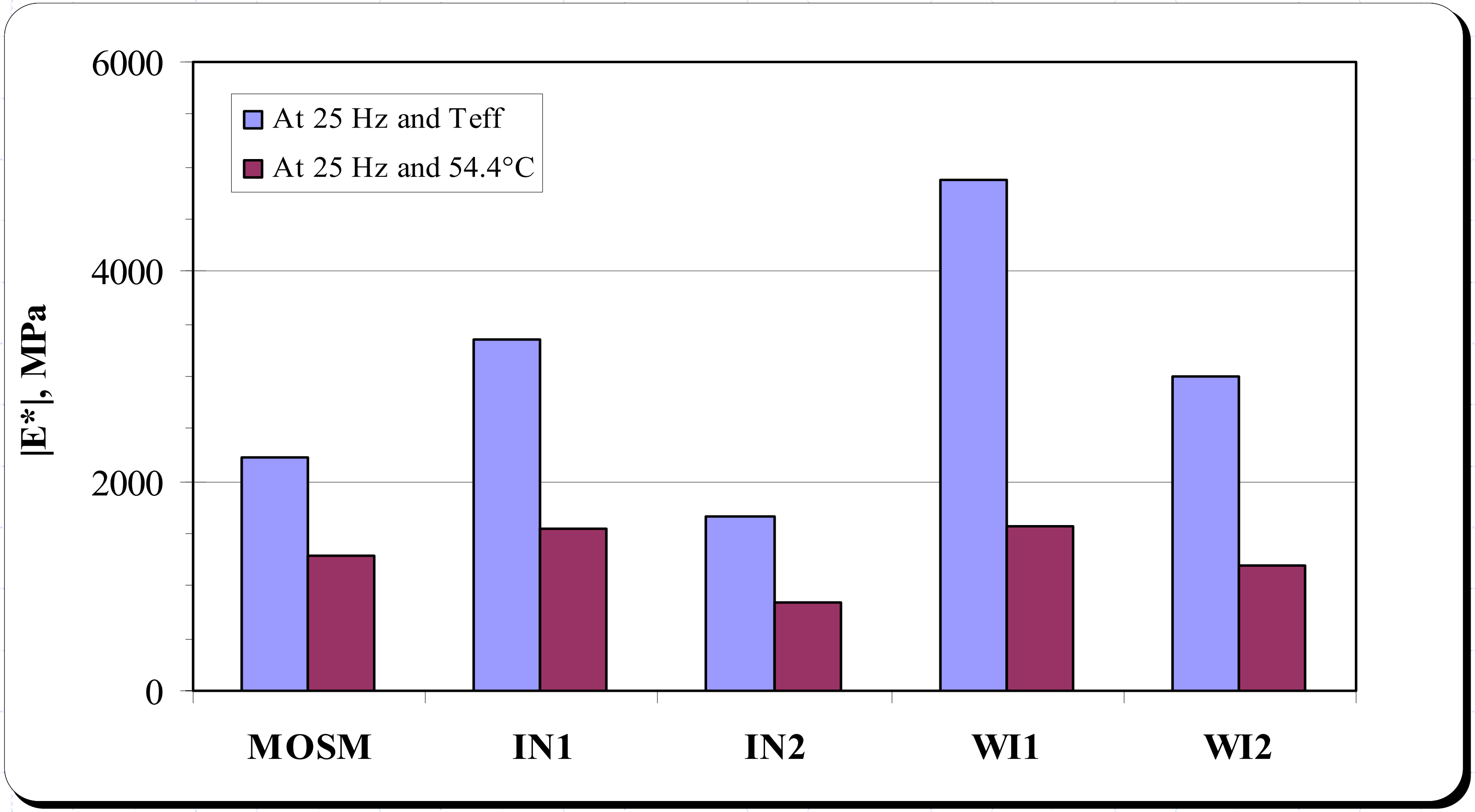


shows both unconf. and conf. (last 5 mixes)

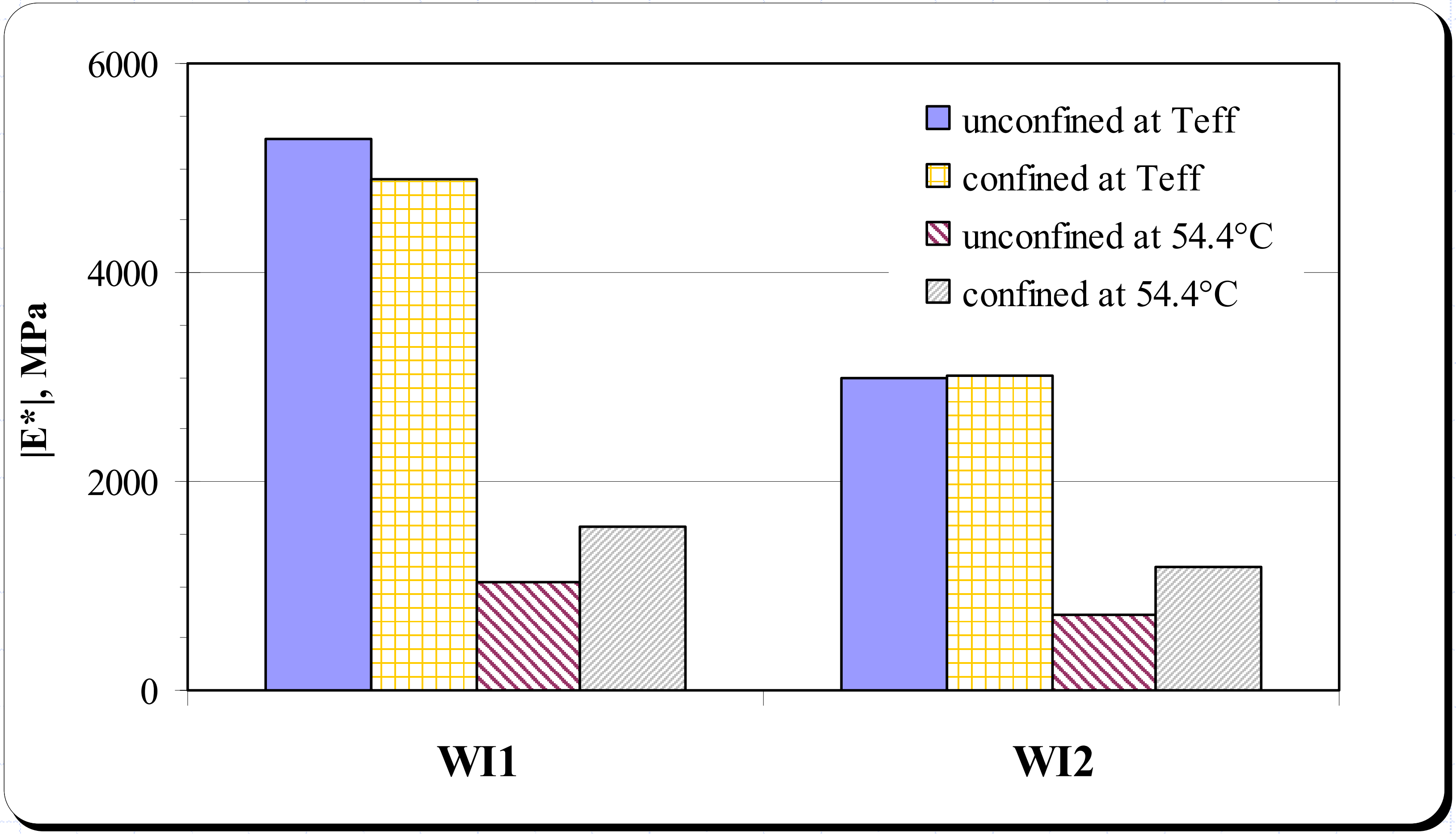
|E*| @ 25 Hz (unconfined)



|E*| @ 25 Hz (confined)

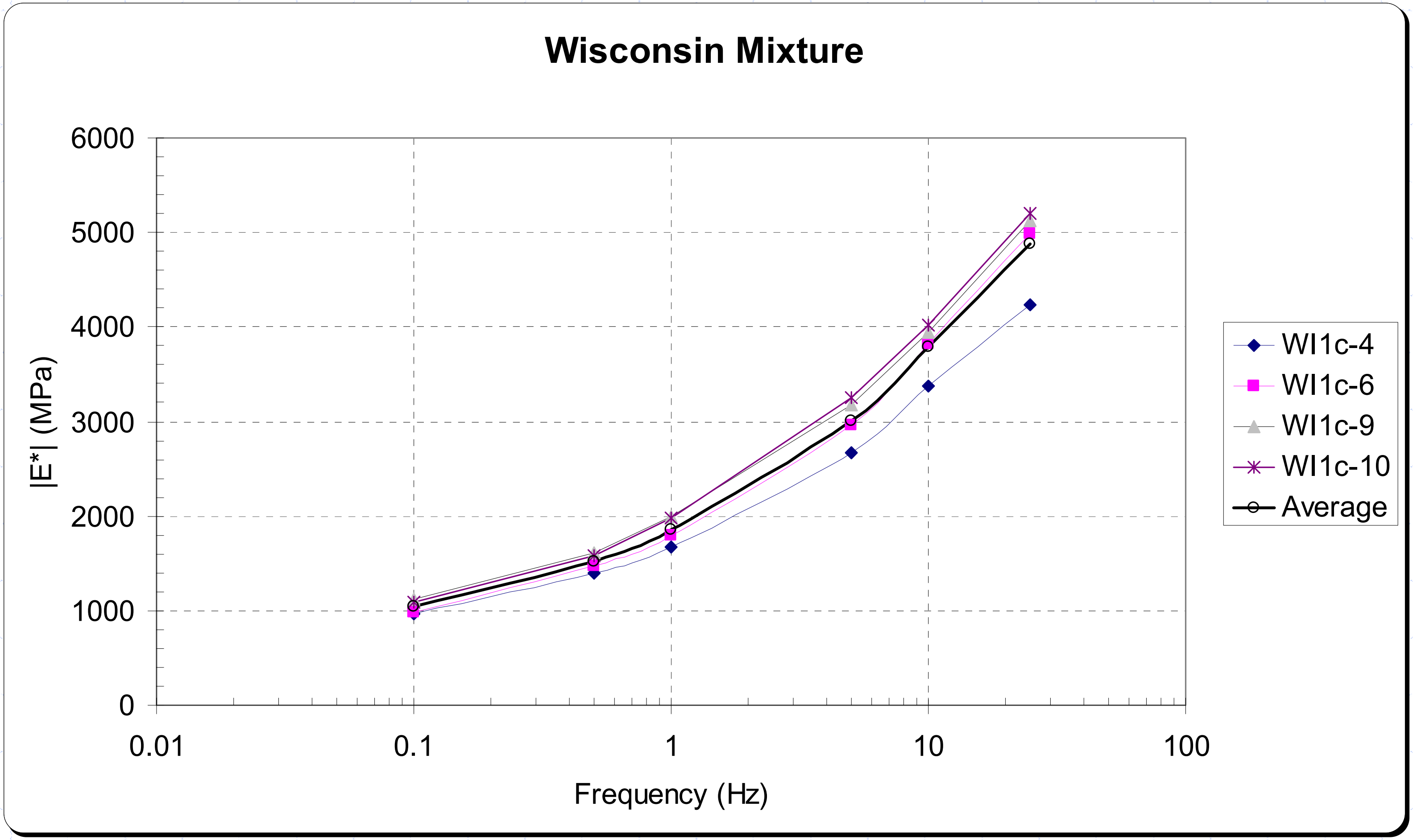


|E*| @ 25 Hz
WI samples--conf. vs. unconf.

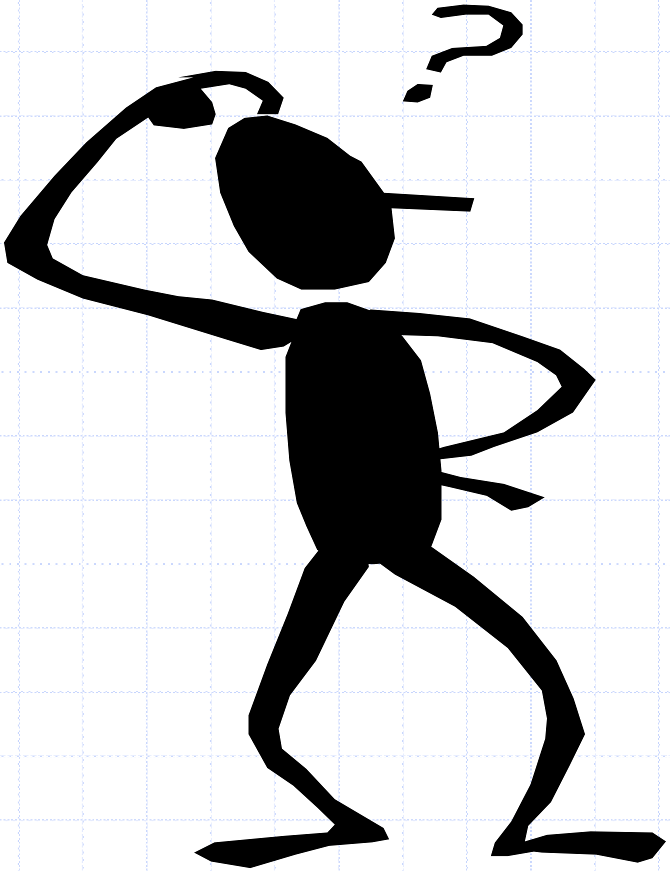


effect of confinement evident at higher temp., as expected.

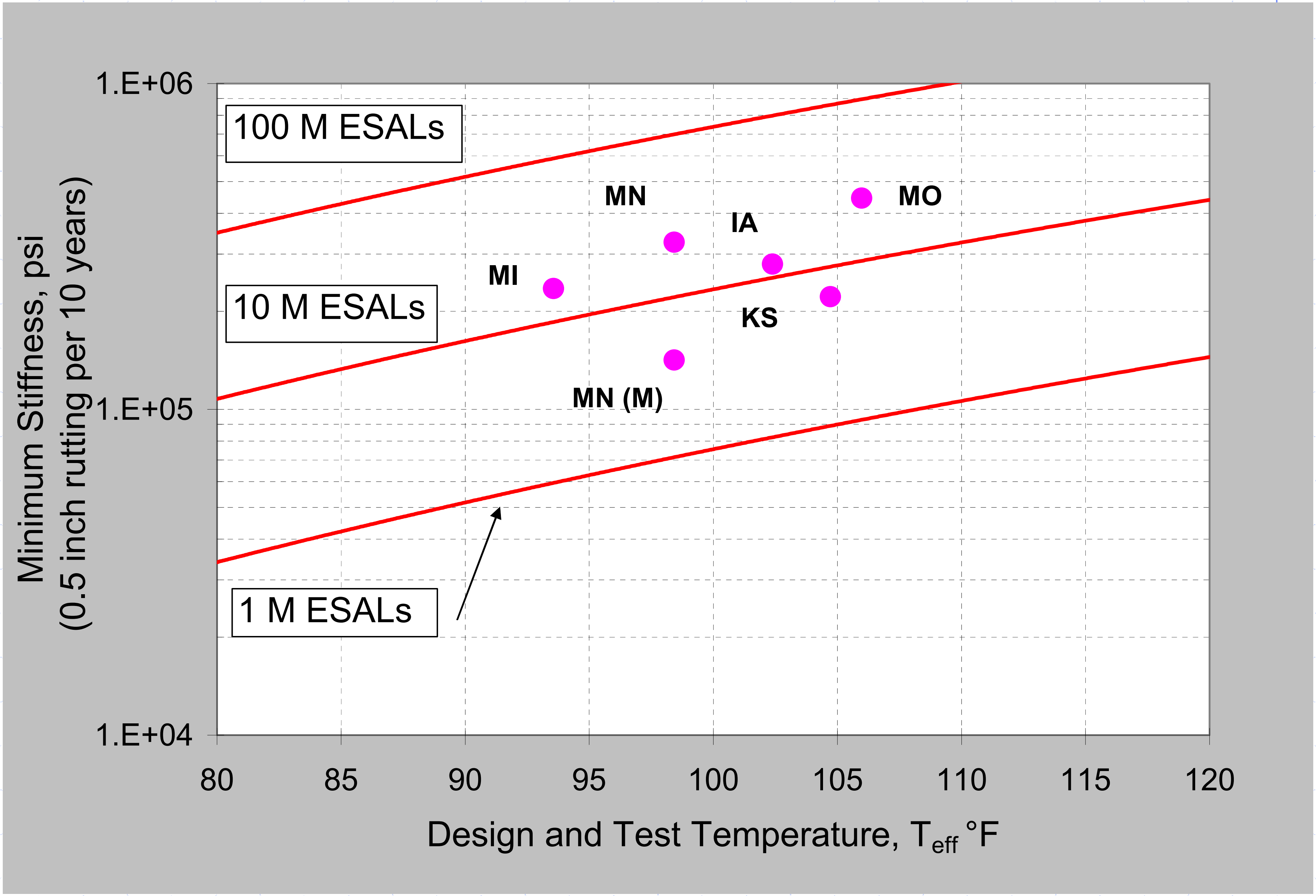
|E*| @ Teff
WI samples--repeatability



What modulus do you need?

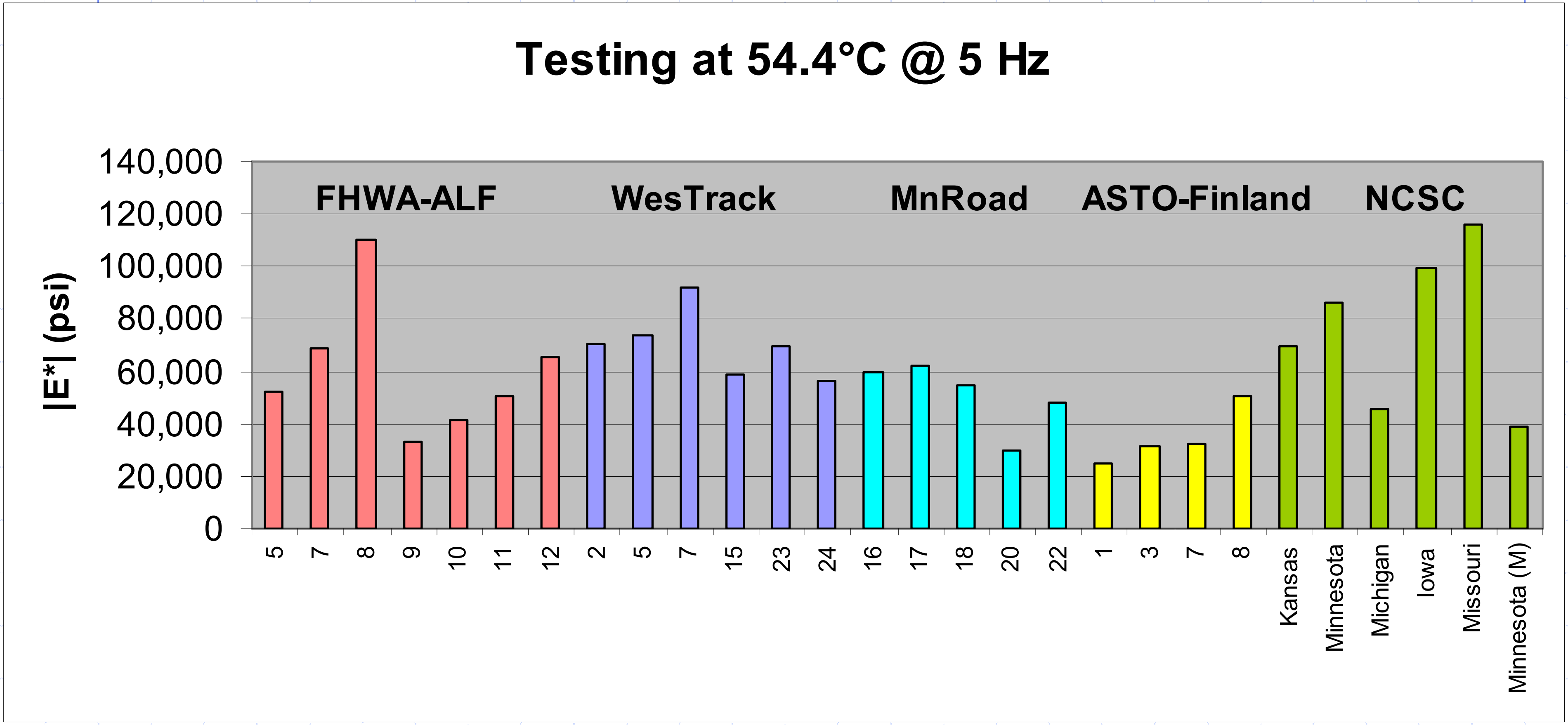


- Preliminary suggestion
- Dr. Terhi Pellinen
- Based on layered elastic analysis, ½” rutting at 10 years
- Not calibrated
- More guidance to come



100 M ESALs
10 M ESALs
1 M ESALs
MN
MO
IA
MI
KS
MN (M)
1.E+06
1.E+05
1.E+04
80
85
90
95
100
105
110
115
120
Minimum Stiffness, psi
(0.5 inch rutting per 10 years)
Design and Test Temperature, T_{eff} °F

Comparison to Other Data



Some Conclusions

- Binder drives stiffness to an extent. Strength test (confined triax) will measure effects of aggregate.
- With lower traffic, you can accept lower stiffness.

Practical Considerations

- Training is essential
- Get manufacturer's training specific to your device
  - Of ten labs in NC region equipped to run test, have five different brands of equipment
- Practice, practice, practice
- Reasonably – two months or more to master, depending on workload

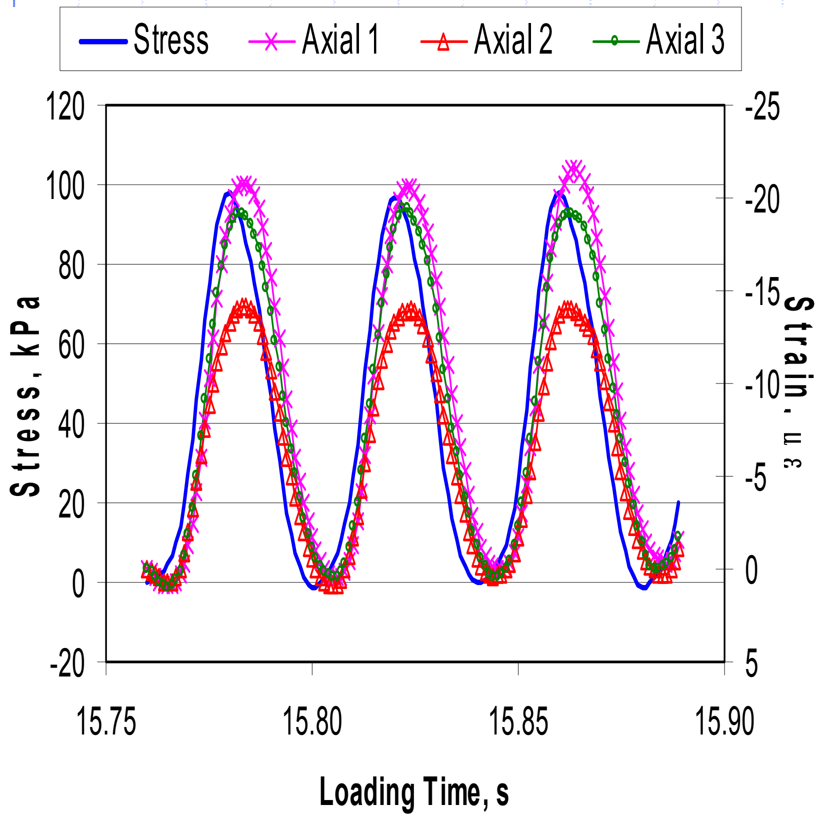
Sample Preparation

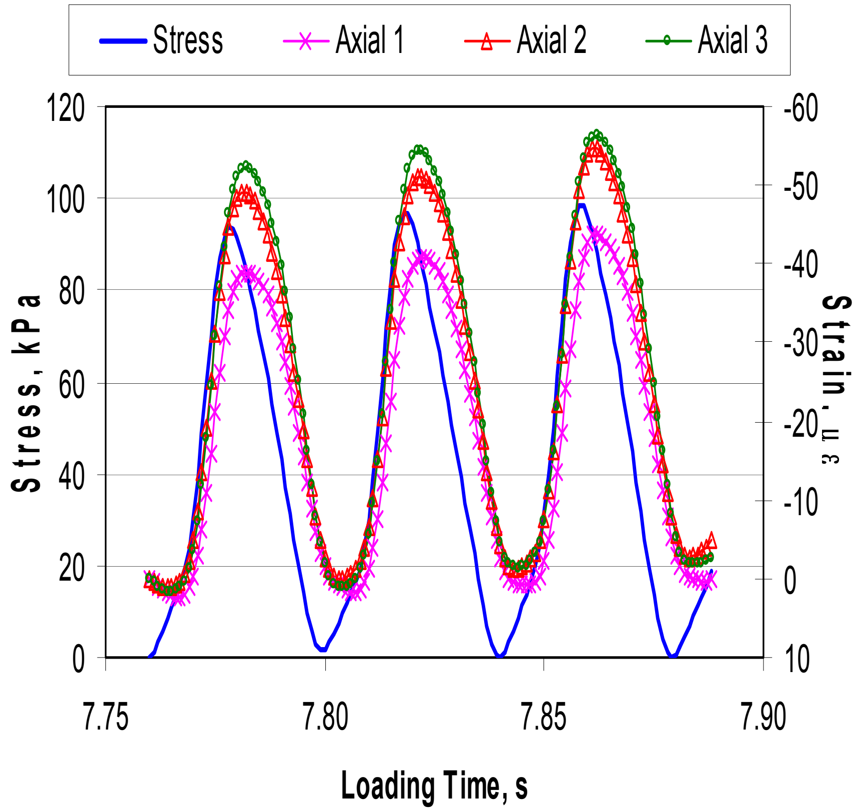
- Critical to good data
- Can your gyratory accommodate tall specimens?
- Automated system will be advantageous, but not essential
- With care and practice, “homemade” rigs can work
  - Don’t rush when coring or sawing

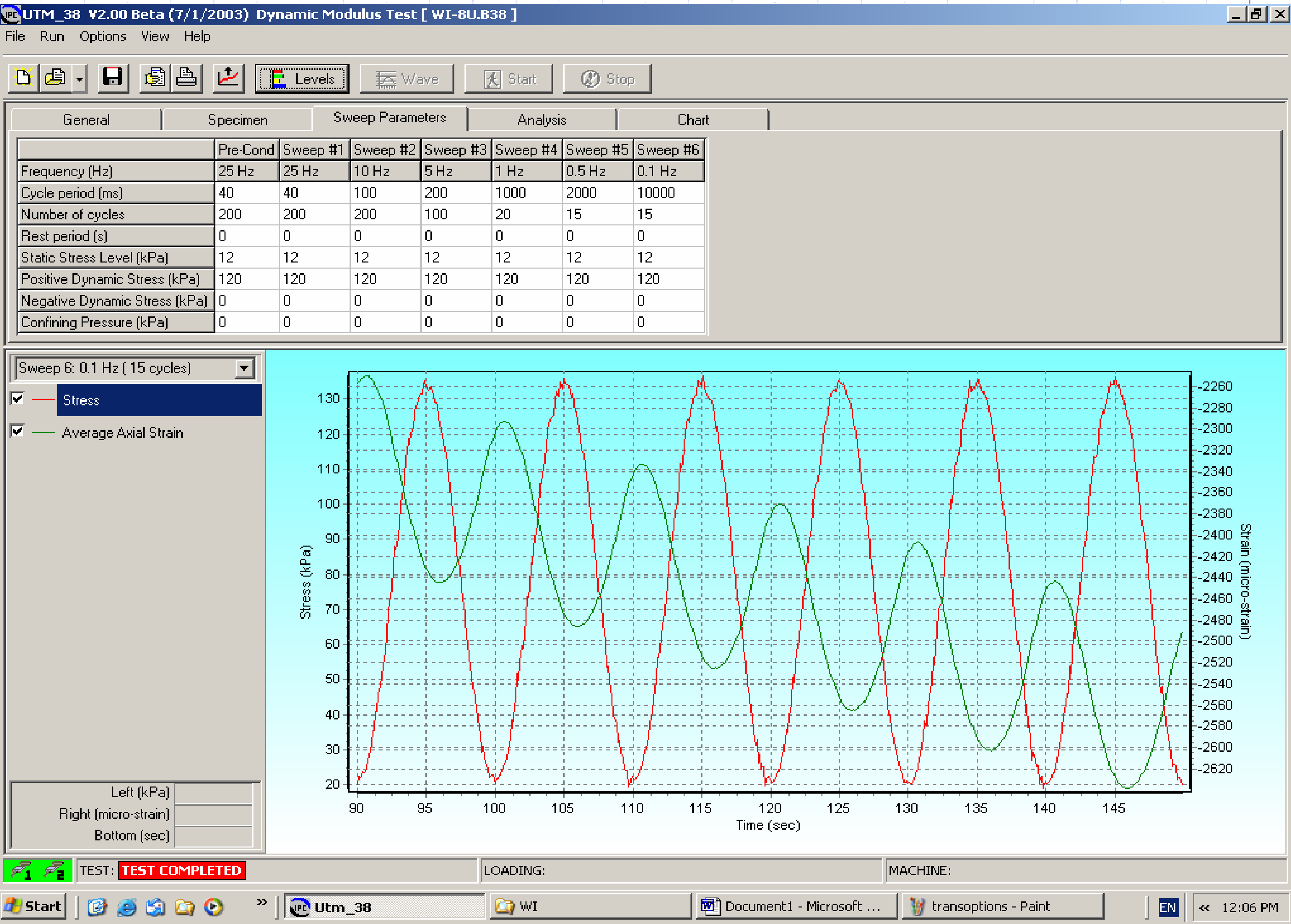
Data Quality Checks

- Observe waveforms during test
  - Adjust gains if needed
  - “First article” devices automatically adjust

Good vs. Bad Waveforms

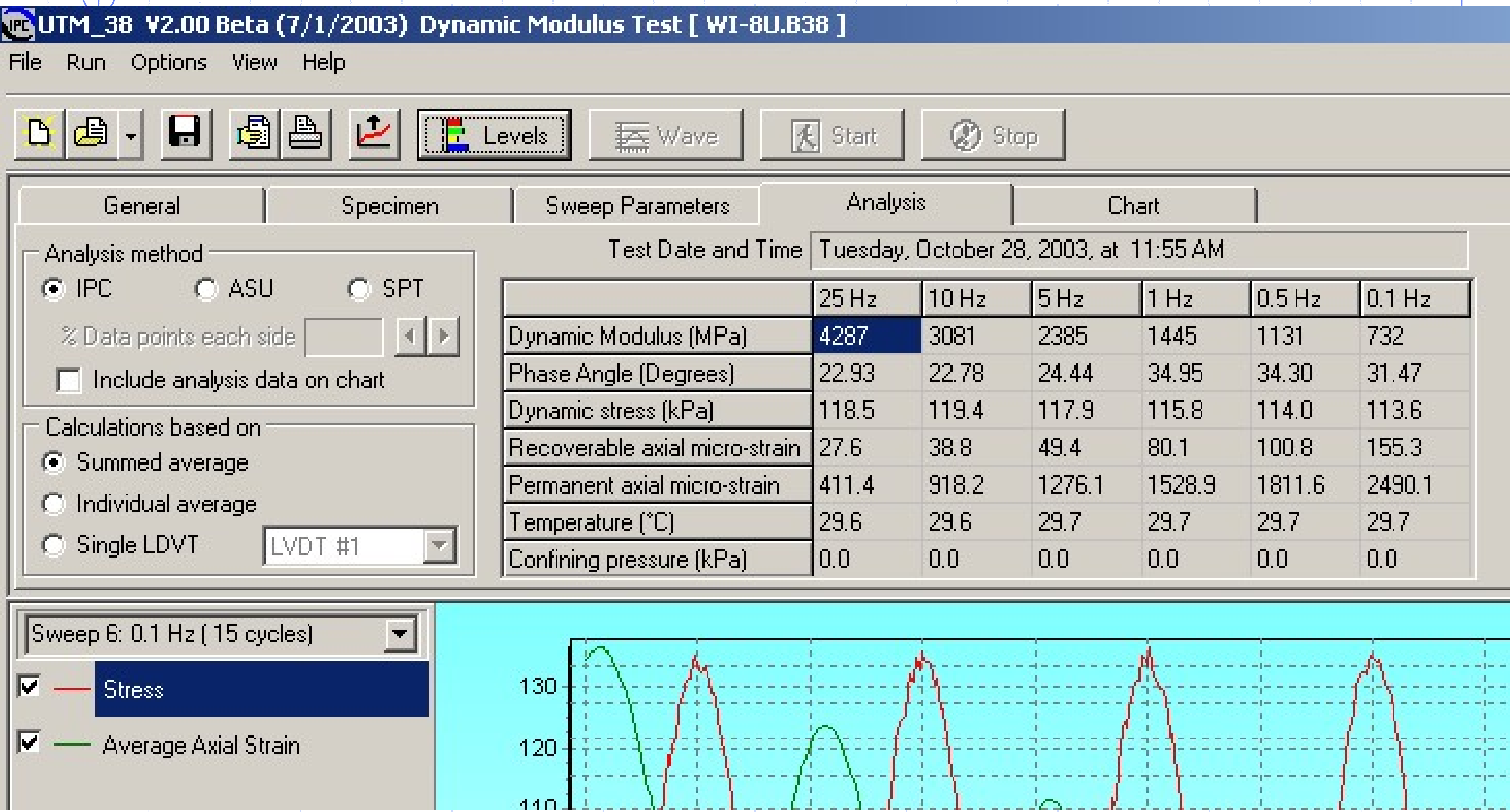






	Pre-Cond	Sweep #1	Sweep #2	Sweep #3	Sweep #4	Sweep #5	Sweep #6
Frequency (Hz)	25 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
Cycle period (ms)	40	40	100	200	1000	2000	10000
Number of cycles	200	200	200	100	20	15	15
Rest period (s)	0	0	0	0	0	0	0
Static Stress Level (kPa)	12	12	12	12	12	12	12
Positive Dynamic Stress (kPa)	120	120	120	120	120	120	120
Negative Dynamic Stress (kPa)	0	0	0	0	0	0	0
Confining Pressure (kPa)	0	0	0	0	0	0	0

Results



	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
Dynamic Modulus (MPa)	4287	3081	2385	1445	1131	732
Phase Angle (Degrees)	22.93	22.78	24.44	34.95	34.30	31.47
Dynamic stress (kPa)	118.5	119.4	117.9	115.8	114.0	113.6
Recoverable axial micro-strain	27.6	38.8	49.4	80.1	100.8	155.3
Permanent axial micro-strain	411.4	918.2	1276.1	1528.9	1811.6	2490.1
Temperature (°C)	29.6	29.6	29.7	29.7	29.7	29.7
Confining pressure (kPa)	0.0	0.0	0.0	0.0	0.0	0.0

Other Data Quality Checks

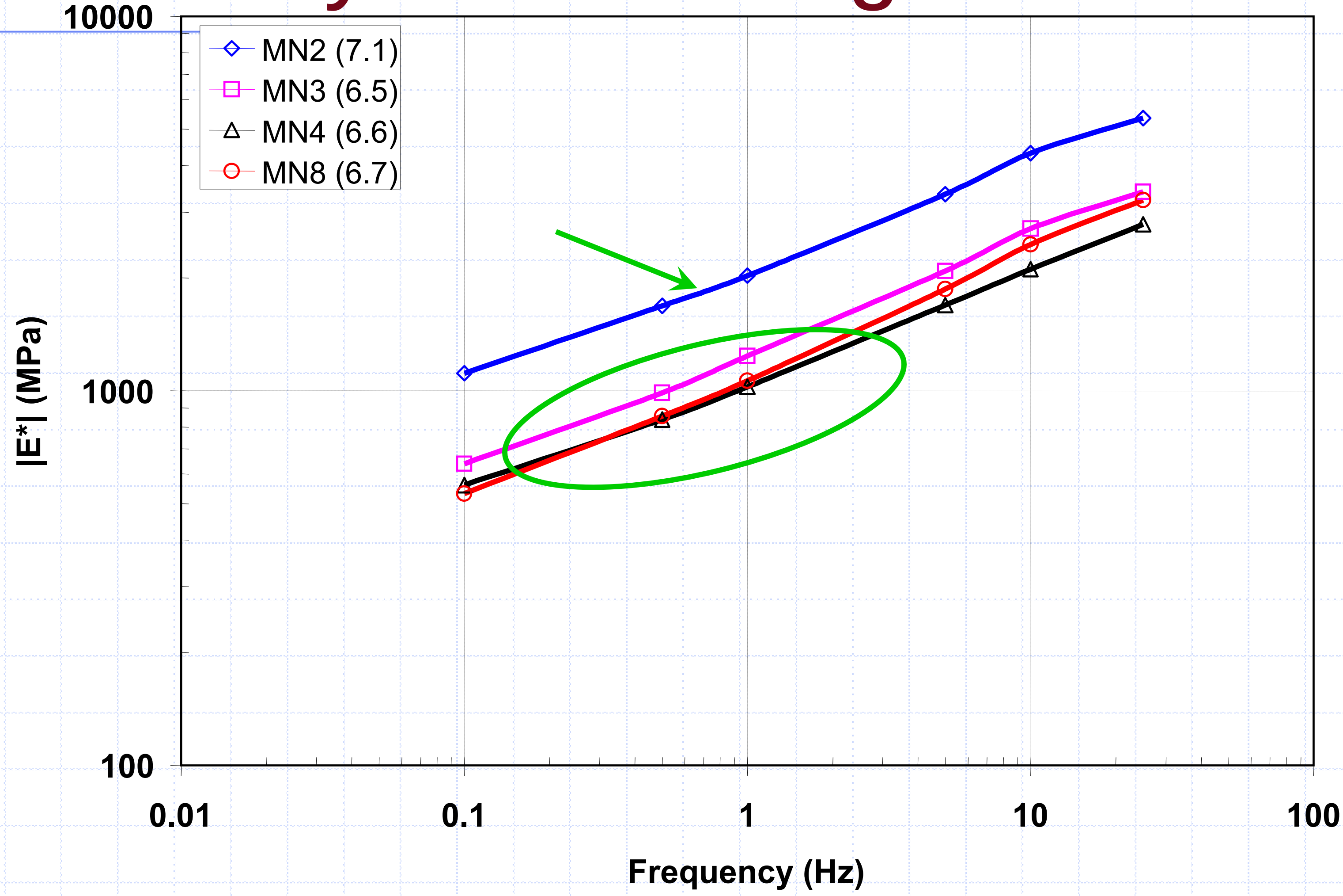
- Plot data on “complex plane” – E_1 vs E_2

$$E_1 = |E^*| \cos \varphi$$

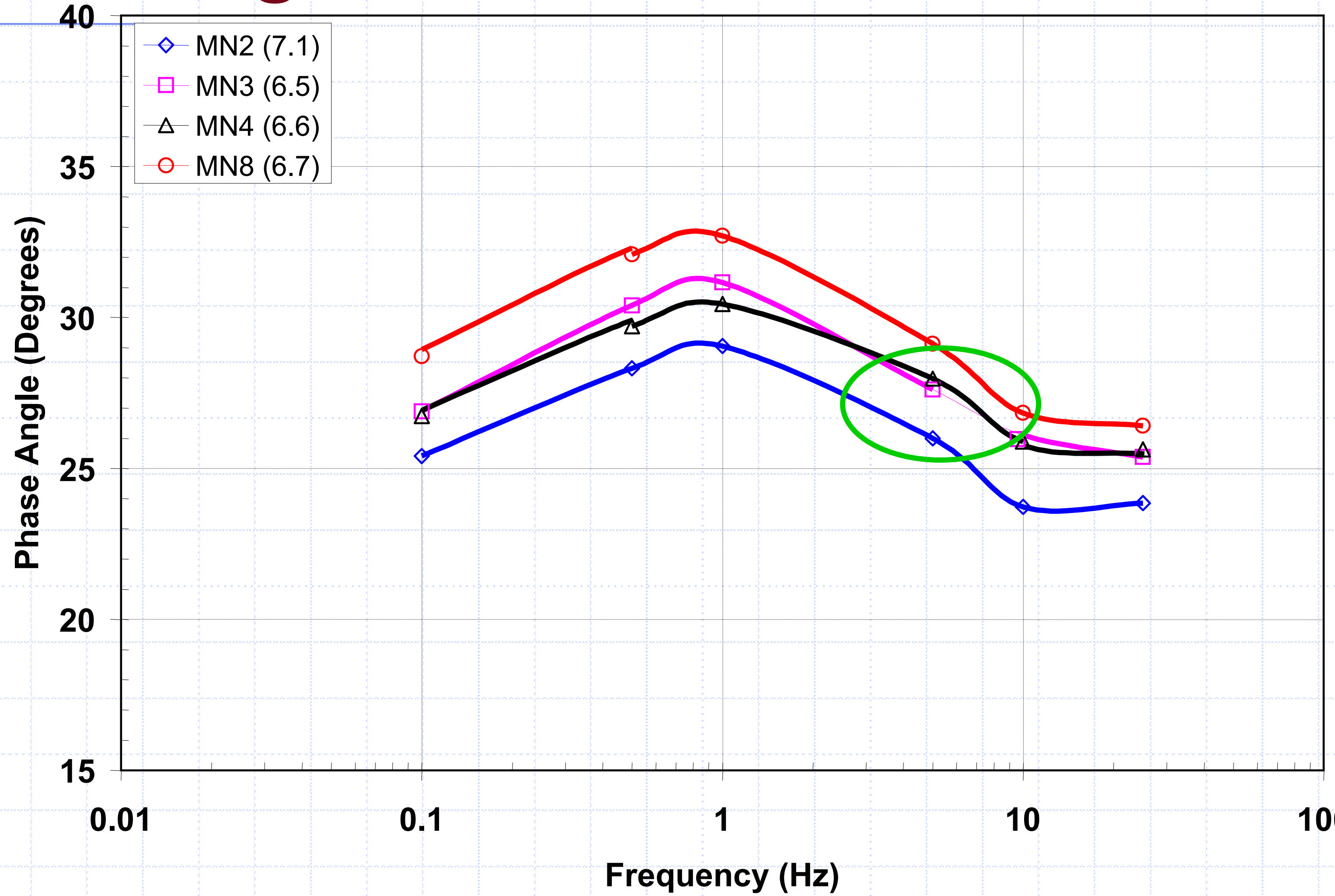
$$E_2 = |E^*| \sin \delta$$

- Plot data to “Black Space” – log |E*| vs. phase angle

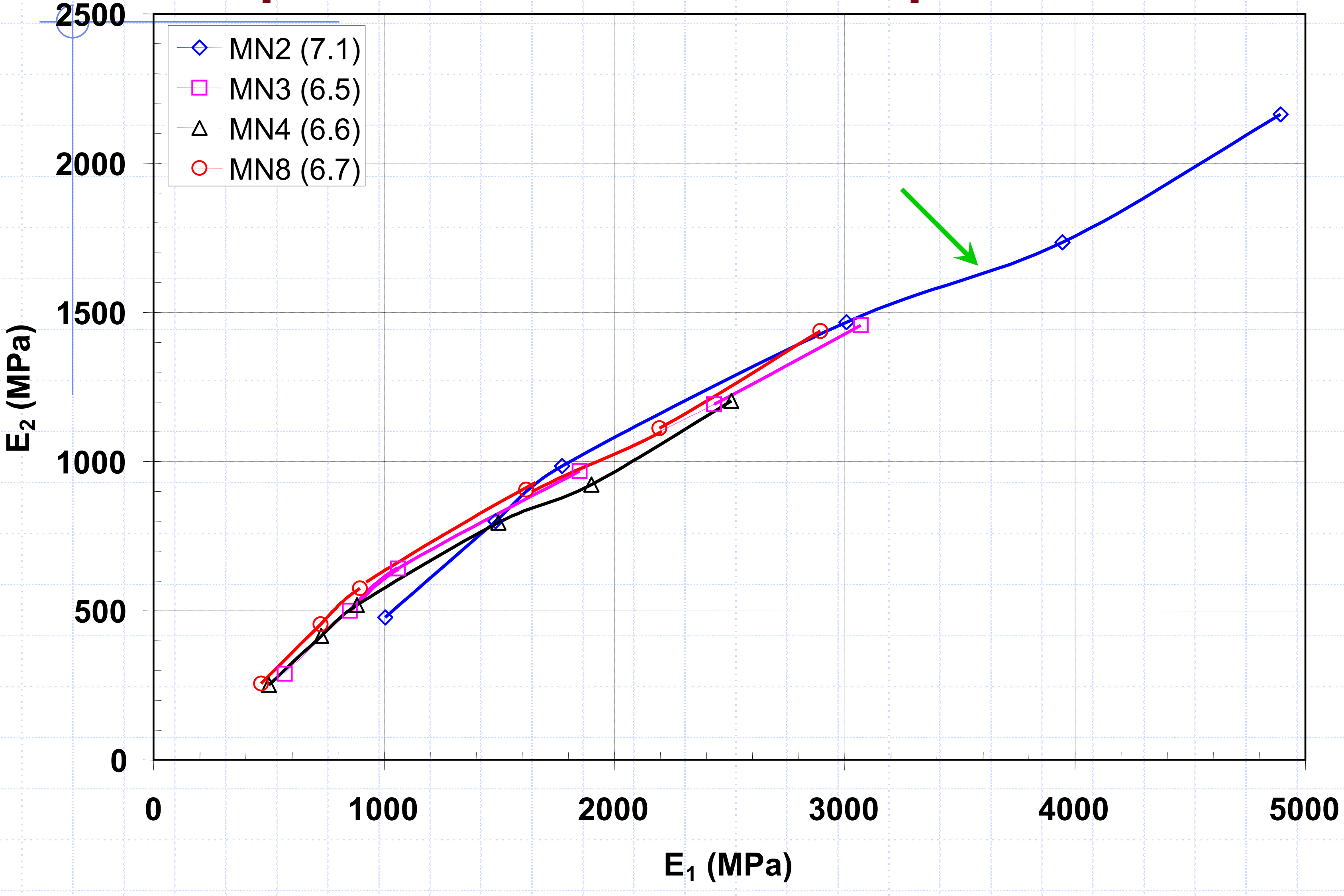
Variability and Tuning Problem



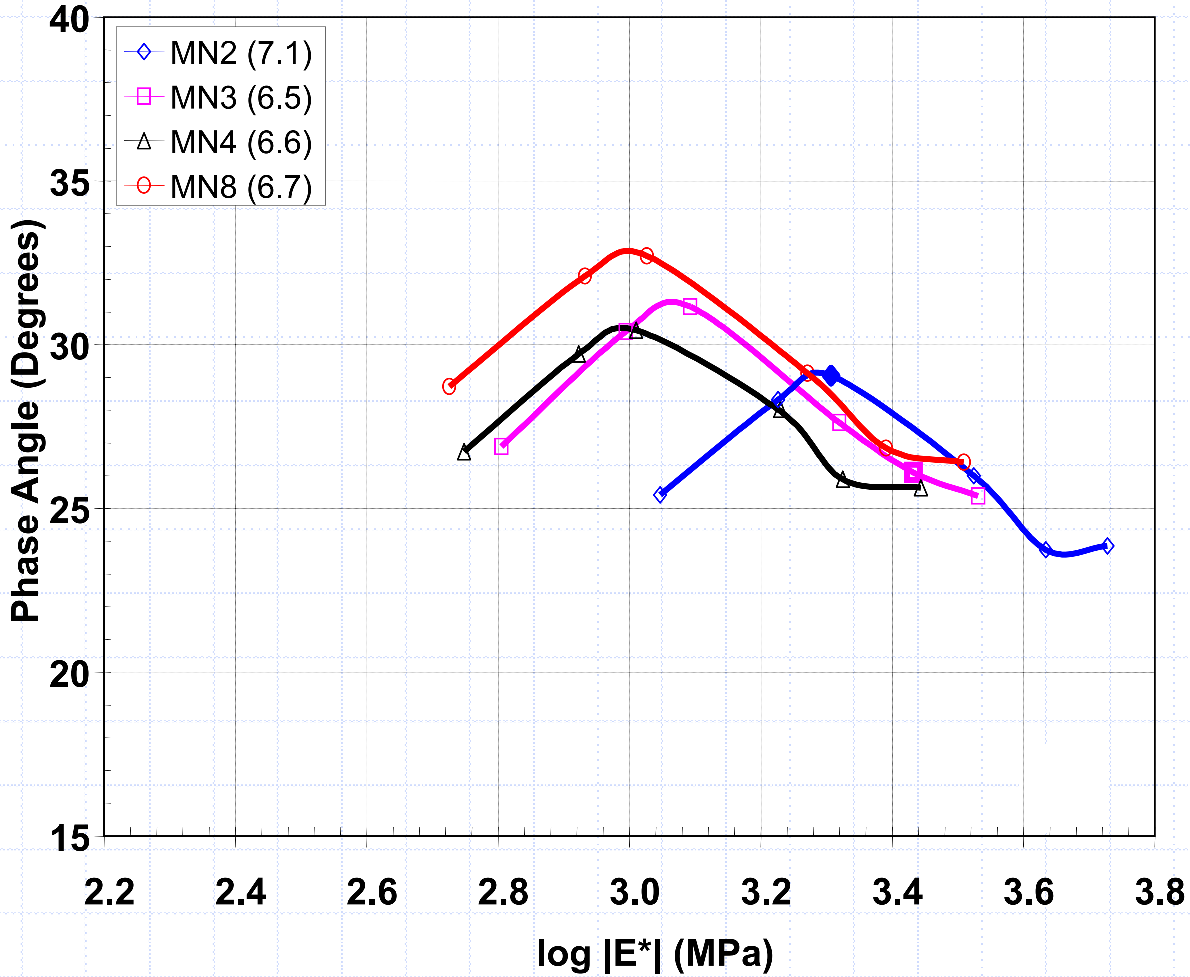
Tuning Problem



Complex Plane – Temp Problem



Black Space - Temp Problem



Lessons Learned

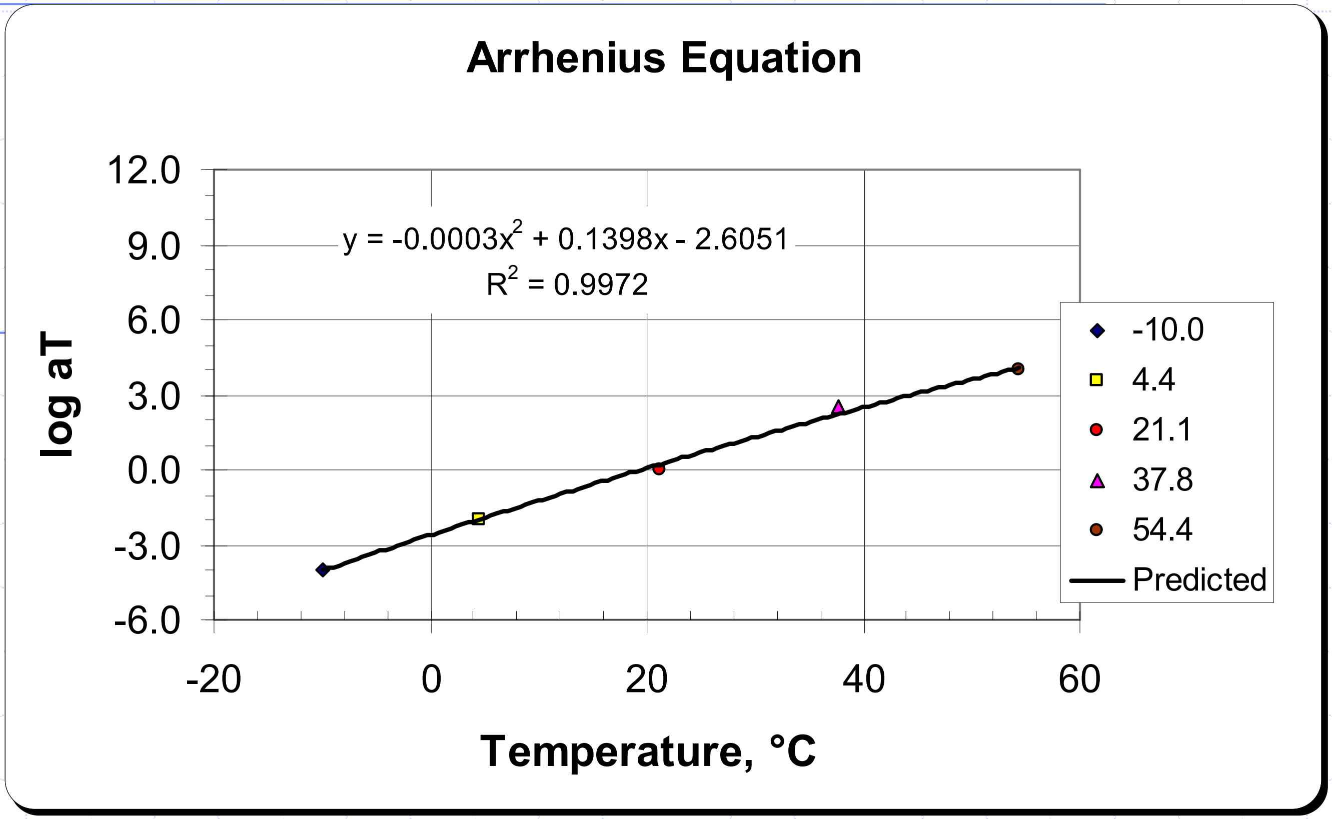
- Training and practice essential
- Sample preparation is key
- Caring and sawing can be accomplished
- Productivity for prep and testing = 8-10 hours over 3-4 days
- Data quality checks important

Uses of Dynamic Modulus

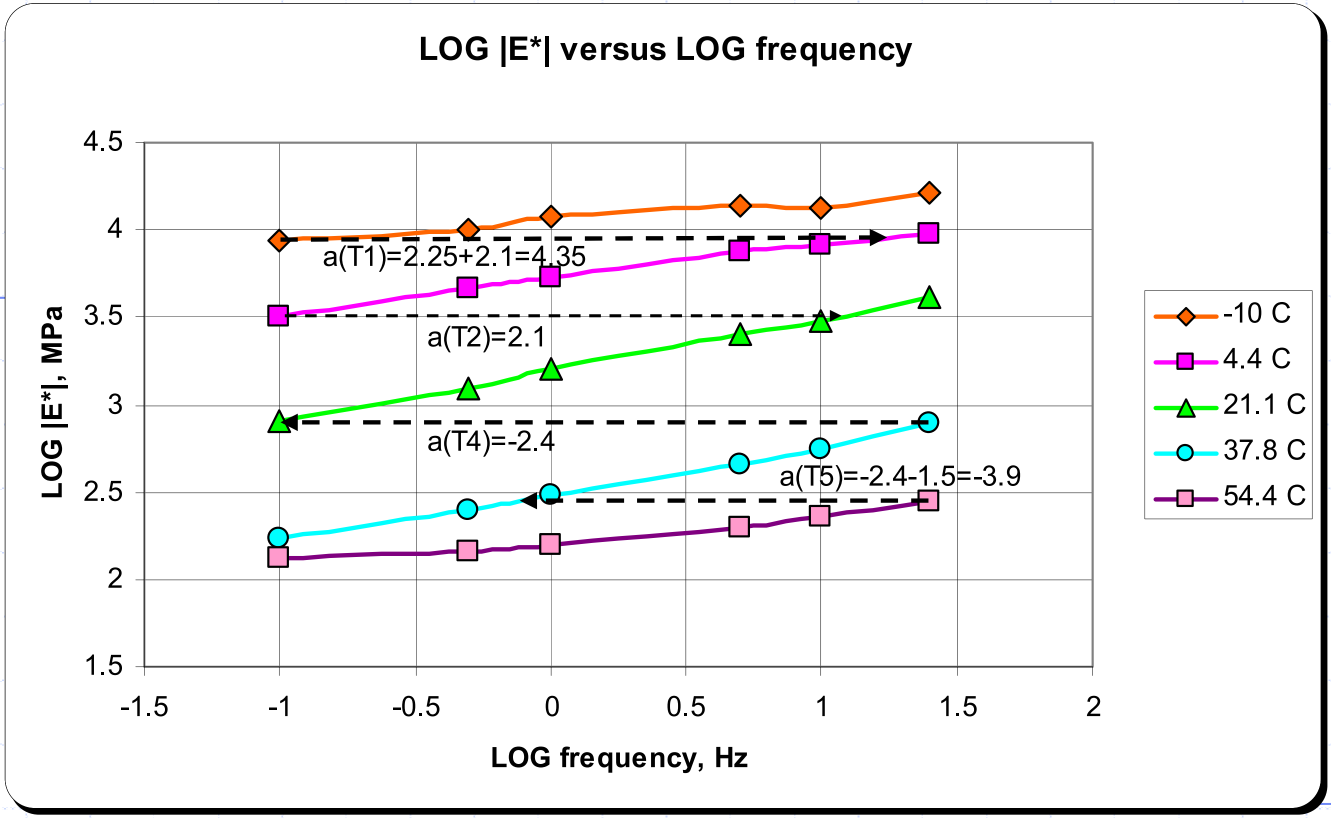
- As a performance test to verify mix design
- To compare different mixes or materials
- For pavement design (MEPDG)

Master Curve

- Test over a range of temperatures or frequencies and use time-temperature equivalence to “shift” curves into one master curve defining material response over a range of conditions
- Easier and quicker to change frequencies and use that to show how response would change at different temperatures

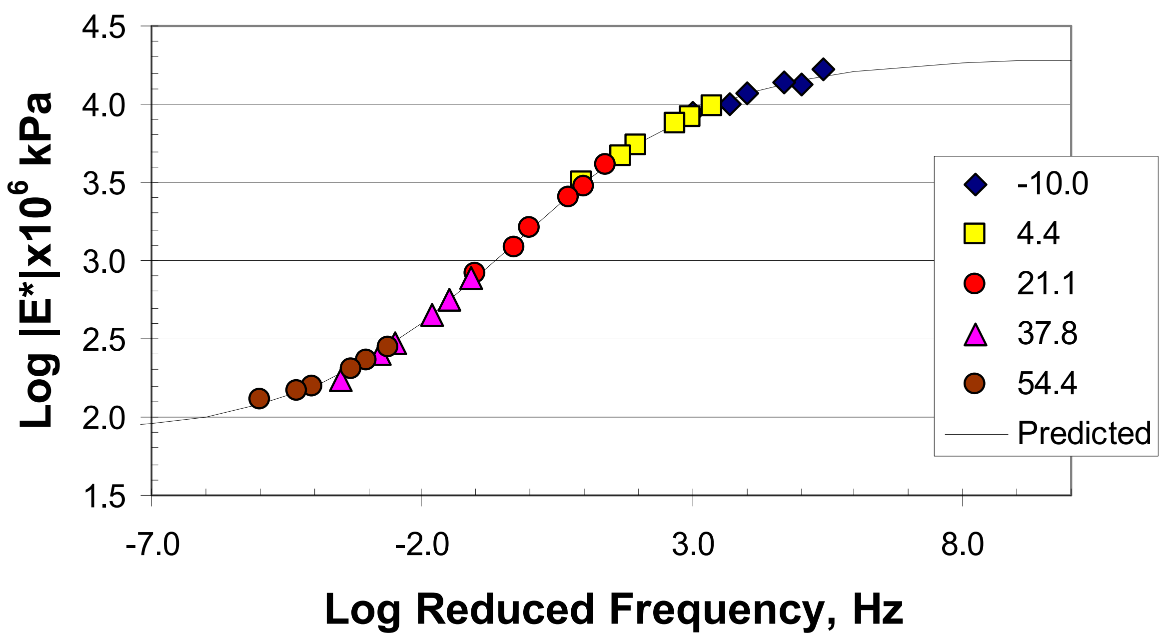


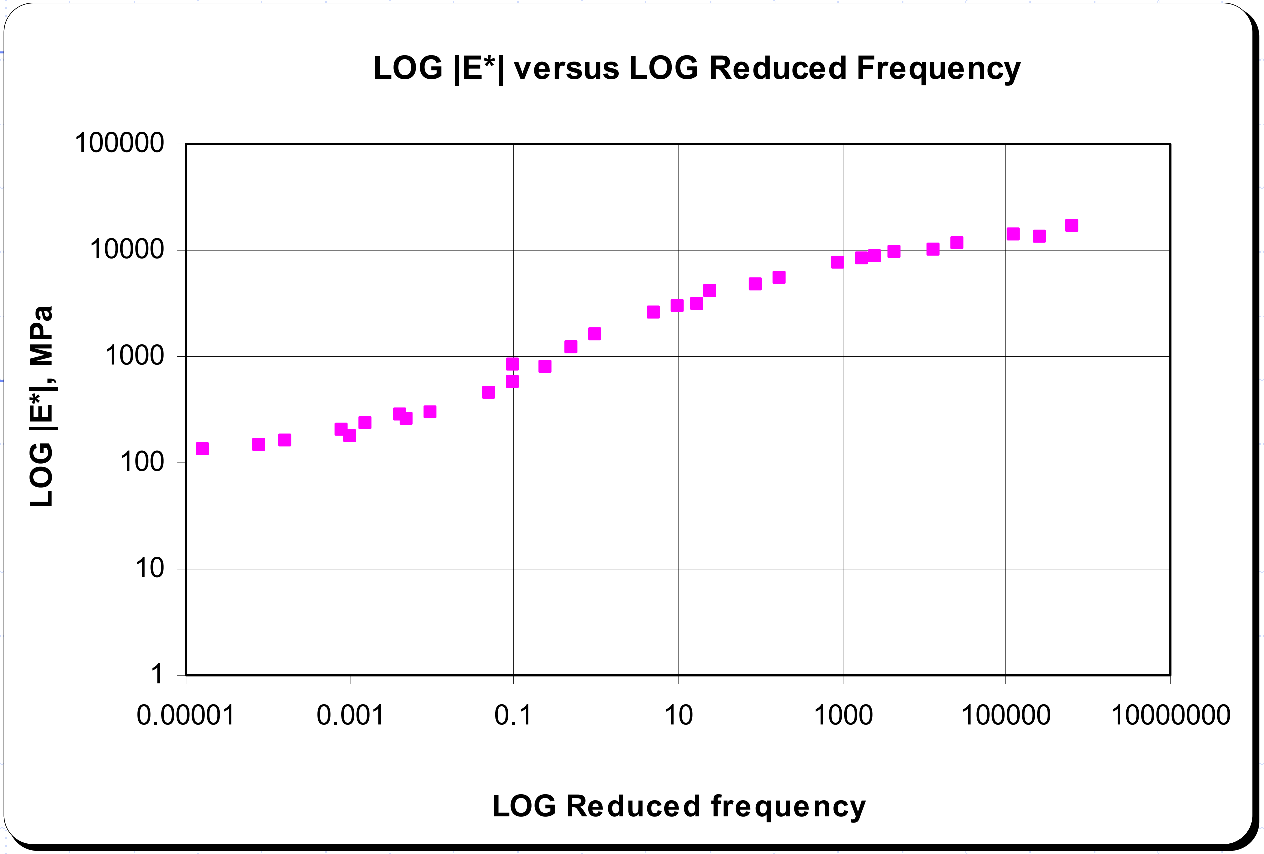
Arrhenius Equation
y = -0.0003x^2 + 0.1398x - 2.6051
R^2 = 0.9972
12.0
9.0
6.0
3.0
0.0
-3.0
-6.0
log aT
-20
0
20
40
60
Temperature, °C
-10.0
4.4
21.1
37.8
54.4
Predicted



LOG |E*| versus LOG frequency
4.5
4
3.5
3
2.5
2
1.5
-1.5
-1
-0.5
0
0.5
1
1.5
2
LOG |E*|, MPa
LOG frequency, Hz
a(T1)=2.25+2.1=4.35
a(T2)=2.1
a(T4)=-2.4
a(T5)=-2.4-1.5=-3.9
-10 C
4.4 C
21.1 C
37.8 C
54.4 C

Arrhenius Equation




LOG |E*| versus LOG Reduced Frequency
100000
10000
1000
100
10
1
0.00001
0.001
0.1
10
1000
100000
10000000
LOG |E*|, MPa
LOG Reduced frequency

Master Curve Generation

- Similar concepts used with binder under MP1a
- Complex mathematics to create master curve
- Use software to accomplish – several options
- NCSC can assist

What's in Store?

- States will be looking at this testing and its applications
  - Probably for several years
- More refinements likely on national level
- Implementation probably several years away

Optional Topic

- For MEPDG, is this testing necessary?
- Witczak and Hirsch models can be used to substitute for actual testing

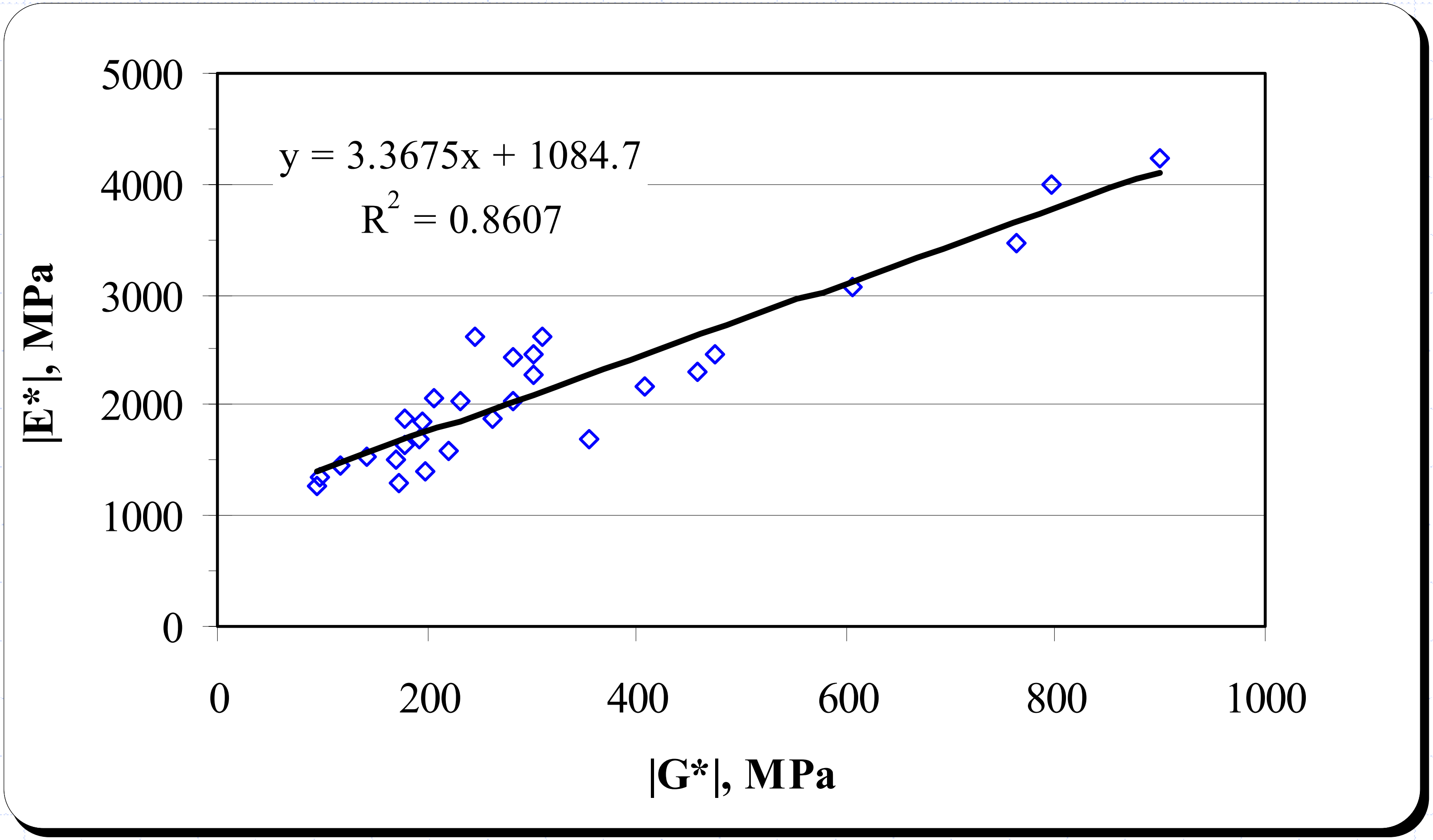
Witczak model -- Input req.

- P_{200} (%)
- P_4 (%)
- $P_{3/4}$ (%)
- $P_{3/8}$ (%)
- V_a (%)
- V_{beff} (%)
- frequency (Hz)
- viscosity (η, x10^6 Poise)

Witczak and Hirsch model -- some additional input req.

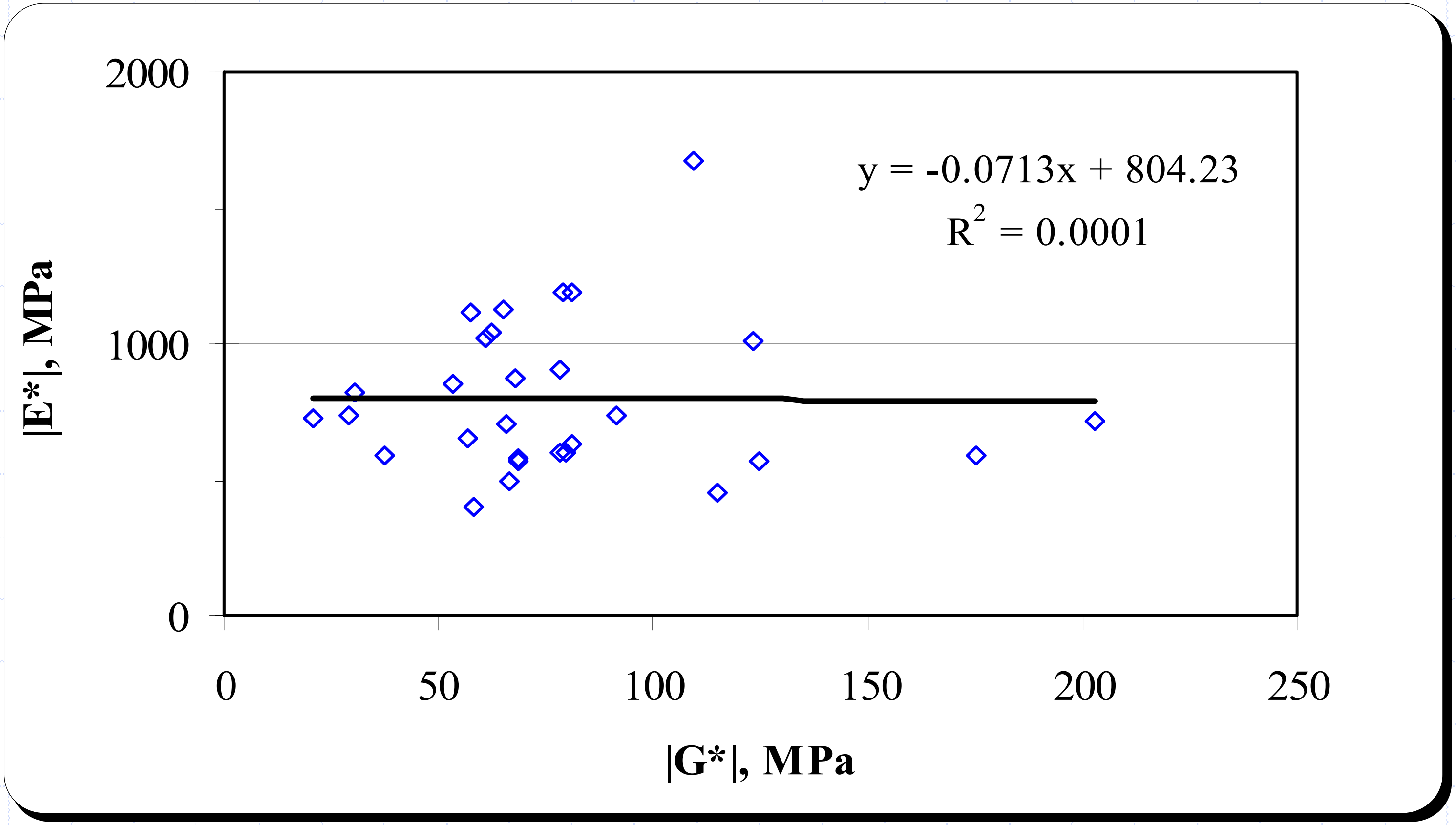
- P_{200} (%)
- P_4 (%)
- $P_{3/4}$ (%)
- $P_{3/8}$ (%)
- V_a (%)
- V_{beff} (%)
- VMA
- VFA
- frequency
- temperature
- A and VTS values (from binder |G*| and δ data)

|E*| versus |G*| @ T_{eff} (10 Hz)



Witczak Model

|E*| versus |G*| @ 54.4°C (10 Hz)



Witczak Model