

NANO → MICRO → MESO → MACRO



Properties of materials
used

Properties of mastic

Properties of mixture

Current Specifications for fatigue cracking:



PG grading of asphalt
binders

???

Beam fatigue / Cyclic
load in indirect tension

Important interactions between asphalt binder and aggregate fines
related to fatigue cracking cannot be ignored !

- 1) stiffening of the matrix due to addition of fines
- 2) crack pinning and crack growth

A variety of approaches to characterize fatigue cracking in asphalt mixes are possible depending on the type of material, test and analysis:

Test Method

- Bending beam test (asphalt mixes)
- Repeated load indirect tension test (asphalt mixes)
- DMA / DSR (asphalt mastics)

Test Mode

- Controlled stress
- Controlled strain

Analysis Method

- Direct methods
- Energy methods
- Crack growth modeling
- Rest periods (recovery)

Test Method

- Bending beam test
(asphalt mixes)
- Repeated load
indirect tension test
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- DMA / DSR
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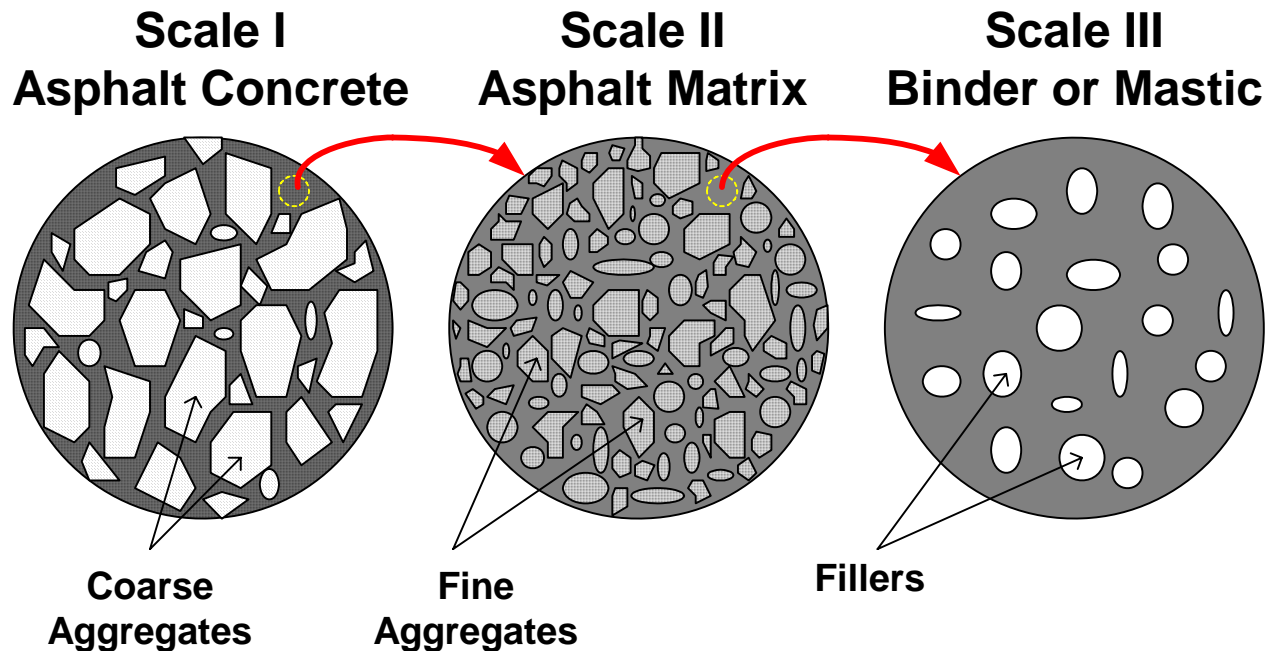
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Scale II represents aggregate < No. 16 Sieve and mastic



Test Method: DMA / DSR (Asphalt Mastics)

Sample preparation:

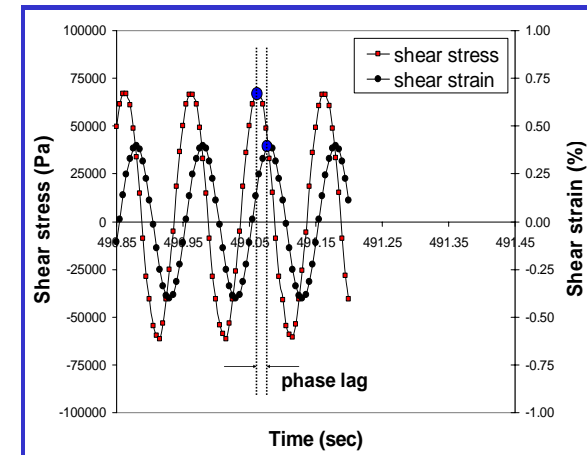
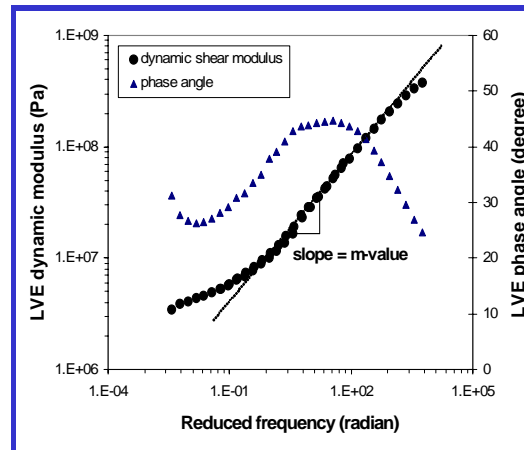
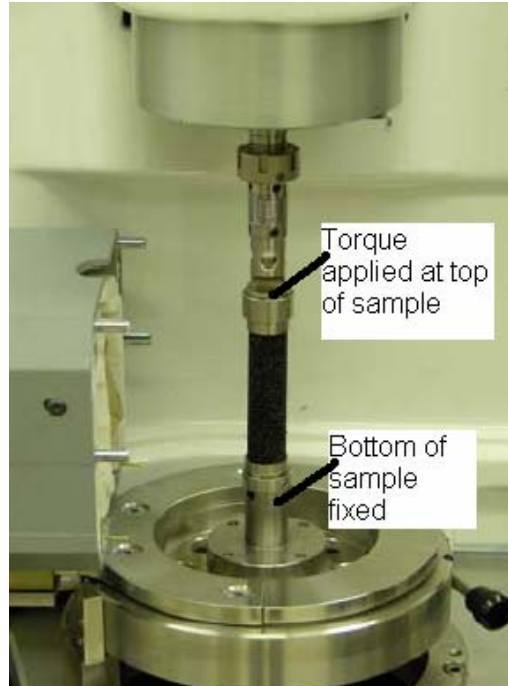
- Similar to HMA compaction using SGC
- Up to 30 samples can be cored from a single SGC compacted specimen



Test Method : DMA / DSR (Asphalt Mastics)

Test procedure and setup:

- Test is conducted by applying constant strain or constant stress and recording response
- G^* and phase angle are determined in real time during the test



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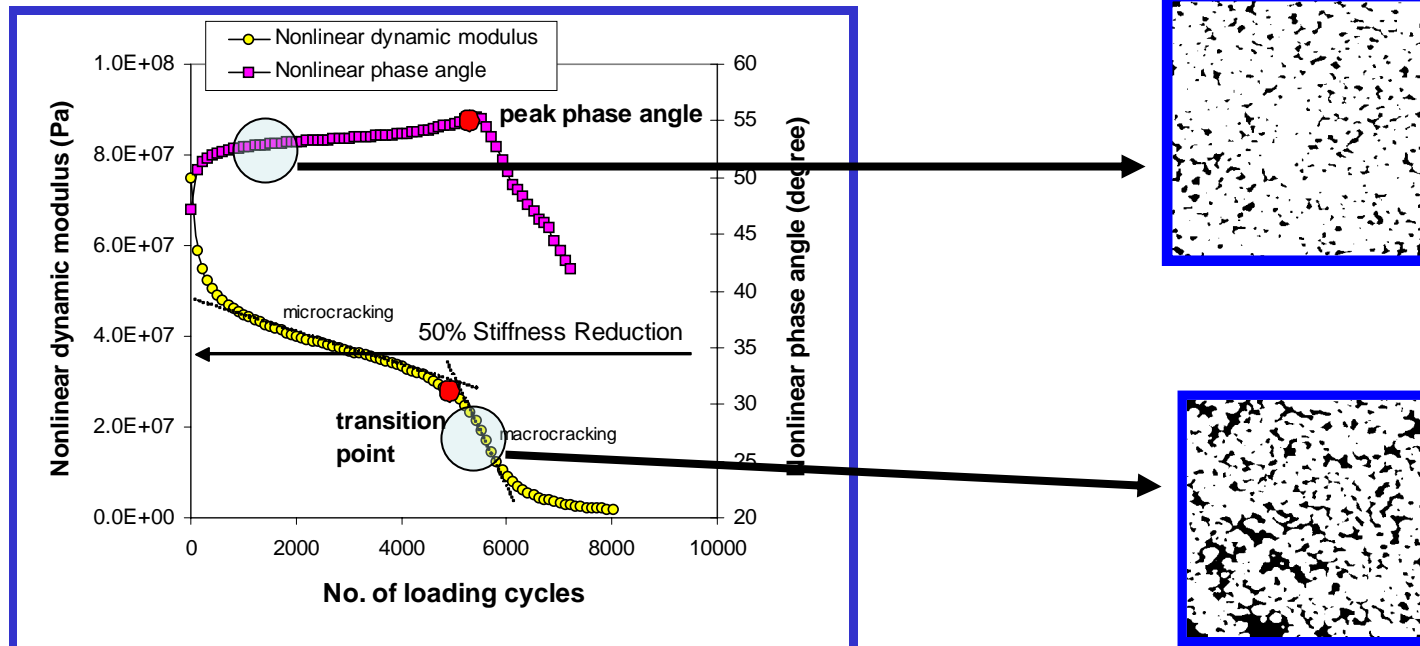
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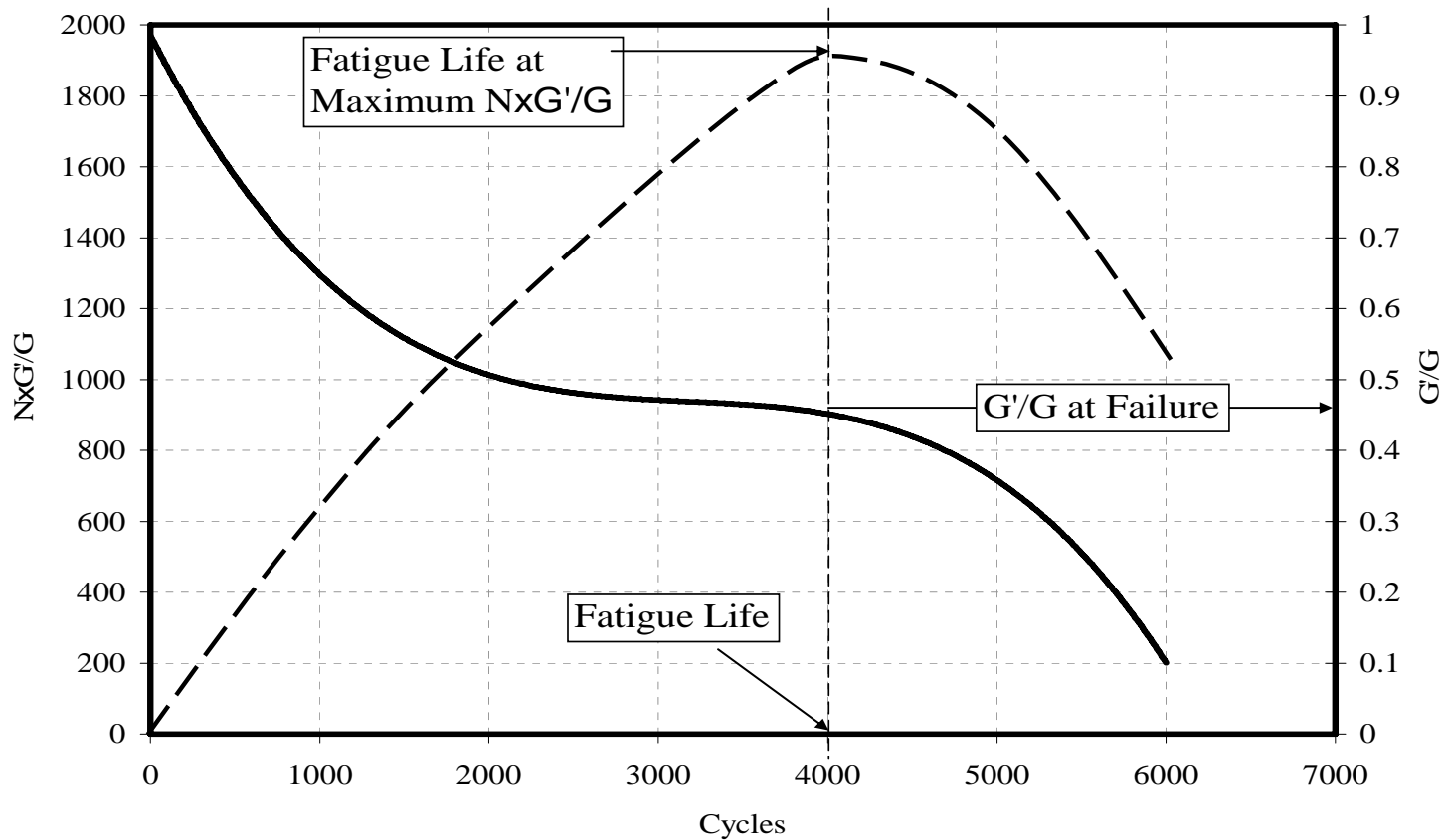
Analysis Methods : Direct Methods

- Direct method to estimate fatigue life is based on the number of load cycles to reach a pre-specified failure criteria
- Classical criteria include 50% reduction in stiffness, FIP (first inflection point), N_t (transition point), and SIP (second inflection point).

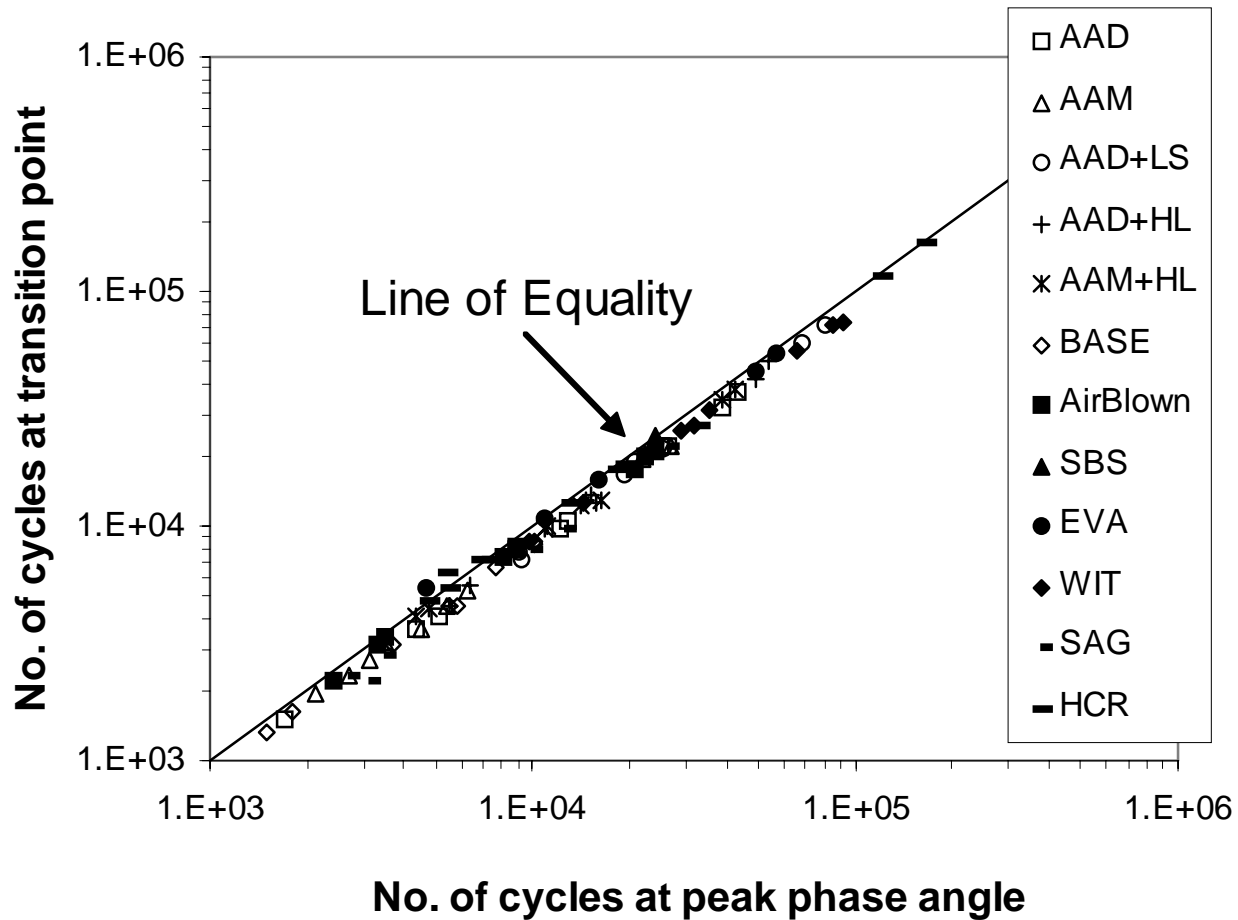


Analysis Methods : Direct Methods

- The transition point, N_t , is calculated as the point where the value $N(G^*_N/G^*_1)$ vs. N reaches a maximum



Cross plot of No. of cycles to peak phase angle and N_t



Mechanistic Fatigue Model

$$N_f = \frac{f(D_f)^k}{k \left(\pi \frac{I_D}{|G^*(\omega)|} C_1 C_2 \right)^\alpha |G^*(\omega)|^{-\alpha}} (\gamma_{\max})^{-2\alpha} = A_1 (\gamma_{\max})^{-B_1}$$

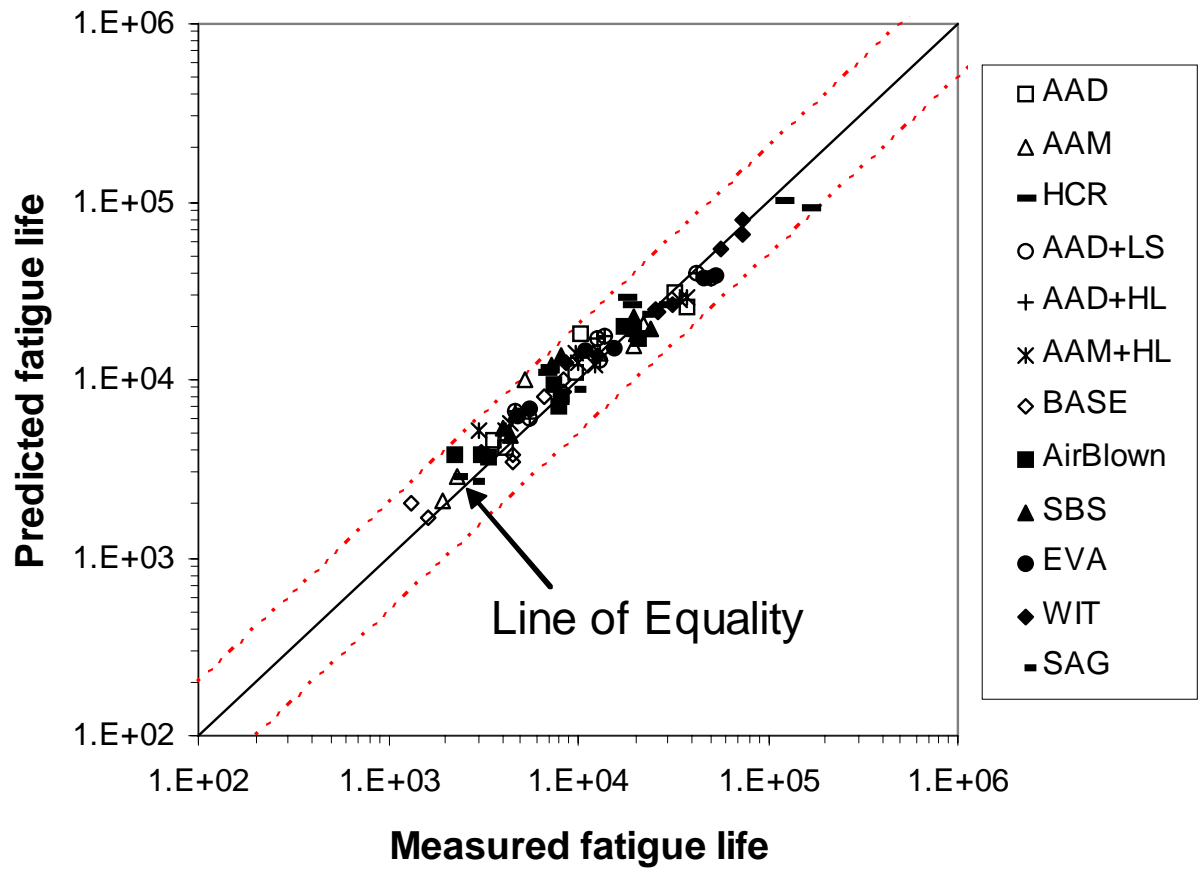
comparable to
phenomenological
regression model

$$N_f = A (\gamma_{\max})^{-B}$$

Comparing mechanistic parameters

Mixture		Mechanistic Fatigue Model Parameters					
		I_D , MPa	C_2	$ G^* $, MPa	α	k	D_f
HL	AAD	29.2	0.512	48.8	1.45	1.71	515.93
	AAM	70.7	0.436	137.7	1.60	1.90	708.76
	AAD+LS	40.6	0.428	61.2	1.60	1.91	778.98
	AAD+HL	45.4	0.338	69.0	1.60	2.06	1113.50
	AAM+HL	98.5	0.295	188.9	1.50	2.06	1053.21
	HCR	17.4	0.262	45.5	2.70	2.99	924.75
PM	BASE	66.2	0.409	132.0	1.20	1.71	810.16
	AirBlown	61.5	0.383	111.7	1.40	1.86	1041.51
	SBS	45.5	0.205	94.8	1.20	1.95	916.31
	EVA	42.1	0.250	78.7	1.65	2.24	1057.83
	WIT	296.8	0.746	369.1	1.90	1.48	1301.86
	SAG	46.3	0.516	81.3	1.70	1.82	937.90

Cross plot between predicted and measured fatigue life



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Analysis Methods : Energy Methods

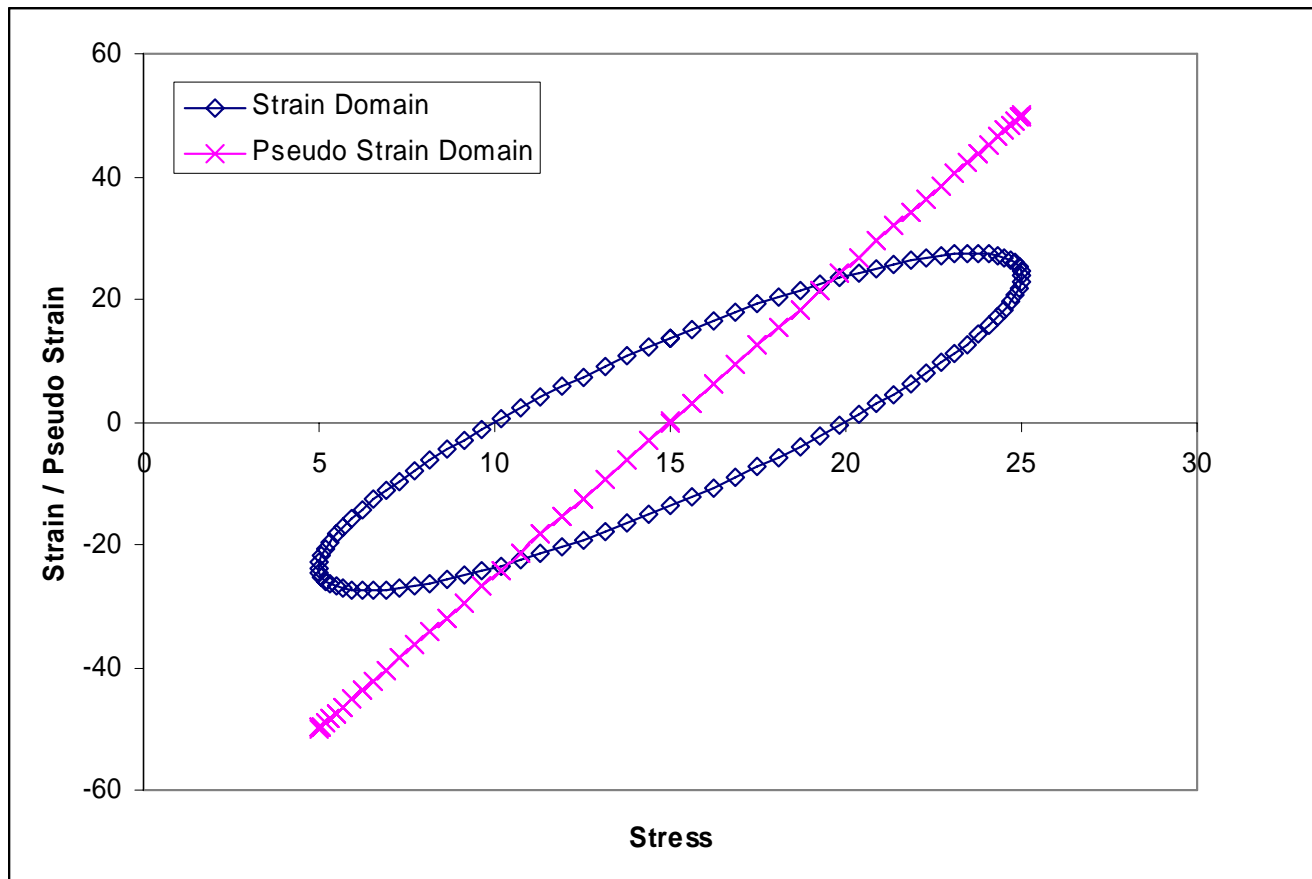
- Direct methods based on number of cycles to a specific failure criteria is reached are empirical and are impacted by external factors such as applied stress level and sample geometry
- Energy methods should account for stress level and mode of loading provided the dissipated energy due to damage is correctly calculated
- Ideally, dissipated energy due to damage is computed after correcting for effects of viscoelasticity and non linearity

Analysis Methods : Energy Methods

- Energy lost due to fracture in perfectly elastic material is easily quantified from hysteresis in stress-strain domain
- For viscoelastic materials hysteresis is also due to viscoelastic relaxation - not only damage
- Viscoelastic effect is eliminated by using stress-pseudo strain domain (based on Schapery's method) in lieu of stress-strain domain

Analysis Methods : Energy Methods

Illustration of undamaged viscoelastic material response in stress – strain domain vs. stress – pseudo strain domain

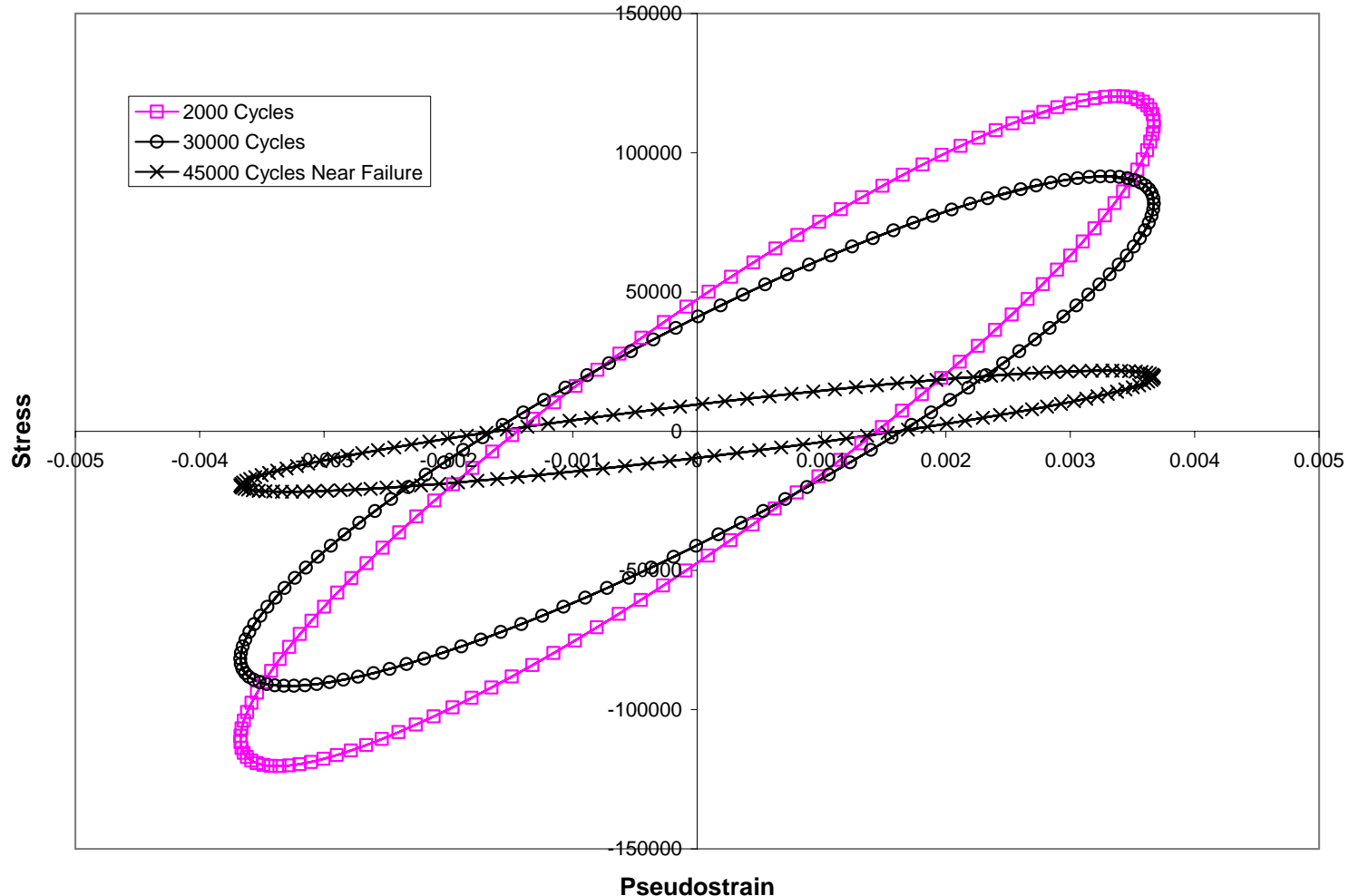


Analysis Methods : Energy Methods

- For a viscoelastic material where damage is occurring, stress – pseudo strain domain records the hysteresis used to monitor damage - referred to as DPSE
- Damage can be computed and summed until failure (CDPSE) as a measure of fatigue cracking resistance

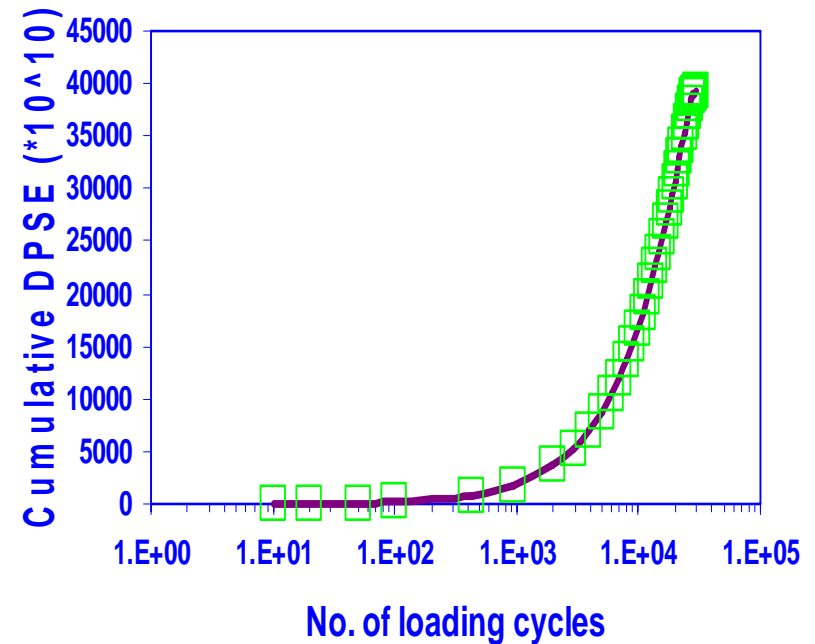
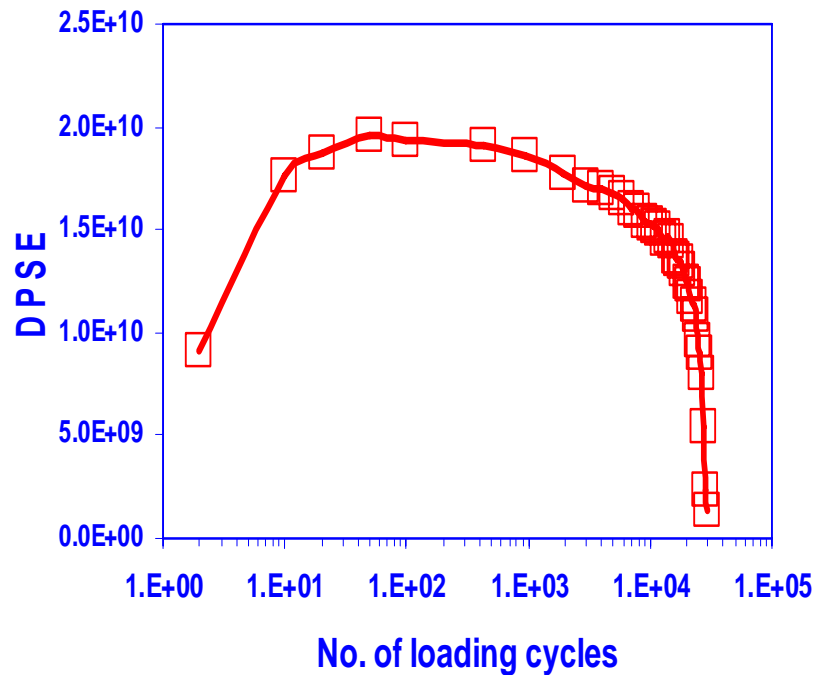
Analysis Methods : Energy Methods

Illustration of damaged viscoelastic material response in stress – pseudo strain domain (controlled-strain)



Analysis Methods : Energy Methods

Illustration of use of DPSE and CDPSE to characterize fatigue cracking of mastics



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Analysis Methods : Crack Growth Modeling

- Direct methods are empirical
- Energy methods are better than direct methods and can characterize fatigue cracking in mastic samples, BUT in order to predict crack growth in a mix a model that unifies various material properties is required
- Crack growth modeling is a powerful tool since it can bring together fundamental material properties such as surface energy and undamaged modulus into a single parameter

DMA Mechanistic Approach

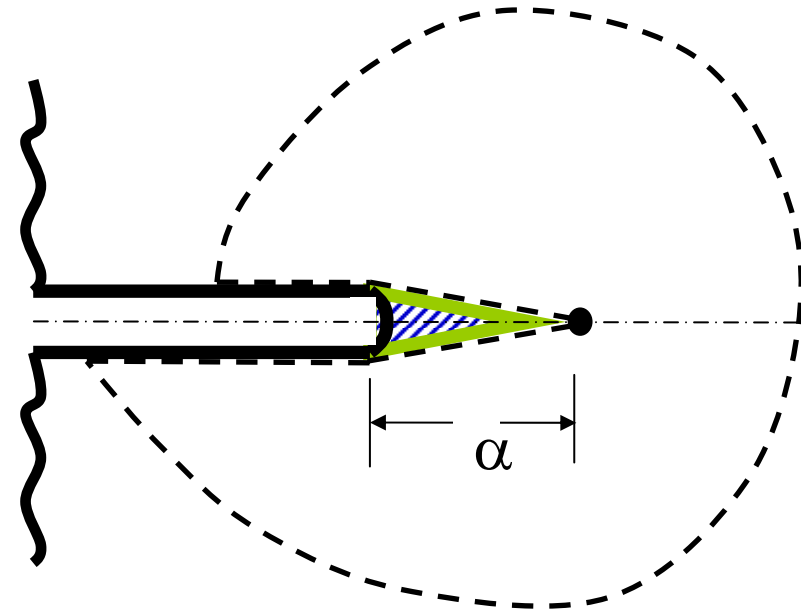
$$\frac{d\bar{r}}{dN} = A [J_R]^n$$

$n = 1 + 1/m$ Tensile strength is constant

$n = 1/m$ Bond energy and α are constants

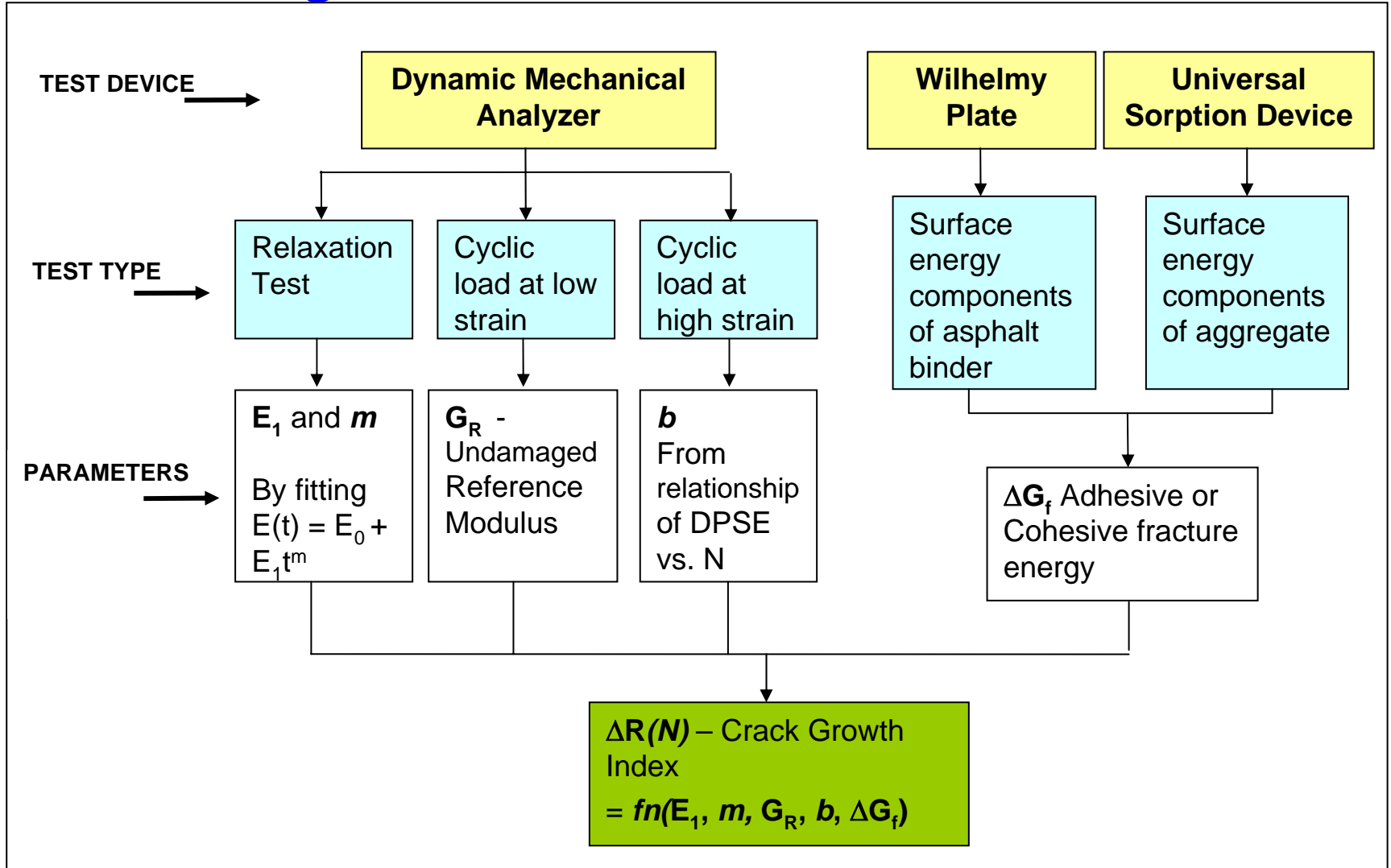
m = is the exponent in the relaxation modulus equation

$$E(t) = E_\infty + E_1 t^{-m}$$

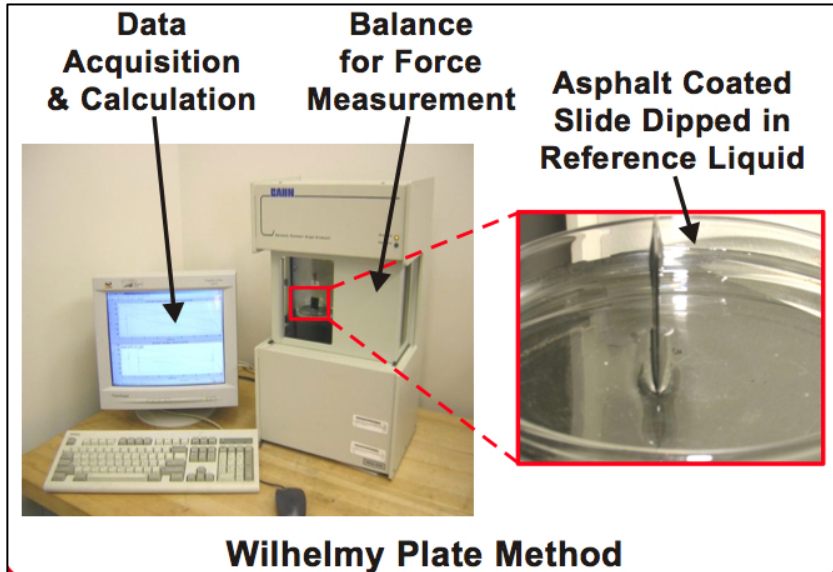


$\alpha(N)$ increases for stress controlled and decreases or is constant for strain controlled

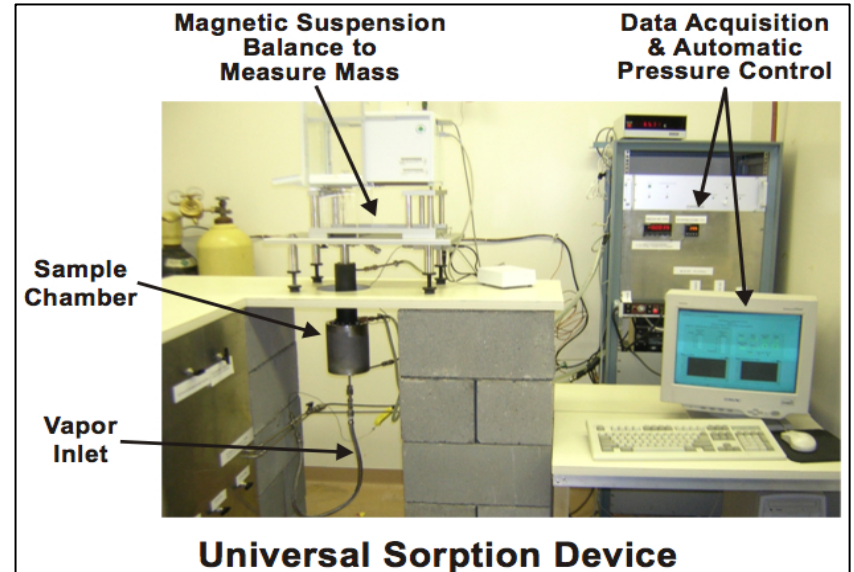
Analysis Methods : Crack Growth Modeling



Surface Energy Measurement



Asphalt: Low energy surface
Contact Angle Method



Aggregate: High energy surface
Vapor Adsorption Method

Surface Energy

Wilhelmy Plate Test

Output: Contact angles

Analysis: Work of adhesion with probe liquids

Result: Three surface energy components

Adsorption Test (USD)

Output: Adsorption isotherm

Analysis: Work of adhesion with probe vapors

Result: Three surface energy components

Performance related parameters:

$$\Delta G_f; \Delta G_{AS}; \Delta G_{WAS}$$

Fracture potential and moisture sensitivity of mastics and mixtures

Applications

Application: Crack Growth Modeling

Example of Application of the Model from a Recent Study

Mix	Fatigue cracking reported from qualitative field observations	ΔR @ 50,000 cycles			
		ΔG_f is adhesive bond energy		ΔG_f is cohesive bond energy	
		Avg.	St. Dev.	Avg.	St. Dev.
A	Good	6.5	0.54	5.9	0.57
B	Intermediate	10.4	2.24	7.6	1.17
C	Fair	15.1	1.34	11.1	1.13

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Application: Comparing Controlled Stress vs. Controlled Strain

- Classical views (Tangella et al. 1990):

Parameter	Test Mode	
	Controlled Stress	Controlled Strain
Asphalt concrete thickness	Thick	Thin
Failure criteria	Complete failure	Not well establish
Fatigue life	Lower	Higher
Sensitivity to mixture variables	Higher	Lower
Rate of dissipated energy	Higher	Lower
Healing effect due to rest periods	More beneficial	Less beneficial

Application: Controlled Stress vs. Controlled Strain

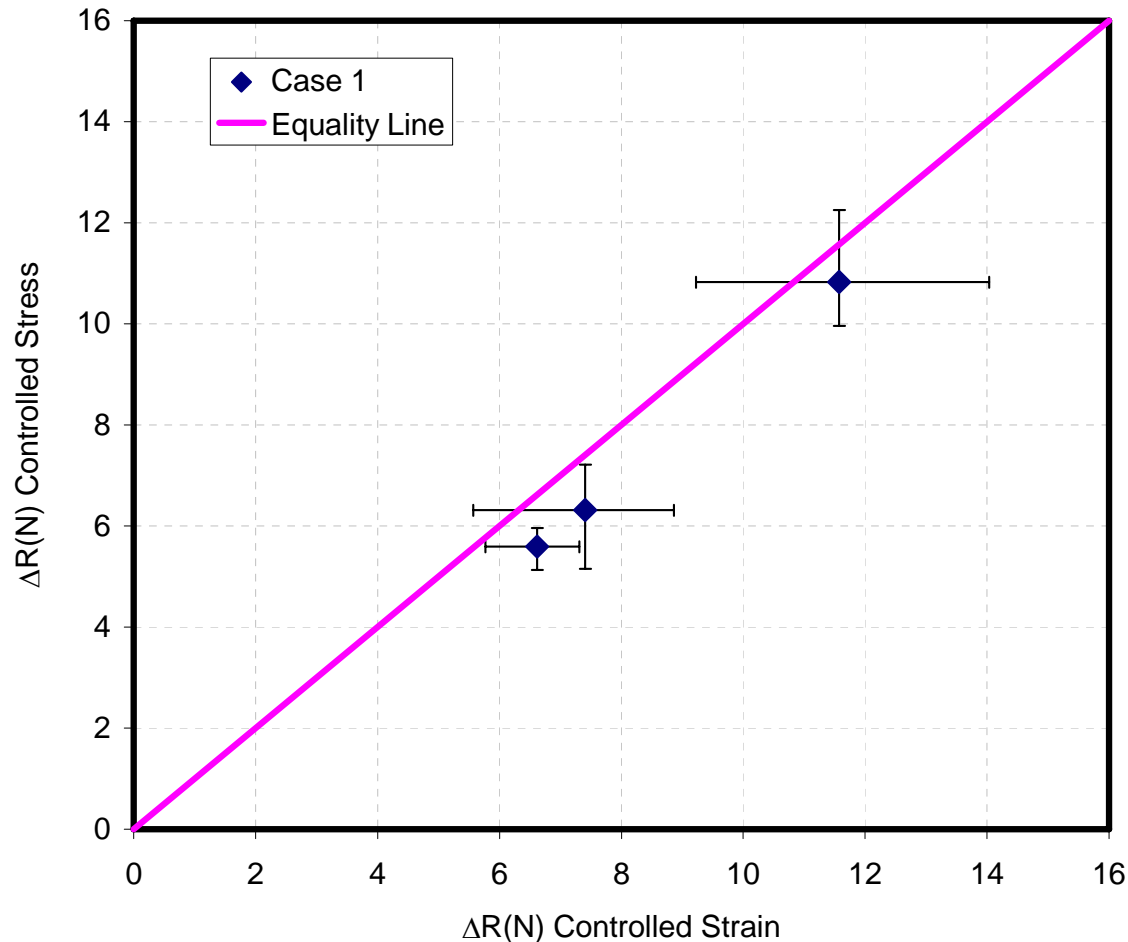
- Empirical criteria such as load cycles to failure, or load cycles to 50% reduction in modulus are inappropriate to unify the two approaches (*Benedetto et al. 2004*)
- Criteria based on energy methods and crack growth model show promising results in unifying the two approaches (*Kim et al. 1997; Lee and Kim, 1998; Ghuzlan and Carpenter 2000; Masad et al. 2006*)
- The total energy to failure should be consistent irrespective of the mode of loading provided failure is well defined in both modes and the dissipated energy due to damage is calculated correctly

Application: Controlled Stress vs. Controlled Strain

- Crack growth modeling approach described earlier can be used to unify control stress and control strain
- The key is the function that relates $\Delta R(N)$ to E_1 , m , G_R , b , ΔG_f is different depending on the mode of loading

Application: Controlled Stress vs. Controlled Strain

Example of unifying results from controlled stress and controlled strain using crack growth modeling

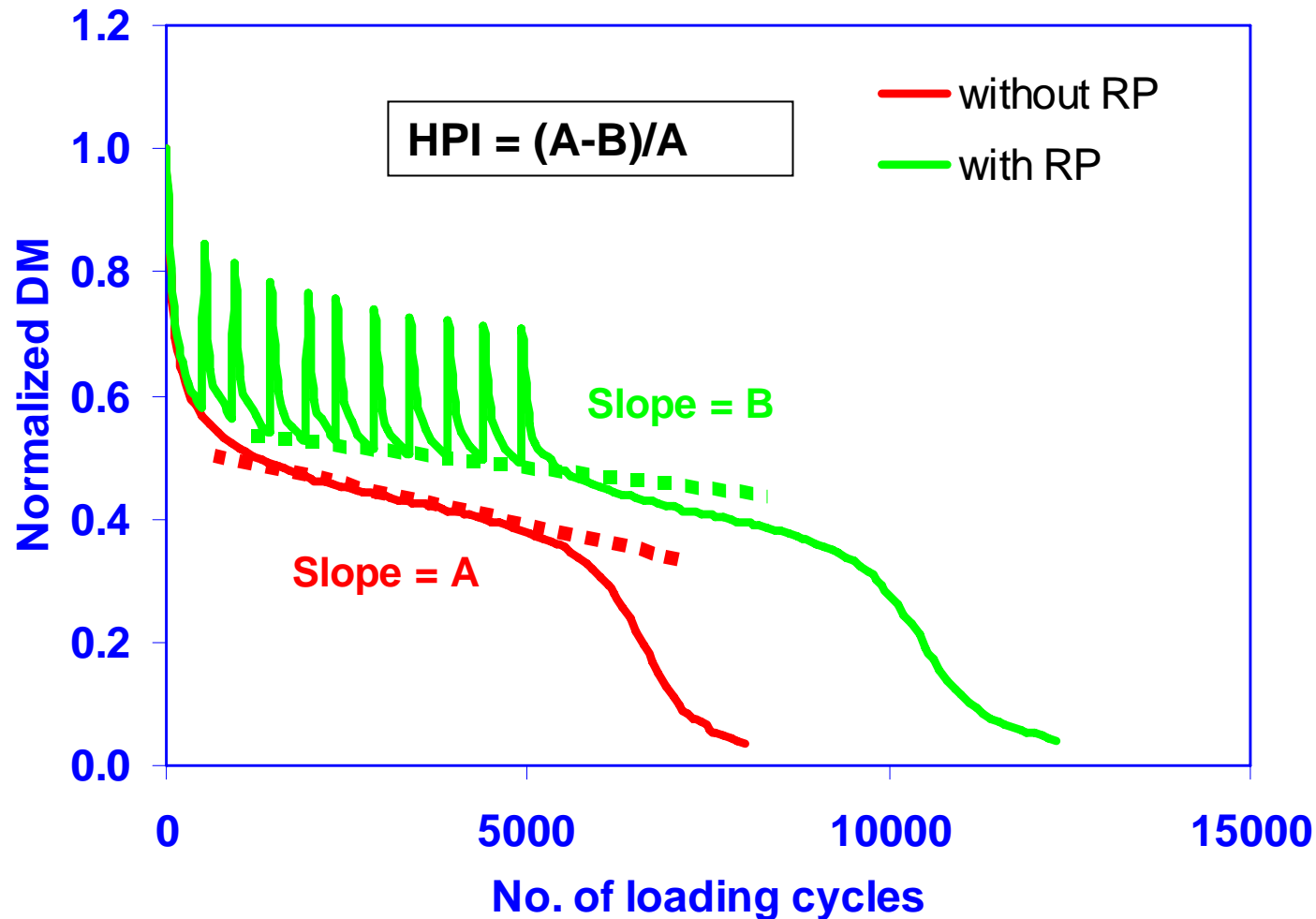


Comparison of Results

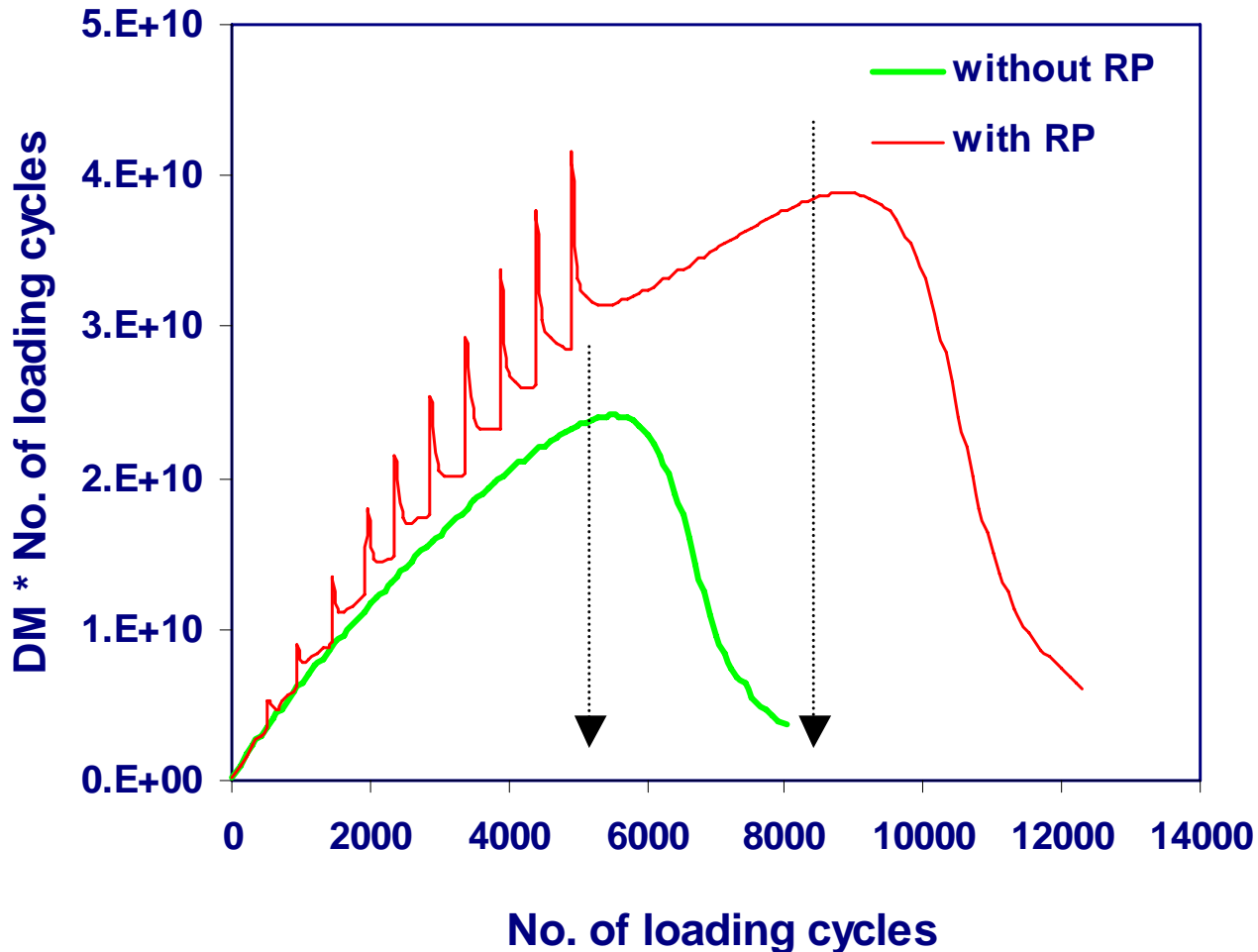
Parameter	Mode of Loading					
	Controlled Strain			Controlled Stress		
	Average	SD	Coef. of Variation (%)	Average	SD	Coef. of Variation (%)
Fatigue Life	69,000	51.41	74.51	139,600	62,870	45.04
Cumulative Dissipated Energy	7.60E+07	5.97E+07	78.66	3.74E+07	1.57E+07	42.04
$\Delta R(N)$, N=50,000	5.79	0.32	5.58	4.52	0.84	18.60
$\Delta R(N)/\ln(N)$	0.54	0.03	5.38	0.47	0.05	10.27

Close for both modes of loading

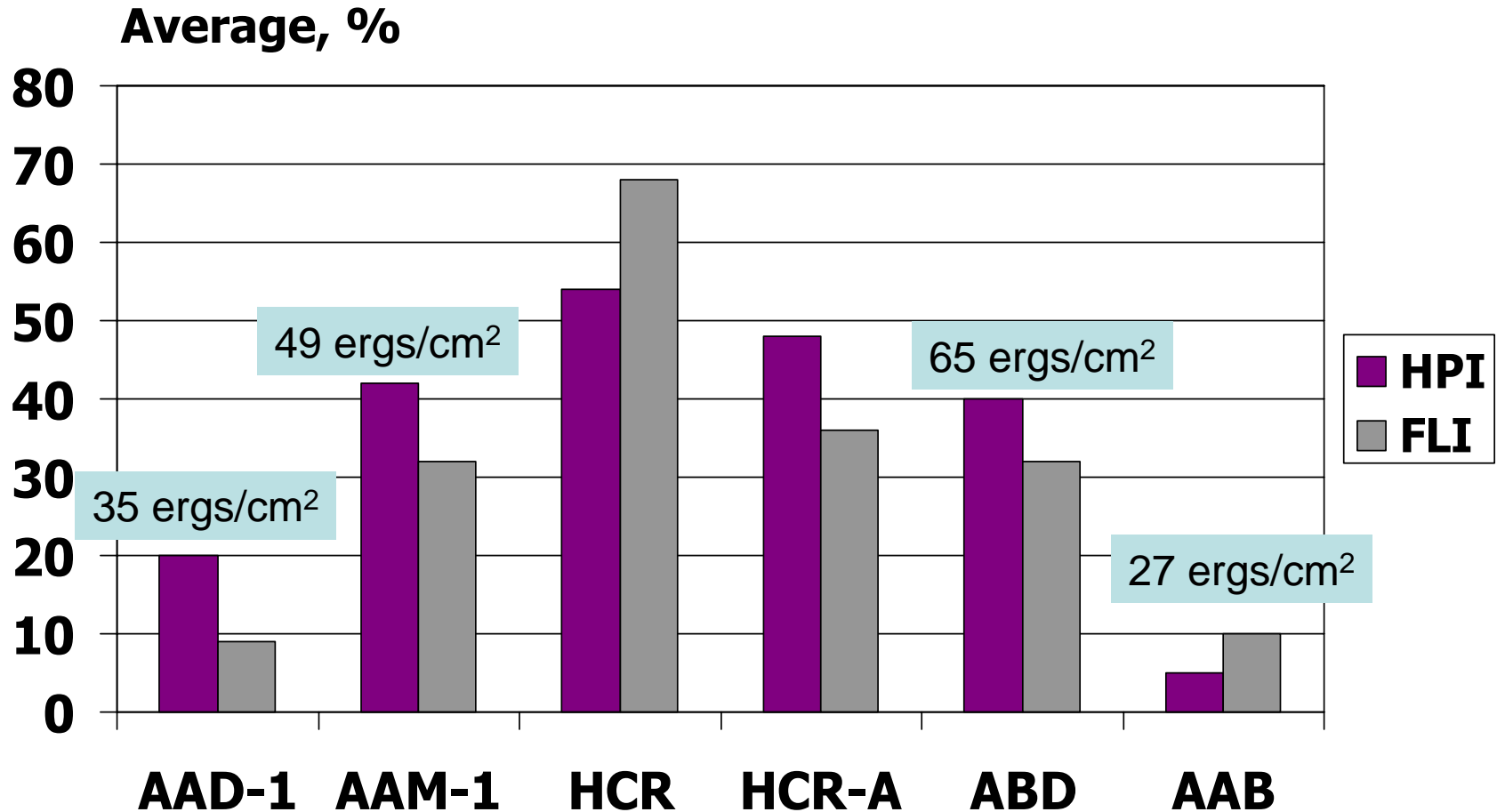
Application: Evaluating healing effect - HPI



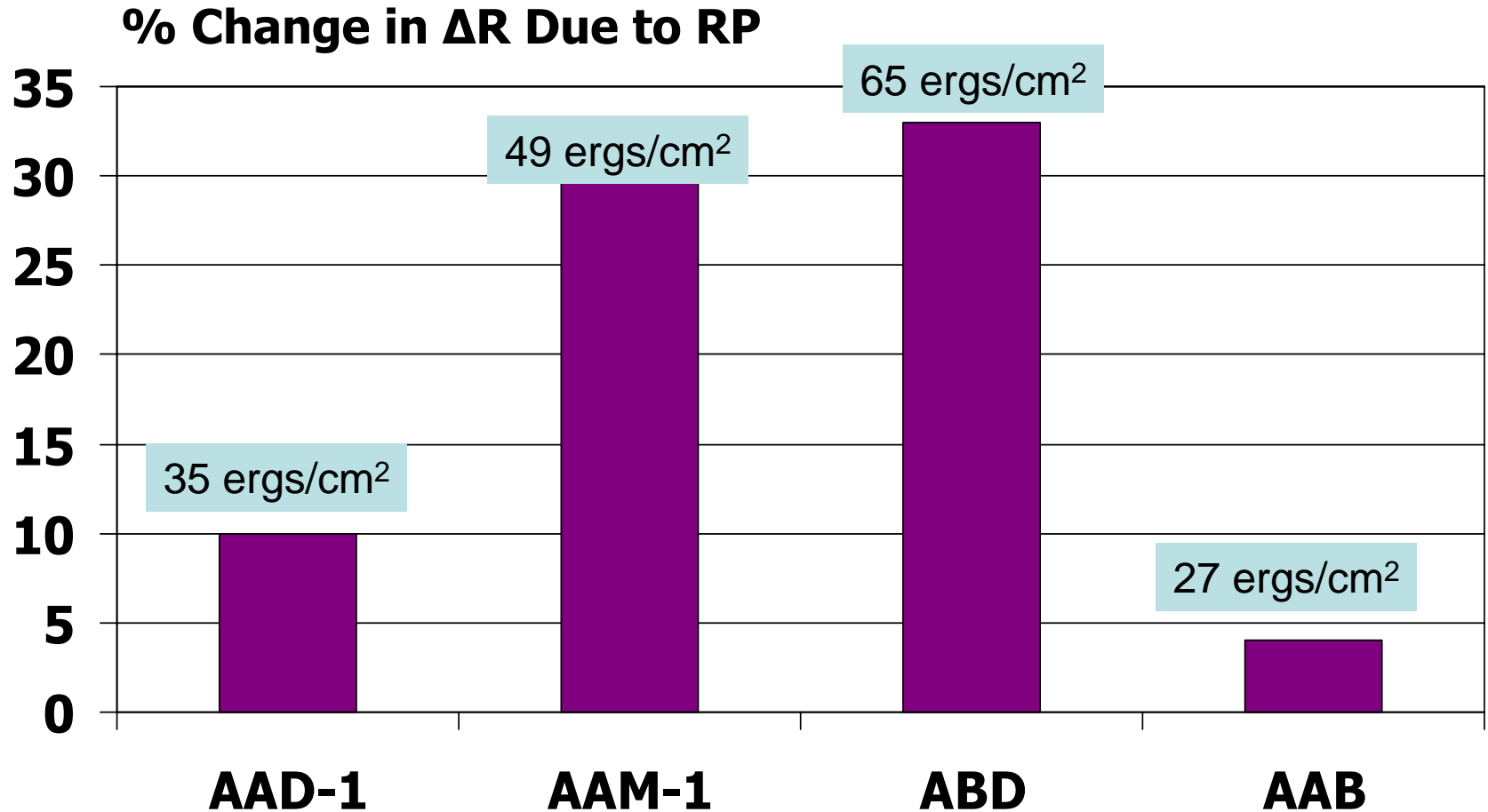
Application: Evaluating effect of rest periods (Fatigue life increase)



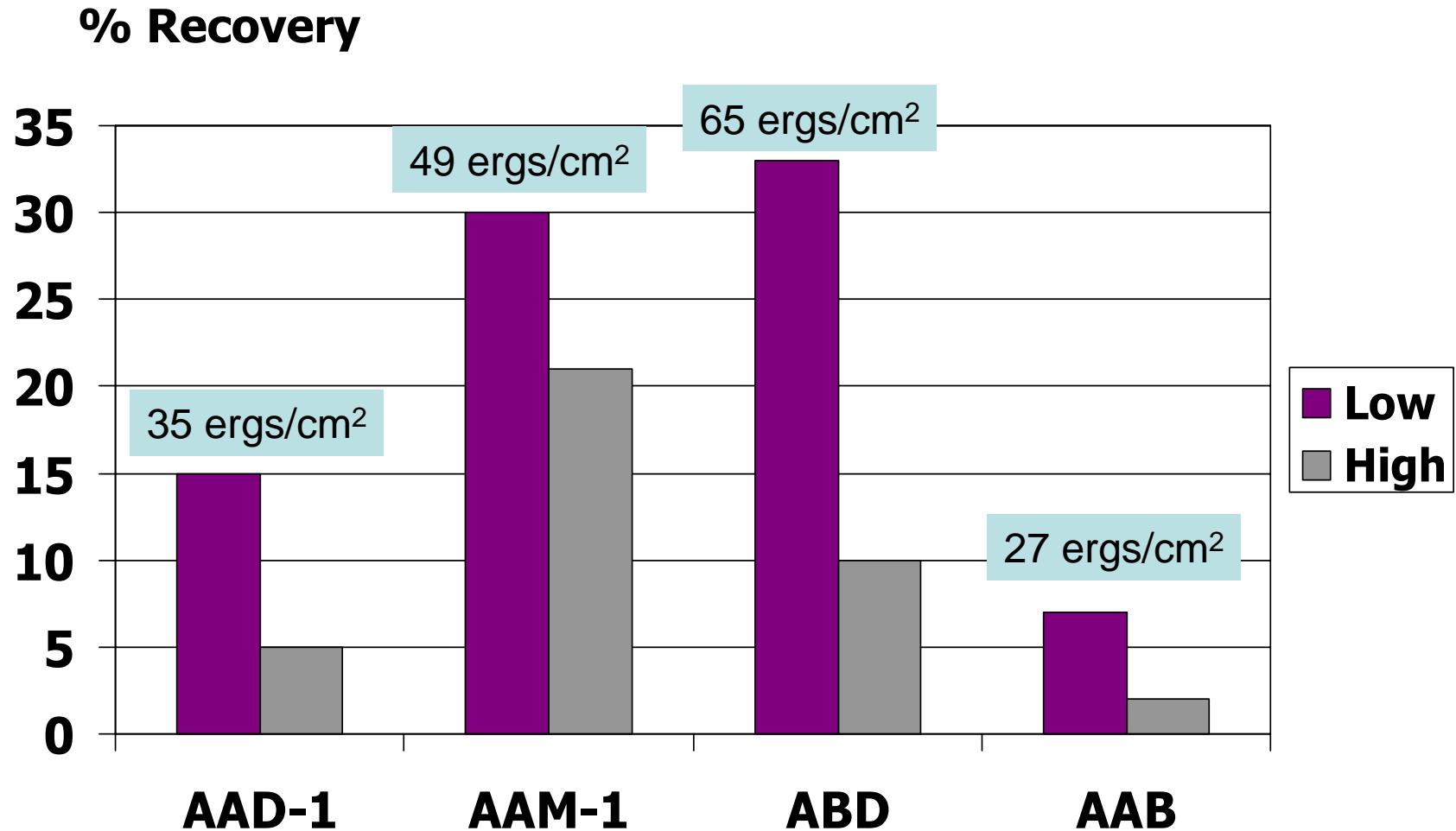
Application: Comparing healing potential



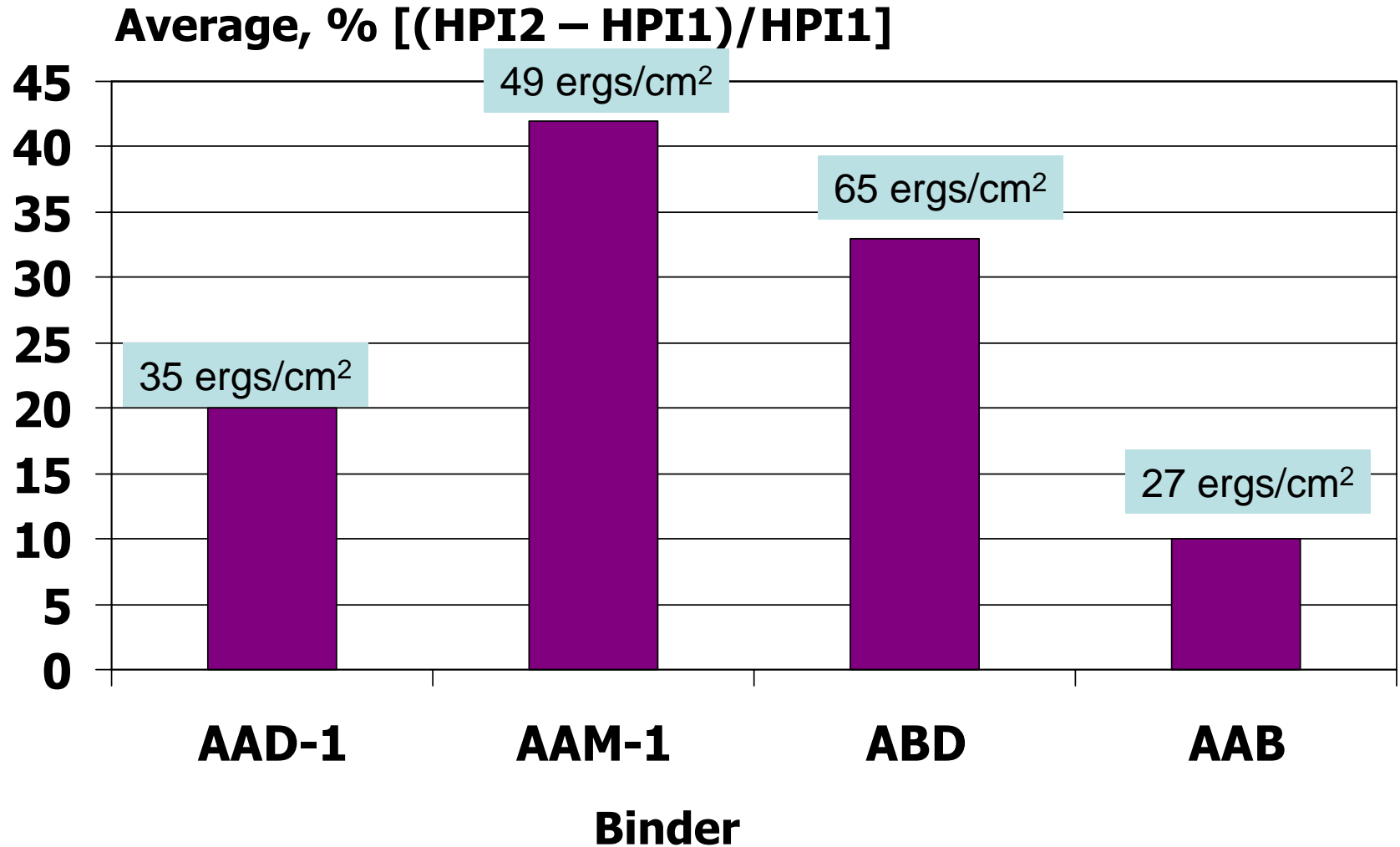
Application: Comparing healing potential



Application: Comparing influence of level of damage on percent recovery in DPSE due to healing



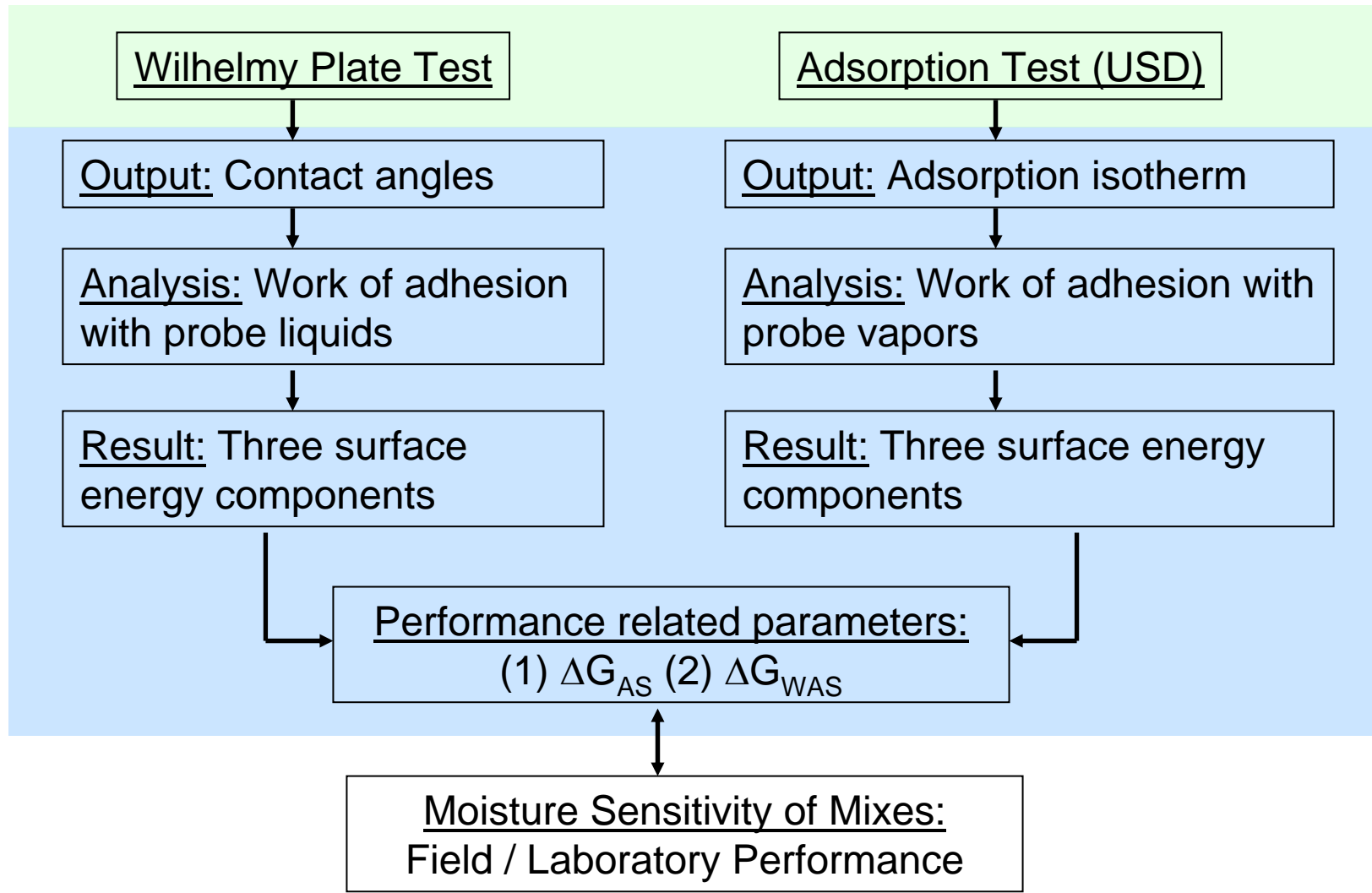
Application: Comparing increase in healing potential when number of rest periods is doubled



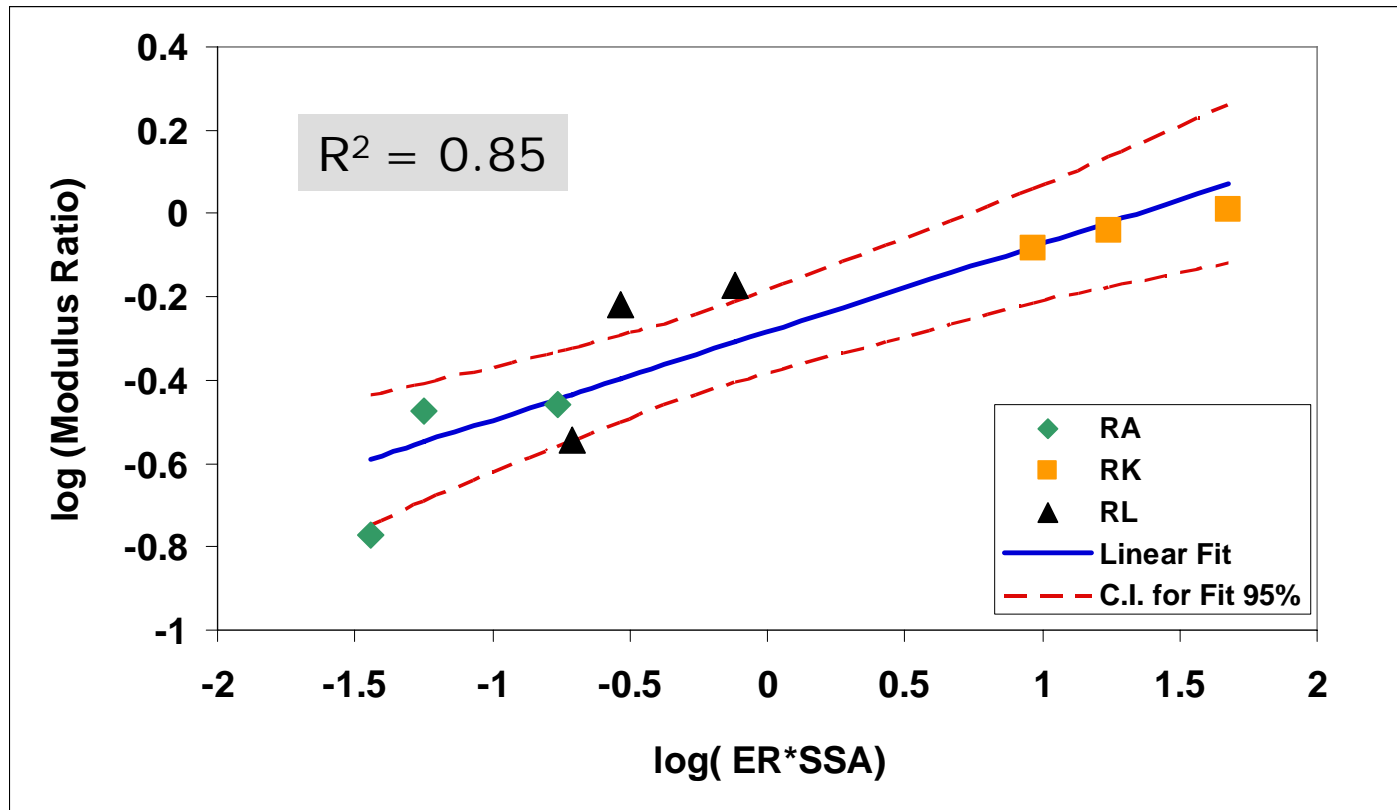
Carpenter and Shen Study (TRB 2006)

- Used ratio of dissipated energy approach
- With inclusion of RP of 9 seconds, fatigue life increased by factor of 10
- Healing at low damage condition is key to understanding endurance limit
- Healing in polymer-modified asphalts is superior

Application: Moisture damage

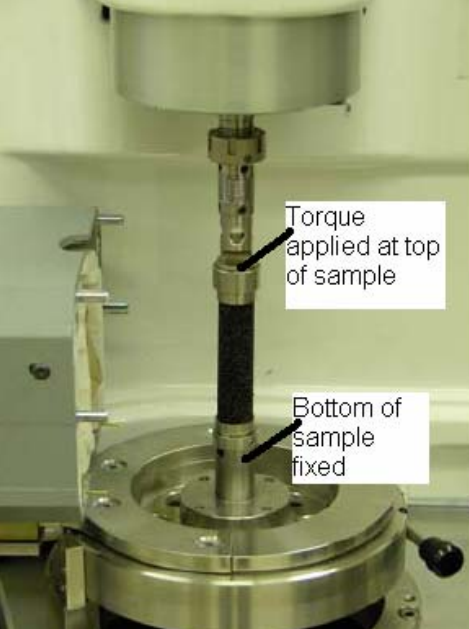


*Tensile Modulus Ratio (wet to dry) v. ER^*SSA*



Asphalt and aggregates can be individually tested to generate an array of values for all possible mixture combinations

	Granite A	Gravel A	Gravel B	Limest one A	Limest one B	Quartzi te A	Sandst one A	Sandst one B	KAG	NAG
PG 64-22 A	0.40	1.05	0.58	0.53	0.74	0.56	1.37	0.88	0.35	0.63
PG 64-22 B	0.65	1.98	1.00	0.86	1.38	0.97	2.54	1.41	0.71	1.08
PG 64-22 C	0.49	1.48	0.76	0.66	1.04	0.74	1.90	1.10	0.51	0.82
PG 64-22 D	0.58	1.38	0.80	0.72	1.03	0.78	1.69	1.10	0.58	0.86
PG 64-22 E	0.61	1.96	0.97	0.83	1.34	0.94	2.57	1.40	0.66	1.05
PG 64-22 F	0.74	2.47	1.18	1.00	1.66	1.14	3.29	1.71	0.81	1.27
PG 64-22 G	0.62	1.92	0.97	0.83	1.34	0.94	2.47	1.37	0.68	1.04
PG 64-22 H	0.47	1.26	0.69	0.62	0.90	0.67	1.63	1.02	0.45	0.75
PG 64-22 I	0.69	2.20	1.08	0.92	1.51	1.05	2.87	1.55	0.75	1.17
PG 64-28 B	0.46	0.93	0.59	0.56	0.70	0.58	1.16	0.83	0.40	0.64
PG 76-22 A	0.72	1.49	0.93	0.87	1.15	0.92	1.79	1.24	0.70	1.00
PG 76-22 B	0.45	1.07	0.62	0.57	0.78	0.61	1.37	0.91	0.40	0.68
PG 76-22 C	0.67	1.24	0.83	0.79	0.99	0.82	1.48	1.09	0.62	0.89
PG 76-22 D	0.60	1.50	0.85	0.77	1.10	0.83	1.88	1.19	0.60	0.92



Fast, repeatable, many replicate samples

Analysis: direct, DE, fracture mechanics (including bond energy)

Monitor of effects of additives, fillers

Monitor of healing potential

Basis for unifying controlled-stress and controlled-strain