Use of Continuum Damage Fatigue Model and Dynamic Mechanical Analysis to Assess the Impact of Polymer Modification on Asphalt Mixtures

Yong-Rak Kim
Dallas N. Little
Renju George

Introduction

- A better understanding of fatigue behavior of asphalt mixtures is required to improve asphalt mixture design and hot mix performance
- Fatigue crack phenomena of asphalt concrete is primarily governed by performance of binder and mastic
- Polymer additives have shown the ability to change the microstructure, morphology, and fracture mechanisms that occur in asphalt binders

Research Motivation

- Experimental results demonstrate the substantial influence of binder modification
- Evidence of complex, synergistic characteristics of modified binders
- Need for better understanding of the material characteristics and damage-induced behavior
- Criteria for selection of materials as mixture components

Research Approach

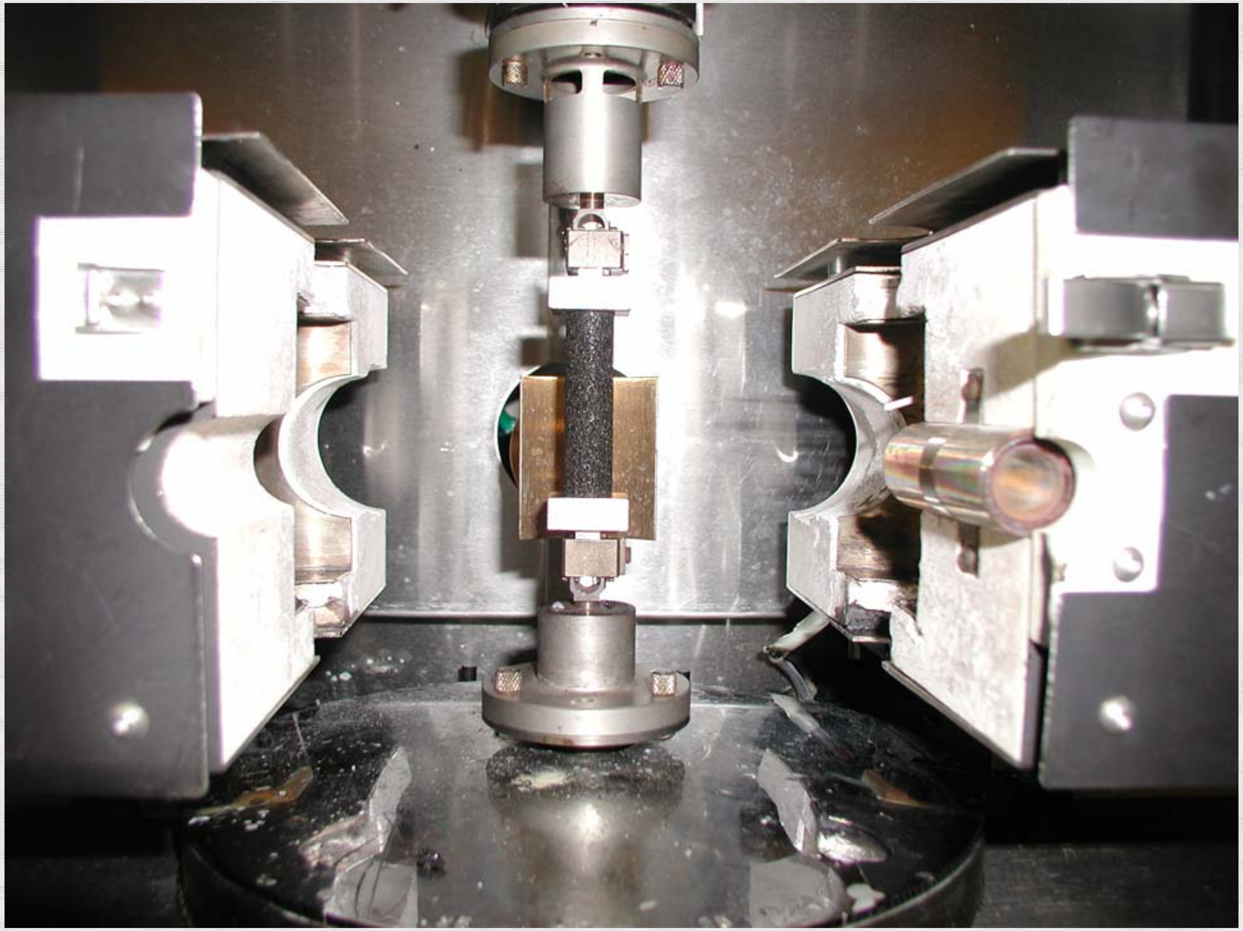
- Use sensitive fatigue testing method for binders and/or mastics
- Measure fundamental material properties as well as damage behavior
- Analyze using mechanics-based approach

Objectives

- Identify fatigue damage and fatigue failure in selected asphalt binders
- Investigate fatigue behavior using mechanistic energy-based model, and
- Evaluate effects of polymer modification on viscoelastic material properties, fatigue resistance, and damage evolution

Testing Equipment

Sand-asphalt Sample Installed



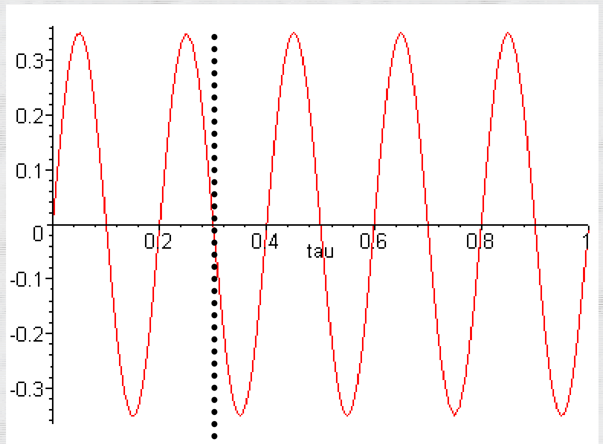
Materials

Binder	Description	Binder Combinations	% of Modifier
BASE	One of two unmodified binders (BASE and FLUX)	Unmodified	
AirBlown	Modified by air blowing	100% FLUX	
SBS-LG	Styrene-Butadiene-Stylene (Linear Grafted)	58.9% FLUX 41.1% BASE	3.75
EVA	Ethylene-Vinyl-Acetate	100% FLUX	5.5
ELVALOY	Particularly fabricated binder	50% FLUX 50% BASE	2.2

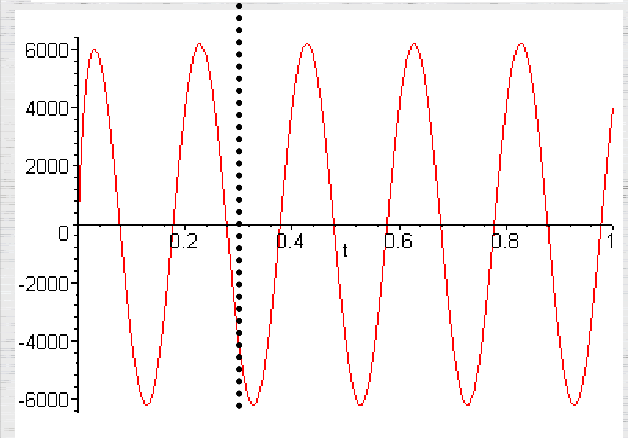
Dynamic Testing (Stain-controlled Torsional Mode)

- **Dynamic strain sweep test to determine linear viscoelastic strain level**
- **Dynamic frequency sweep test to obtain linear viscoelastic material properties**
- **Dynamic time sweep test to simulate fatigue damage**

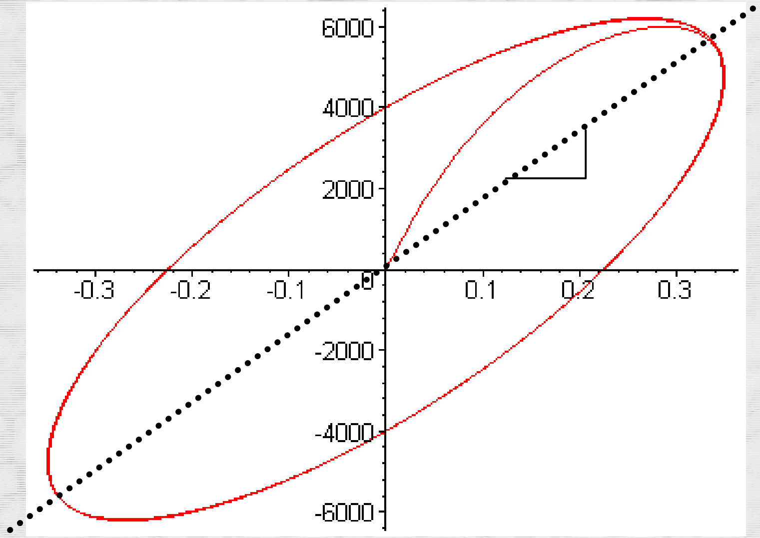
Oscillatory Viscoelastic Behavior without Damage



Strain

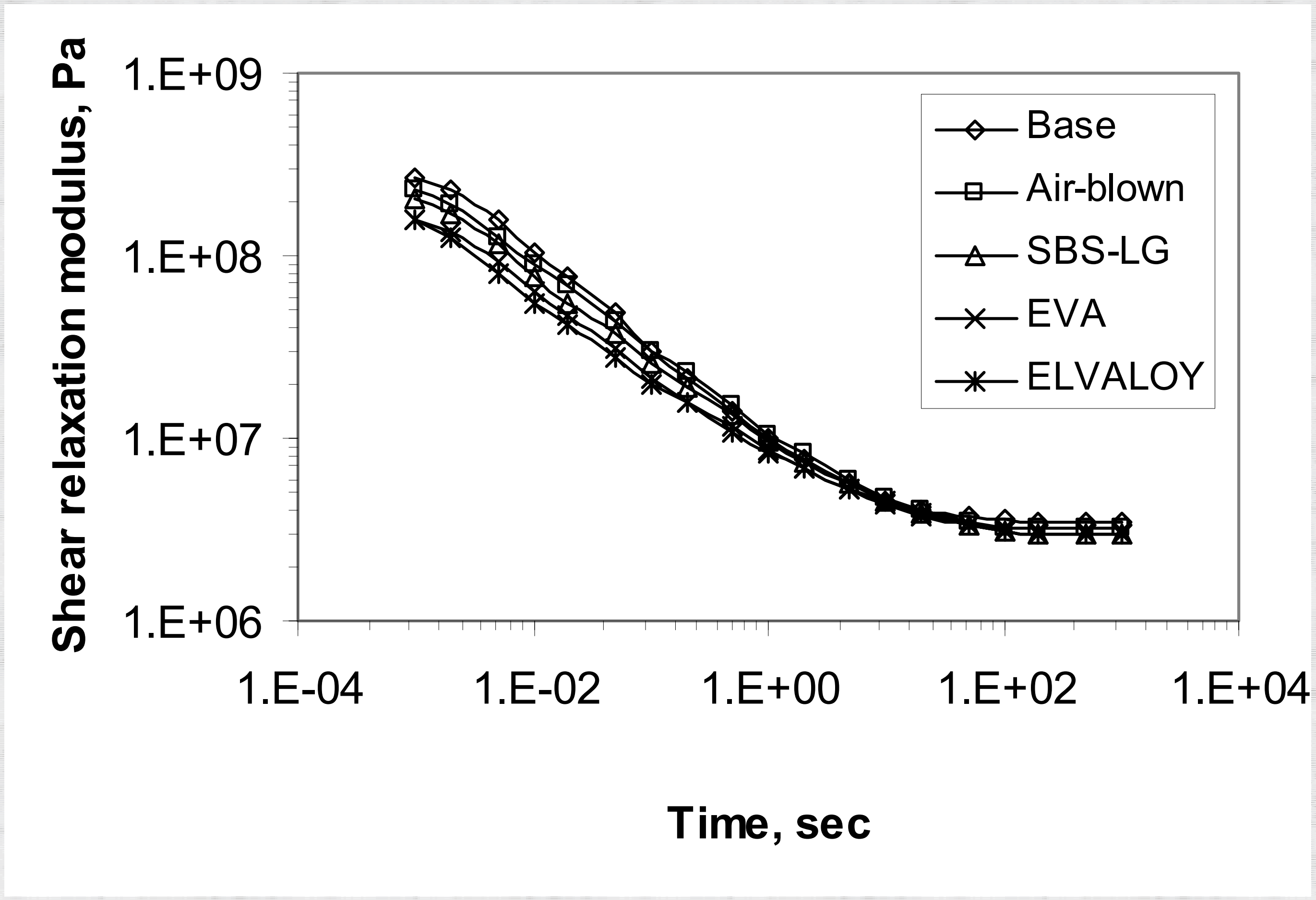


Stress

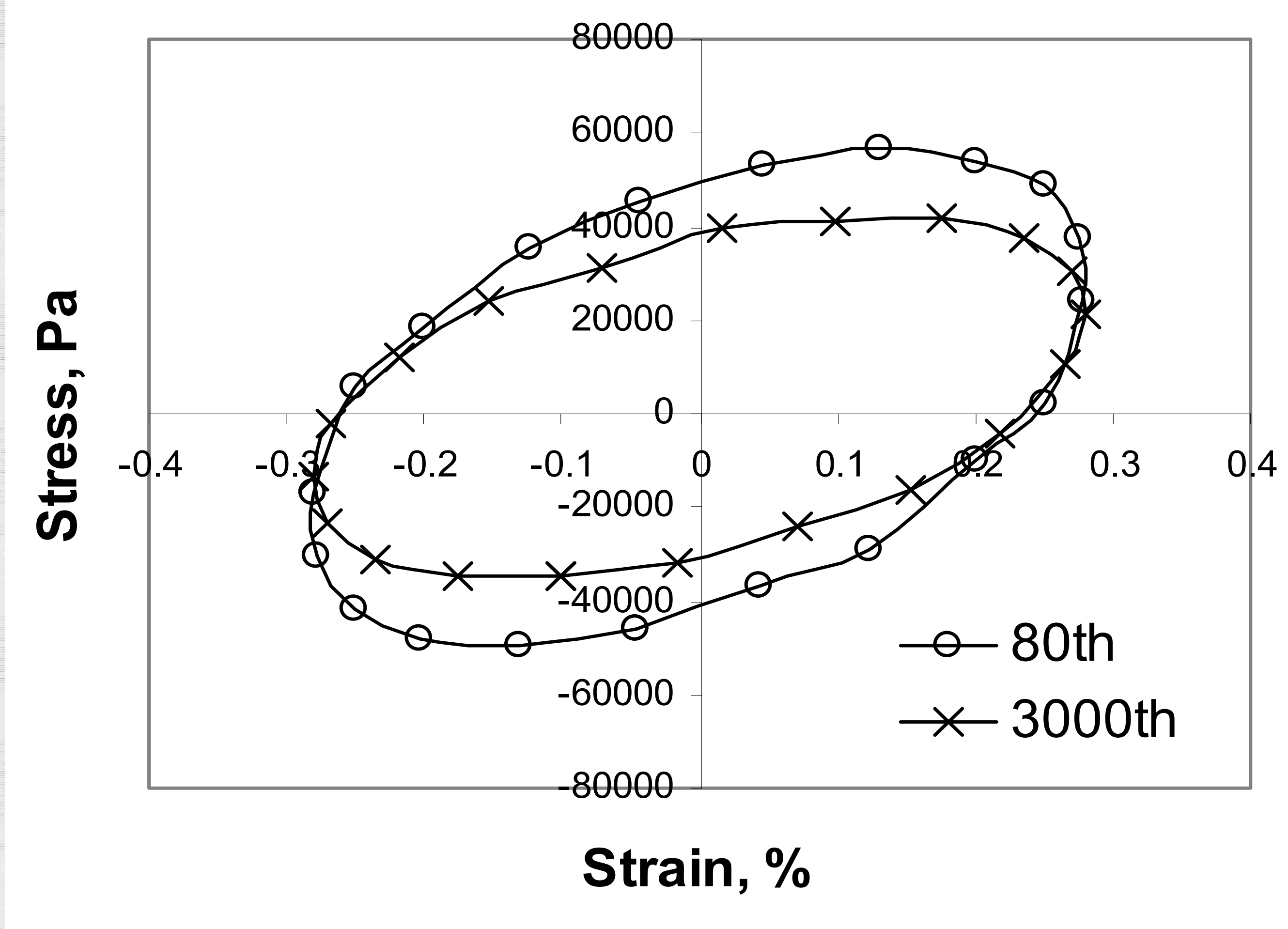


Stress - Strain Hysteresis Loop
(slope: LVE dynamic modulus)

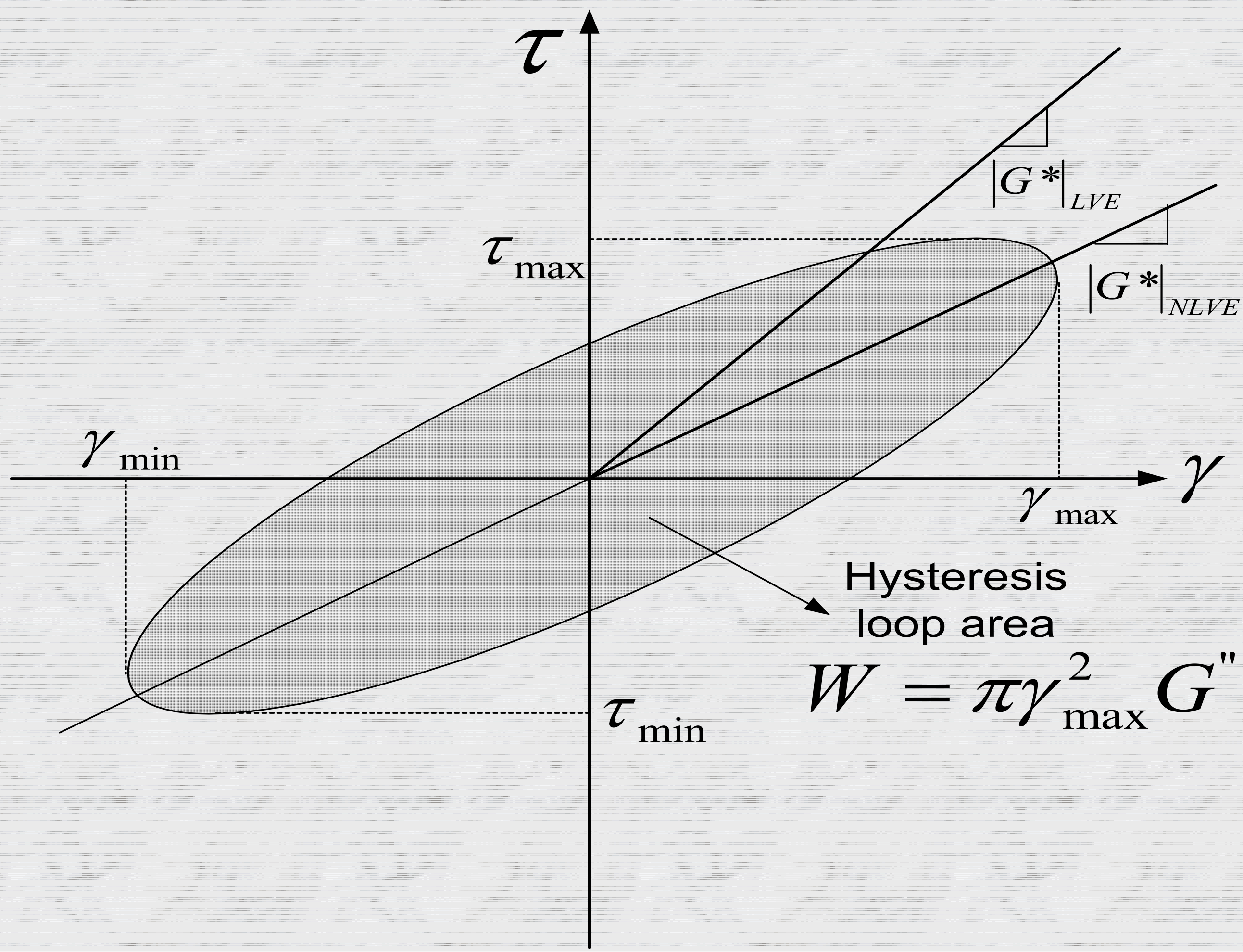
LVE Material Properties



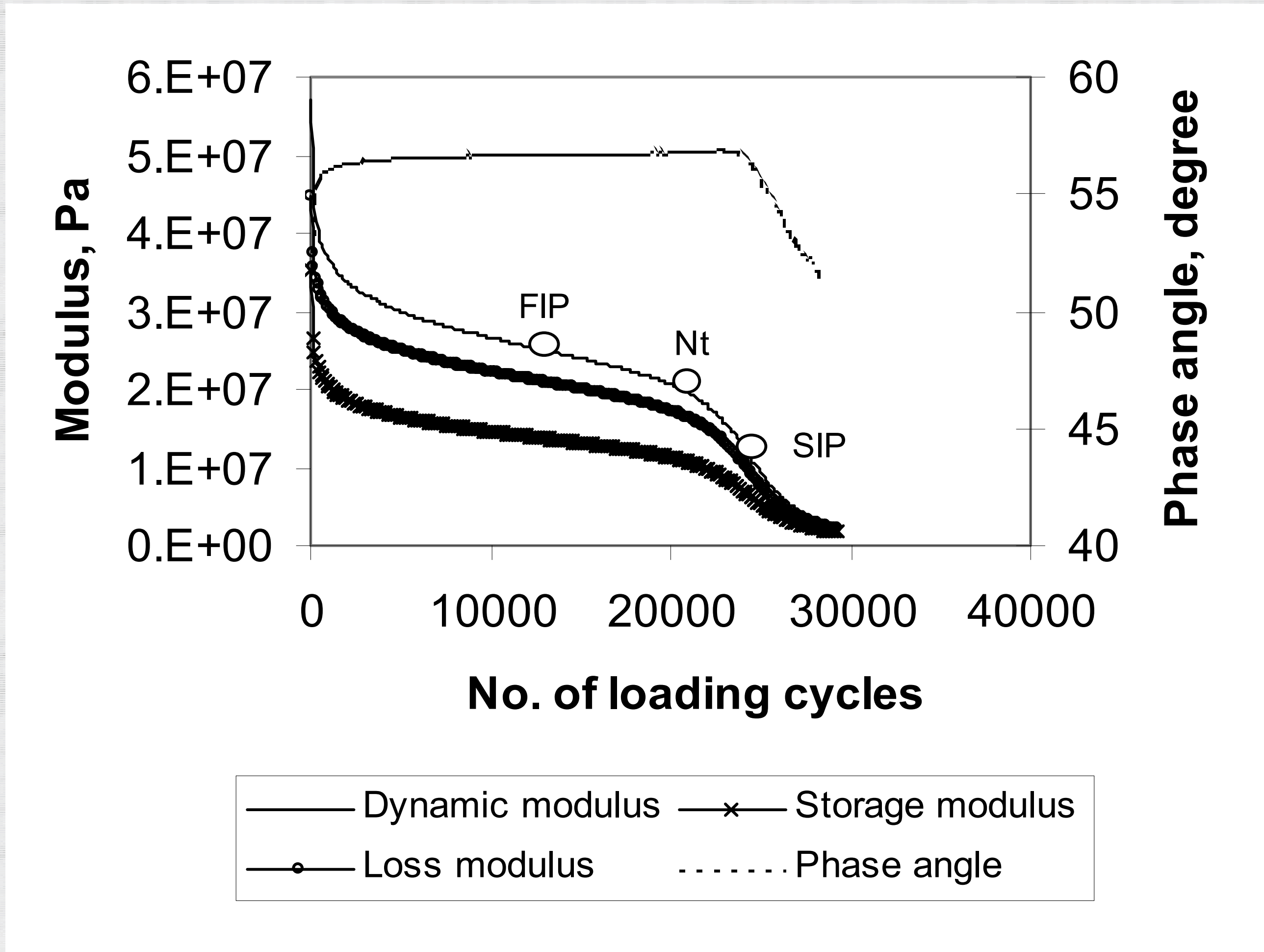
Oscillatory Viscoelastic Behavior with Fatigue Damage



Dissipated Strain Energy



Typical Fatigue Test Result



Nonlinear Modulus

$$G_{NL}^{*} = \frac{\tau_m}{\gamma_m} e^{i\phi}$$

Complex Modulus

$$G_{NL}^{'} = \frac{\tau_m}{\gamma_m} \cos\phi$$

Storage Modulus

$$G_{NL}^{''} = \frac{\tau_m}{\gamma_m} \sin\phi$$

Loss Modulus

$$\left|G_{NL}^{*}\right| = \sqrt{(G_{NL}^{'})^2 + (G_{NL}^{''})^2}$$

Dynamic Modulus

Energy-based Fatigue Life Prediction Model

$$\tau_{m,i} = I\left|G^*(D)\right|_i \gamma_{m,i}$$ **Constitutive Equation**

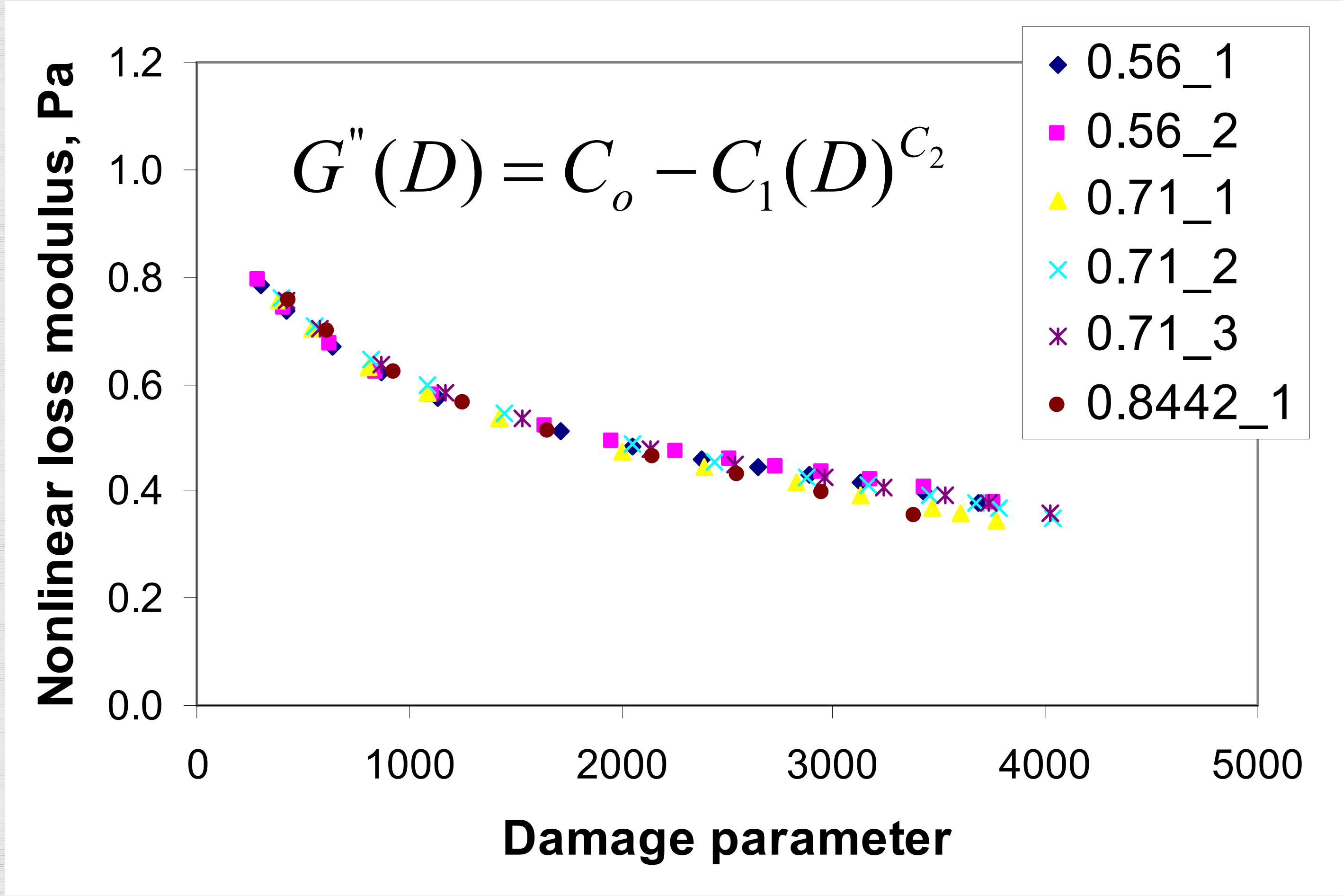
$$W(D)_i = \pi I \gamma_{m,i} \tau_{m,i} \sin\phi(D)_i = \pi I (\gamma_{m,i})^2 G''(D)_i$$

$$\frac{dD}{dN} = \left(-\frac{\partial W}{\partial D}\right)^{\alpha}$$ **Damage Evolution Law**

$$\frac{\partial G''}{\partial D} = \frac{\partial G''}{\partial N}\frac{\partial N}{\partial D}$$ **Chain Rule**

$$D \cong \sum_{i=1}^{N}\left[\pi I(\gamma_{m,i})^2 (G''_{i-1} - G''_i)\right]^{\frac{\alpha}{1+\alpha}} (N_i - N_{i-1})^{\frac{1}{1+\alpha}}$$

Nonlinear Loss Modulus vs. Damage Parameter



Fatigue Life Prediction Model

$$N_f = \frac{{D_f}^k}{k(\pi I C_1 C_2)^\alpha} (\gamma_m)^{-2\alpha}$$

$$k = 1 + (1 - C_2)\alpha$$

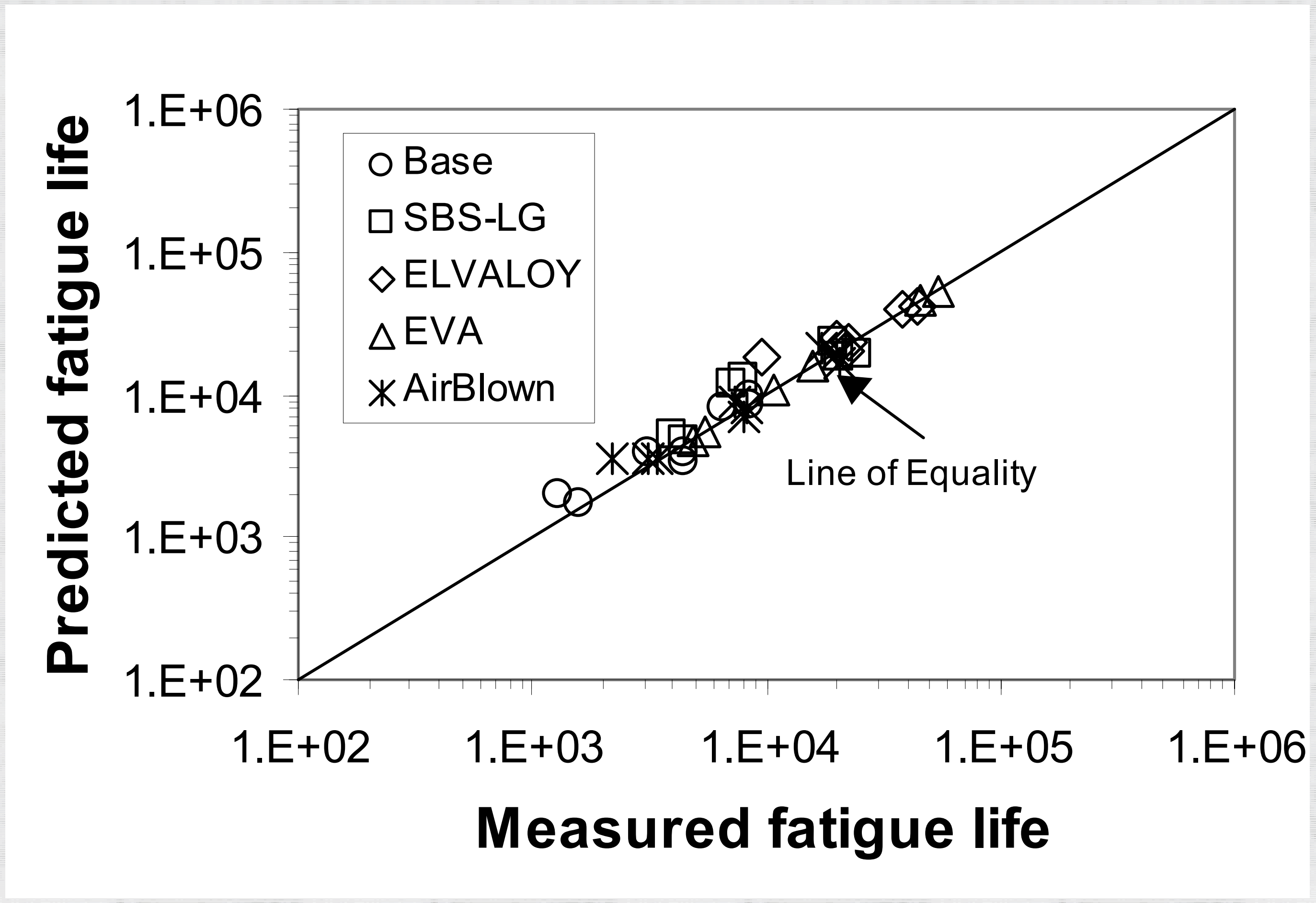
D_f : Damage Parameter at Fatigue Failure

$$N_f = A'(\gamma_m)^{-B'}$$

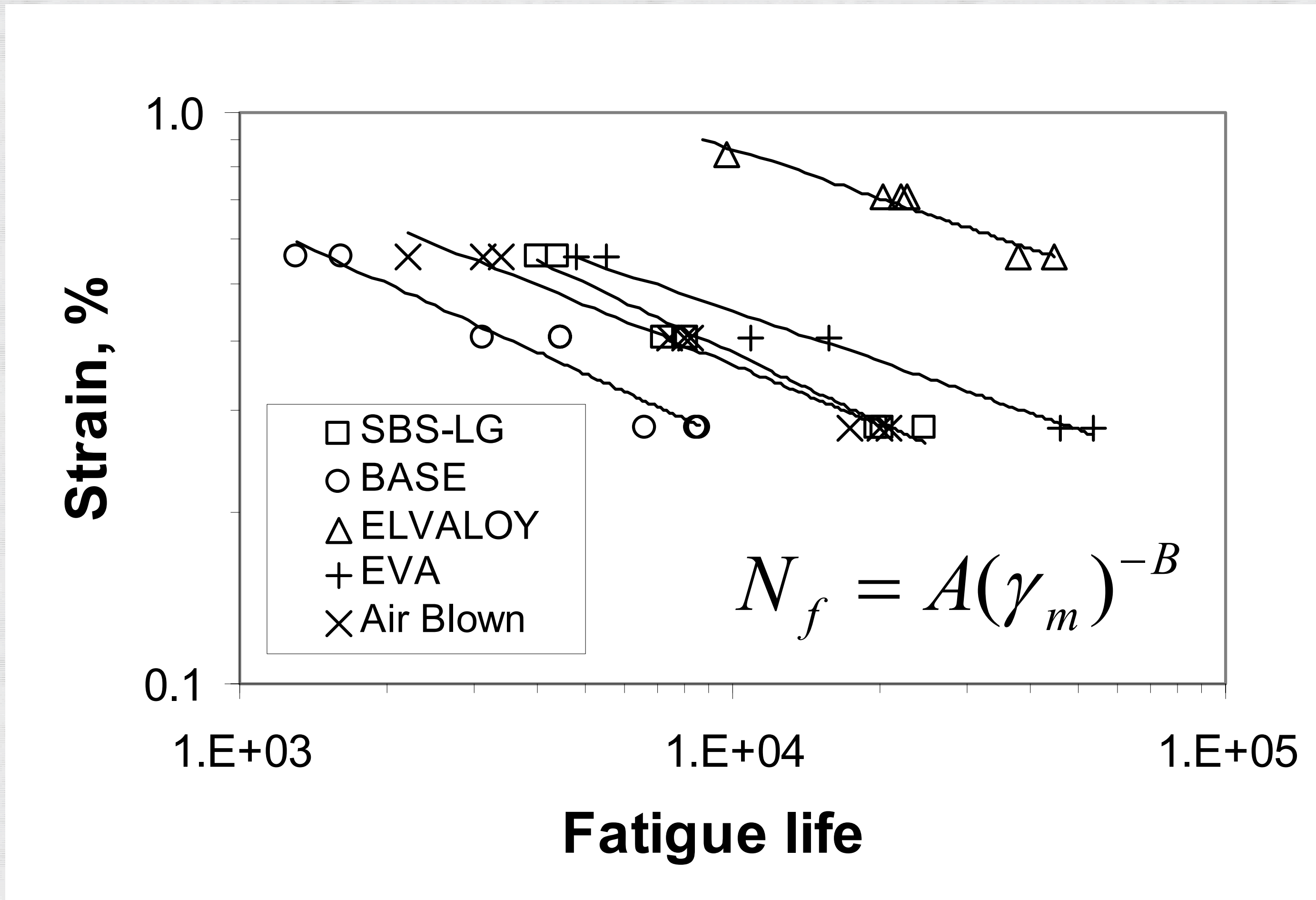
$$A' = \frac{{D_f}^k}{k(\pi I C_1 C_2)^\alpha}$$

$$B' = 2\alpha$$

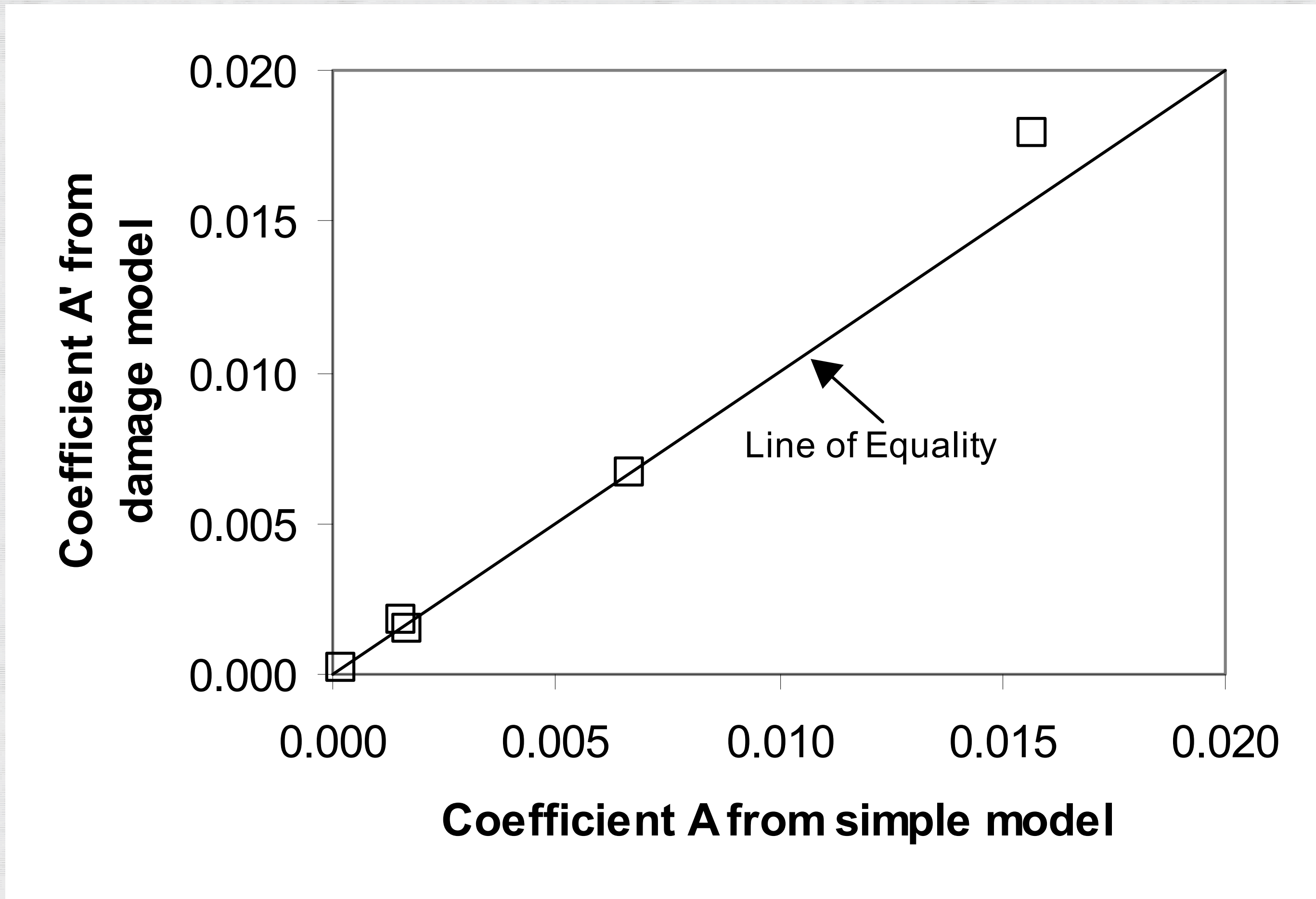
Predicted from Model vs. Measured



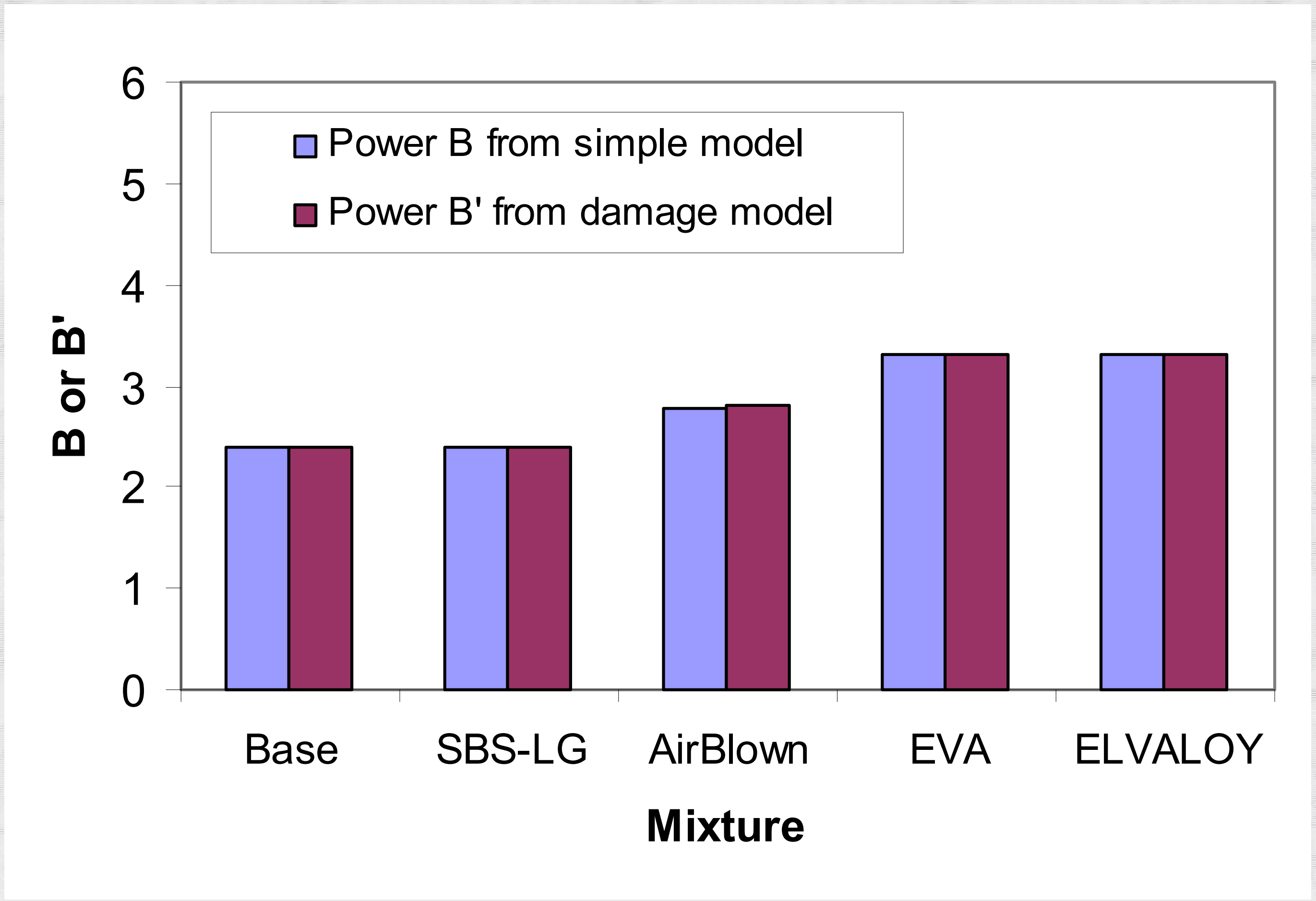
Fatigue Test Results



Comparison (Model Coefficient)



Comparison (Model Exponent)



Meaning of Mechanistic Model Parameters

- I : initial modulus
- k : combined effect of C_2 and α
  - higher k value typically extend fatigue life
- D_f : damage parameter at failure
  - higher value indicating better ability in fatigue damage accumulation
- C_1,C_2 : regression constants
  - higher value indicating faster damage evolution
- α : material parameter

Mechanistic Model Parameters

	Mechanistic Fatigue Model					
Mixture	Average I , Pa	C_2	C_1C_2	α	k	Average D_f
BASE	54200000	0.4146	0.01236	1.2	1.70248	2068.109
AirBlown	47000000	0.4126	0.01085	1.4	1.82236	2326.488
SBS-LG	36770000	0.2201	0.03843	1.2	1.93588	2324.728
EVA	34000000	0.2604	0.03364	1.65	2.22034	2210.086
ELVALOY	24580000	0.0983	0.08447	1.65	2.48781	3777.567

General Trends

- I : decrease (soft material shows longer fatigue life)
- k : increase (slow rate of damage evolution)
- C_2 : decrease (slow rate of damage evolution)
- D_f : increase (better capability in accumulating total fatigue damage)

Conclusions

- **Polymer modification affects fundamental changes in material characteristics and fatigue behaviors**
- **Fatigue damage and failure can be successfully identified by proposed testing and analysis**

Conclusions, cont'd

- Polymer additives contribute to extended fatigue life in strain-controlled fatigue testing
- Polymer additives soften binders and provide better resistance to microcracking due to a lower rate of damage evolution and a higher capability for total damage accumulation