Fatigue Endurance Limits for Perpetual Pavements

By

Waleed Zeiada, Ph.D.

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Ira A. Fulton Schools of Engineering
ARIZONA STATE UNIVERSITY

Civil, Environmental, and Sustainable Engineering
Tempe, AZ 85287-5306

Outline

- Background
- Research Statement and Objectives
- Testing Plan and Design of Experiment
- Endurance Limit (EL) Algorithm Development
- Development of SR Models
- Comparison of EL from Uniaxial and Beam Fatigue
- Incorporating EL Methodology into AASHTOWare-ME
- Conclusions, and Recommendations

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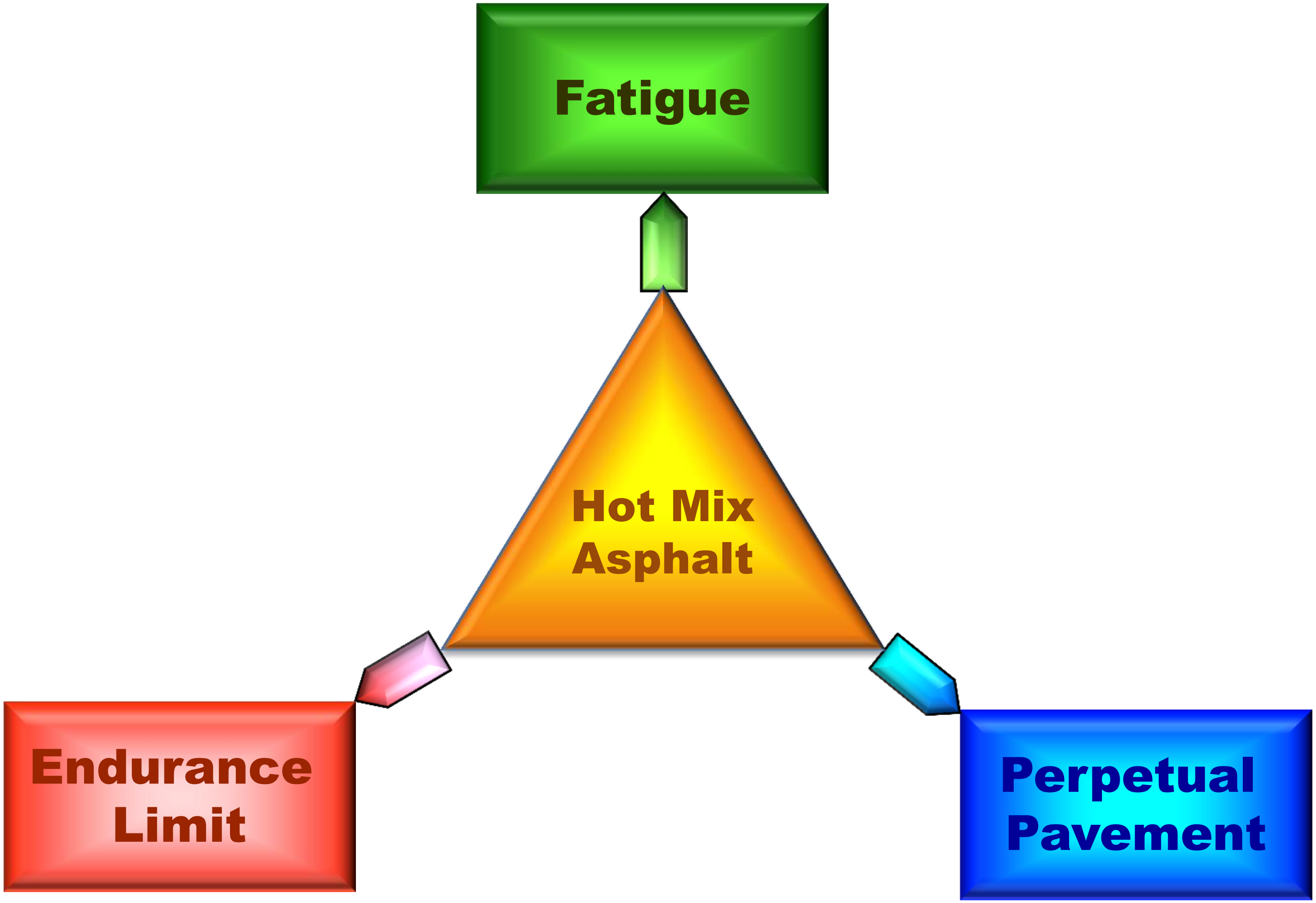
Background


Fatigue
Hot Mix Asphalt
Endurance Limit
Perpetual Pavement

HMA Fatigue Damage/Cracking

- **Definition:** A load associated damage due to repeated traffic loading.

- **Description:** Three different stages

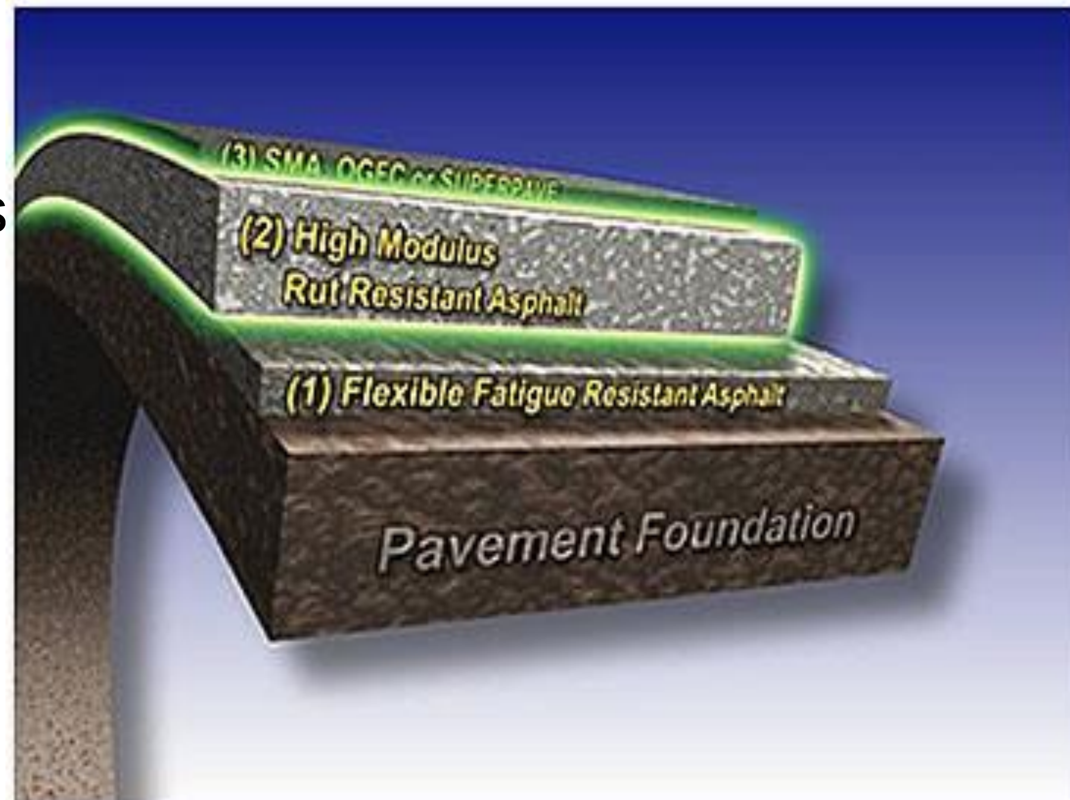
Early Stage

Intermediate Stage

Final Stage

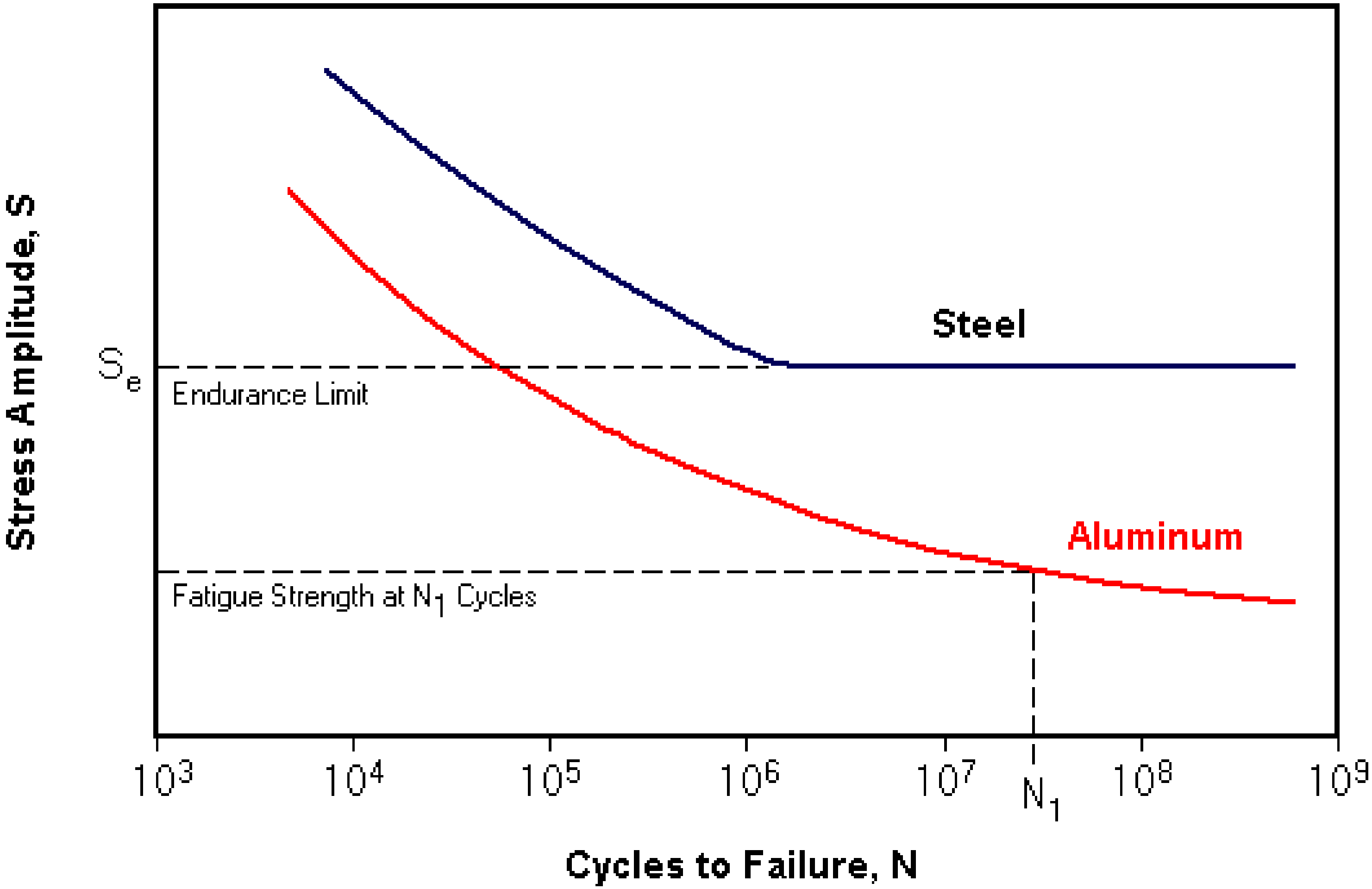
Perpetual Pavements

- **Definition:** Term used to describe a long lasting HMA pavements.
- At least 50 years
- Full depth asphalt, 1960s
- Three HMA layer system
- Increases pavement recycling
- Cost savings
- Environmental benefits.

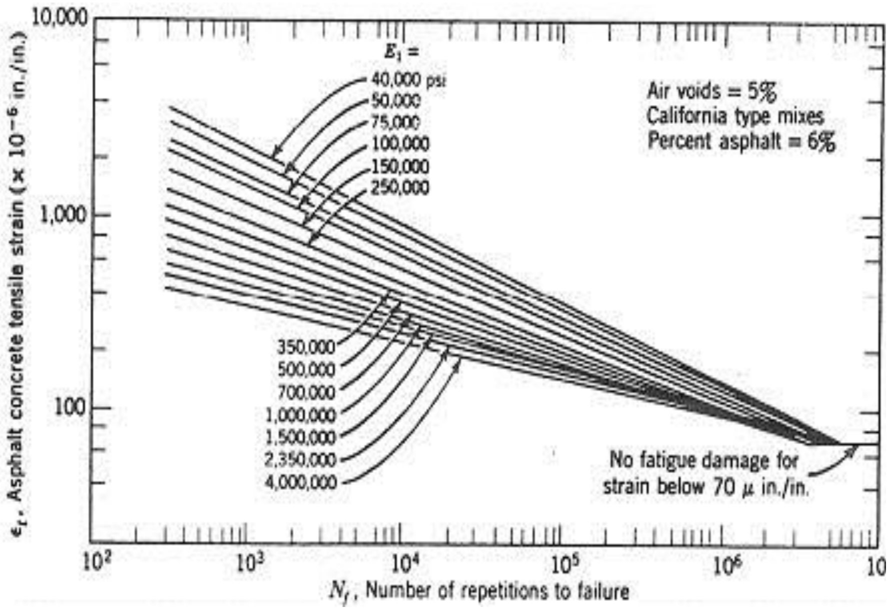


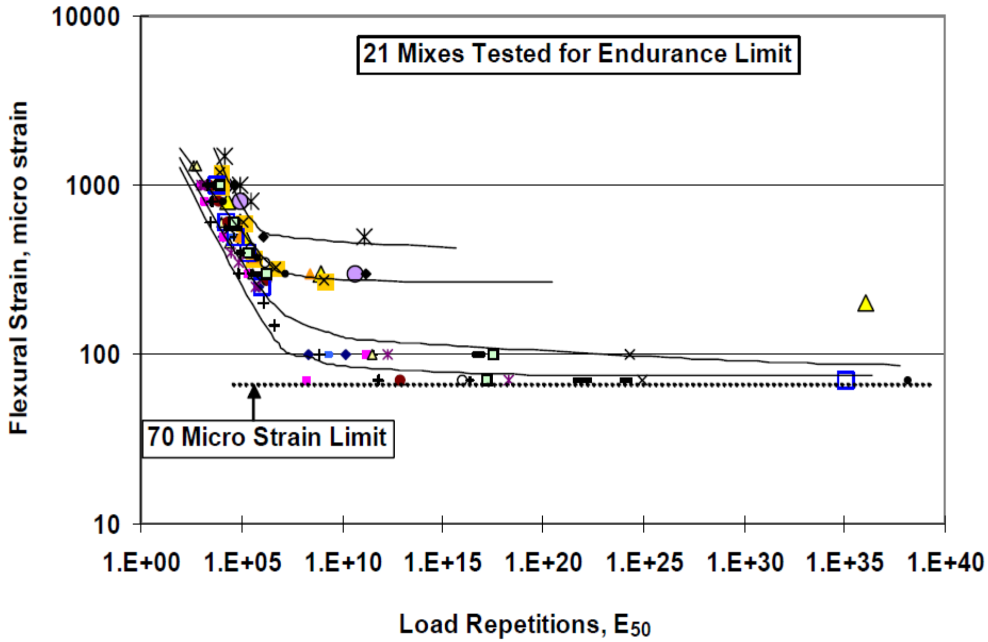
Endurance Limit

- **Definition:** Wöhler (1870)



Does HMA Exhibit an Endurance Limit?





Monismith et al., 1970

Carpenter et al., 2003

- **HMA EL (Prowell et al., 2009):**

Strain level yields 50 millions load repetitions until failure

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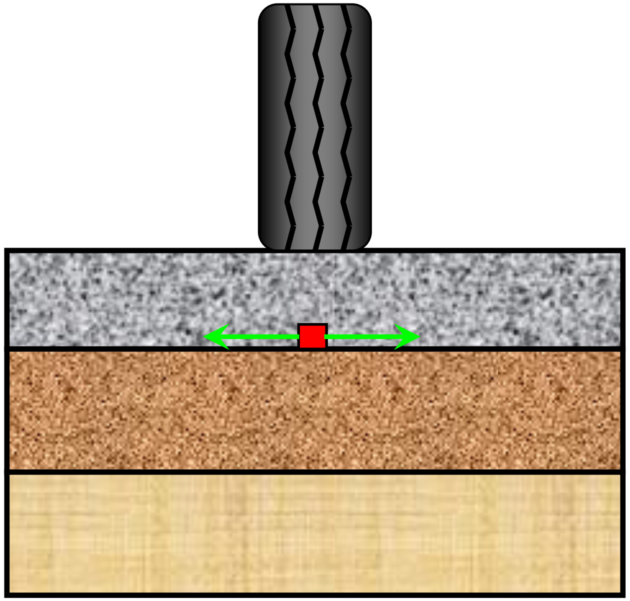
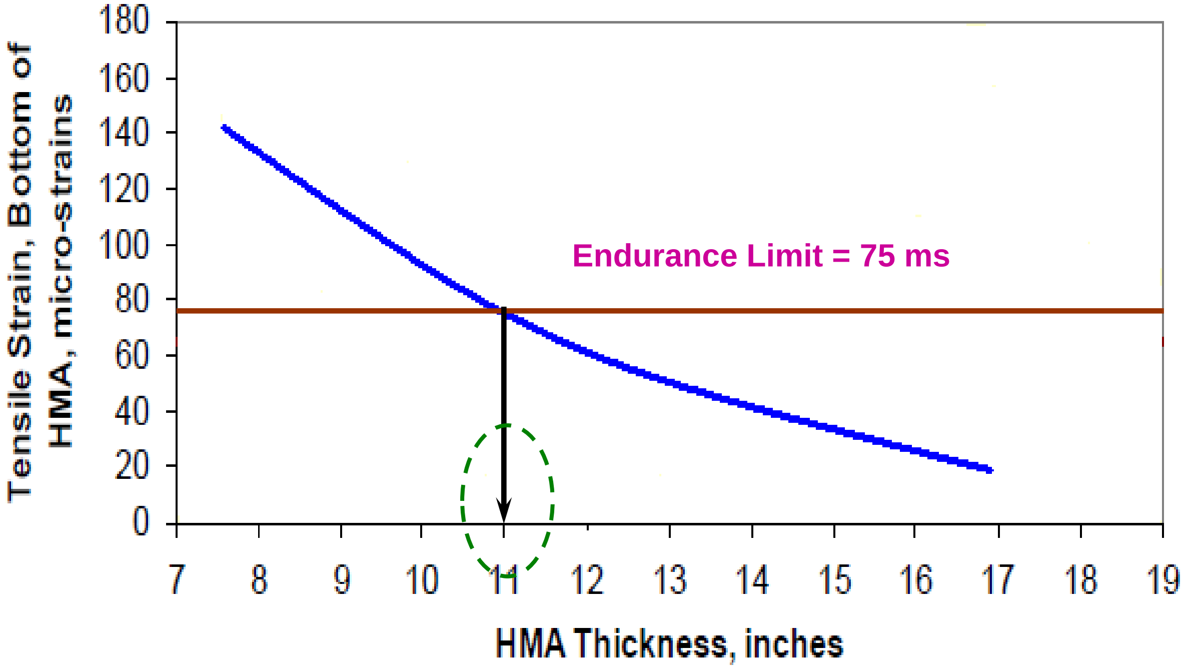
Perpetual Pavement Design Concept





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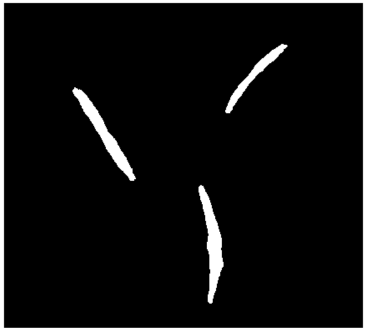
Research Problem Statement and objectives

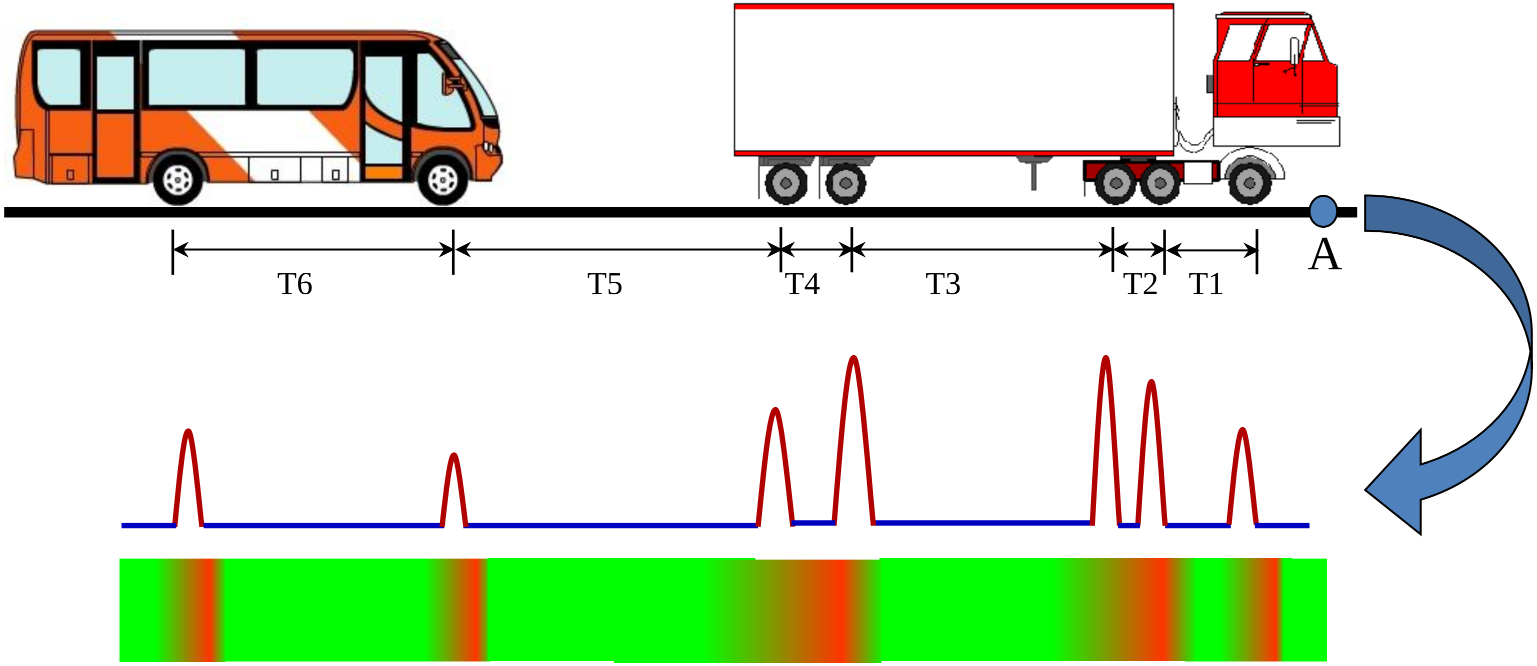
- The EL concept has not been totally implemented in AASHTOWare Pavement ME Design software
- No current methodology to consider the effect of the environmental conditions, traffic condition, mix design, and material properties together in the EL calculations

- Develop an algorithm to determine EL that is compatible with the AASHTOWare-ME software

New EL Definition

- EL is a result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods





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Factors Affecting Fatigue and EL

Factors	
Asphalt Content (%)	Binder Grade
Air Voids (%)	Aggregate Type
Temperature (°F)	Filler Percent
Rest Period (seconds)	Aggregate Gradation
Tensile Strain (µs)	Test Type

- ❑10 Factors with 3 levels: 3^10 = 59049 tests
- ❑Three replicates: 69049 * 3 = 177147 tests
- ❑Assuming average of 10 hours per test
- ❑ Total of **202** years

Selected Factors

Factors	No. of Levels
Asphalt Content, AC (%)	4.2, and 5.2
Air Voids, Va (%)	4.5, and 9.5
Temperature, T (°F)	40, 70, and 100
Rest Period, RP (seconds)	0, 5, 1, and 10
Tensile Strain, ε_t (μs)	L, M, and H
Binder Type	PG 58-28, 64-24, and 76-16

Test Type

Beam Fatigue Test

Uniaxial Fatigue Test

Binder Type			PG 58-28				PG 64-22				PG 76-16			
Binder Content			4.2		5.2		4.2		5.2		4.2		5.2	
Air Voids (%)			4.5	9.5	4.5	9.5	4.5	9.5	4.5	9.5	4.5	9.5	4.5	9.5
Temperature, F	Tensile Strain	Rest Period (sec)												
40	L	0					U	U		U				
		1												
		5					U	U	U	U				
		10												
	M	0					U		U	U				
		1						U						
		5						U	U	U				
		10							U					
	H	0								U				
		1							U					
		5					U							
		10												
70	L	0					U	U	U					
		1												
		5					U	U		U				
		10							U					
	M	0					U	U		U				
		1							U					
		5					U	U	U	U				
		10												
	H	0												
		1								U				
		5												
		10												
100	L	0					U		U	U				
		1					U			U				
		5						U	U					
		10												
	M	0						U	U	U				
		1												
		5					U	U		U				
		10						U						
	H	0						U						
		1												
		5								U				
		10												
Total Number of Combinations			**Beam Fatigue = 190**						**Uniaxial Fatigue = 51**					

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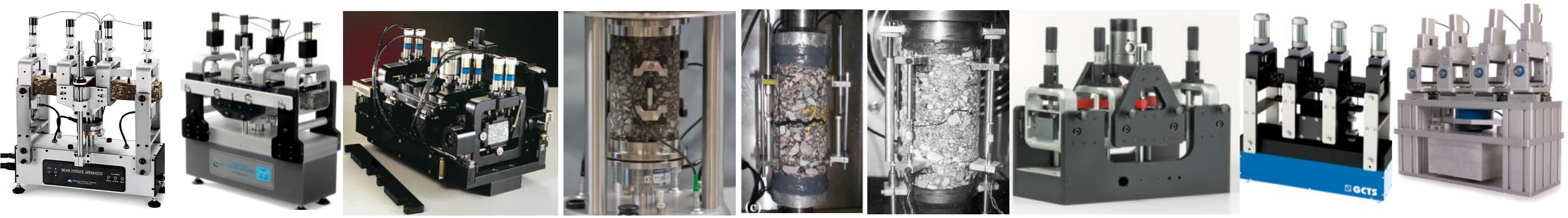
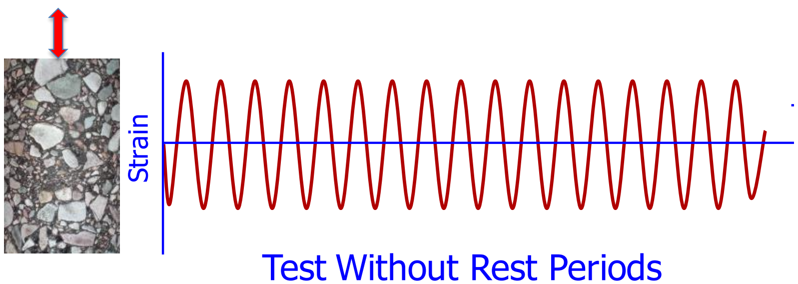
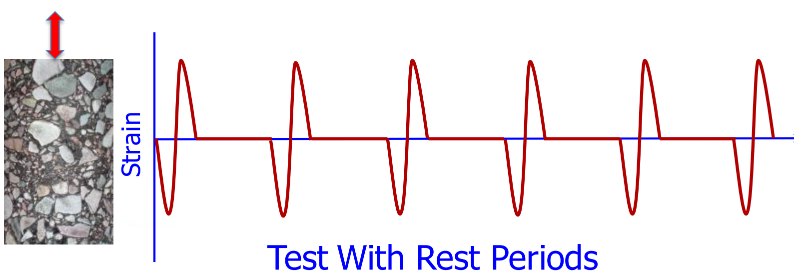
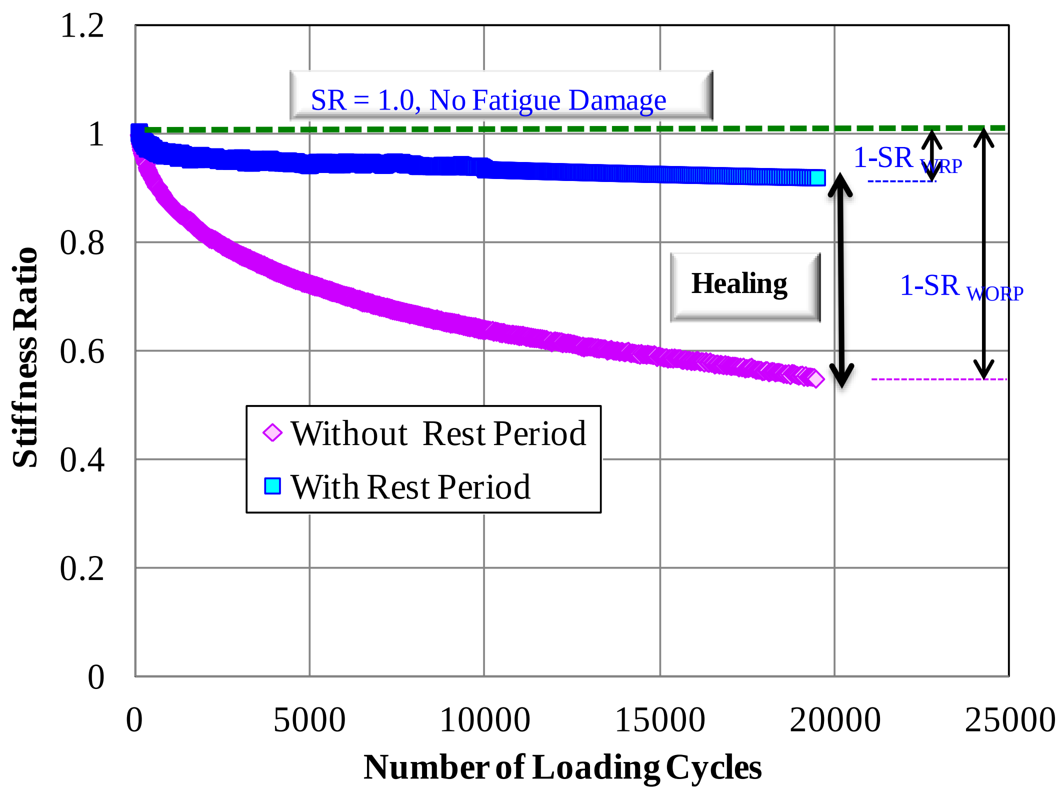
Healing of Micro-cracks



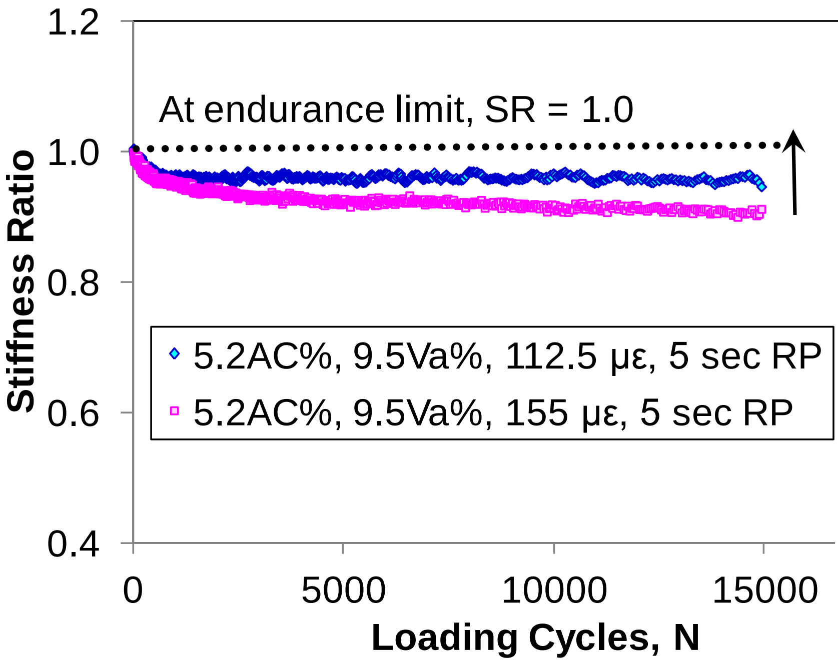


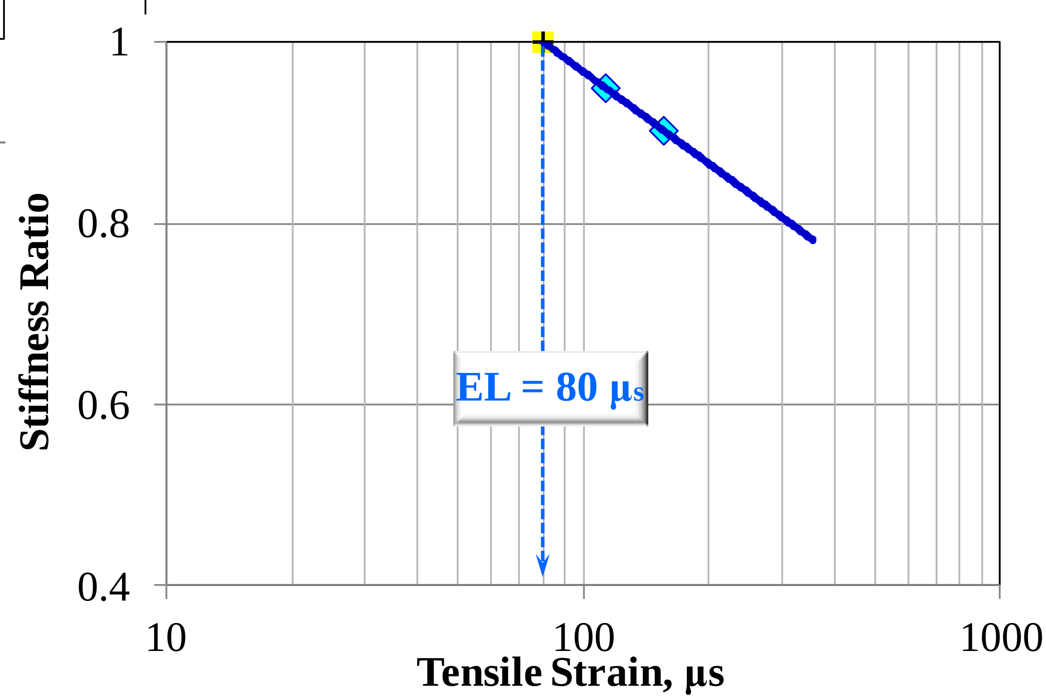




Algorithm Development for HMA Endurance Limit

- Determination of Endurance Limit Using SR





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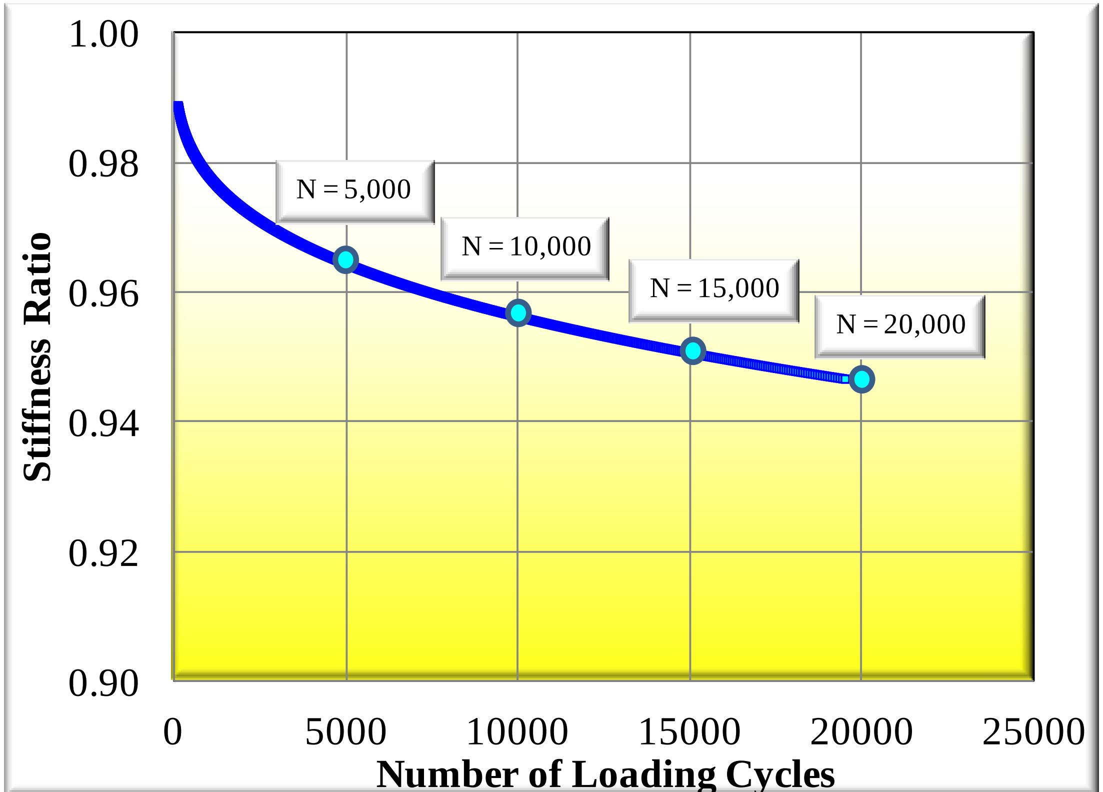
First Generation SR Model

$$SR = f\ (T, AC, V_a, \varepsilon_t\ , RP, BT, \text{and } N)$$

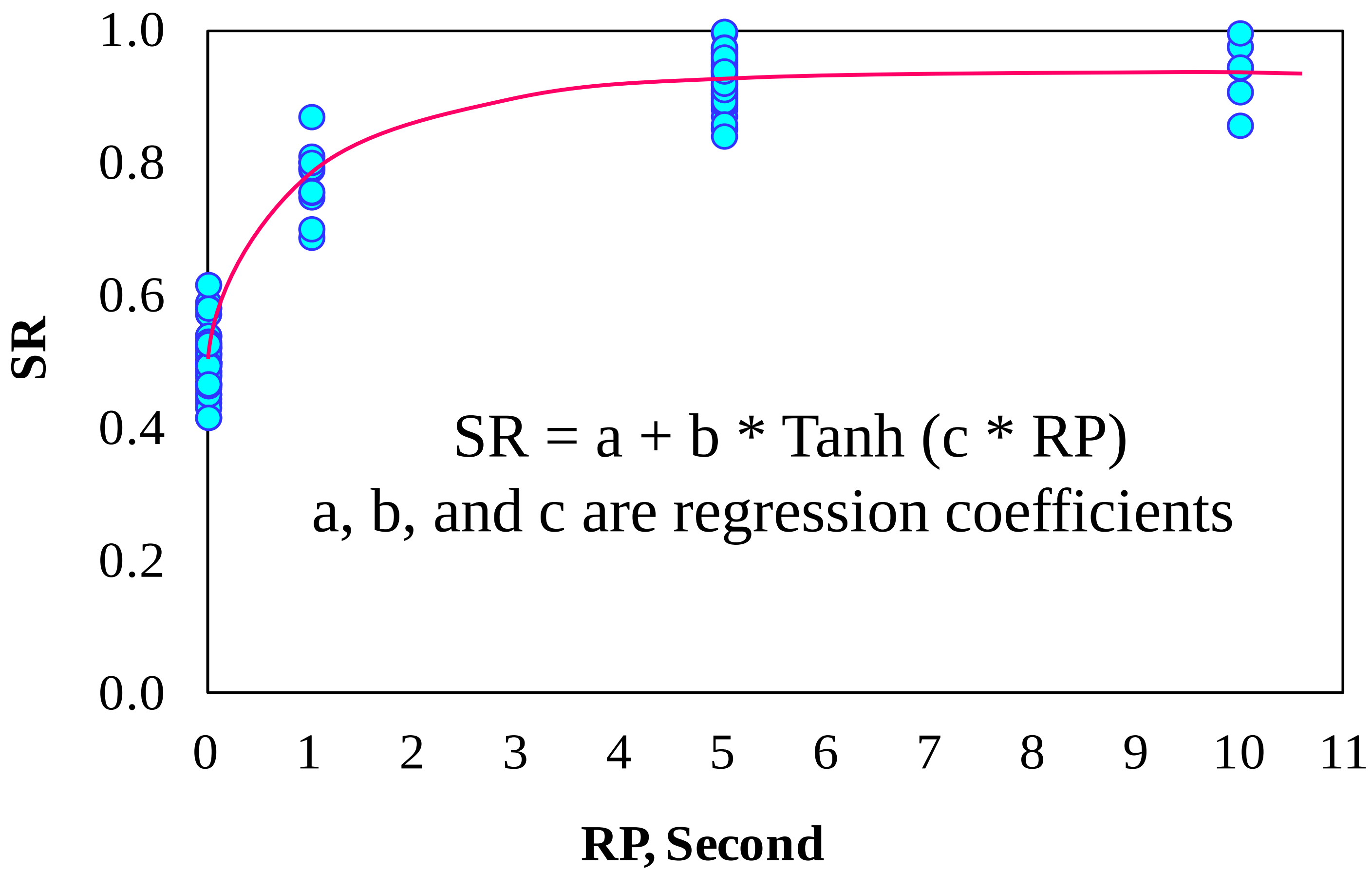
AC	= Asphalt content, %
V_a	= Air voids, %
ε_t	= Tensile Strain, µs
T	= Temperature, °F
RP	= Rest period, sec
BT	= Binder Type
N	= Number of cycles



First Generation SR Model

- Form of First Generation SR Model

Effect of Rest Period

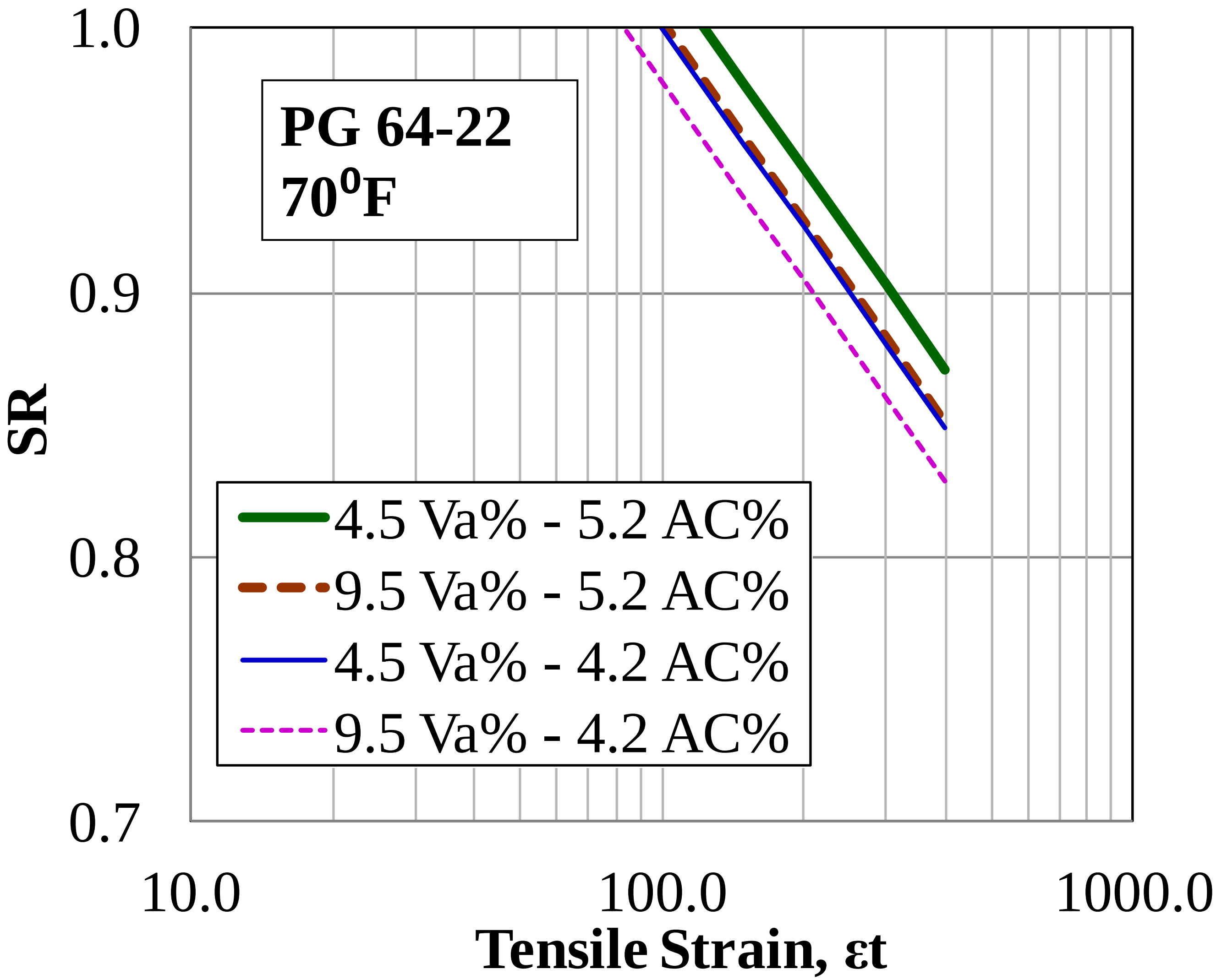


First Generation SR Model

- $R^2_{adj} = 0.979$

$$SR = 0.1564774 + (0.00079*BT) + (0.070059744*AC) + (0.00393*V_a) + (0.10095*RP) - (1.268*10^{-7}*N_f) - (0.0024676*T) - (0.0001677*BT*AC) + (3.29961\text{x}10^{-5}*BT*RP) + (3.488*10^{-6}*BT*T) + (0.00794848*AC*RP) - (0.0042225*V_a*RP) + (0.0006044*AC*T) - (0.0001035*V_a*T) - (2.889*10^{-8}*RP*N_f) + (2.9191*10^{-9}*N_f*T) - (0.0025*RP*T) - (3.97*10^{-7}*BT^2) - (1.20135*10^{-5}*T^2) + (8.434*10^{-8}*BT^2*AC) - (2.8756*10^{-8}*BT^2*RP) + (1.9558*10^{-6}*AC*T^2) + (6.6137*10^{-7}*V_a*T^2) - (1.582*10^{-11}*N_f*T^2) + (1.262\text{x}10^{-5}*RP*T^2) - (1.176*10^{-6}*V_a*RP*T^2) + (3.124*10^{-12}*N_f*RP*T^2) - (7.4*10^{-7}*BT*AC*T) + (3.92*10^{-7}*BT*RP*T) + (0.00013185*V_a*RP*T) + (2.19*10^{-9}*N_f*RP*T)$$

EL Values From First Generation SR Model



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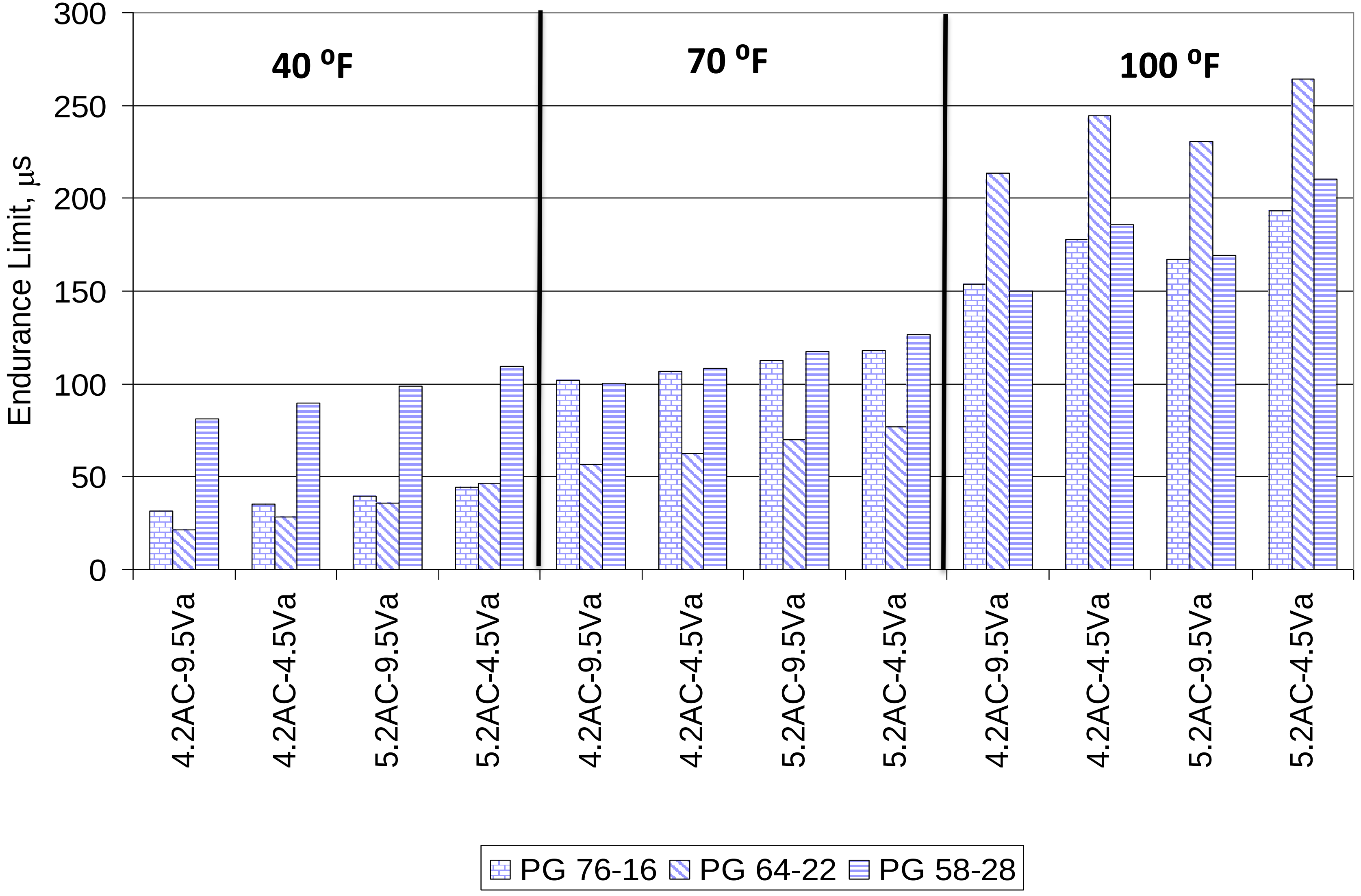


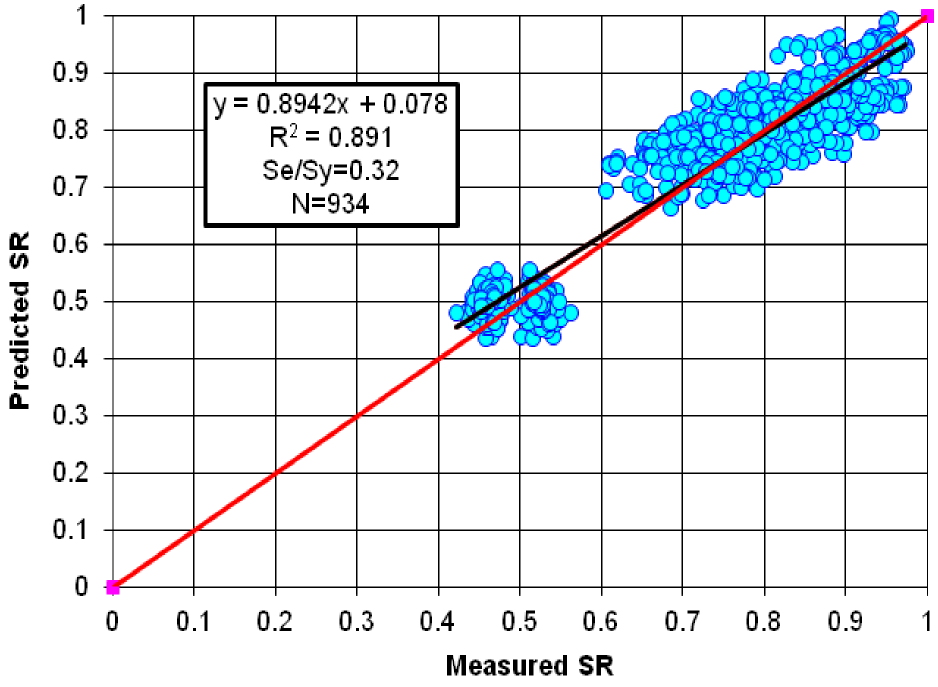
Second Generation PSR Model

- BT, T, AC, V_a were replaced by initial stiffness, E_o

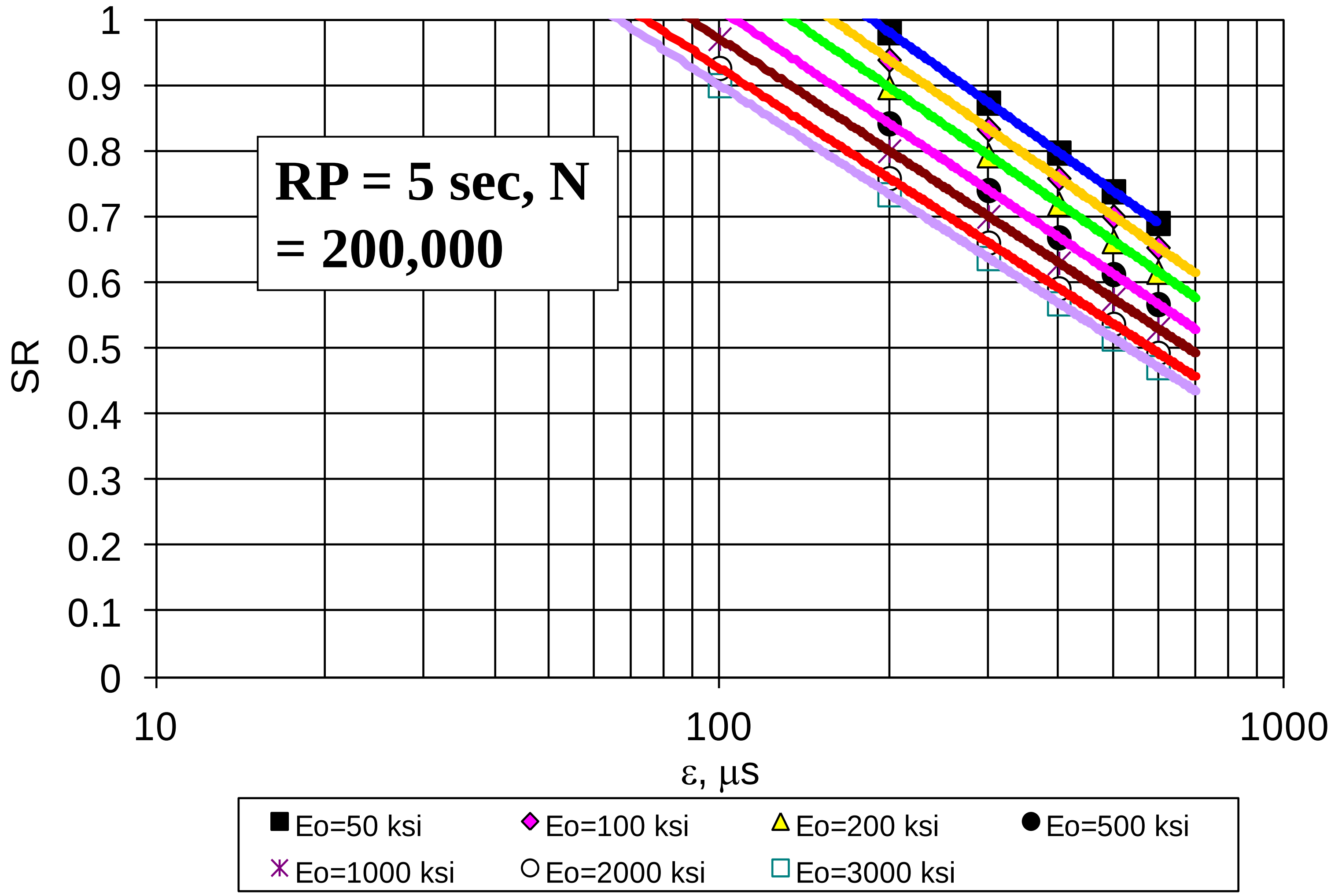
SR = f (E_o, ε_t , RP, and N)

- $R^2_{adj} = 0.891$

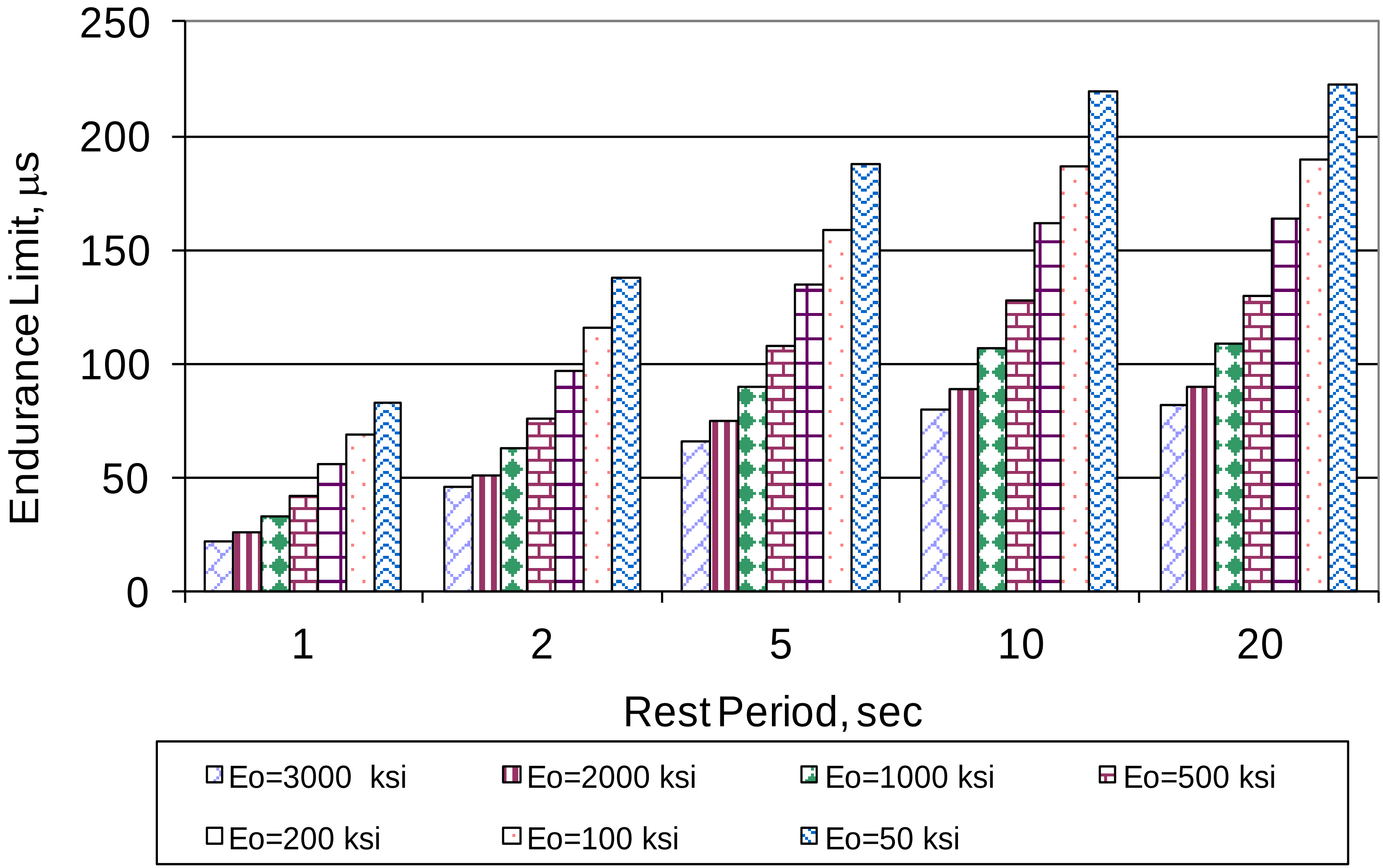
$$SR=2.0844-0.1386*\log(E_o)-0.4846*\log(\varepsilon_t)-0.2012*\log(N)+1.4103*\tanh(0.8471*RP)+0.0320*\log(E_o)*\log(\varepsilon_t)-0.0954*\log(E_o)*\tanh(0.7154*RP)-0.4746*\log(\varepsilon_t)*\tanh(0.6574*RP)+0.0041*\log(N)*\log(E_o)+0.0557*\log(N)*\log(\varepsilon_t)+0.0689*\log(N)*\tanh(0.0259*RP)$$



Second Generation SR Model



EL from Second Generation SR Model



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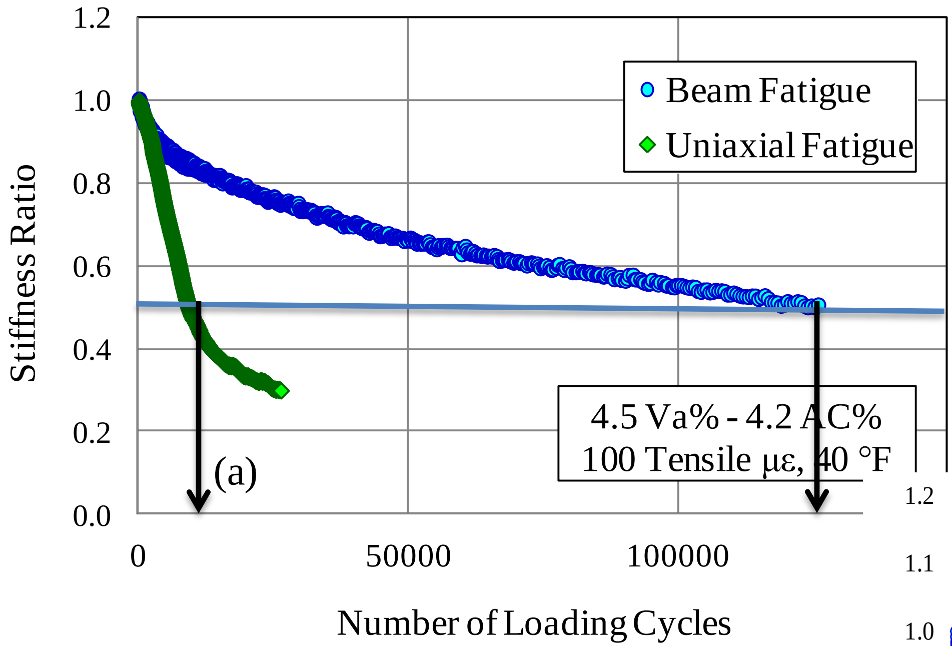
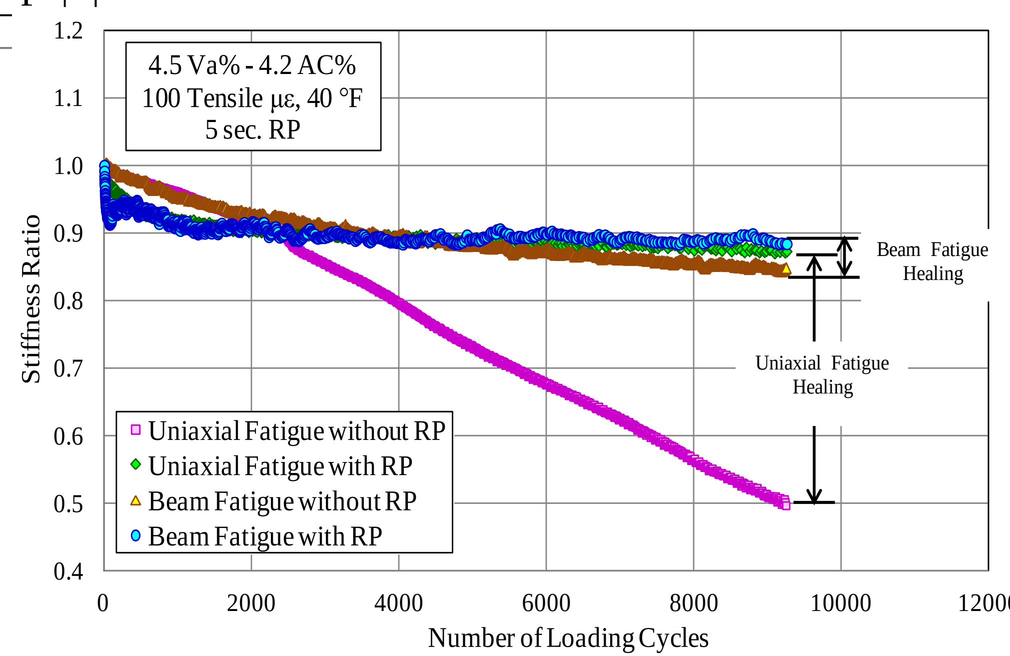
Beam Fatigue Versus Uniaxial Fatigue Tests

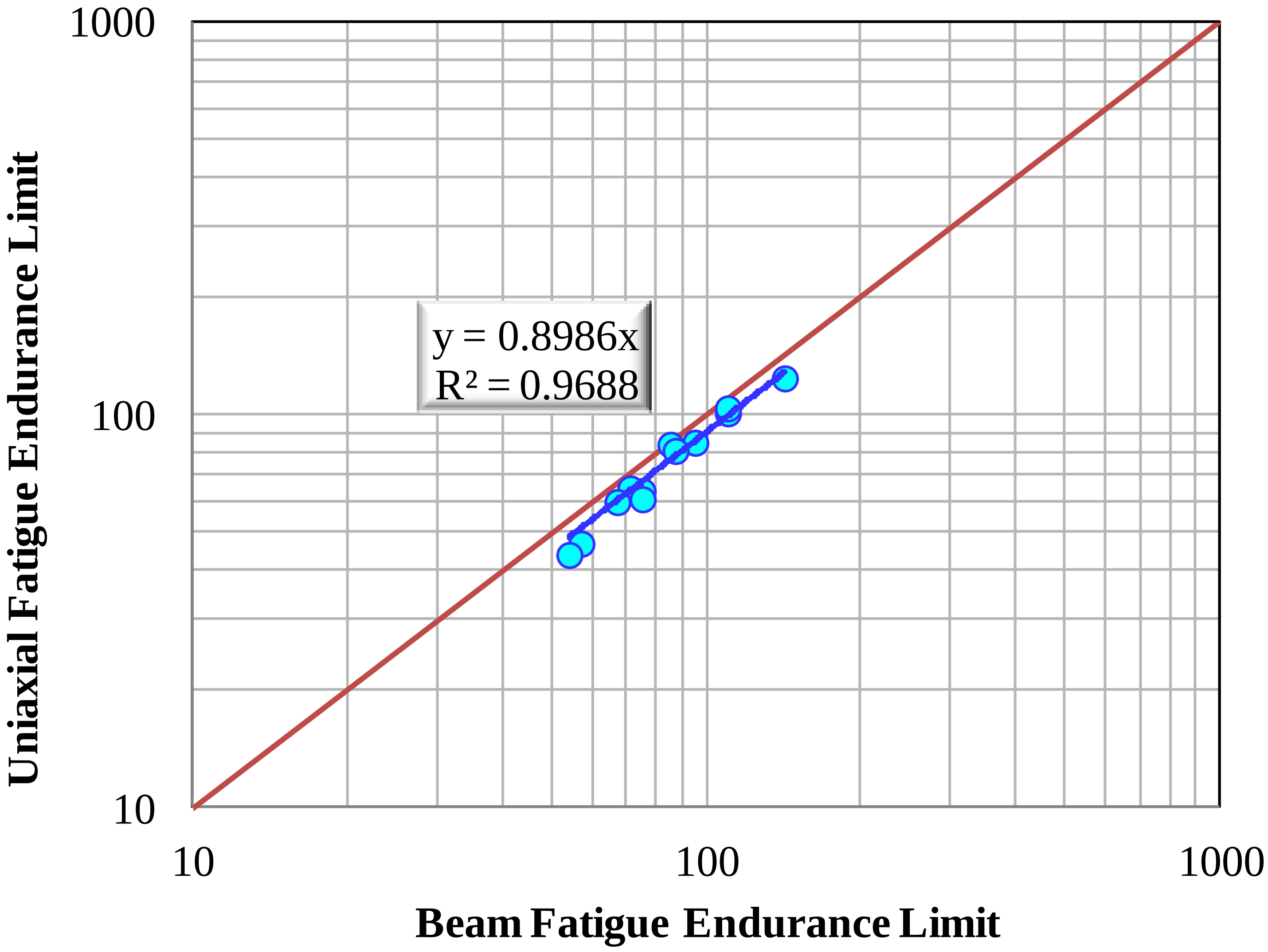


Damage Comparison

Healing Comparison



Uniaxial Fatigue Versus Beam Fatigue



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Incorporation of EL into AASHTOWare-ME

1. Calculation of Endurance Limit

$$SR = f\ (E_o, \varepsilon_t, N, \text{and } RP)$$

- E_o, Initial Stiffness (ksi)
- N = Number of cycles

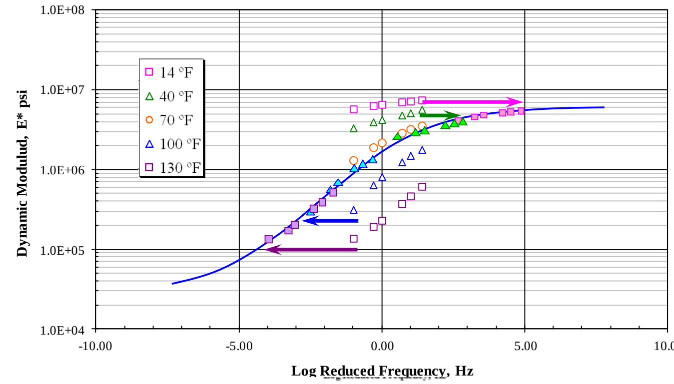
N of 20,000 is recommended

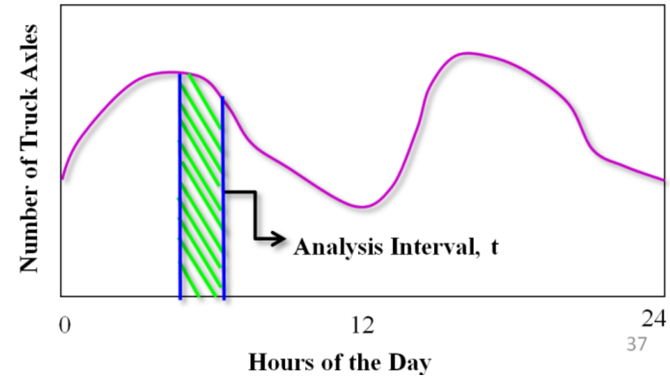
- RP= Rest Period (sec)

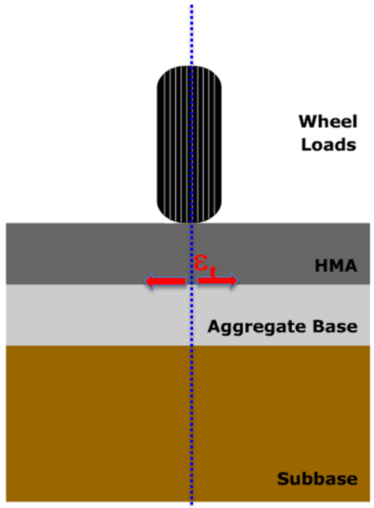
$RP = t / \sum(NT)$

- ε_t, Tensile Strain, μs

Tensile Strain is equal to the Endurance Limit at PSR = 1.0





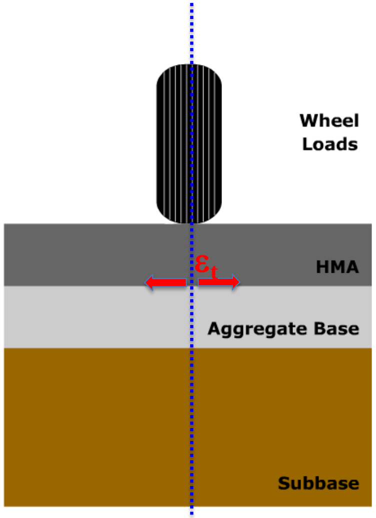


Incorporation of EL into AASHTOWare-ME

2. Incorporation of EL into Fatigue Damage

$$D_i = \Sigma\,(n_i / Nf_i)$$

D = Fatigue Damage
n_i = Actual traffic for period i (Traffic Demand)
Nf_i = Allowed Traffic in period i (Traffic Capacity)



If the calculated EL < the actual ε_t, Damage is count

If the calculated EL ≥ the actual ε_t, the Ni is infinity and the Damage is zero

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Conclusions

- HMA exhibits endurance limit
- Mixtures using softer binders exhibit higher endurance limits than mixtures using stiffer binders
- High binder contents and low air voids produced the high endurance limit values
- Endurance limit values were higher at high temperatures
- The endurance limit values from the beam fatigue exhibit similar trends compared to those of the uniaxial fatigue test
- The endurance limits obtained in this study can be incorporated in the AASHTOWare-ME

Recommendations

- Field calibration is needed
- Consider other types of aggregates, and mixes such as warm mix asphalt, asphalt rubber, and polymer modified mixtures

Acknowledgement

- NCHRP 944-A Project Panel
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  - Dr. Matthew Witczak
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  - Mr. Con Sinadinos, Mr. Alan Feeley, and Mr. Stephen King

Questions!