

Endurance Limit of HMA Mixtures to Prevent Fatigue Cracking in Flexible Pavements

NCHRP 9-38

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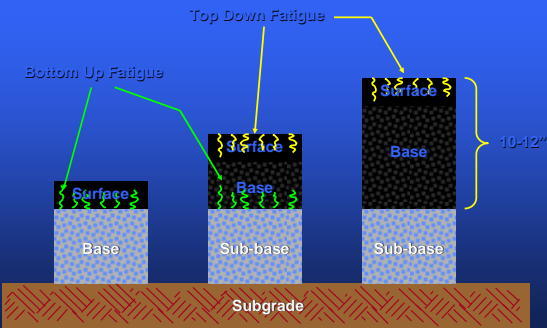


Fatigue Cracking

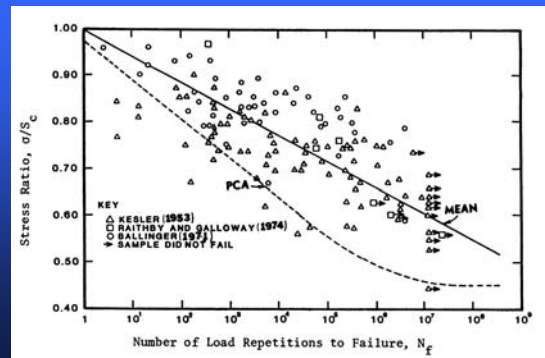


Photo courtesy of FHWA

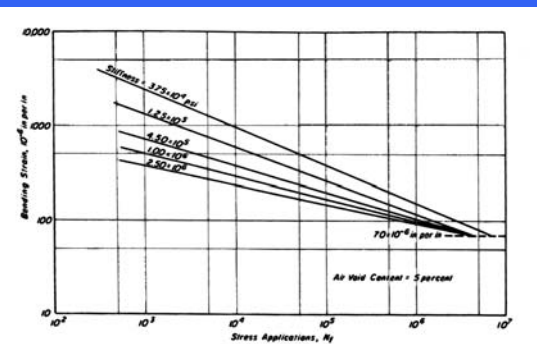
Flexible (Asphalt) Pavement Fatigue



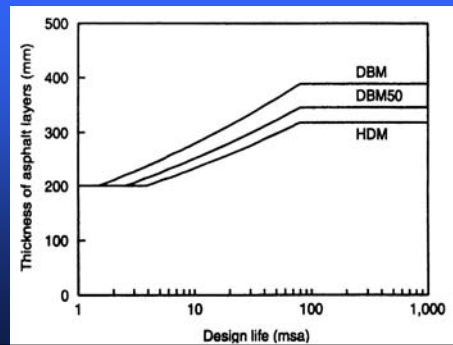
Definition of Endurance Limit for PCC (Huang)



Concept of Endurance Limit for HMA (Monismith and Mclean)



Long Life Pavement (Nunn)

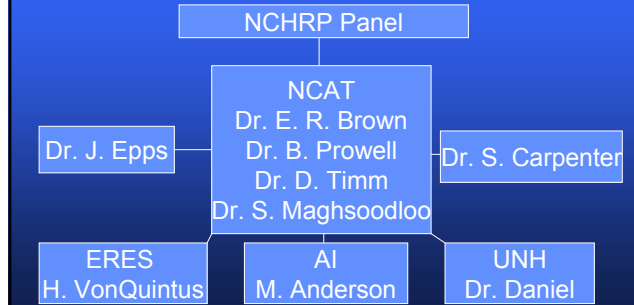


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Objectives

- Confirm existence of Endurance Limit
- Effect of Material Properties on Endurance Limit
- Shortcut method to determine Endurance Limit
- Suggested changes to design guide to include Endurance Limit

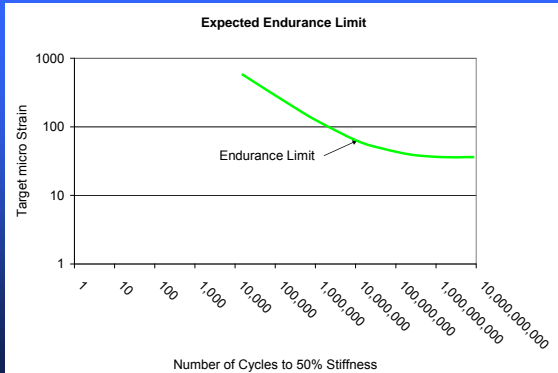
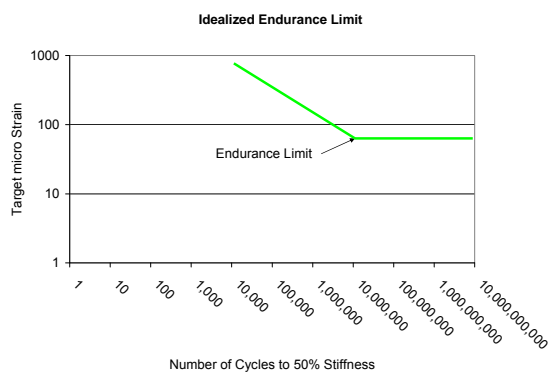
Team



Defining the Endurance Limit

What is the Endurance Limit?

- HMA Fatigue Endurance Limit – A level of strain below which there is minimal fatigue damage over an essentially infinite number of loading cycles, which would not lead to failure; failure being bottom-up fatigue cracking
- Axles loads resulting in pavement strains less than the endurance limit do not cause damage!



Practical Definition of the Endurance Limit

- Nunn defined long-life pavement as those that last 40 years without structural strengthening

Practical Definition of the Endurance Limit

- Max. passenger cars per hour (65 mph) = 2350
- One truck replaces 2.5 cars in rolling terrain = 940 trucks/hour; 22,560 trucks/day; 329,376,000 trucks in 40 years
- 25% trucks = 10,152 trucks/day or 148,219,200 trucks in 40 year
- Class 9 vehicle 4 load repetitions (steer axle would be lighter) = 592,876,800 repetitions for 25% trucks
- Typically, not all trucks are loaded.
- Washington DOT study suggests 1.2 ESALs per Class 9 vehicle or 395,251,200 ESALs for 100% trucks in 40 years

Practical Definition of the Endurance Limit

- 500 million load repetitions is approximate maximum in 40 years
- Assumes shift factor of 10 supported by SHRP
- Endurance Limit is that laboratory strain that provides for 50 million cycles to failure

Test Plan



Beam Fatigue
AASHTO T321

Beam Fatigue Testing

- Micro-strain levels:
 - 800
 - 400
 - 200
 - 100
 - 70
 - 50
- Two replicates at each strain level
- Test to highest strain level where both replicate survive 50 million cycles

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Test Plan

NMAS	AC%	Granite			
		58-28	64-22	67-22	76-22 Elastomer
19.0	Optimum	B	B	B, U	B, U
	Opt. +0.7			B, U	B, U

- Modified testing to a maximum of 50 million cycles.
- Testing to be conducted at progressively lower levels until two replicates last 50 million cycles.
- Additional tests at intermediate strain level to better define endurance limit.

B = beam fatigue, U = uniaxial tension

Mix Design

- 19.0 mm NMAS used at 2003 NCAT Test Track
- Fine-graded granite/limestone blend
- Optimum AC = 4.5%
- PG 67-22 and PG 76-22 binders

PG 64/67-22 Binder Test Data

Test	Value, kPa	Failure Temp.
G*/sin δ Orig. at 64	1.702	68.4
G*/sin δ RTFO at 64	4.268	69.1
G*(sin δ) PAV at 25	2805	20.4

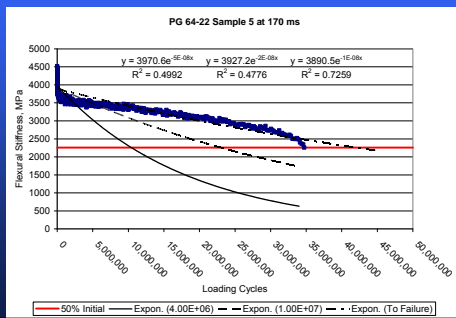
Test Results

Data Analysis

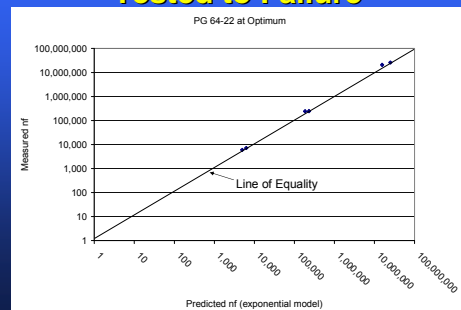
- Beam Fatigue
 - Stiffness vs Nf
 - Exponential Model
 - Logarithmic Model
 - Power Model
 - Weibull Function
 - Ratio of Dissipated Energy
- Uniaxial Tension

Goal: Accurately estimate fatigue life near endurance limit.

Exponential Model Recommended by AASHTO T321



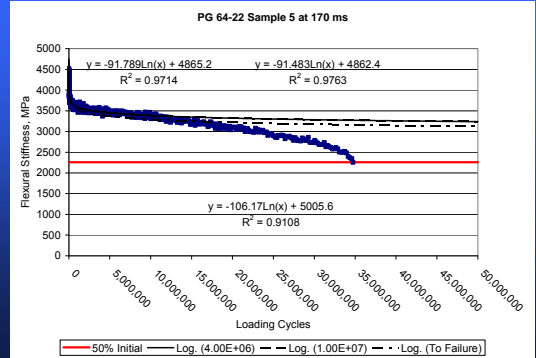
Exponential Life Comparisons Tested to Failure



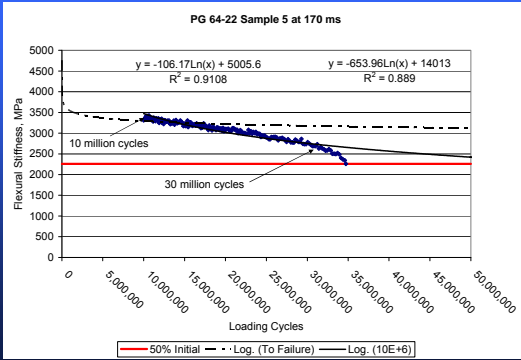
Conclusions Regarding Exponential Model

- Good match to measured failure if sample tested to failure
- Tends to under-predict fatigue life when extrapolating test results
- Not recommended for predicting Nf near endurance limit

Logarithmic Model



Logarithmic Model



Conclusions Regarding Logarithmic/Power Model

- Extrapolation from a low number of cycles (10 million or less) can result in significant overestimation of Nf
- When testing to 50 million cycles, important to match slope at high number of cycles
- May be best method of estimating fatigue life at strain levels equal to or less than the endurance limit

Weibull Function

$$S(t) = \exp(-\lambda \times n^\gamma)$$

- S(t) = probability of survival until time t
- λ = scale parameter (intercept)
- γ = shape parameter (slope)

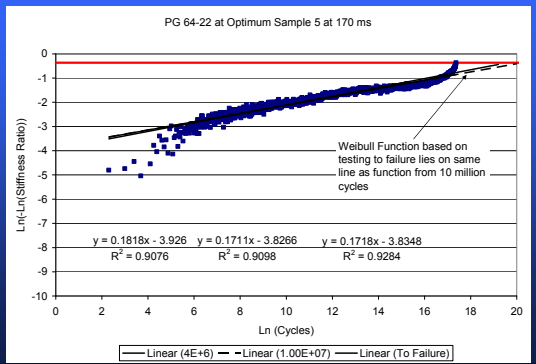
Solved by linear regression of:

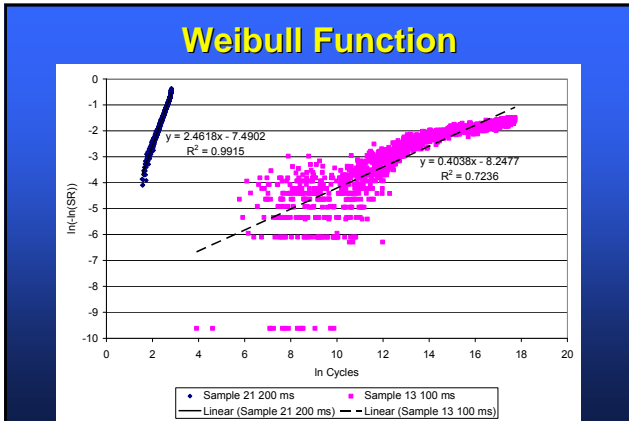
$$\ln(-\ln(SR)) = \ln(\lambda) + \gamma \times \ln(n)$$

SR = stiffness/initial stiffness

Applied to HMA by Tsai et al 2002

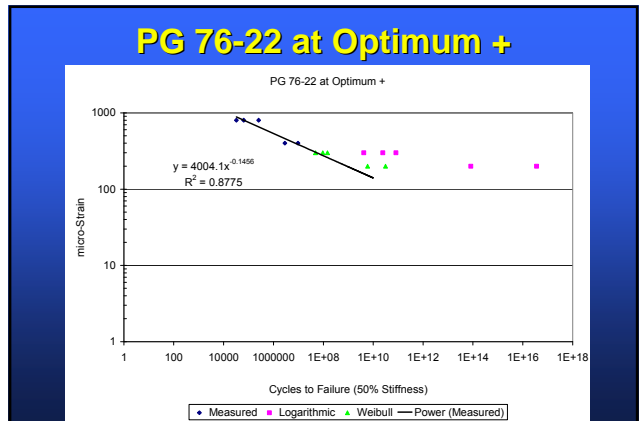
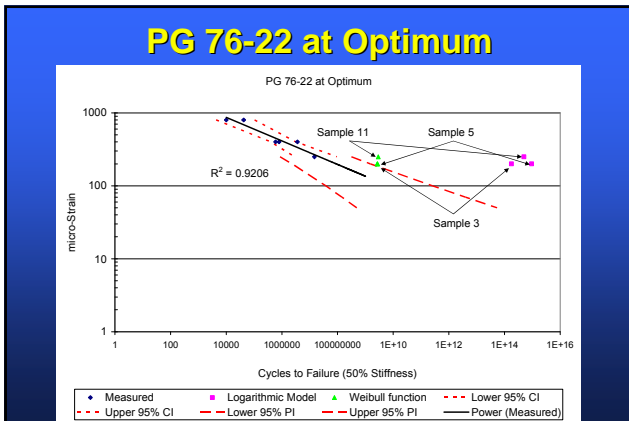
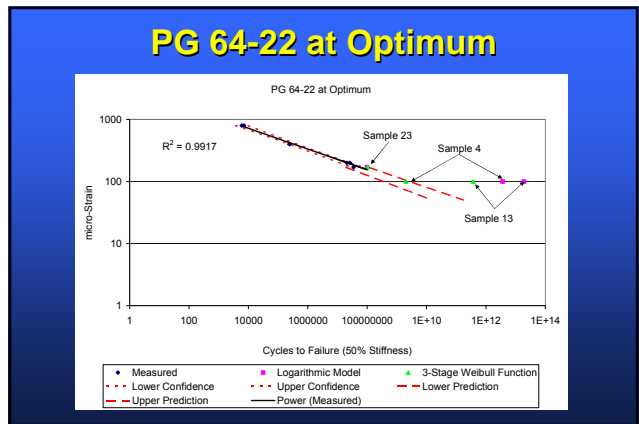
Weibull Function





- ### Conclusions Regarding Weibull Function
- Appears data can be extrapolated from a lower number of cycles
 - Prediction of Nf generally good. Believed to underestimate Nf at strain levels less than the endurance limit
 - Flattening of slope near endurance limit may be indicative of endurance limit.
 - Single stage Weibull Function does not account for change in slope (resulting in lower estimate of Nf described above)

Indications of the Endurance Limit based on Stiffness



Prediction Intervals for Endurance Limit

- Endurance limit for PG 64-22
 - 148 micro-strain = 50 million cycles
 - 131 micro-strain = 100 million cycles
- Endurance limit for PG 76-22
 - 129 micro-strain = 50 million cycles
 - 113 micro-strain = 100 million cycles
 - Visually approximately 225 microstrain, but results more variable
- Slight indication of higher endurance limit for optimum plus binder content

Ratio of Dissipated Energy

Ratio of Dissipated Energy

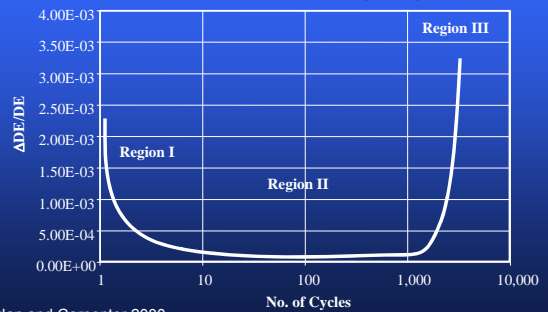
$$RDEC = \left(\frac{W_n - W_{n+x}}{W_n} \right) \div x$$

where,

- RDEC = ratio of dissipated energy
- W_n = total dissipated energy at cycle n
- W_{n+x} = total dissipated energy at cycle n+x
- X = the number of cycles between the two data points

Shen and Carpenter 2005

Plateau Value (PV)

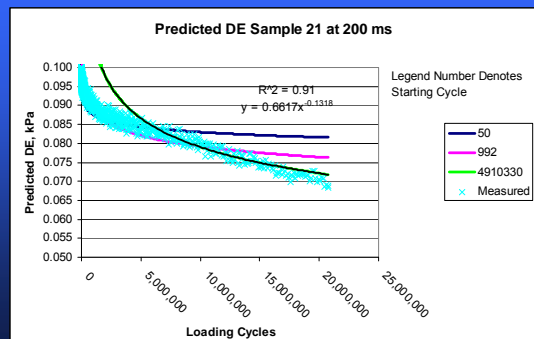


Khuzlan and Carpenter 2000

Steps to Determining PV

- Fit power model to stiffness vs loading cycle data (for tests terminated prior to failure)
 - Early cycles often need to be neglected
 - Determine number of cycles to 50% stiffness
- Fit power model to dissipated energy vs loading cycle data
 - Early cycles often need to be neglected
- Calculate RDEC at number of cycles = 50% initial stiffness

Example of Dissipated Energy Data

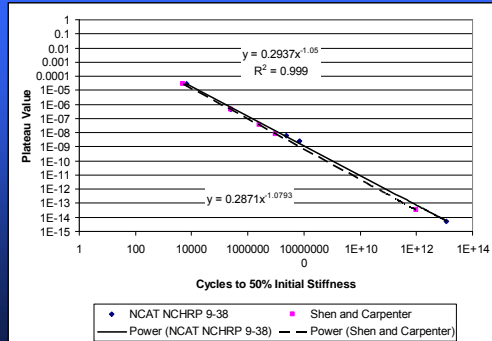


PG 64-22 at Optimum

Micro-Strain	Replicate 1		Replicate 2	
	Nf	PV	Nf	PV
800	6000	3.7E-5	7130	2.1E-5
400	246220	6.3E-7	242380	3.2E-7
200	2.6E+7	5.3E-9	2.1E+7	6.4E-9
170	3.5E+7	4.7E-9	9.9E+7	5.4E-10
100	3.6E+12	9.3E-15	1.9E+13	6.4E-16

Critical PV for long life = 8.57E-9

PV vs. Nf



Mini Round Robin for Beam Fatigue

Round Robin Test Matrix

Lab/Mix	PG 64-22 at Optimum	PG 64-22 at Optimum Plus	PG 76-22 at Optimum
NCAT	X	X	X
Asphalt Institute	X	X	X
University of Illinois	X	X	X
VA Transportation Research Council	X		
SEM Materials	X		
University of California	X		

Precision Estimates

Code	Average of all Labs	Std. Dev. Between Cell Averages (S _c)	Repeatability Standard Deviation (S _r)	Reproducibility Standard Deviation (S _k)	Between Lab Standard Deviation of Lab Means (S _l)	Within-Lab Coefficient of Variation, %	Between-Lab Coefficient of Variation, %
PG 64-22 at 800 ms	8.629	4.360	3.396	5.167	3.894	39.4	59.9
PG 64-22 at 400 ms	370.628	345.965	169.147	372.512	331.896	45.6	100.5
PG 76-22 at 800 ms	9.970	2.881	6.395	6.395	0	64.1	64.1
PG 76-22 at 400 ms	551.804	304.135	364.582	425.572	219.525	66.1	77.1

Predicting Endurance Limit

- Test three samples each at 400 and 800 micro-strain
- Transform data (log-log)
- Fit regression
- Calculate strain level corresponding to 95% one-sided lower prediction limit for 50 million cycles
- Run three beams at predicted strain level to 12 million cycles
- Extrapolate with Weibull Function

Summary of Predicted Endurance Limits

Binder	Predicted	95% One-Sided Lower Prediction Limit
PG 58-28	105	76
PG 64-22	89	75
PG 67-22	182	130
PG 67-22 Optimum +	176	141
PG 76-22	195	148

Using Endurance Limit for Pavement Design

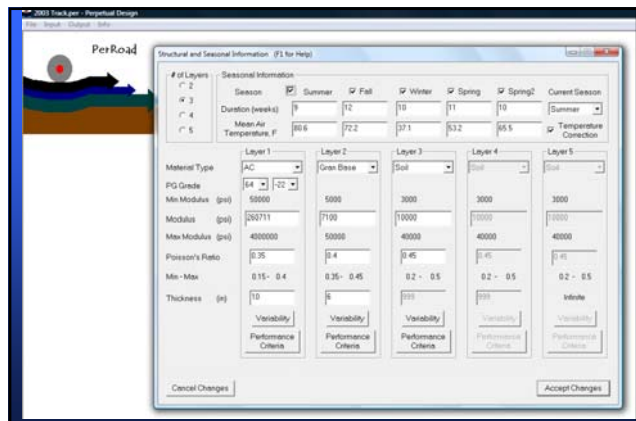
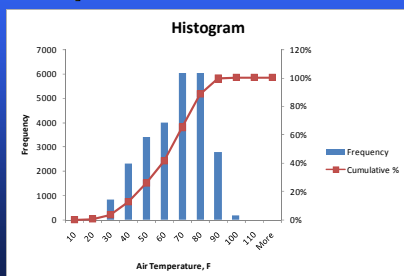
M-E Methods

- Design procedures that use equivalent axles and equivalent temperatures (DAMA)
- Design procedures that use equivalent temperatures but axle load distribution (PerRoad)
- Design procedures that calculate and use pavement temperatures at specific depths (MEPDG)

PerRoad

- Deflections calculated based on average temperature for up to five seasons
 - Equation to adjust HMA stiffness
- Uses single definition of endurance limit
- Uses field transfer function for loads exceeding endurance limit
- Probabilistic calculations (Monte Carlo Simulation)

2003 Test Track Temperature Distribution



What is the Effect of Predicted Endurance Limit on Pavement Thickness?

- PG 67-22 at Optimum AC%
 - Predicted Endurance Limit = 182 micro-strain - Test Track perpetual thickness = 15 in.
 - 95% One-Sided Lower Prediction Limit = 130 micro-strain – Test Track perpetual thickness = 18 in.
 - Test Track Traffic = 100 million ESALs in 20 years

Conclusions

- 500 million load repetitions is a practical maximum for 40 years of traffic
- Thus, considering a shift factor of 10, 50 million cycles in the lab approximates the maximum number of load repetitions
- The single-stage Weibull function offers a conservative approach to extrapolate fatigue stiffness data

Conclusions (Continued)

- The Logarithmic model fits samples tested below the endurance limit if some early cycles are ignored
- The PV identified by Shen and Carpenter indicates long life, but not necessarily the endurance limit
 - Determining the PV requires a double extrapolation
- Endurance limit can be extrapolated from testing to 10 – 12 million cycles

Conclusions (Continued)

- There is an endurance limit
- An endurance limit of approximately 150 micro-strain was indicated for the PG 64-22 mix; 225 micro-strain for the PG 76-22 mix
- Optimum plus asphalt content may increase the endurance limit slightly

Questions?

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