Designs Factors for Flexible and Rigid Pavement Design

Workshop & Lectures on Pavement Engineering, Maintenance and Management

References

- *Pavement Analysis and Design*, Y.H. Huang, 2004
- *Principles of Pavement Design*, Yoder and Witczak, 1975
- Manual for *Professor Training Course in Asphalt Technology*, National Center for Asphalt Technology
- National Highway Institute (NHI) Training Course 131064A, *Introduction to Mechanistic Design of New and Rehabilitated Pavements*

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Design Factors

- Traffic and Loading
- Materials
- Environment
- Failure Criteria
- Reliability

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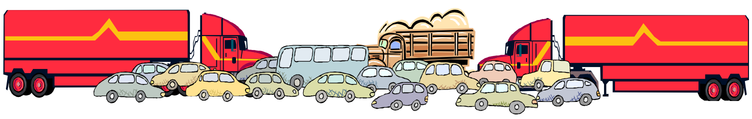
Traffic

- Primary Design Input
- Consideration
  - Traffic Volume
  - Mixed Traffic
  - Variable Vehicle and Axle Weights
  - Predicting Future Traffic
  - Lane Distributions



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Traffic Volume

- AADT is the average daily traffic volume in all lanes in both directions
- AADT = (total yearly traffic volume) / 365
- T = percentage of truck

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Mixed Traffic

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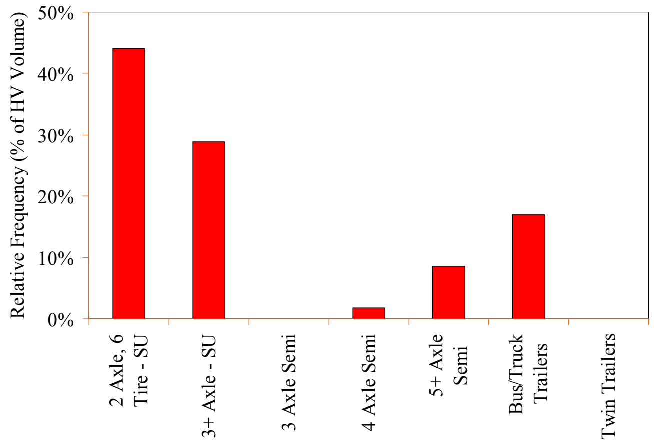
Mixed Traffic – Vehicle Distributions



Mn/DOT 1994 Geotechnical and Pavement Manual, Rural CSAH or County Roads

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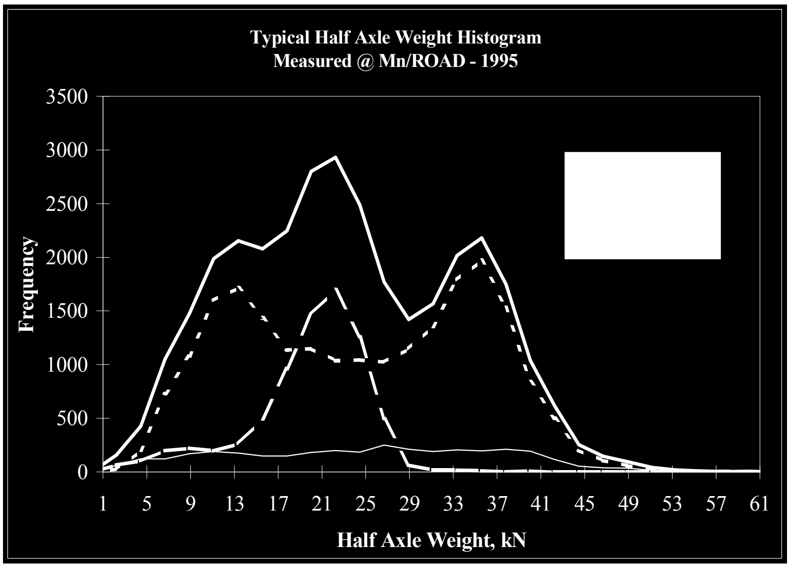
Mixed Traffic – Variable Axle Weight



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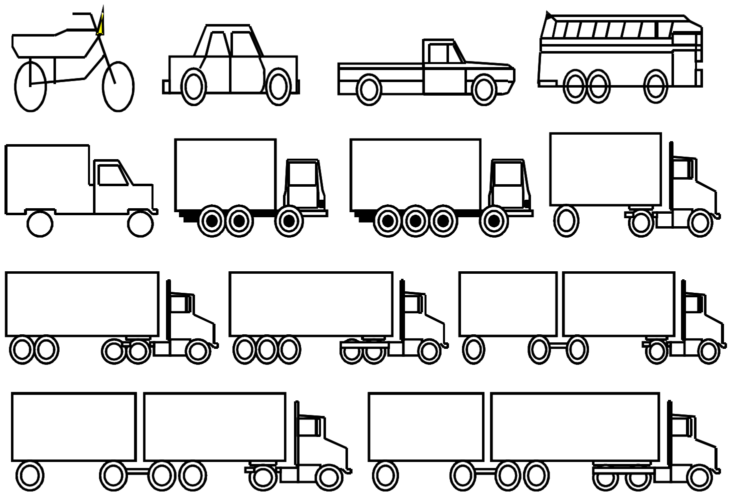
Vehicle Classification



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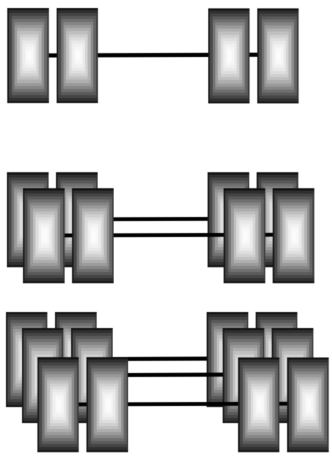
Mixed Traffic – Axle Configurations

- Single
- Tandem
- Tridem



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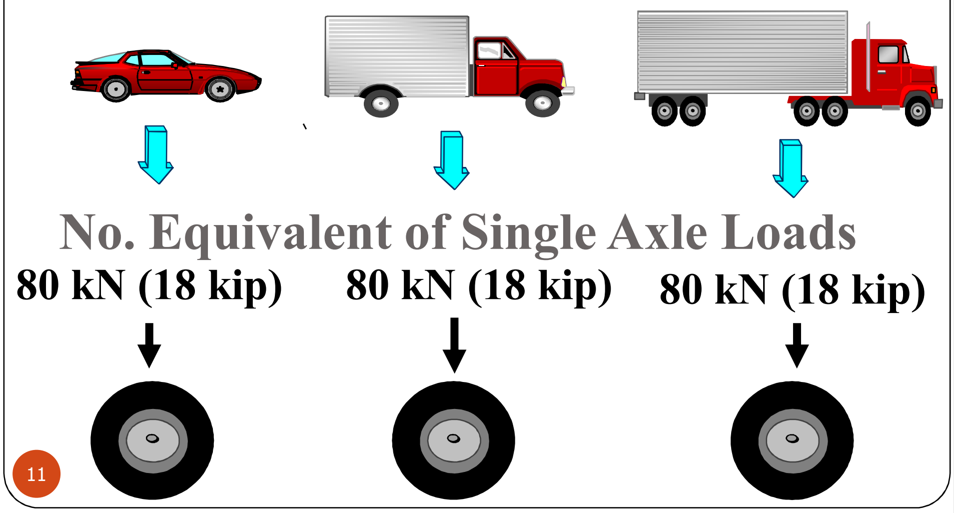
Conversion of Mixed Traffic to Equivalent of Single Axle Loads



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Concept of Equivalent Single Axle Loads (ESALs)

- Convert mixed traffic into equivalent 80-kN (18-kip) single axles
- Equivalent axles based on loss in serviceability measured at the AASHO Road Test
- Load equivalent factors used for the conversion

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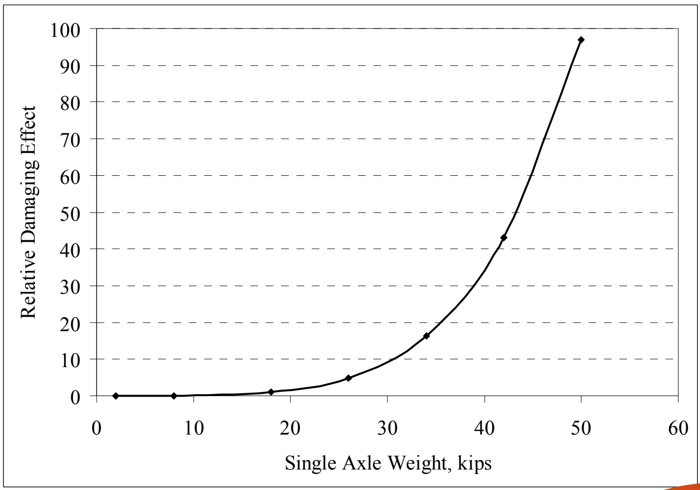
Relative Damage

AASHO Road Test – Empirical Relationship

- 4^{th} Power Law



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Equivalent Axle Load Factor

- Defines the damage to pavement by any axle load relative to the damage induced by a single load (18 kip).
- Design is based on number of passes of single axle load.
- Equivalent load factor used depends on pavement conditions.
- Load factors are based on experience but can be derived theoretically.
- AASHO is the most commonly used procedure.

$$ESAL = \sum_{i=1}^{m} F_i n_i$$

m = number of axle group,

i = axle load group,

F_i = equivalent axle load factor,

n = number of passes.

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Flexible Pavement
AASHTO Equivalent Factors:

$$\log\left(\frac{W_{tx}}{W_{t18}}\right) = 4.79\log(19) - 4.79\log(L_x + L_2) + 4.33\log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$$

$$EALF = \left(\frac{W_{t18}}{W_{ttx}}\right)$$

Theoretical Analysis: there are different criteria proposed by different organizations.

- Asphalt Institute (failure criterion):
- Deacon (1960) (layer theory):

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3}$$

$$EALF = \left(\frac{W_{t18}}{W_{ttx}}\right) = \left(\frac{\varepsilon_x}{\varepsilon_{18}}\right)^4$$

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Theoretical Analysis (cond't):

$$EALF = \left(\frac{L_x}{18}\right)^4 \qquad EALF = \left(\frac{L_x}{L_s}\right)^4$$

criterion based on permanent deformation:

$$N_d = f_4(\varepsilon_c)^{-f_5}$$

W_{t18} = number of single loada pplication to time, t
W_{tx} = number of x-axle load applications at the end of time, t
ε_x = tensile stress at the bottom of asp. layer due to x-axle load,
ε_{18} = tensile stress at the bottom of asp. layer due to 18 kip axle load,
L_x = the load in kip on one signle axle,
L_2 = axle code, 1,2,..

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Determining Vehicle Factors

- Average damaging effect of vehicle
- Consider axle weight distribution for particular vehicle type

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Example – Truck Equivalency Factor

Axle Load, kips	LEF		Number of Axles		A18 Kip EAL's
Singles					
3-5	0.002	x	1	=	0.002
5-7	0.01	x	5	=	0.05
7-9	0.034	x	15	=	0.51
9-11	0.088	x	57	=	5.016
11-13	0.189	x	63	=	11.907
13-15	0.36	x	17	=	6.12
23-25	3.03	x	3	=	9.09
Tandems					
27-29	0.495	x	50	=	24.75
29-31	0.658	x	72	=	47.376
31-33	0.857	x	85	=	72.845
33-35	1.09	x	120	=	130.8
35-37	1.38	x	25	=	34.5
			Total A18s	=	342.966
ESAL Vehicle Factor=	Total A18s / # of Trucks	=	342.966 / 165	=	2.078

ESALs/Vehicle

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Predicting Future Traffic

- How fast will traffic grow?
- What is the design level of traffic?
- Examine historical trends
  - Develop best estimate of future growth rate
- Apply growth factor to current volume

$$Growth\ Factor = \frac{(1+g)^n - 1}{g}$$

- Assumptions
  - There is steady growth in traffic volumes
  - All other distributions remains relatively constant over the design period

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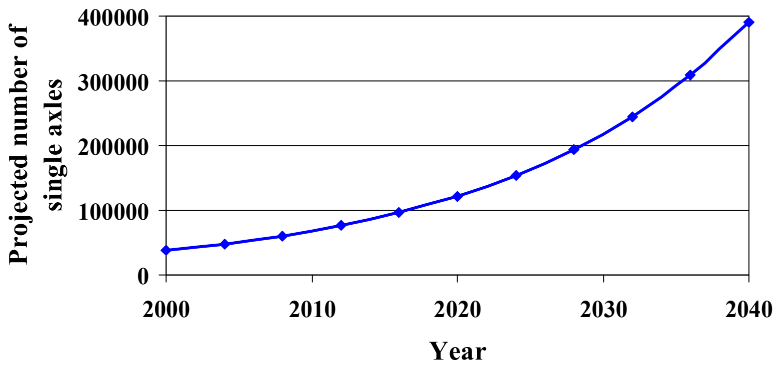
Example of Single Axle Growth



Lane and Directional Distributions

- Typically design for 'heaviest' loaded lane
- Develop best information regarding lane distribution

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Lane and Directional Distributions

- Typical Assumptions
  - Directional distribution = 50%
  - Lane Distribution

# Lanes/Direction	%Traffic In Design Lane
1	100
2	80-100
3	60-80
4	50-75

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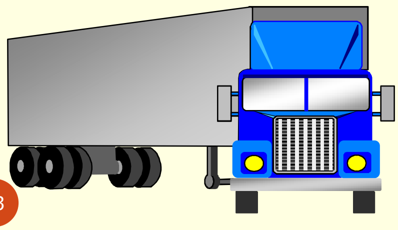
Example of Lane Distribution

ADT 20,000	ADT 60,000
75% trucks →	53% trucks →
25% trucks →	39% trucks →
	8% trucks →



Design for worst case!!

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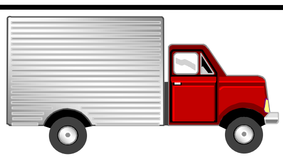
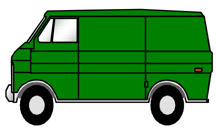
Example of Directional Distribution

Percentage of trucks traffic traveling in one direction



53% →

← 47%



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Total Design Life ESAL

- The design life or performance period is the cumulative expected 18-kip ESAL

$$ESAL = \left(\sum_{i=1}^{m} p_i F_i \right) (ADT)_0 (T)(A)(G)(D)(L)(365)(Y)$$

p_i = percentage of total repetitions for the ith group
F_i = EALF for the ith load group
$(ADT)_0$ = average daily traffic at the start of the design period
T = percentage of trucks in the ADT
A = average number of axles per truck
G = growth factor
D = directional distribution factor
L = lane distribution factor
Y = design period in years

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Load Spectra

- Deal with load variability directly
  - Load configurations
  - Tire pressures
  - Axle spacing
- Use mechanistic analysis to predict state of stress beneath each load
  – Empirically relate stresses to performance

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Sources of Traffic Data

- Traffic Data Monitoring Systems
  - Automatic traffic recorders (ATR)
  - Automatic vehicle classification (AVC)
    - Determine configuration of vehicle and divide vehicles into different classes
  - Weigh-in-motion (WIM)
    - Axle weights/counts and vehicle classification

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Materials

- Asphalt Materials
- PCC Materials
- Cementitiously Stabilized Materials
- Non-stabilized granular base/subbase
- Subgrade soils
- Bedrock

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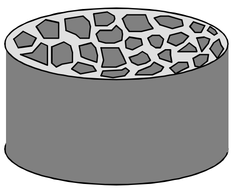
Asphalt Materials

- Resilient Modulus
- Dynamic Modulus
- Fatigue Characteristics
- Permanent Deformation

Asphalt Modulus



- Function of
  - Temperature
  - Rate of loading
  - Age
  - Volumetric properties
- Use of time-temperature superposition to determine "master curve"
- As the temperature increases, the modulus decreases
- As loading time increases, the modulus decreases
- As HMA ages with time, the modulus increases

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Asphalt Modulus

- Resilient Modulus
  - Compression
  - Indirect Tension
- Dynamic Modulus
  - Measured-Compression
  - Calculated from regression equation

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Resilient Modulus

$$M_r = \frac{\sigma_D}{\varepsilon_r}$$

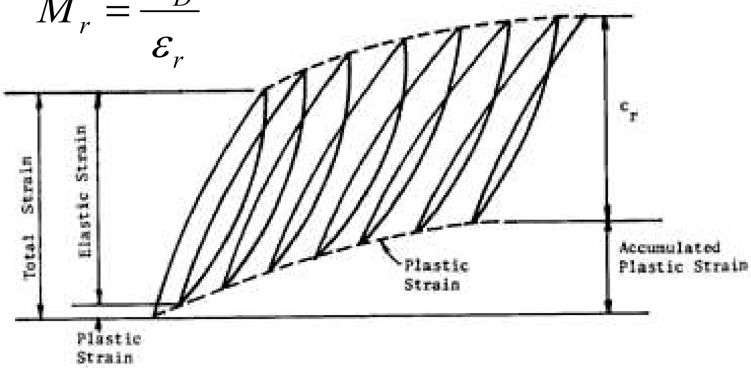

Figure 7.1 Strains under repeated loads.

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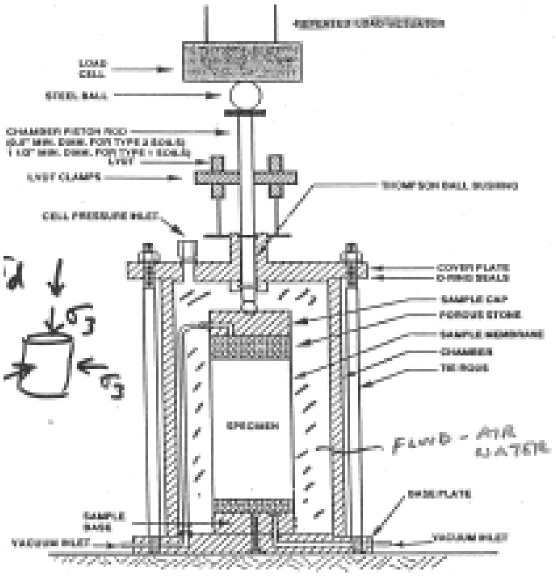
Compression Test for Mr



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Test Condition

- Sample size: 4in. (102mm) in diameter and 8in. (203mm) in height
- Sample conditioning 50-200 cycles to ensure uniform deformation
- Test at 3 temperatures: 41F, 77F, and 104F (5, 25, and 40C)
- 20psi (138kPa) haversine loading with a duration of 0.1s and a rest of 0.9s

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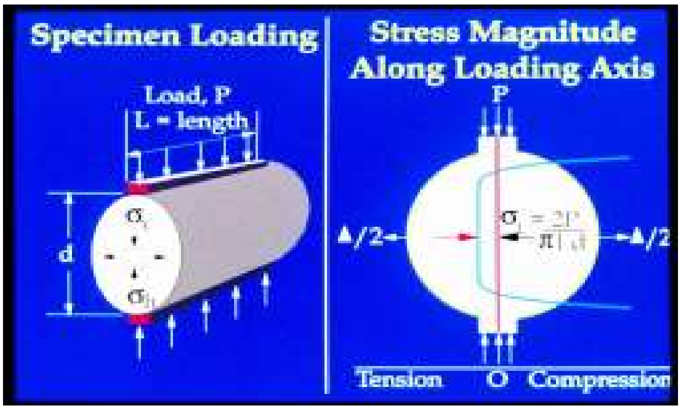
IDT Test for Mr



$$M_r = \frac{P(\nu + 0.2734)}{\delta t}$$

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Test Condition

- ASTM(1989b) D4123-82
- Sample size: 4in. (102mm) in diameter and 2.5in. (64mm) thick
- Sample conditioning 50-200 cycles to ensure uniform deformation
- Test at 3 temperatures: 41F, 77F, and 104F (5, 25, and 40C)
- P = 40 to 60lb. (180 to 270kN) with a load duration of 0.1s applied every 3s

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Dynamic Modulus E*

- Difference between MR and E*
  - MR: use any waveform with a given rest period
  - E*: use sinusoidal or haversine loading with no rest period
- E* is used to describe the stress-strain relationship of visco-elastic materials

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Dynamic Modulus Test

- ASTM (1989b) D3497-79
- Compressive haversine loading
- At temperatures of 41, 77, and 104F (5, 25, and 40C)
- At frequencies of 1, 4, and 16Hz for each temperature
- E* is the ratio between the axial stress and the recoverable axial strain

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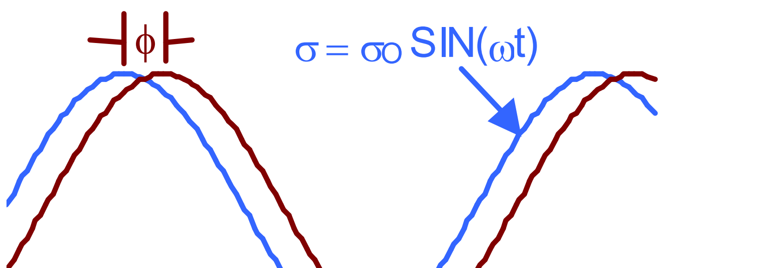
Dynamic Modulus



$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

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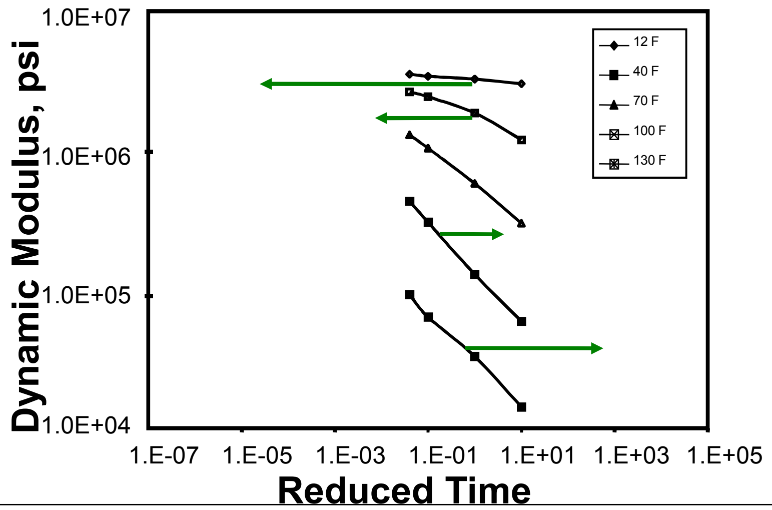
Dynamic Modulus Master Curve



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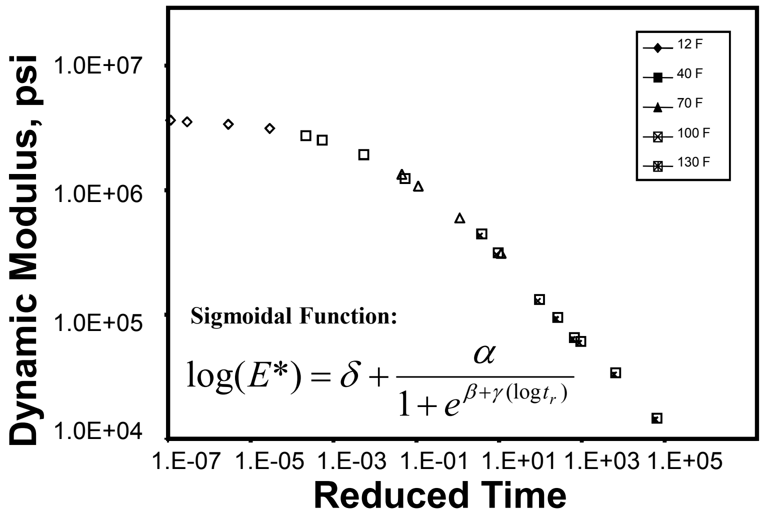
Dynamic Modulus Master Curve



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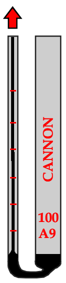
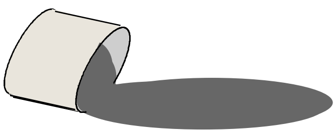
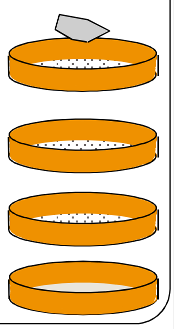
Dynamic Modulus Equation

- Function of:
  - Asphalt binder viscosity
  - Loading frequency
  - Air void content
  - Effective asphalt content
- Cumulative percent retained on
  - 19-mm
  - 9.5-mm
  - 4.76-mm
- Percent passing 0.075-mm sieve







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Fatigue Characteristics

Fatigue testing

- Four-point bending beam (third-point bending)
- Three-point bending beam (center-point bending)
- Cantilever beam
- Indirect tensile (IDT)

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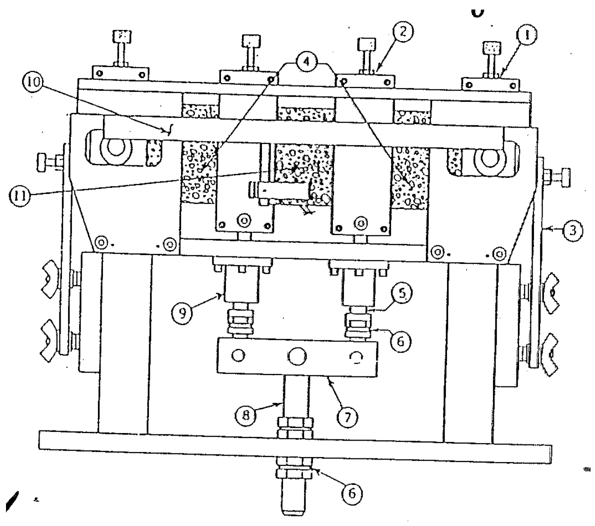
Four-Point Bending Beam Fatigue Test (AASHTO T-321)



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Testing Conditions

- Loading modes
  - Controlled stress & controlled strain
- Temperature: 20C
- Haversine wave shape @ 10Hz frequency
- Test results
  - For each cycle, report: stress, strain, flexural stiffness, phase angel, temperature, energy…
- Failure criteria:
  - Controlled stress: complete fracture
  - Controlled strain: 50% initial flexural stiffness reduction

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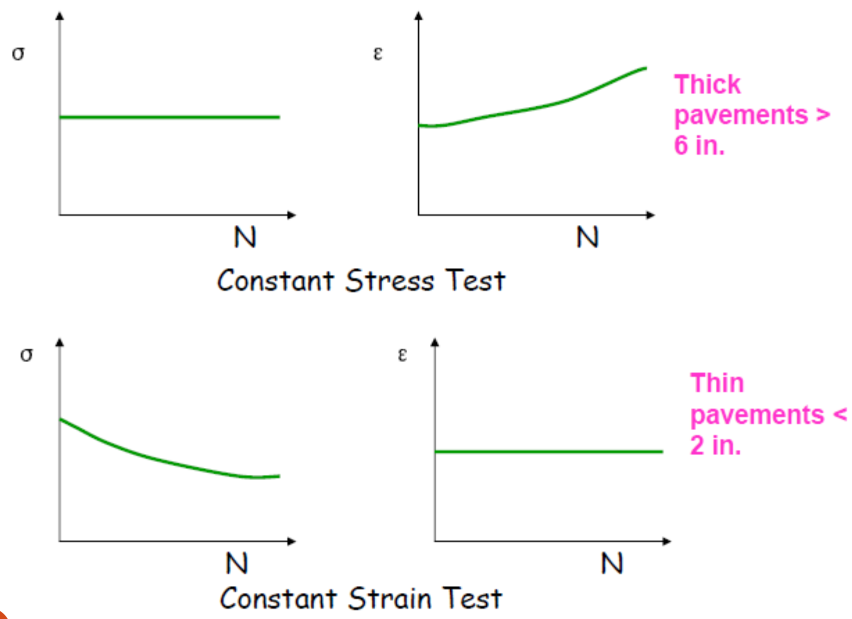

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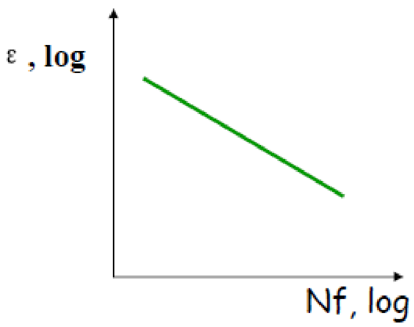
Fatigue Data Analysis



$$N_f = k_1 \varepsilon^{-k_2}$$

$$N_f = k_1 E^{-k_3}$$

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Permanent Deformation

- Asphalt rutting
- Granular material rutting
- Subgrade rutting

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Testing Method

- Repeated load test
  - Similar as resilient modulus test except that loads up to 100,000 repetitions
  - Record the deformation at a number of designated cycles

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Rutting Models

Two categories

1. Subgrade strain model: Control subgrade rutting by limiting subgrade compressive strain on top of subgrade
2. Permanent deformation model: Account for the permanent deformation properties for each layer in determining the total deformation occurs at the pavement surface

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1. Subgrade strain model

control subgrade rutting

$$Nf = f_4(\varepsilon_v)^{-f_5}$$

Organization	f_4	f_5	Allowable Rut Depth, mm (in)
Asphalt Institute	1.365×10^{-9}	4.477	13 (0.5)
Shell (revised 1985) 50% Reliability 85% Reliability 95% Reliability	 6.15×10^{-7} 1.94×10^{-7} 1.05×10^{-7}	 4.0 4.0 4.0	13 (0.5)
U.K. Transport and Road Research Laboratory — (85% Reliability)	6.18×10^{-8}	3.95	10 (0.4)
Belgian Road Research Center	3.05×10^{-9}	4.35	10 (0.4)

(after Huang 1993)

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2. Permanent Deformation Model

control permanent deformation in AC layers

$$\log(\varepsilon_p) = a + b(\log N)$$

$$\varepsilon_p = AN^b$$

Where :
ε_p = permanent strain
N = number of repeated loas repititions
A, a, b = regression coefficient

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Resilient Modulus of Unbound Materials and Soils

Resilient Modulus – Unbound Materials & Soils

- Nonlinear, elastic-plastic material
- Stress dependent behavior
  - Stress softening (fine-grained soils)
  - Stress hardening (coarse-grained materials)
- Resilient (= Recoverable) deformation
- Rapidly applied loads
  - Similar to those from wheel loads
- Relates to elastic component of response only

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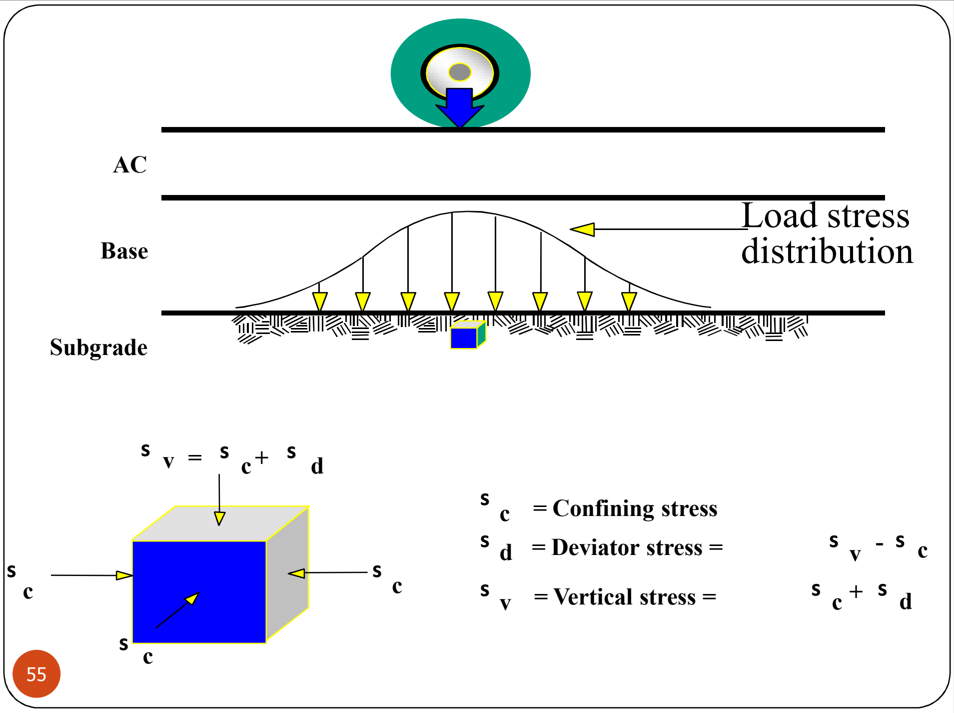

Determining Resilient Modulus

- Lab Test: AASHTO T 294-92 (SHRP)
  - Undisturbed
  - Disturbed, remolded and compacted
  - Input to AASHTO design procedure
- Estimate from various procedures
  - Backcalculation of deflections
  - Soil properties
  - Unconfined compressive strength
  - CBR

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Resilient Modulus – Unbound Materials & Soils

- Typical load pulse
  - Haversine loading
  - 0.1 second loading time
  - 0.9 second rest period

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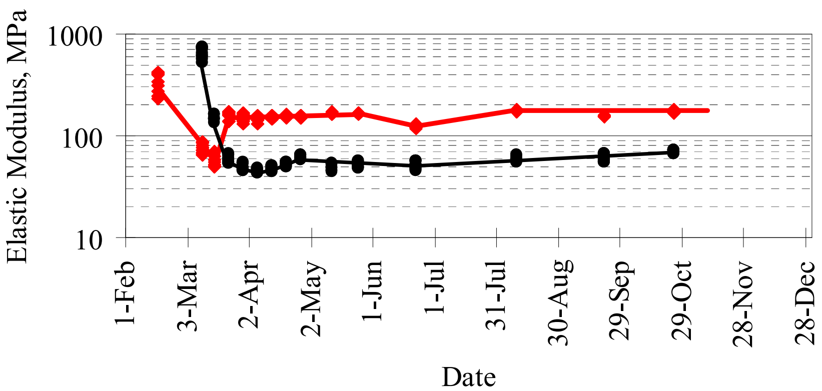
Seasonal Effects on Unbound Layers



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PCC Materials

- Modulus of Rupture or Flexural Strength
- Split Tensile Strength
- Compressive Strength
- Elastic Modulus
- Interrelationships

Modulus of Rupture

- Indicator of tensile strength
- Profound effect on fatigue cracking potential of PCC slab
- Test method ASTM C78
  - Simple beam
  - Third point loading

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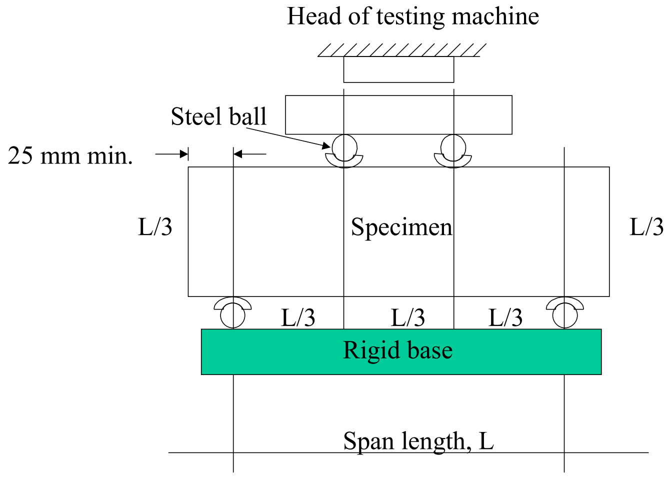
Modulus of Rupture— Third Point Loading



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Factors Affecting PCC Flexural Strength

- Mix constituents
  - Cement type, cement content, aggregates
- Presence and type of admixtures
- w/c ratio
- Curing conditions
- Age
- Test method and equipment

} Maturity (Curing conditions, Age)

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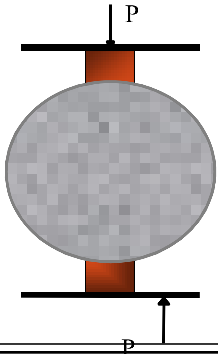
Splitting Tensile Strength

- Lower than M_R from modulus of rupture test
- Ratio between two typically ranges from 0.6 to 0.7
- ASTM C496



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Compressive Strength

- Universal indicator of PCC quality
- Used in process control, but not as primary input in pavement design
- Function of :
  - Aggregate size, shape, and type
  - Cement composition
  - Water-cement ratio
  - Admixtures
  - Curing

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Elastic Modulus

- Static modulus of elasticity
- Static modulus approximately 0.8 of modulus from rapid load applications
- ASTM C469

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Factors Affecting PCC Elastic Modulus

- The relative proportions of paste and aggregate
- Ratio of water to cementitious materials (w/(c+p))
- Aggregate characteristics

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Relation of Flexural Strength to Compressive Strength for PCC

$$MR = 9.5 f_c^{0.5}$$

MR = Flexural Strength, psi (Modulus of Rupture)
f_c = Compressive Strength, psi

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Relation of Elastic Modulus to Compressive Strength for PCC

$$E = 0.043 \rho^{1.5} f_c^{0.5}$$

E = Elastic modulus, psi
f_c = Compressive Strength, psi
ρ = PCC unit weight, pci

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Other Material Properties

Other PCC Properties

- Coefficient of Thermal Expansion
- Coefficient of Drying Shrinkage (ASTM C490)

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Poisson's Ratio

- Ratio of lateral strain to axial strain
- Generally insensitive to stress and strain in response of asphalt pavement system
- Determined using static test, dynamic test, or wave propagation

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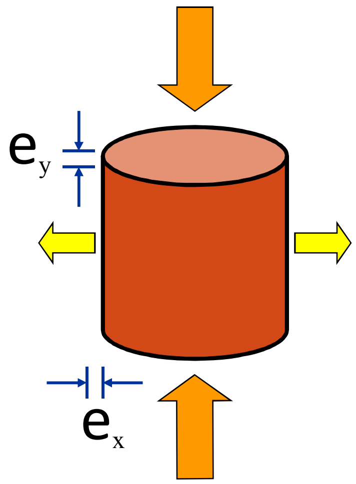
Poisson's Ratio



$$m = \frac{e_y}{e_x}$$

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Typical Poisson's Ratios

- Bituminous Road Materials
  - $0.15 \leq \mu \leq 0.50$
- Unbound Base
  - $0.30 \leq \mu \leq 0.40$
- Subgrade
  - $0.10 \leq \mu \leq 0.50$
- Portland Cement Concrete (static value)
  - $0.15 \leq \mu \leq 0.18$

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Environment/Climatic Factors

- Precipitation/Moisture
- Temperature
- Wind
- Sunshine
- Freeze-thaw cycles

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Environment / Climatic Conditions

- Environmental conditions affect
  - HMA strength and modulus
  - PCC strength and modulus
  - PCC slab curvatures
  - Frost-susceptible soil behavior
  - Pavement construction

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Moisture Effects

- Moisture-related damage falls into these categories
  - Weakening of pavement layers
  - Degradation of pavement material (stripping and erosion of AC, erosion of other materials, D-cracking of PCC)
  - Loss of bond between layers

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Effect of Temperature on Material Properties

- Freeze-Thaw effects
  - Impact on frost-susceptible soils
  - Material durability
- Temperature effect on asphalt modulus
  - High temperatures lead to lower moduli and vice versa
- Temperature gradients in PCC
  - Significantly affect stresses

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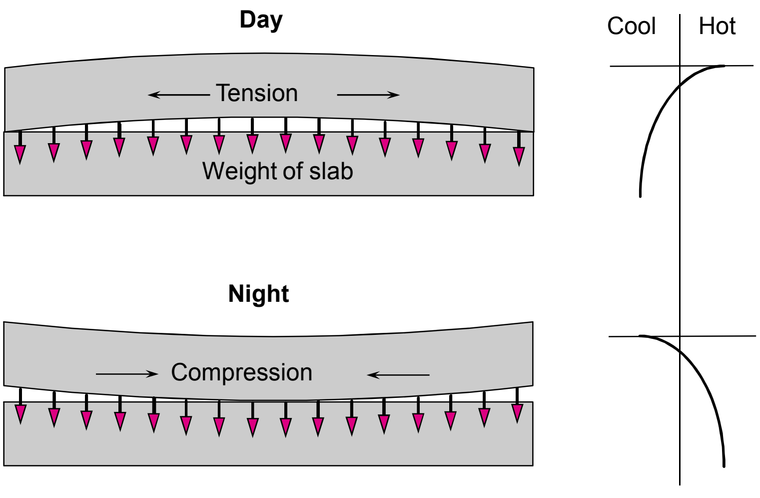
Thermal Gradients in PCC Slabs



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Failure Criteria

- Functional Failure
  - Ride Quality / Serviceability
- Structural Failure
  - Fatigue Cracking
  - Rutting

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Serviceability-Performance Assumptions

- Highways are for comfort & convenience of users
- Highways may be subjectively rated by users
- Serviceability can be expressed as mean rating by all users
- Physical distress can be related to subjective evaluation
- Performance can be expressed by serviceability history

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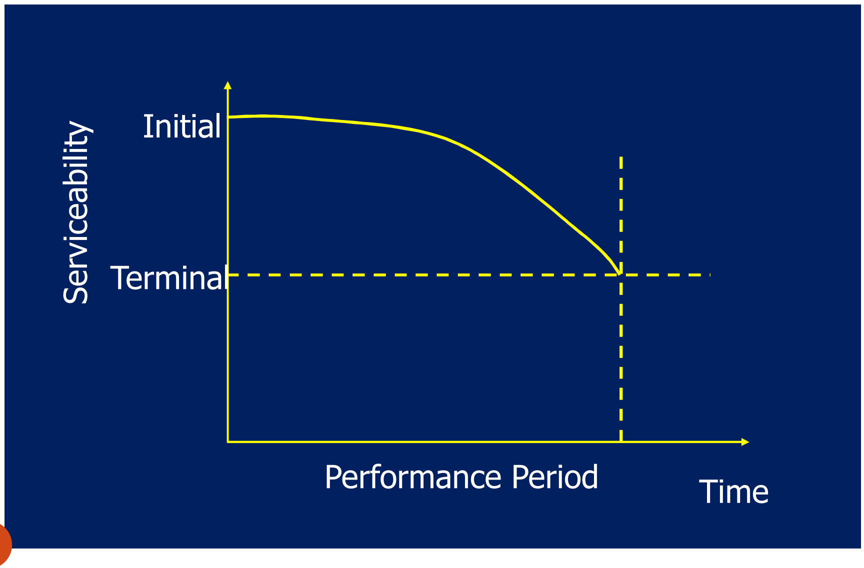
Serviceability-Performance



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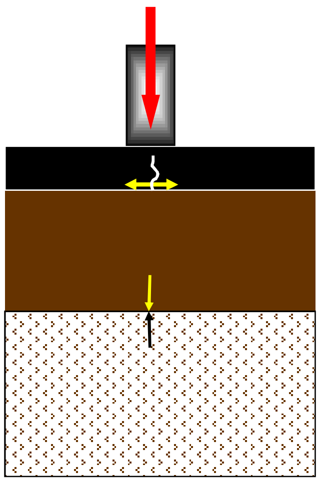
Structural Performance

- Fatigue Cracking
  - Tensile strain at bottom of HMAC
- Rutting
  - Compressive and Shear Stresses
  - May occur in ANY pavement layer
    - Typically control stresses at top of subgrade



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Flexible Pavement Distresses

- Fatigue Cracking
- Rutting
- Thermal Cracking
- Thermal Fatigue Cracking

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Structural Performance - Fatigue

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Structural Performance - Rutting



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Structural Performance – Thermal Cracking

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Rigid Pavement Distresses

- Fatigue Cracking
- Pumping or Erosion
- Faulting, Spalling, and Joint Deterioration

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Structural Performance-Joint Faulting

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Structural Performance-Spalling

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Structural Performance-Joint Deterioration

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Reliability

- Definitions
  - Reliability = 1 – P[Failure]
  - "The reliability of a pavement design-performance process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period."
    - 1993 AASHTO Guide

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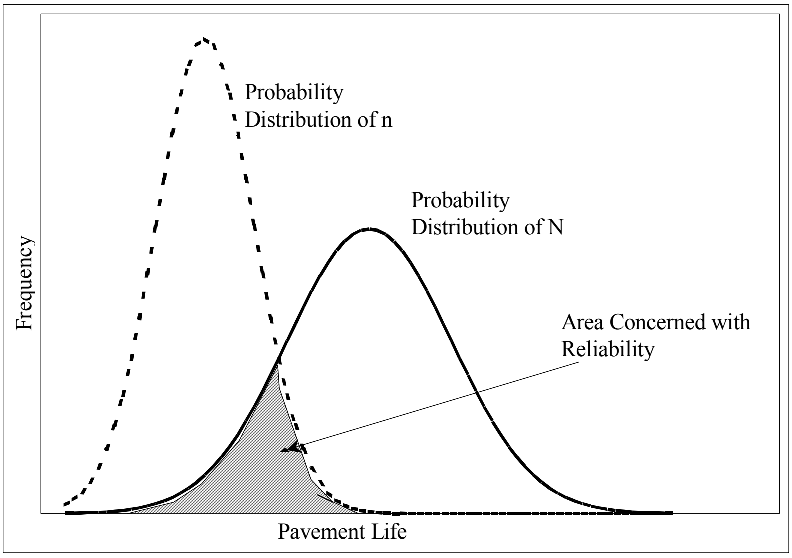
Reliability



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Summary of Design Factors

- Traffic
  - Types and variability of loads
- Materials
  - Material categories and related properties
- Environment/Climate
  - Moisture and Temperature
- Types of distress
  - Serviceability
  - Specific modes of distress
- Reliability

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