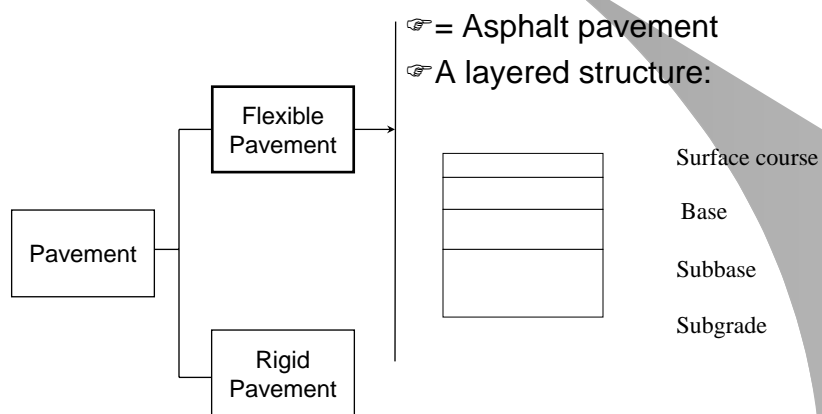


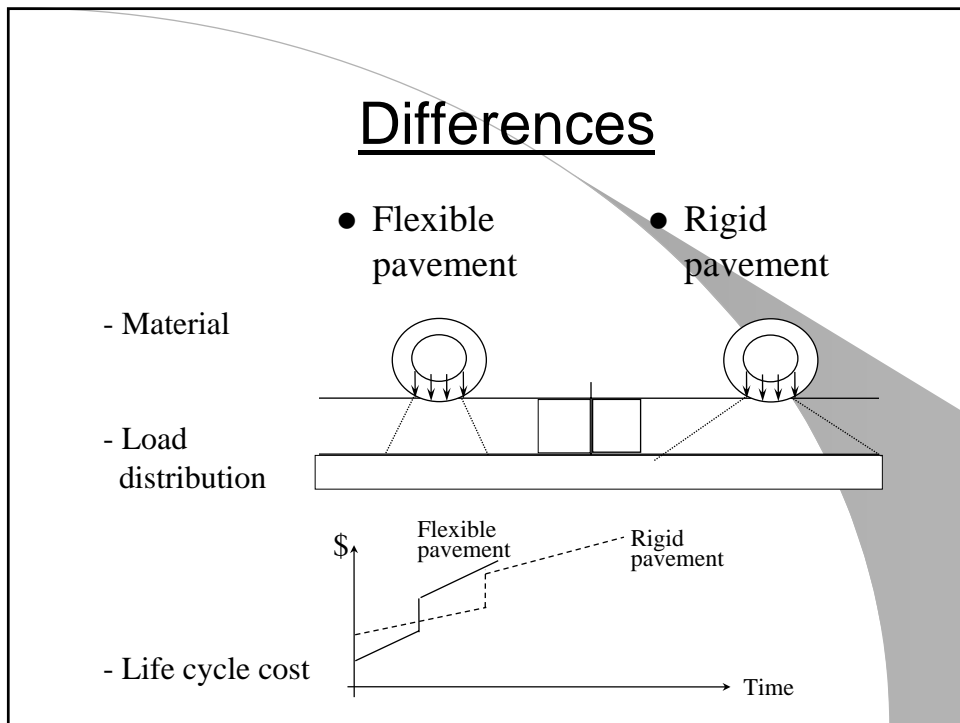
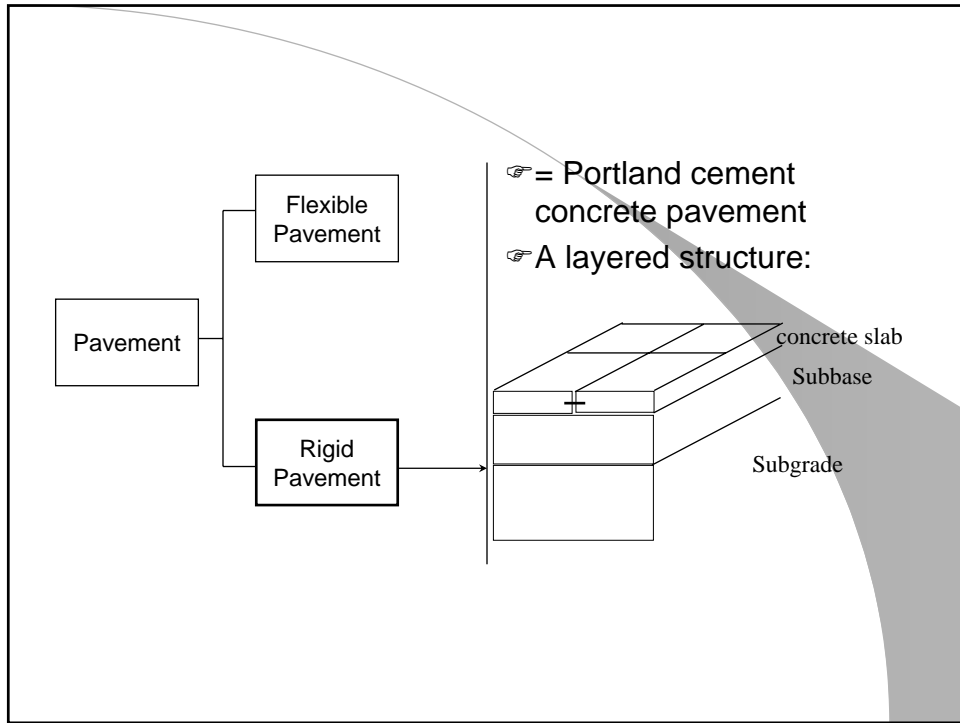
6. Pavement Design

- Introduction
- Traffic Load Analysis
- Paving Materials
- Flexible Pavement Design
- Rigid Pavement Design

6.1 Introduction

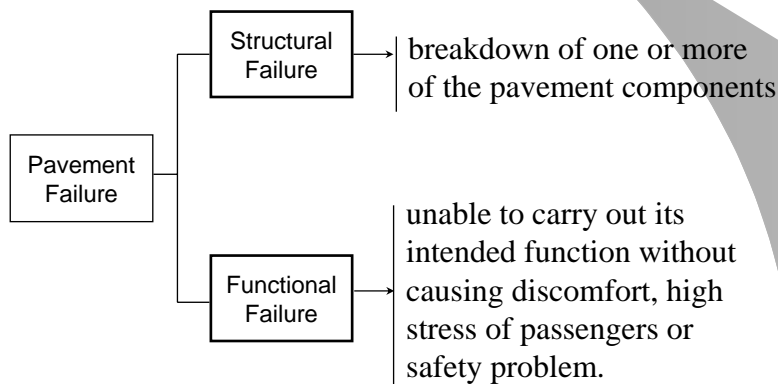
6.1.1 Pavement Types and Structural Components





6.1.2 Pavement Distress, Design Factors, Serviceability

Distress Types

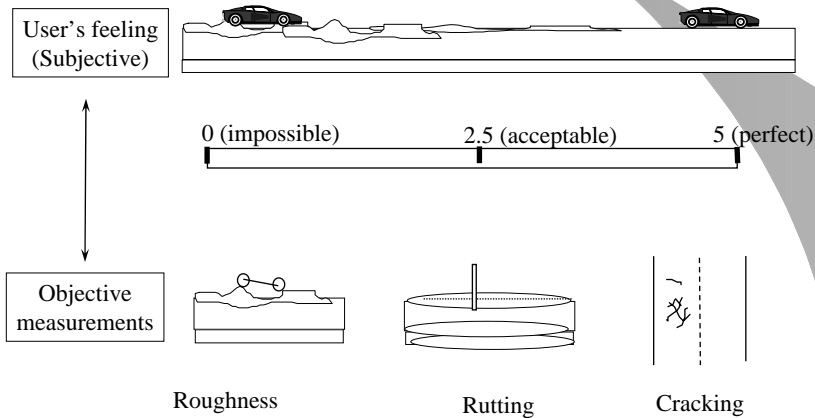


Factors Causing Distresses

- *Traffic*: Excessive load; high repetition of loads; high tire pressures
- *Climatic and environmental conditions*: Frost; volume change of soil; freezing and thawing and improper drainage
- *Material*: disintegration
- Age
- Others: construction and maintenance

Pavement Evaluation

“What is an acceptable pavement?”
“How to define the failure of pavement?”

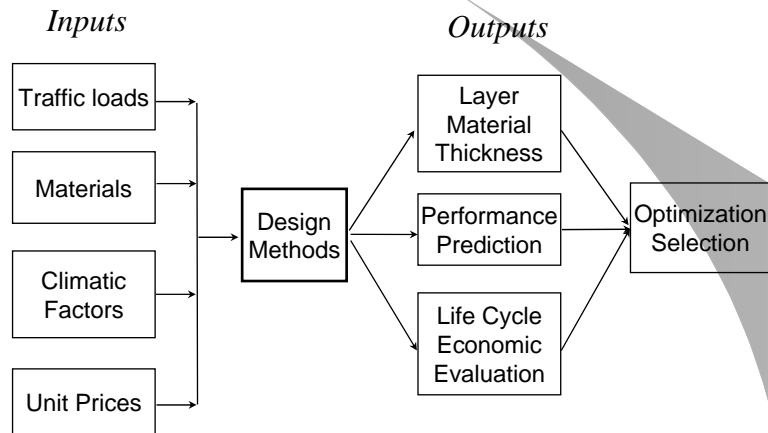


6.1.3 Design Principles

Design Tasks:

- Failure criteria?
- How long? Design Period
- Materials?
- Layers?
- Thickness?

Functional Scope of Pavement Design



6.2 Traffic Load Analysis

6.2.1 Characteristics of Traffic Loadings

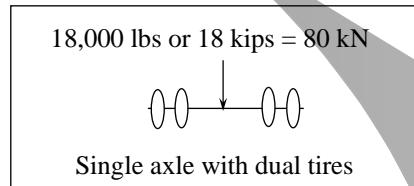
- Mixed vehicle types, axle loads and configuration, tire pressures ...
- Traffic volume variation:
 - by time
 - by direction
 - by lane?



6.2.2 Conversion of Axle Loads

- For design purpose, different vehicle (axle) loads need to be converted into axle loads of a common (standard) type

- Standard axle load:



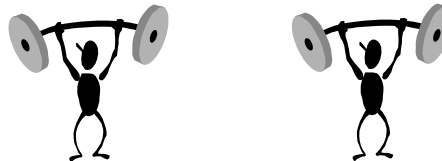
- The number of passes of any given axle load can be converted into the number of passes of the standard axle load based on the concept Load Equivalent Factor (LEF):

$$\text{LEF} = \frac{\text{damage by axle load A}}{\text{damage by a standard axle load}} \Rightarrow \text{LEF of axle load A}$$

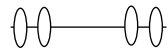
How to Determine LEF?

Factors influencing LEF:

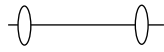
- Axle load (weight), axle and wheel configuration..
- Pavement types and pavement structure ?
- Performance criterion (how is the damage defined?):
rutting, cracking, ...



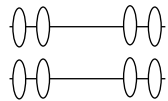
Axle and Wheel Combinations



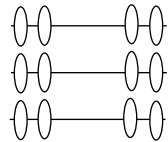
Single axle with dual tires



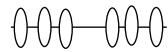
Single axle with single tire



Tandem axle with dual tires



Tridem axle with dual tires



Others ...

A Simplified Formula For LEF (AASHTO)

$$\text{LEF} = \left(\frac{\text{specific axle load}}{18,000 \text{ lbs}} \right)^4 \Rightarrow \text{Fourth Power Law}$$

Note: This simplified formula is for illustration purpose only, the actual formula is much more complicated (commonly provided in a tabular format)!

Example 6.1: What is the difference in damage to the pavement between a pass of passenger car and a pass of a pickup truck?

1000 lbs/axle



2000 lbs/axle

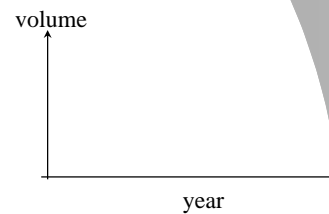


6.2.3 Equivalent Single Axle Loads (ESAL's)

- *Definition:* Summation of equivalent 18,000 lbs (or 18 kips, or 80 kN) single axle loads used to combine mixed traffic to design traffic

6.2.4 Estimation of ESAL's

- Historical traffic pattern:
 - Traffic volume by vehicle types/axle loads by types
 - Directional distribution: 50/50 split ?
 - Lane distribution (Table 4.11)
- Traffic Growth and Forecast



– Procedure:

- Determine the design period (n)
- Obtain present AADT and vehicle combinations
- Determine present ESAL's/day/direction
- Adjust it based on lane distribution
- Predict traffic growth rate -> Traffic Growth Factor (TGF)
- Calculate Design ESAL's/lane for the design period:

$$\text{Design ESAL's} = (\text{Present ESALs/day/direction/lane}) * 365 * \text{TGF}$$

Example 6.2:

Determine the design ESAL for a four-lane roadway with the following design information:

– Two directional AADT = 10,000 vehicles/day with

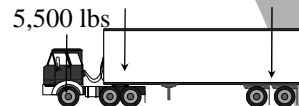
- car = 90%

1000 lbs/axle



- Truck semi-trailer = 10%

15,000 lbs/tandem

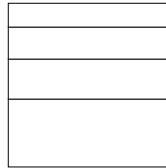


– Growth rate: 3%

– Design period: 20 years

6.3 Materials Characterization

- Why ?
- Materials and Their Characteristics?
- ...



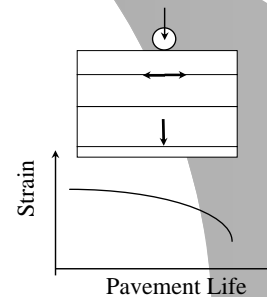
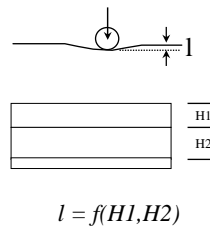
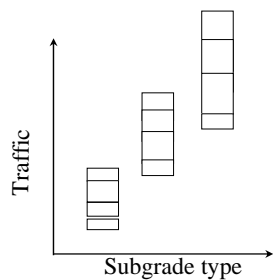
6.3.1 Test Types

- Routine Tests:
 - California Bearing Ratio Tests (CBR)
 - Plate Loading Test
 - Triaxial Test
- Layered Input Parameter Tests
 - Resilient Modulus Test
 - Wave Propagation Test
- Fundamental Distress Property Tests
 - Fatigue
 - Permanent Deformation Test

6.4 Flexible Pavement Structural Design

Types of Structural Design Methods

- Experience-based: pavement is selected based on traffic and subgrade type based on a look-up table
- Empirical-based: pavement is determined based on empirical relationship between expected pavement performance and structural parameters
- Mechanistic-Empirical: pavement is designed based on stress/strain calculation and material fatigue functions



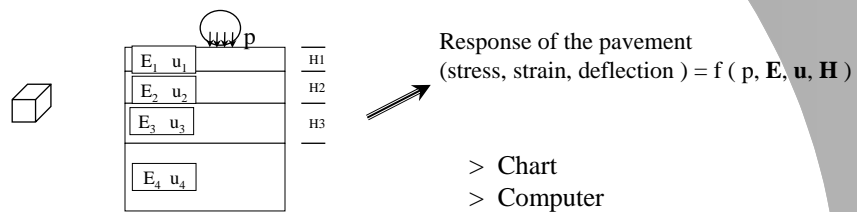
Design Methods For Flexible Pavements

- Standard Sections
- Surface Deflection Based Method
- **Asphalt Institute (AI) Method**
- **AASHTO Design Method**
- Others

6.4.1 Mechanistic-Empirical Design Method (e.g. AI Method)

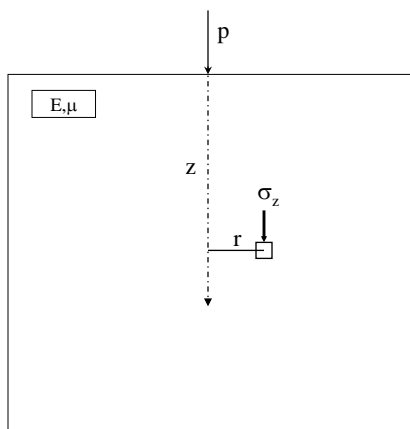
● Principles

- Consider pavement structure as multi-layered elastic system characterized by Modulus of elasticity (E) & Poisson's ratio (μ)



● A Simplified Case: Boussinesq Theory

- Stress and Strain under a point load on a single-layer system



6.4.2 AASHTO Design Method

- Background:

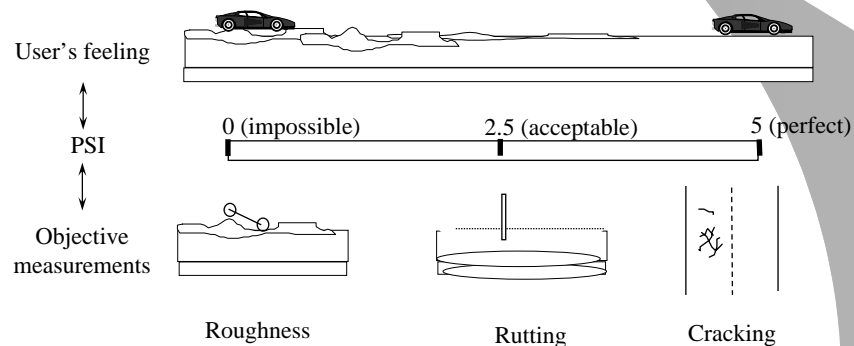
- developed based on extensive AASHO Road Test in Ottawa, Illinois, late 50's ~early 60's
- Guide was published in 1961, 1972, 1986, 1993

- Design Consideration

- pavement performance
- traffic
- roadbed soil
- materials
- environment
- drainage
- reliability
- life-cycle costs

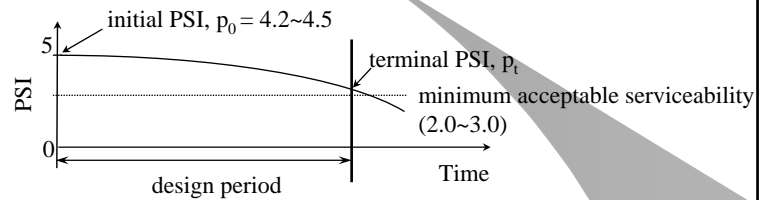
- Serviceability

- Serviceability: a subjective measure reflecting the ability of a pavement to serve the traffic (users).
- Serviceability is expressed as the present serviceability index (PSI) with value ranging from 1~5:



● Performance

- Defined as Serviceability (PSI) changing pattern over time

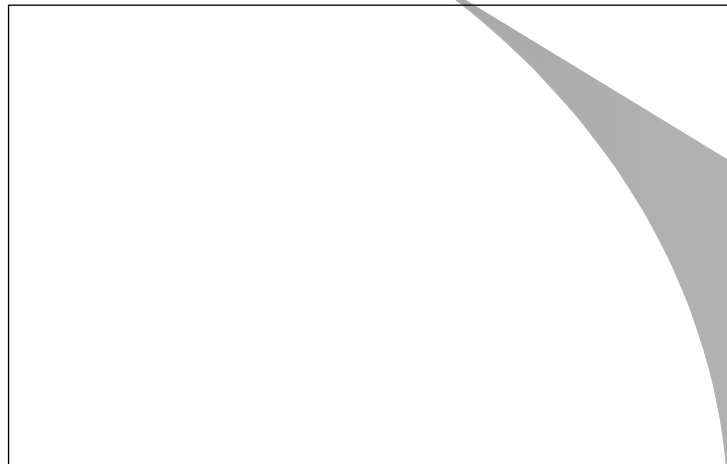


- Design philosophy:
- Factors influencing pavement performance
 - Traffic load
 - Environmental factors
 - Structure (materials + thickness)

Load test + regression \implies $PSI = f(\text{traffic}, \text{environment}, \text{structure})$

● Performance - cont.

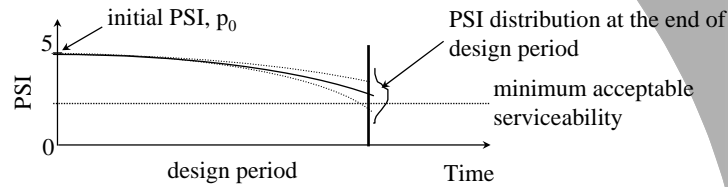
- Empirical Equation: Design Equation



– Traffic load (W_{18}): cumulative ESAL's (80-kN)

~ mixed traffic and axle loadings? ~ prediction?

– Reliability (Z_R): the probability that the serviceability will be maintained at adequate levels from a user's point of view, through the design life of the facility



Uncertain factors:
~ Traffic loading
~ Structure - materials
~ Environmental factors

Selection of Reliability:
~ Functional classifications?
~ Urban or rural

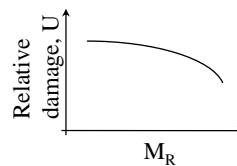
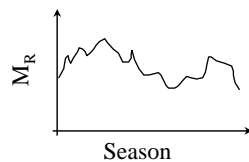
– Overall standard deviation factor (S_0): a factor representing the designer's ability to predict the variation of the traffic and performance

$$S_0 = 0.4 \sim 0.5 \text{ (flexible pavement)}$$

– Desired serviceability loss, $PSI = p_0 - p_t$

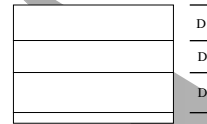
$$\text{e.g., } PSI = 4.2 - 2.5 = 1.7$$

– Effective roadbed soil Resilient Modulus (M_R): reflect the strength of the soil, an equivalent to the combined effect of all the seasonal modulus values.



– **Structure Number (SN)**: a comprehensive index representing the overall structural strength of a pavement :

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$$



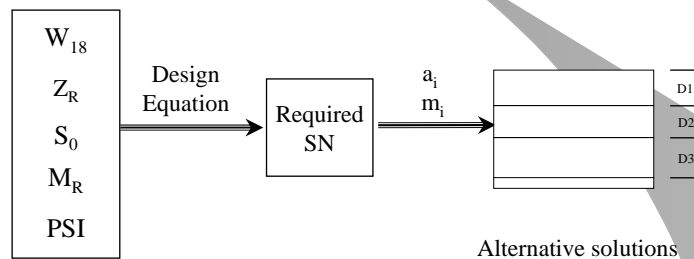
a_1, a_2, a_3 - layer coefficients for layer i (Table),
It is the AASHTO way to characterize the material properties
 $= f (CBR, E \dots)$

m_2, m_3 - drainage coefficient for layer i (Table)

D_1, D_2, D_3 - actual thickness for layer i (to be determined !!)

● Summary

– Input and Output



– Solution to the Design Equation

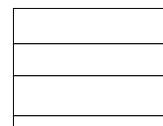
- Nomograph
- Computer (DARWin 3.0)

Example 6.3:

– Data:

- Design period: 10 years
- $p_0 = 4.2$; $p_t = 2.5$
- $M_r = 15$ ksi (103.43 Mpa)
- $R = 95\%$; $S_0 = 0.4$
- Traffic: current annual daily ESAL's = 2500, and no traffic growth is expected during the design period
- Three layer structure with

$$m_2 = m_3 = 1.0$$



D1=4 in. HMA: $a_1 = 0.40$

D2=? soil cement: $a_2 = 0.20$

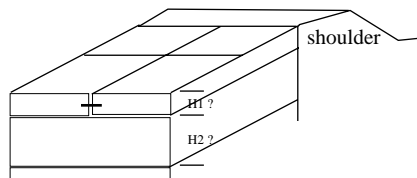
D3=? crushed stone: $a_3 = 0.10$

– Design:

- determine D2, D3?
- how many years would you estimate the designed pavement would last if you want to be 99% confident?

6.5 Rigid Pavement Design

6.5.1 Introduction



Design Tasks:

- Thickness design
- Joint design

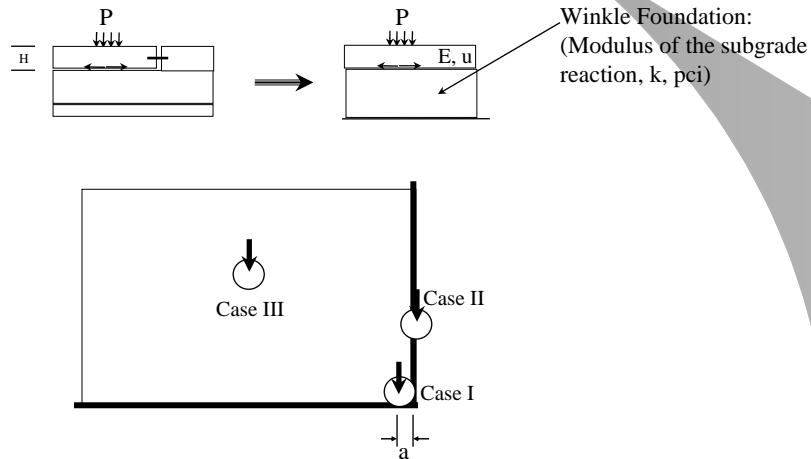
6.5.2 Design Methods:

- Portland Cement Association (PCA) - Canadian PCA: CPCA method
- **AASHTO method**

6.5.3 PCA Method

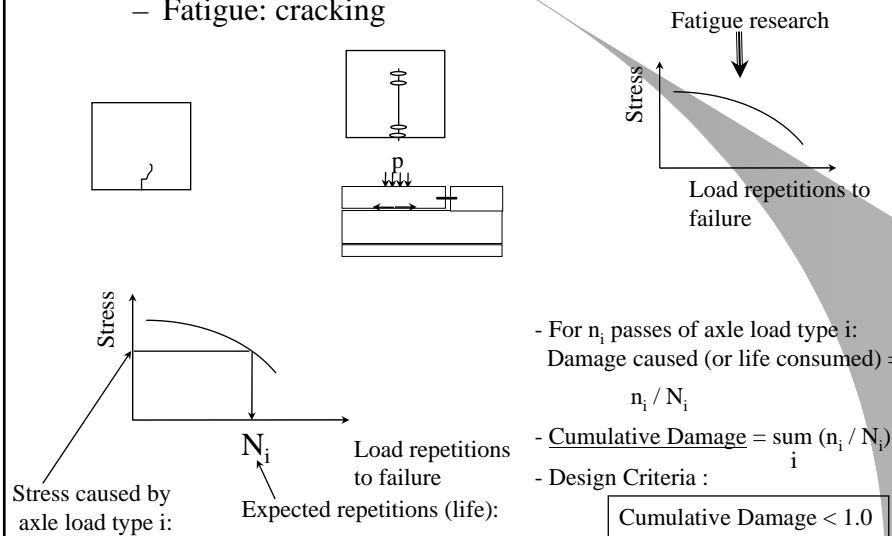
■ Stress and Deflection Caused by Axle Load

– Westergard Theory



■ Failure Patterns and Design Criteria

– Fatigue: cracking

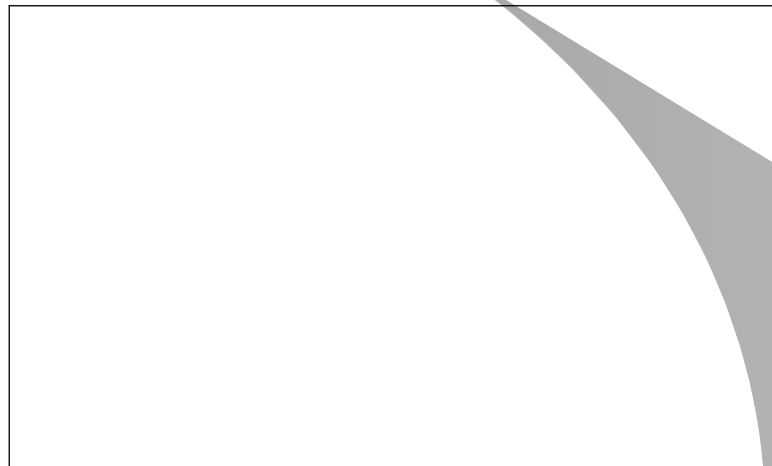


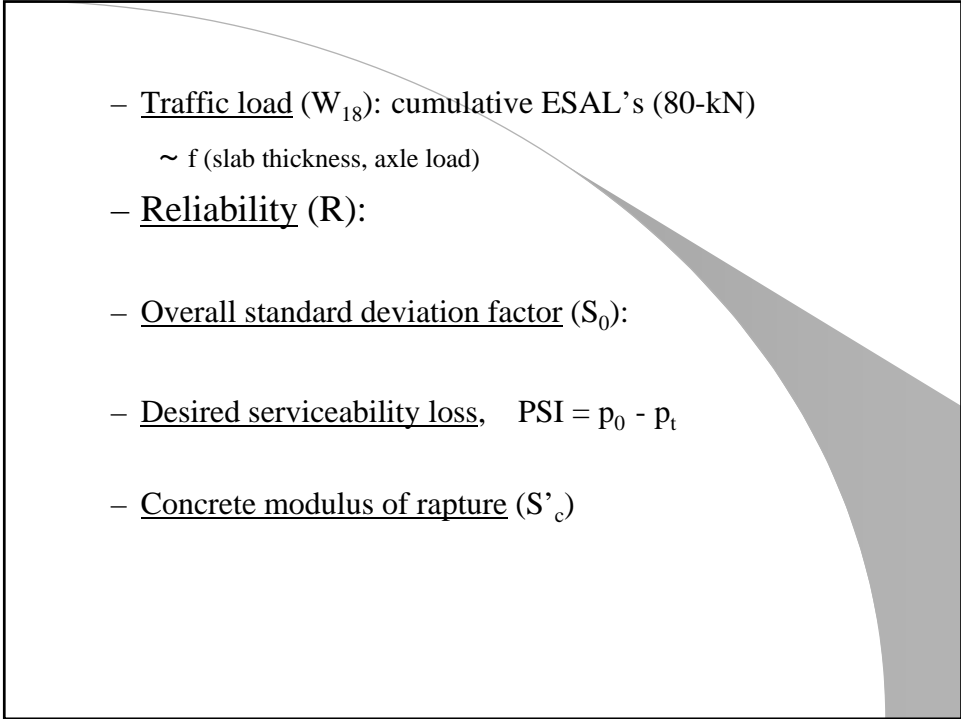
Example 6.4:

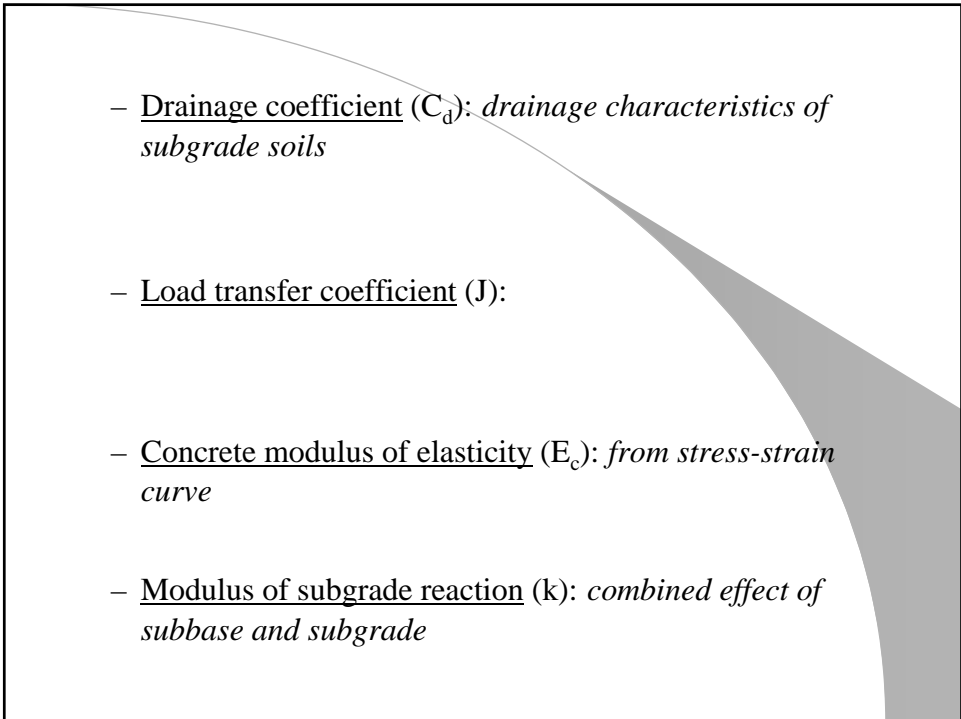
You are asked to design a rigid pavement over a crushed stone subbase with modulus of subbase-subgrade reaction of 200 pci. After considering the expected traffic loads that the pavement is expected to bear during the design period and the fatigue performance of the concrete, your design objective is simplified to control the corner deflection of the concrete slab to a maximum value of 0.055 in. under equivalent wheel load of 15,000-lb (circular area) with tire pressure of 100 psi. The concrete has a modulus of elasticity of 4.5 million psi with a Poisson ratio of 0.18. What is the minimum thickness required?

6.5.4 AASHTO Design Method:

– Design Equation

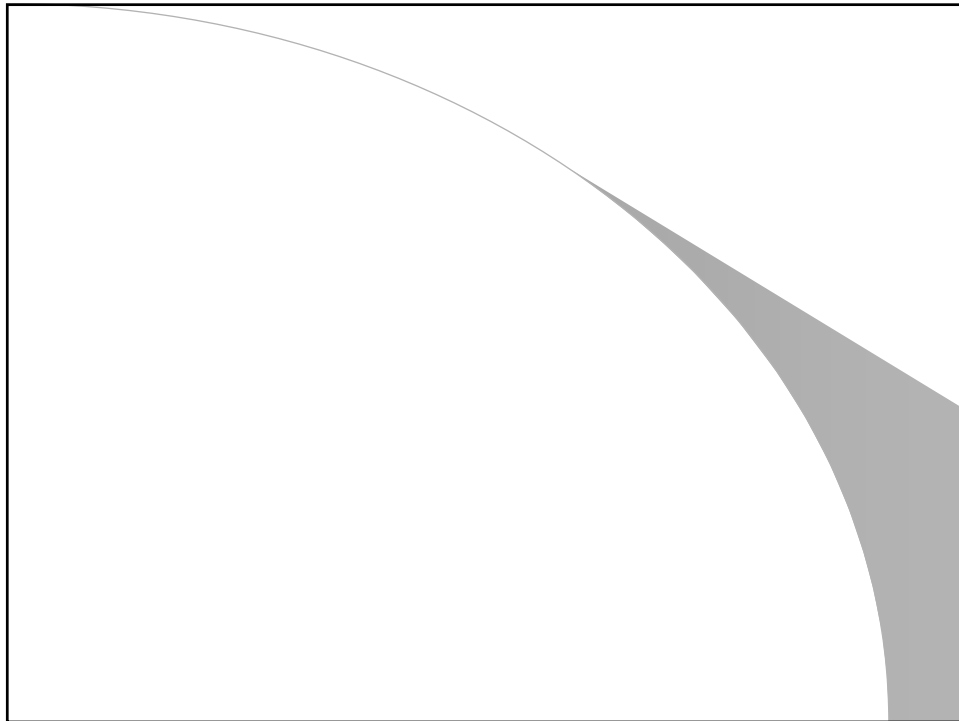


- 
- Traffic load (W_{18}): cumulative ESAL's (80-kN)
~ f (slab thickness, axle load)
 - Reliability (R):
 - Overall standard deviation factor (S_0):
 - Desired serviceability loss, $PSI = p_0 - p_t$
 - Concrete modulus of rupture (S'_c)

- 
- Drainage coefficient (C_d): *drainage characteristics of subgrade soils*
 - Load transfer coefficient (J):
 - Concrete modulus of elasticity (E_c): *from stress-strain curve*
 - Modulus of subgrade reaction (k): *combined effect of subbase and subgrade*

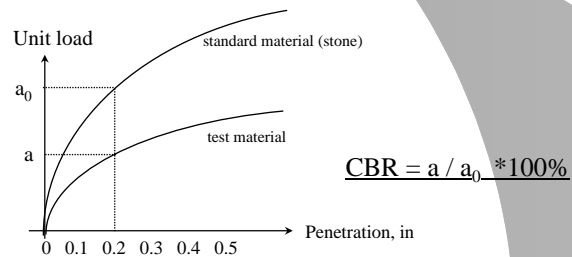
Example 6.5

An arterial highway is designed with a combination of rigid pavement and flexible pavement. Both pavements are expected to last the same number of years and to support a traffic composed entirely of trucks with volume of 150 passes per day. Each truck has one 20-kip single axle and one 40 kip tandem axle. Initial PSI and terminal PSI are assumed to be 4.5 and 2.5 respectively. A reliability of 90% and an overall standard deviation of 0.4 are applied in both designs. The rigid pavement section is designed with 8-in. concrete slab over a subbase with a modulus of subbase-subgrade reaction of 200 pci. The concrete has a modulus of elasticity of 4.5 million psi and a modulus of rupture of 900 psi. A load transfer coefficient of 3.0 is used along with a drainage coefficient of 0.8. The flexible pavement section requires a design structure number of 4.0. What is the assumed soil resilient modulus used in the flexible pavement design?



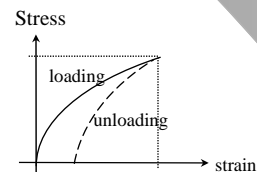
6.3.2 CBR Tests

- By the California Division of Highways in 1929
- Purpose: determine the suitability of a material for the use as a subgrade or base course material in highway construction
- Test



6.3.3 Resilient Modulus Tests

- M_r , a measure of the elastic property of a material (soil, granular ..).



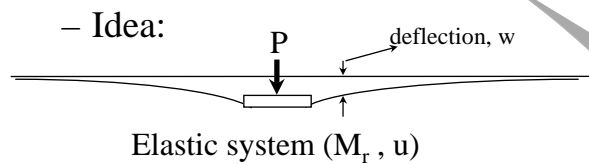
- Importance of M_r
 - used in stress-strain calculation in pavement structure

- Method 1: Laboratory Testing

- Test method: Triaxial Test
- Advantage:
 - test under controlled conditions
- Problem:
 - representiveness of samples
 - moisture condition
 - loading condition



- Method 2: In-situ Modulus Determination



Back-calculation => M_r

- Advantages:
 - More realistic;
 - can be used for evaluating existing pavement structure
- also called NDT (non-destructive test)

- Method 3: Empirical Correlation

- Idea: $M_r = f(\text{CBR})$?
- Advantages:
 - FWD may not be available
 - low cost;
 - initial evaluation and calculation (for new construction)
- Suggested relationship by AI (Asphalt Institute):

$$M_r = 10.3 \text{ CBR}$$

6.3.4 Fatigue and Permanent Deformation Tests

- **Fatigue:** the phenomena of repetitive load-induced cracking due to a repeated stress or strain level below the ultimate strength of the material
- **Fatigue Test:** repeated load flexure device with beam specimens



$$N_f = f(\text{strain or stress})$$

- **Permanent deformation:**
 - densification: volume change
 - shear deformation