AASHTO and AUSTROADS Pavement Design

Workshop & Lectures on Pavement Engineering, Maintenance and Management

References

- AASHTO Design Guide for Design of Pavement Structures, 1993
- *Pavement Analysis and Design*, Y.H. Huang, 2004
- AUSTROADS, Pavement Design: a Guide to the Structural Design of Road Pavements, 2004

Pre-Road Test Design Methods

- Pre - 1920s
- Experience and soil mechanics
- Goal: Protect the subgrade

- Result: Same pavement thickness despite changing soil conditions

Types of Design Methods

- Empirical
- Limiting Shear Failure
- Limiting Deflection
- Regression Based on Road Tests
- Mechanistic-Empirical Methods

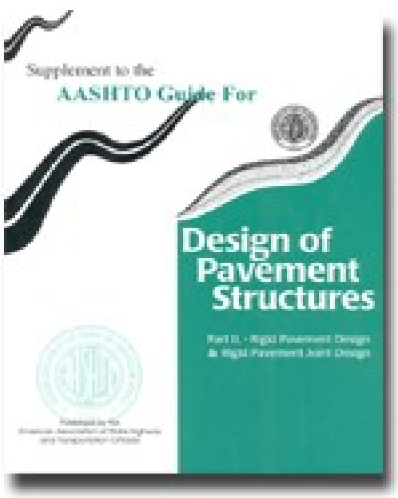
Road Test Regression Methods

- Well controlled experiment
- Use regression techniques to develop performance prediction equations
- Widely used
- Strictly limited to conditions of road test

AASHTO Flexible Pavement Design

AASHTO Design Guide

- Soil support replaced with resilient modulus
- Design reliability
- Resilient modulus to select layer coefficients
- Drainage considered
- Environmental factors such as frost heave, swelling soil
  thaw weakening
- Life cycle costing to evaluate alternatives



AASHTO Design Considerations

Expansion of the guide included:

- Incorporation of **Reliability**
- **Resilient Modulus** replacement of the Soil Support Value
- Layer Coefficients based on Resilient Modulus
- Incorporation of **Drainage**

Design Equation for AASHTO Flexible Pavements

1986 Revision (1993 equation is the same):

$$\log W_{18} = Z_R S_0 + 9.36\log(SN+1) - 0.20 + \frac{\log\left(\frac{4.2-p_t}{4.2-1.5}\right)}{0.4+\frac{1094}{(SN+1)^{5.19}}} + 2.32\log M_R - 8.07$$

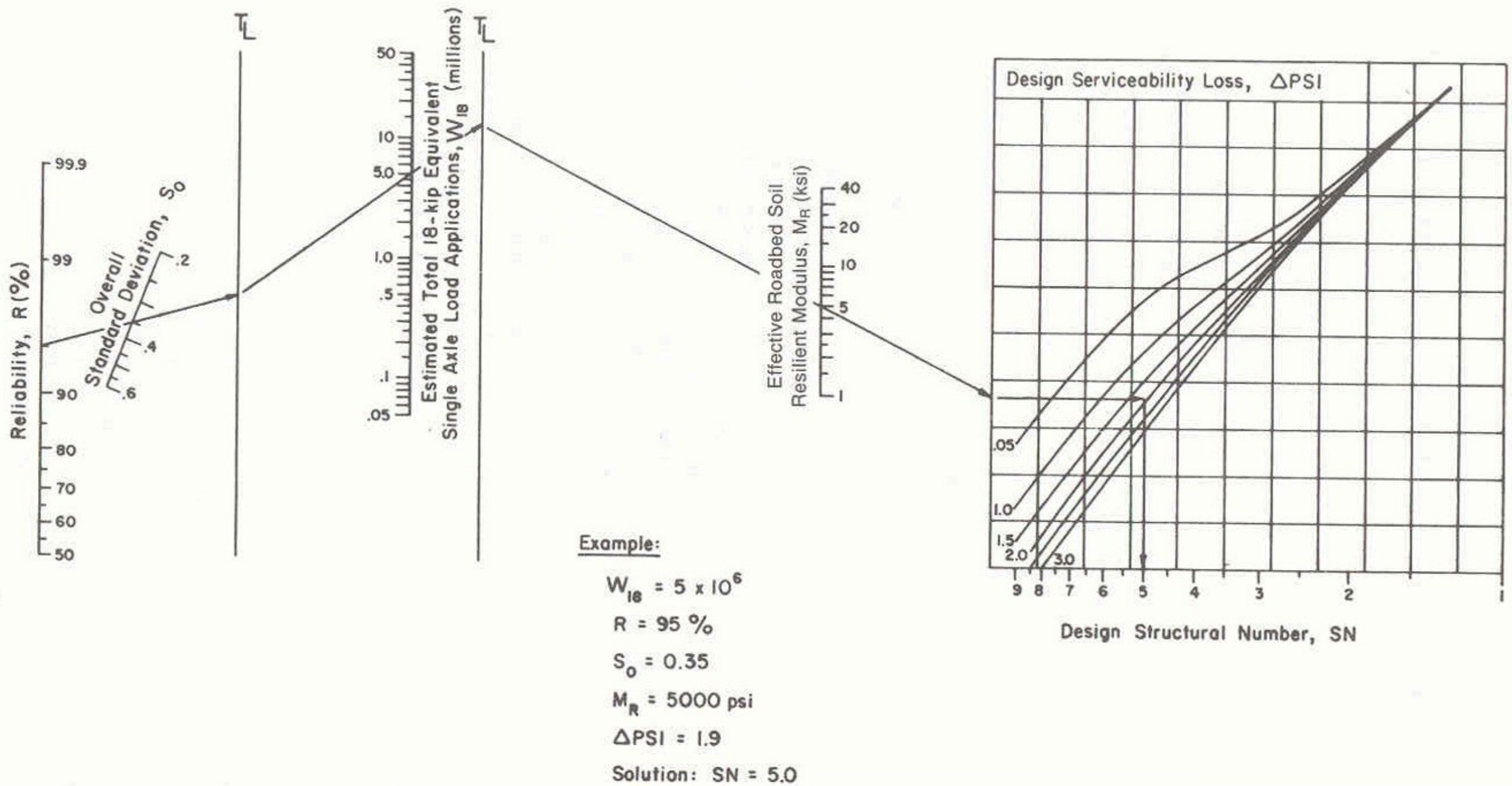
where:

W_{18}	= Total Life Flexible ESAL's
Z_R	= normal deviate for reliability R
S_0	= standard deviation
SN	= Structural Number
p_t	= Terminal Serviceability Index
M_R	= effective roadbed soil resilient modulus

AASHTO '93 Flexible Pavement Design Nomograph

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R * S_o + 9.36 * \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$



AASHTO Flexible Pavement Design Variables

- **Time** (Design Life)
- **Traffic** (Total Design Life ESAL)
- **Reliability** (“Safety Factor”)
- **Serviceability** (ΔPSI)
- **Soil Resilient Modulus** (Seasonal Variation)
- **Structural Number** (SN)

AASHTO Time (Design Life)

- **Performance Period**

  - Time to first rehab or time between rehabs

  - Use practical performance period for given pavement type

- **Analysis Period**

  - Life of pavement, including rehabilitations

TABLE 11.13 Guidelines for Length of Analysis Period

Highway conditions	Analysis period (years)
High-volume urban	30–50
High-volume rural	20–50
Low-volume paved	15–25
Low-volume aggregate surface	10–20

Source. After AASHTO (1986).

AASHTO Traffic

- Total Design Life ESAL
- The cumulative expected ESAL.

Total Design Life ESAL Calculation

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

p_i: percentage of total repetitions for the i^{th} group
F_i: EALF for the i^{th} 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

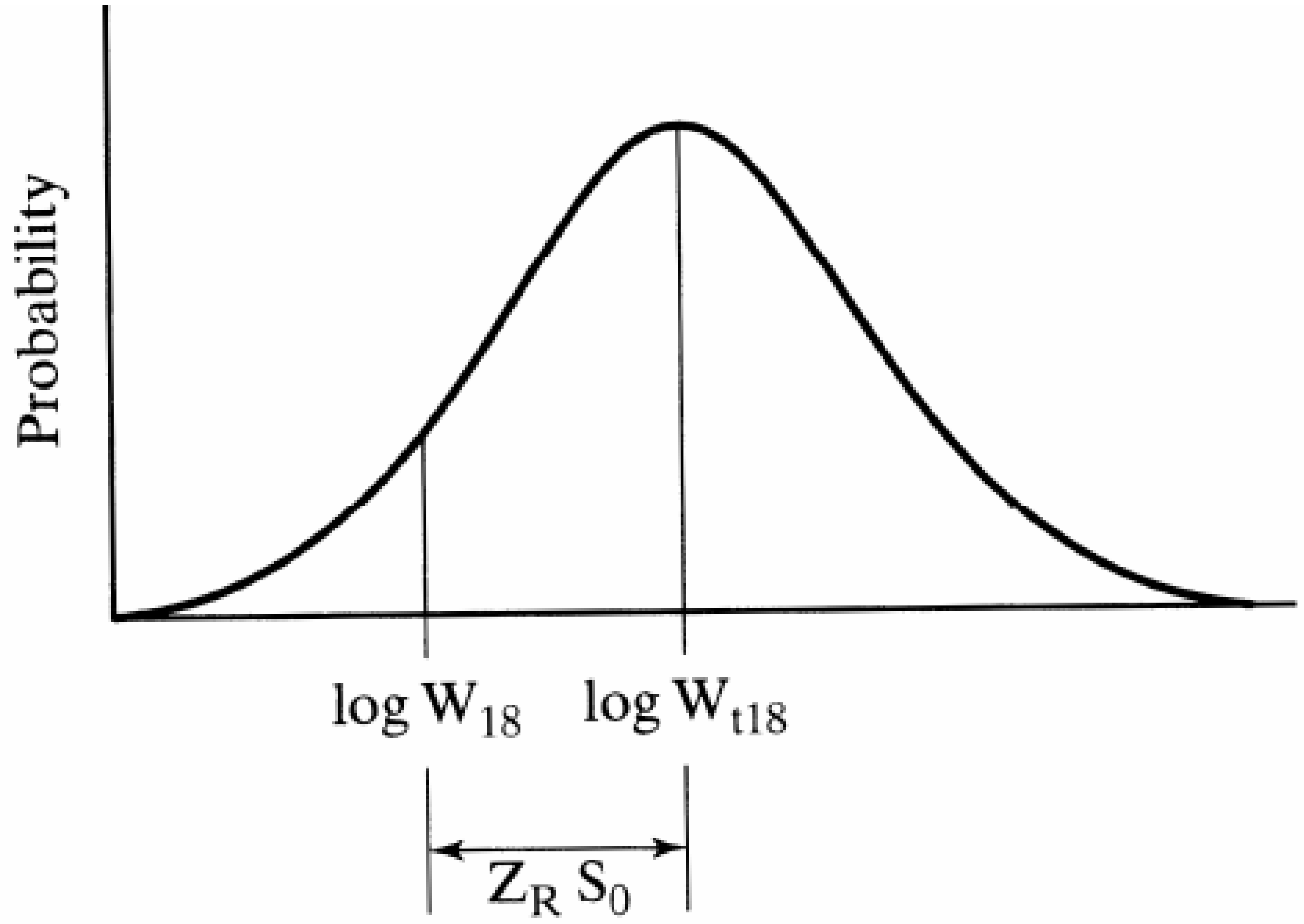
AASHTO Reliability ("Safety Factor")

- Incorporates some degree of certainty into the design process to ensure that the various design alternatives will last the analysis period.

Functional Classification	Recommended level of reliability	
	Urban	Rural
Interstate / Freeways	85-99.9	80-99.9
Principal Arterials	80-99	75-95
Collectors	80-95	75-95
Locals	50-80	50-80

Suggested Standard Deviation (S_0) = 0.45

Reliability (%)	Standard Normal Deviate(Z_R)
50	0.000
60	-0.253
70	-0.524
75	-0.674
80	-0.841
85	-1.037
90	-1.282
95	-1.645
98	-2.054
99	-2.327
99.9	-3.090
99.99	-3.750


Probability
log W18
log Wt18
ZR S0

AASHTO Serviceability (ΔPSI)

- PSI – describing physical characteristics of pavements which can be measured objectively and then related to subjective evaluations of comfort
  - ~ roughness, cracking, patching, rut depth
- $\Delta PSI = PSI_i - PSI_t$
  - PSI_i: initial serviceability (immediately after construction) ~4.2
  - PSI_t: terminal serviceability (lowest acceptable level before remedial action must be taken) dependent on roadway classification, typically 2.5 for highway
- $\Delta PSI = f(\text{traffic, environment})$

Loss of Serviceability

- The total loss of serviceability can be computed with the following equation:
  - $\Delta PSI = \Delta PSI_{TRAFFIC} + \Delta PSI_{SWELL/FROST\ HEAVE}$

where

- ΔPSI = total loss in serviceability
- $\Delta PSI_{TRAFFIC}$ = serviceability loss due to ESALs
- $\Delta PSI_{SWELL/FROST\ HEAVE}$ = serviceability loss due to swelling and/or frost heave of roadbed soil

- The effects of frost heave and swelling can be reduced by replacement or treatment of soil.

Roadbed Soil Resilient Modulus (AASHTO)

- The effective roadbed soil resilient modulus is an equivalent modulus that would result in the same damage if seasonal modulus values were actually used.

$$1.18\times10^{8} M_R^{-2.32} = \frac{1}{n}\sum_{i=1}^{n}\left(1.18\times10^{8} M_{R_i}^{-2.32}\right)$$

Relative damage u_f:

$$u_f = 1.18\times10^{8} M_R^{-2.32} = \frac{1}{n}\sum_{i=1}^{n}\left(1.18\times10^{8} M_{R_i}^{-2.32}\right) = \frac{\sum u_{f_i}}{n}$$

- Tak

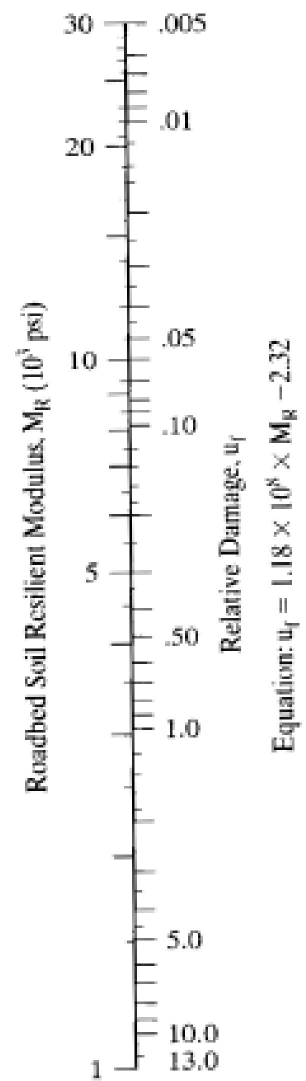
$$\overline{u_f} = \frac{\sum u_f}{n}$$

on)

Roadbed Soil Modulus (AASHTO)

Determine seasonal moduli based on correlations with soil moisture and temperature conditions, or from NDT testing

Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.	15,900	0.02
Feb.	27,300	0.01
Mar.	38,700	0.00
Apr.	50,000	0.00
May	900	16.52
June	1,620	4.22
July	2,340	1.80
Aug.	3,060	0.97
Sept.	3,780	0.59
Oct.	4,500	0.39
Nov.	4,500	0.39
Dec.	4,500	0.39
Summation: $\Sigma u_f =$		25.30

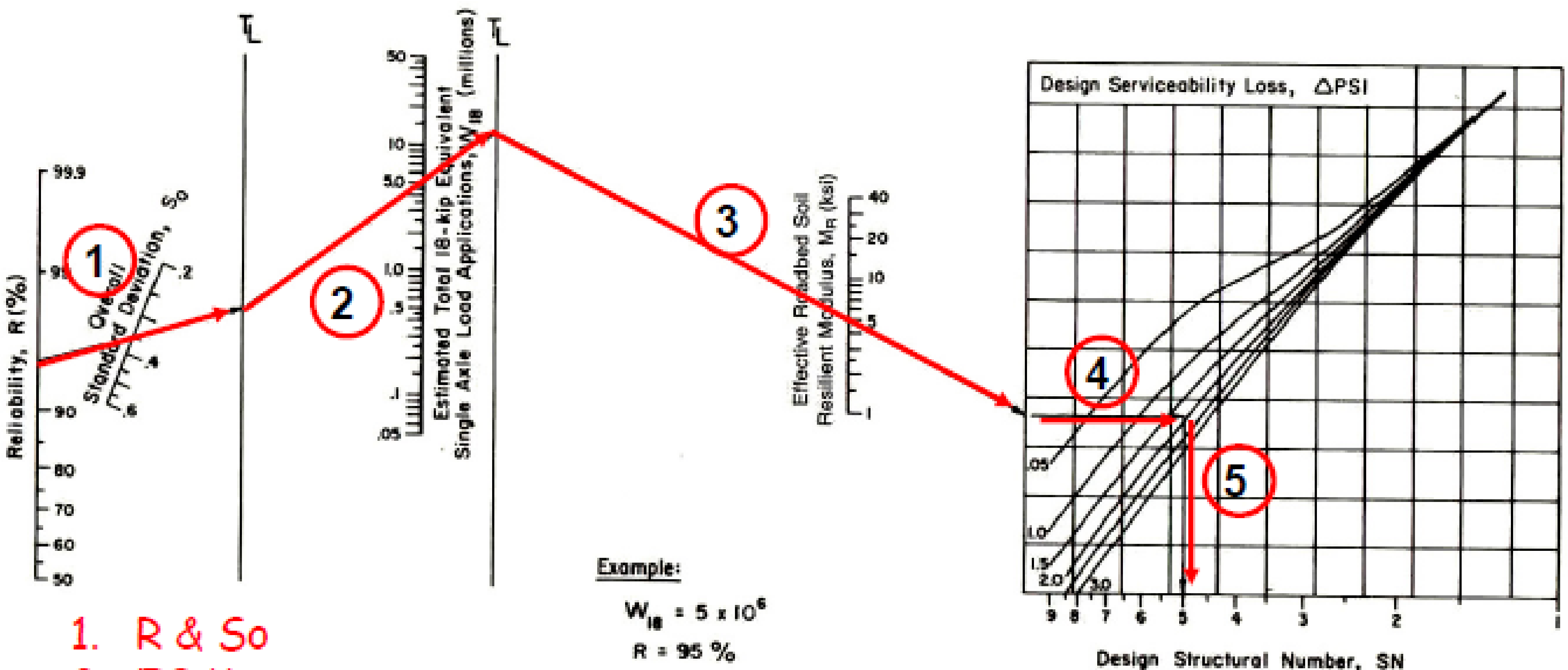


Average: $\bar{u}_f = \frac{\Sigma u_f}{n} = \underline{2.11}$

Effective Roadbed Soil Resilient Modulus, M_R (psi) = 2,200 (corresponds to $\bar{u}_f$)

AASHTO SN Nomograph

$$\log W_{18} = Z_R S_0 + 9.36\log(SN+1) - 0.20 + \frac{\log\left(\frac{4.2-p_t}{4.2-1.5}\right)}{0.4+\frac{1094}{(SN+1)^{5.19}}} + 2.32\log M_R - 8.07$$



Example:

W_{18} = 5 x 10^6

R = 95 %

S_0 = 0.35

M_R = 5000 psi

ΔPSI = 1.9

Solution: SN = 5.0

1. R & So
2. ESALs
3. M_R
4. ΔPSI
5. SN

Structural Number (SN)

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3$$

- Layer Coefficients ($\mathbf{a_i}$)
- Drainage Coefficients ($\mathbf{m_i}$)
- Minimum Layer Thicknesses ($\mathbf{D_i}$)

AASHTO Structural Number

- SN
  - "An abstract number expressing the structural strength of a pavement required for given combinations of soil support, total traffic in terms of ESALs, terminal serviceability and environment."
  - $SN = a_1D_1 + a_2m_2D_2 + \ldots + a_nm_nD_n$

Layer Coefficients (a_i)

Asphalt Concrete Surface Course:

$$a_1 = 0.44$$

Untreated and Stabilized Base Courses:

$$a_2 = 0.249(\log E_2) - 0.977$$

Granular Subbase Course:

$$a_3 = 0.227(\log E_3) - 0.839$$

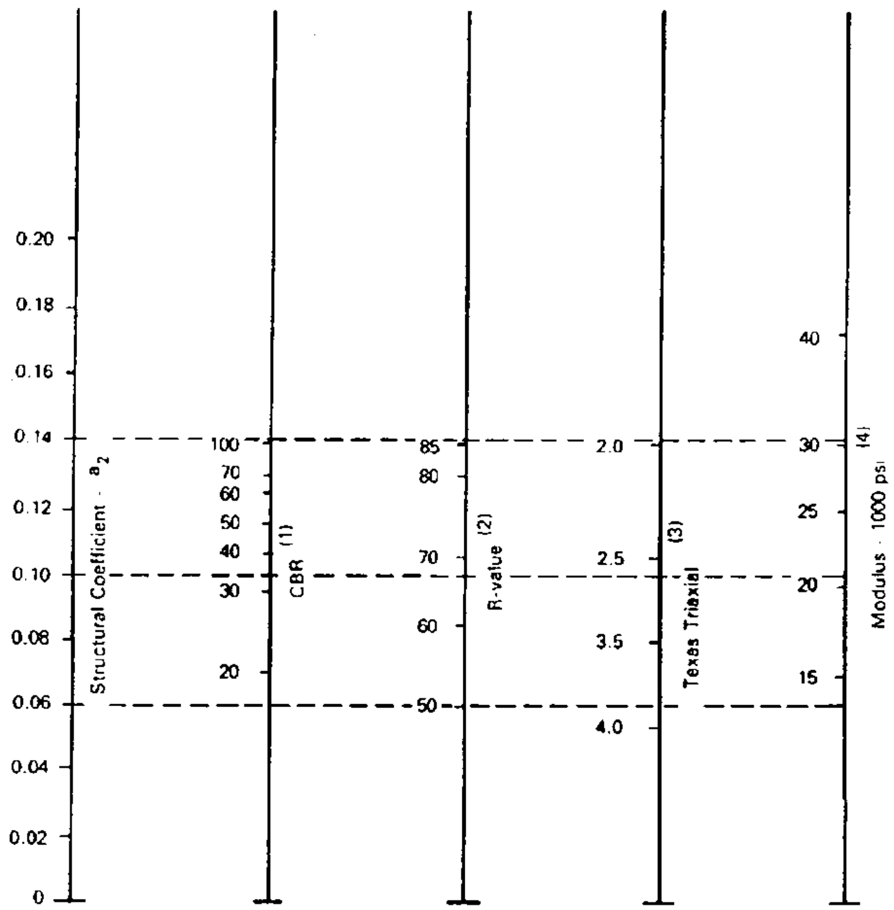
where:

$$E_i = K_1 \theta^{K}{}_2$$

Base and Subbase Modulus (AASHTO)

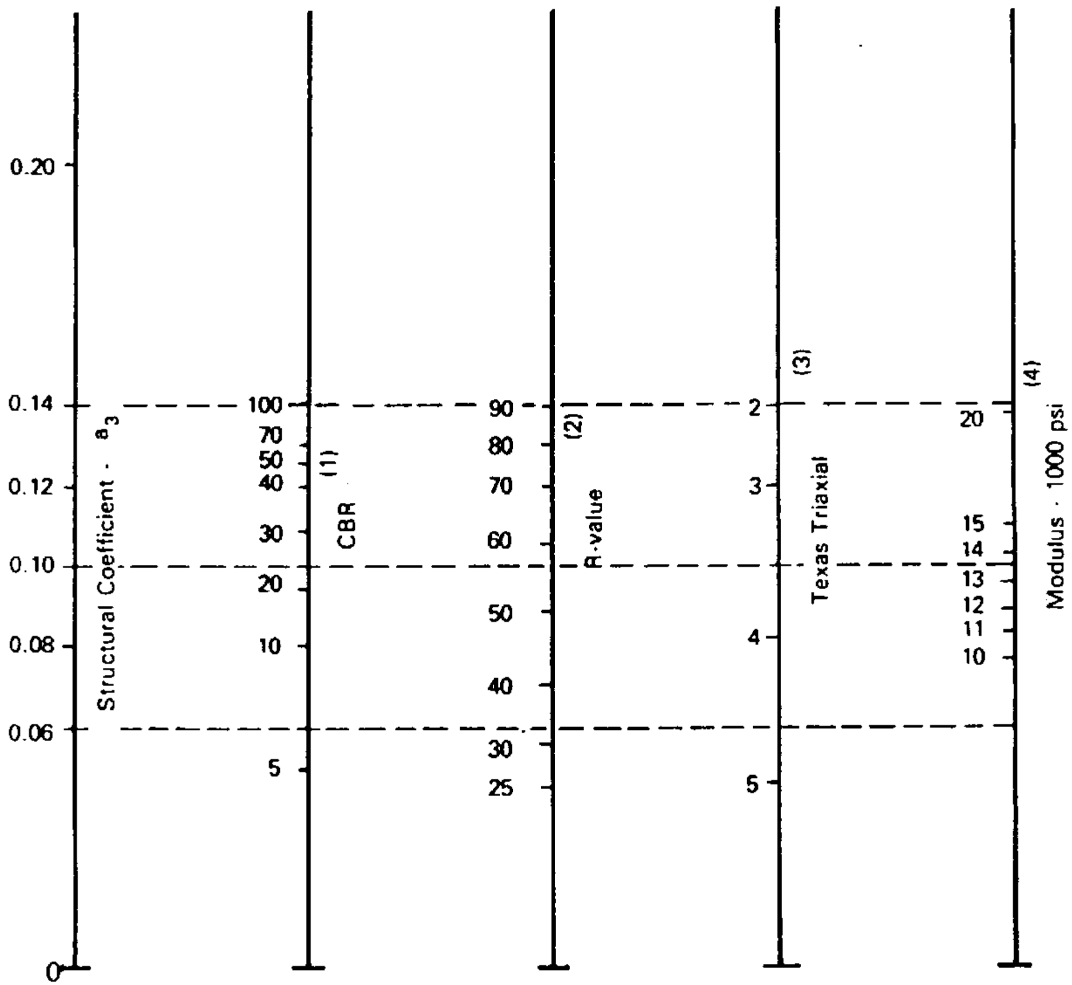
- May be determined by variety of methods
  - CBR
  - R-Value
  - Triaxial
  - Resilient Modulus
- Capture seasonal variation
- Convert to layer coefficient
  - a_i

Base Layer Coefficients (AASHTO)



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas
(4) Scale derived on NCHRP project *(3)*.

Subbase Layer Coefficients (AASHTO)



(1) Scale derived from correlations from Illinois.

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.

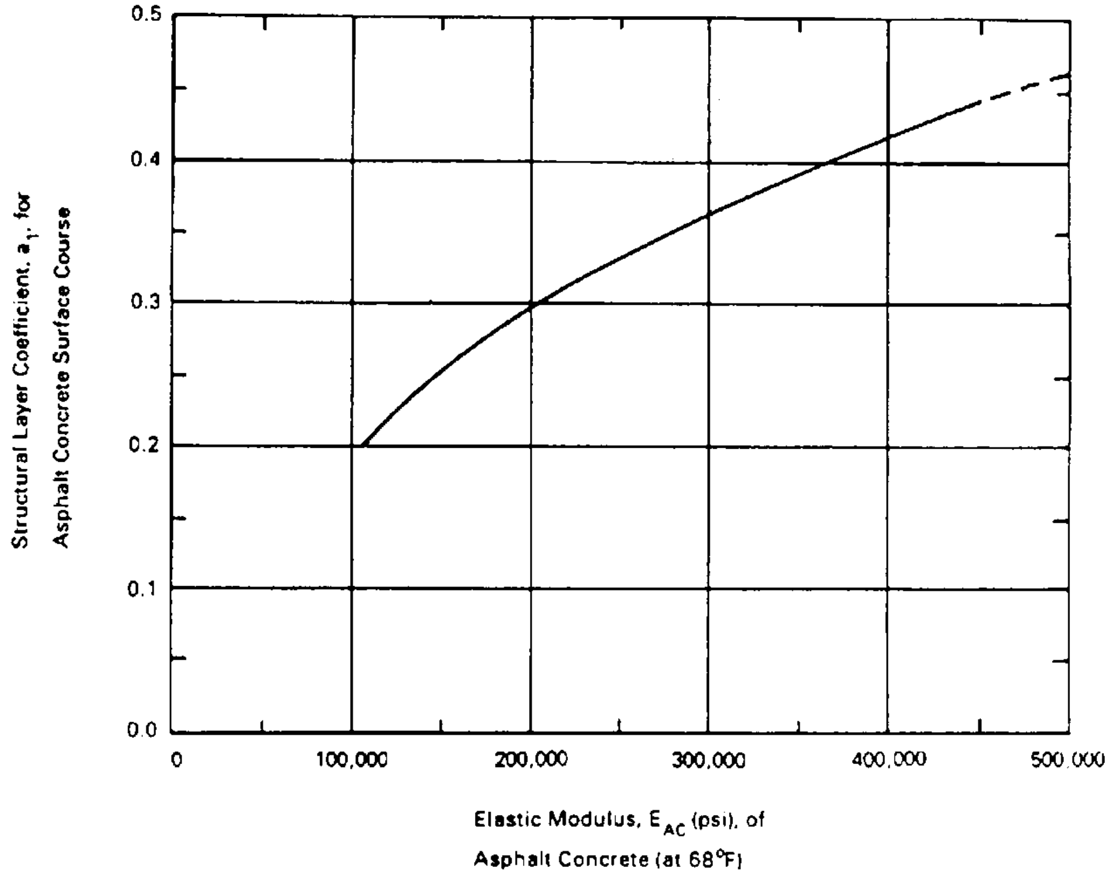
(3) Scale derived from correlations obtained from Texas.

(4) Scale derived on NCHRP project *(3)*.

Asphalt Concrete Modulus

- Function of temperature
- Account for seasonal changes
- Correlate to layer coefficient
  - a_i

Asphalt Concrete layer Coefficient (AASHTO)



AASHTO Drainage Coefficients (m_i)

- The quality of drainage is measured by the length of time for water to be removed from bases and subbases and depends primarily on their permeability.

- The percentage of time during which the pavement structure is exposed to moisture levels approaching saturation depends on the average yearly rainfall and the prevailing drainage conditions

AASHTO Drainage Coefficients (m_i)

TABLE 11.20 RECOMMENDED DRAINAGE COEFFICIENTS FOR UNTREATED BASES AND SUBBASES IN FLEXIBLE PAVEMENTS

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	2 hours	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1 day	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1 week	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1 month	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	Never drain	1.05–0.95	0.95–0.75	0.75–0.40	0.40

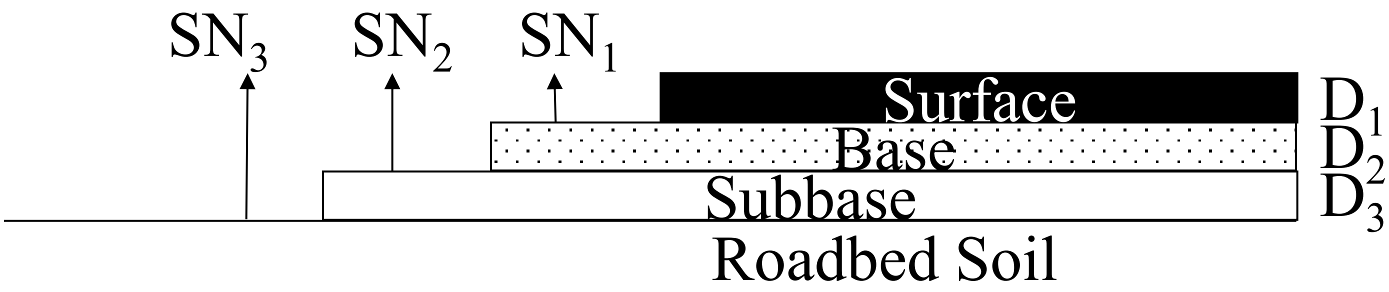
Source. After AASHTO (1986).

Design Procedure

Determine SN required above each layer

Find thickness to satisfy SN above each layer

AASHTO Layer Thickness Determination



Use E2 in Nomograph…Solve for D_1

$$SN_1 = a_1 D_1$$

Use E3 in Nomograph…Solve for D_2

$$SN_2 = a_1 D_1 + a_2 m_2 D_2$$

Use M_R in Nomograph…Solve for D_3

$$SN_3 = a_1 D_1 + a_2 m_2 D_2 + a_3 m_3 D_3$$

AASHTO Rigid Pavement Design

AASHTO Rigid Pavement Design Variables

- Thickness
- Serviceability (p_o, p_t)
- Traffic (ESALs, E-18s)
- Load Transfer (J)
- Concrete Properties (S'_c, E_c)
- Subgrade Properties (k)
- Drainage (C_d)
- Reliability (R, s_o)

Design Equation for AASHTO Rigid Pavements

$$\text{Log(E-18)} = Z_R * s_o + 7.35 * \text{Log}(D + 1) - 0.06 + \left[\frac{\text{Log}\left[\frac{\Delta PSI}{4.5 - 1.5}\right]}{1 + \frac{1.624 * 10^7}{(D + 1)^{8.46}}} \right]$$

$$+ (4.22 - 0.32p_t) * \text{Log}\left[\frac{S'_c * C_d * \left[D^{0.75} - 1.132\right]}{215.63 * J * \left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]} \right]$$

AASHTO Design Serviceability

- **Initial Serviceability, p_o**

The condition immediately after Construction

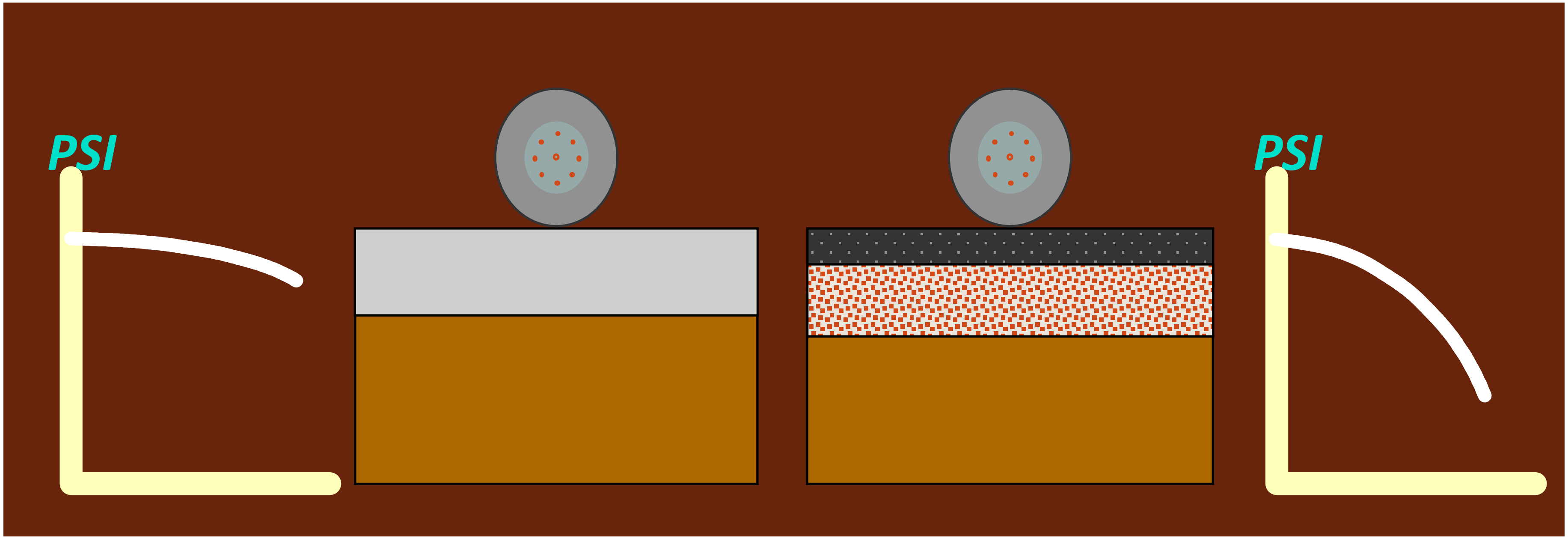
Concrete = 4.5

Asphalt = 4.2

Using current construction techniques, concrete roads can have p_o = 4.7 to 4.8

Load Equivalency Factors

For a Given Pavement Structure and a Given Serviceability Loss:



$$\frac{\textit{\# of Repetitions of X-kip Load on Axle Type Y}}{\textit{\# of Repetitions of 18-kip Load on a Single Axle}}$$

AASHTO Design Load Equivalency Factors

Concrete Response $\neq$ Asphalt Response

Since pavement responses are different, the equivalency factors are different. When multiplying the actual traffic by the different equivalencies, you get different E-18's

AASHTO Design Traffic

ESALs GENERATED BY DIFFERENT VEHICLES/DAY

VEHICLE	NUMBER	RIGID ESALs	FLEXIBLE ESALs
Single Units 2 Axle	20	6.38	6.11
Busses	5	13.55	8.73
Panel Trucks	10	10.89	11.11
Semi-tractor Trailer 3 Axles	10	20.06	13.41
Semi-tractor Trailer 4 Axles	15	39.43	29.88
Semi-tractor Trailer 5 Axles	15	57.33	36.87
Automobile, Pickup, Van	425	1.88	2.25
Total	500	149.52	108.36

AASHTO Design Load Transfer

- The Load Transfer Coefficient, J-factor, accounts for stress load transfer across a joint or crack.
  - Used to minimize corner cracking

    Dowels

    Yes - Plain or Mesh Reinforced

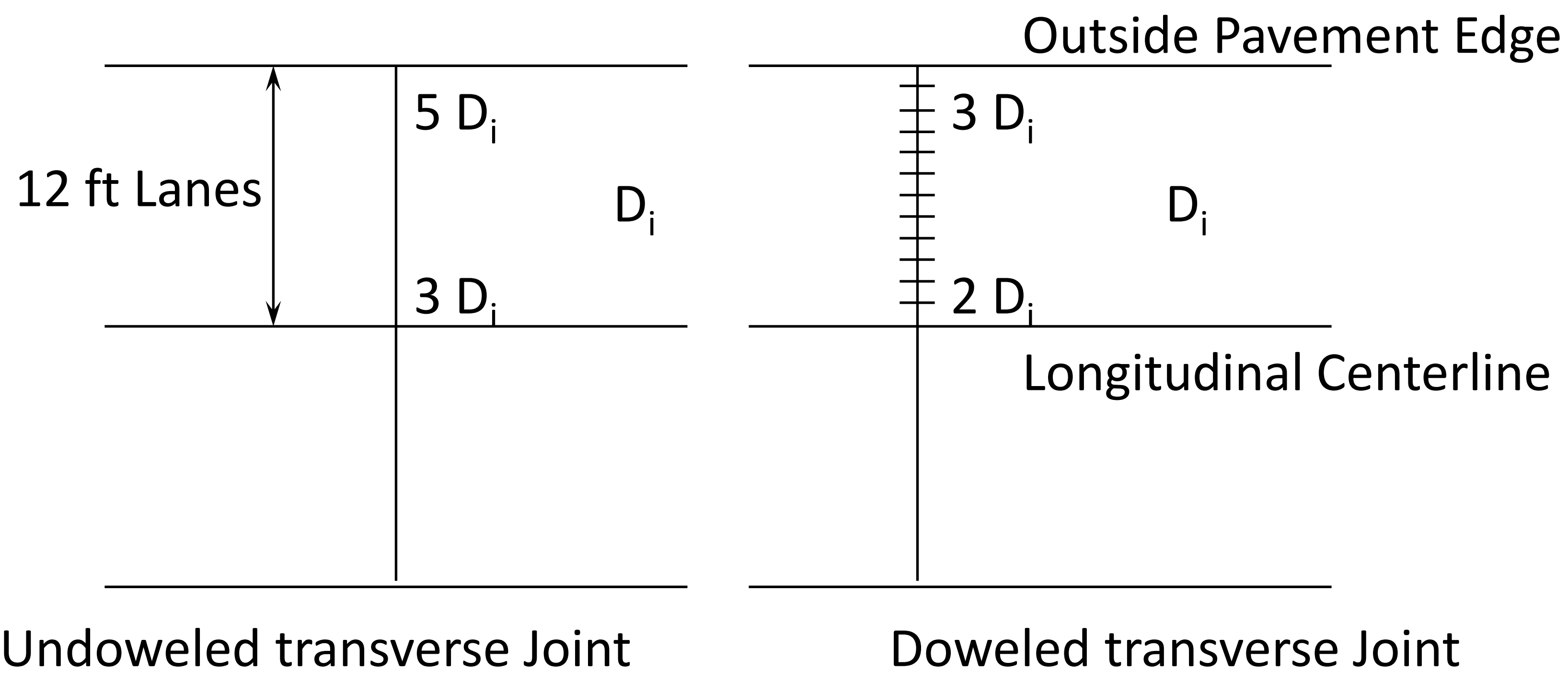
    No - Plain Undoweled

    Continuously Reinforced

    Tied Shoulder or Curb and Gutter
- Does not control or account for faulting
  - Does effect deflections.

AASHTO Design Load Transfer, J

Deflections in Concrete Pavement



AASHTO Design Load Transfer, J

Load Transfer Coefficients for Typical Designs

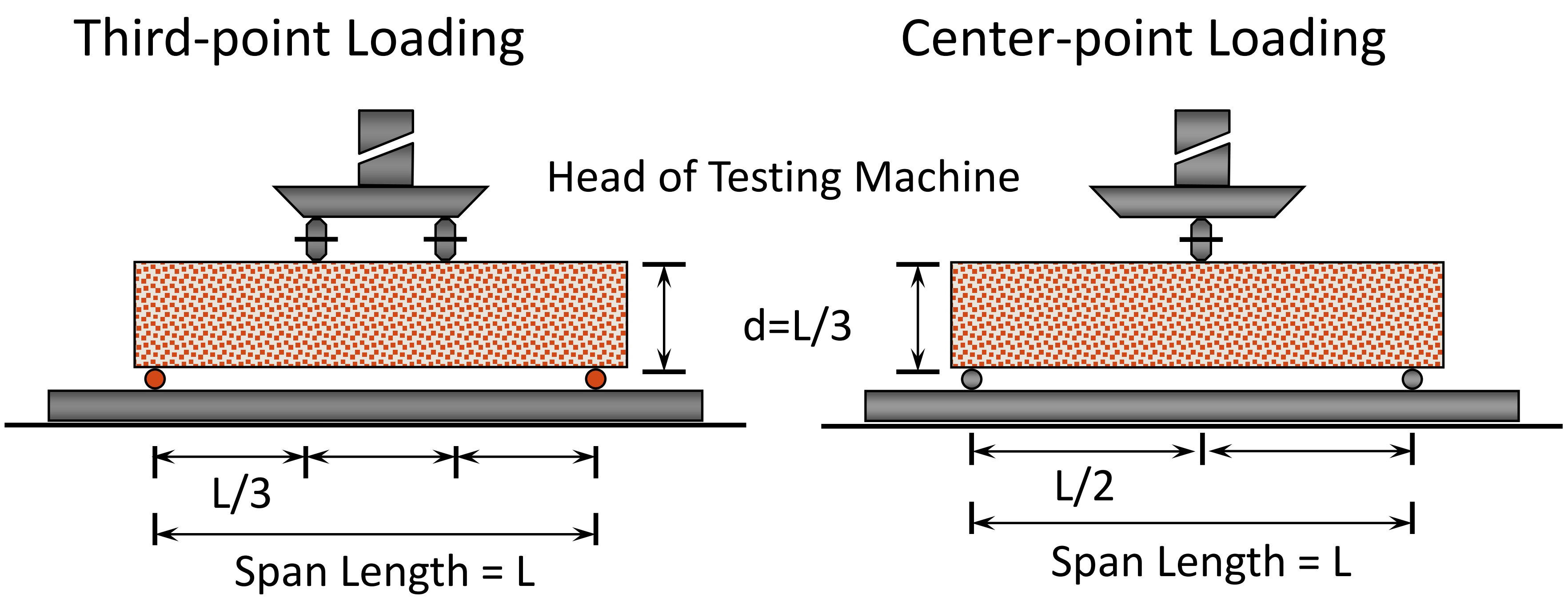
ESALs (millions)	Edge Support						Pavement class
	Doweled and mesh reinforced		Aggregate interlock		Continously reinforced		
	No	Yes	No	Yes	No	Yes	
under 0.3	3.2	2.7	3.2	2.8	---	---	Local Streets & Roads
0.3 - 1	3.2	2.7	3.4	3.0	---	---	
1 - 3	3.2	2.7	3.6	3.1	---	---	
3 - 10	3.2	2.7	3.8	3.2	2.9	2.5	Arterials and Highways
10 - 30	3.2	2.7	4.1	3.4	3.0	2.6	
over 30	3.2	2.7	4.3	3.6	3.1	2.6	

AASHTO Design Concrete Properties

- Two concrete properties that influence pavement performance
  - Flexural Strength (Modulus of Rupture), S'_c
    - 3rd-Point Loading
  - Modulus of Elasticity, E_c

AASHTO Design Concrete Properties

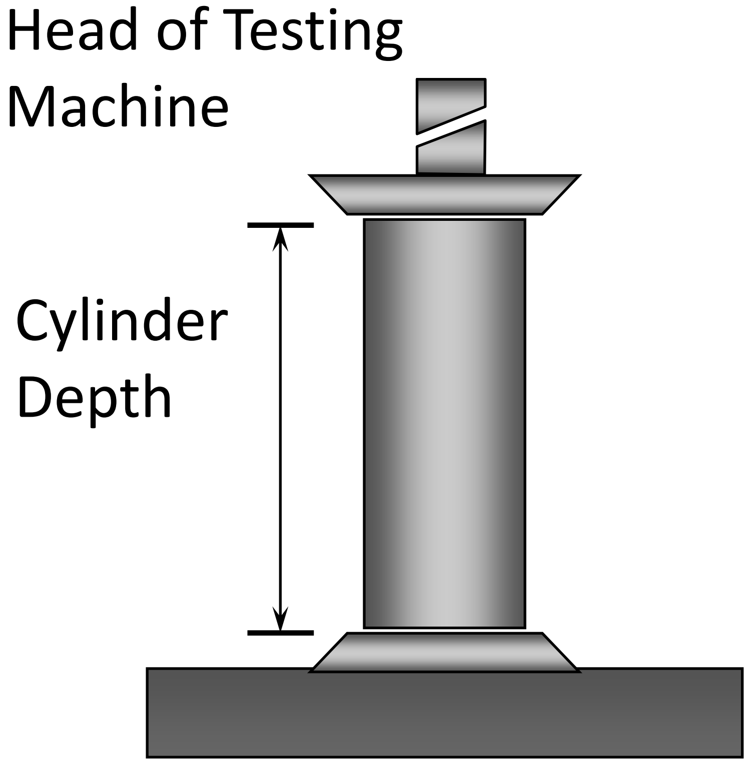
Flexural Strength (S'_c) Determination



AASHTO Design Concrete Properties

Compressive Strength f'_c

$$S'_c = 8\text{-}10\sqrt{f'_c}$$



- f'_c = Compressive Strength (psi)
  S'_c = Flexural Strength (psi)

AASHTO Design Concrete Properties

Comparison of f'_c & S'_c

Compressive Strength	Third Point Flexural Strength	Center Point Flexural Strength
3000	492	579
3500	532	626
4000	569	669
4500	603	710
5000	636	748
5500	667	785
6000	697	820

Note: Third point ≈ Center point * 0.85

AASHTO Design Concrete Properties

- Modulus of Elasticity
- $E_c = 6750\ S'_c$
- $E_c = 57{,}000\ (f'_c)^{0.5}$

Flexural Strength	Modulus of Elasticity
600 psi	3,900,000 psi
650 psi	4,200,000 psi
700 psi	4,600,000 psi

AASHTO Design Concrete Properties

- Typical Standard Deviation
  - Ready-mix Concrete: 7-13%
  - Central-mix Concrete: 5-12%
- Standard Normal Deviate

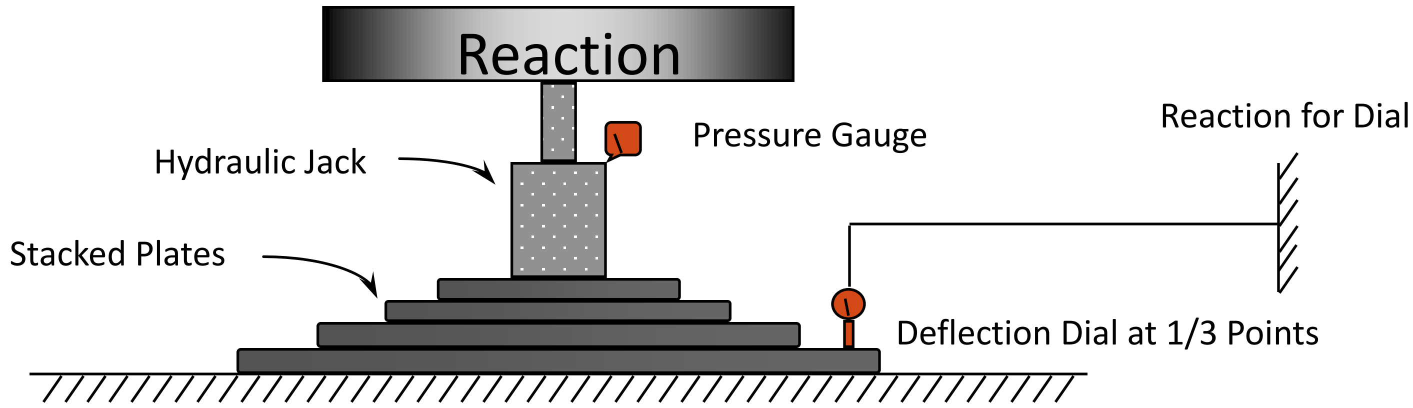
Reliability (R)	Z_R
50	-0.000
75	-0.674
90	-1.282
95	-1.645
99	-2.327

AASHTO Design Subgrade Properties

- Two are two subgrade properties that influence concrete pavement design
  - Modulus of Subgrade Reaction, k-value
  - Loss of Support

AASHTO Design Subgrade Properties

- Modulus of Subgrade Reaction, k



k (psi/in) = unit load on plate / plate deflection

AASHTO Design k-Value Determination

- AASHTO uses the k-value for design, but basis the soils characterization on the Resilient Modulus, M_R.
- 1. Determine M_R
  - AASHTO test Method T 274
  - Correlations to CBR or R-values
- 2. Convert M_R to K-value

AASHTO Design k-Value Determination

- After determining the Resilient Modulus, M_R, convert M_R to k-value for design.
- No subbase

  $K\ (psi/in) = M_R/19.4$
- Subbase

  Fig. 3.3 from Part II

AASHTO Design Loss of Support

- Accounts for the expected loss of support by subbase / subgrade erosion and differential movements.
- Decreases the effective or composite k-value for a subbase / subgrade based on the size of void that may develop beneath the slab.
- LOS = 0 models the soil conditions at the AASHO road test.

AASHTO Design Loss of Support

TYPE	*Modulus*	*Historical k-value*	*LOS=0*	*AASHTO k-value LOS=1*	*LOS=2*	*LOS=3*
Silts & Clays	3,000	100	--	--	22	11
Granular	30,000	150-250	--	79	29	13
Bituminous Treated	100,000	350-450	300	93	--	--
Cement Treated	1,000,000	400-500	445	128	--	--

AASHTO Design Subgrade Strength

- Typical Soil Relationships

Soil Type	*Strength*	*k-value (psi / in.)*	*Mr (psi)*	*CBR*
Silts / Clays	**Very Low**	**50-100**	**1000-1900**	**<3**
Fine grained	**Low**	**100-150**	**1900-2900**	**3-5.5**
Sands	**Medium**	**150-220**	**2900-4300**	**5.5-12**
Gravely soils	**High**	**220-250+**	**4300-4850**	**>12**

AASHTO Design Subgrade Strength

If you do not know the structural coefficient of a subbase layer use:

$$a_{granular} = 0.249(\log E_{granular}) - 0.977$$

$$a_{granular} = 0.0045 \sqrt[3]{E_{granular}}$$

For lime-modified soil example:

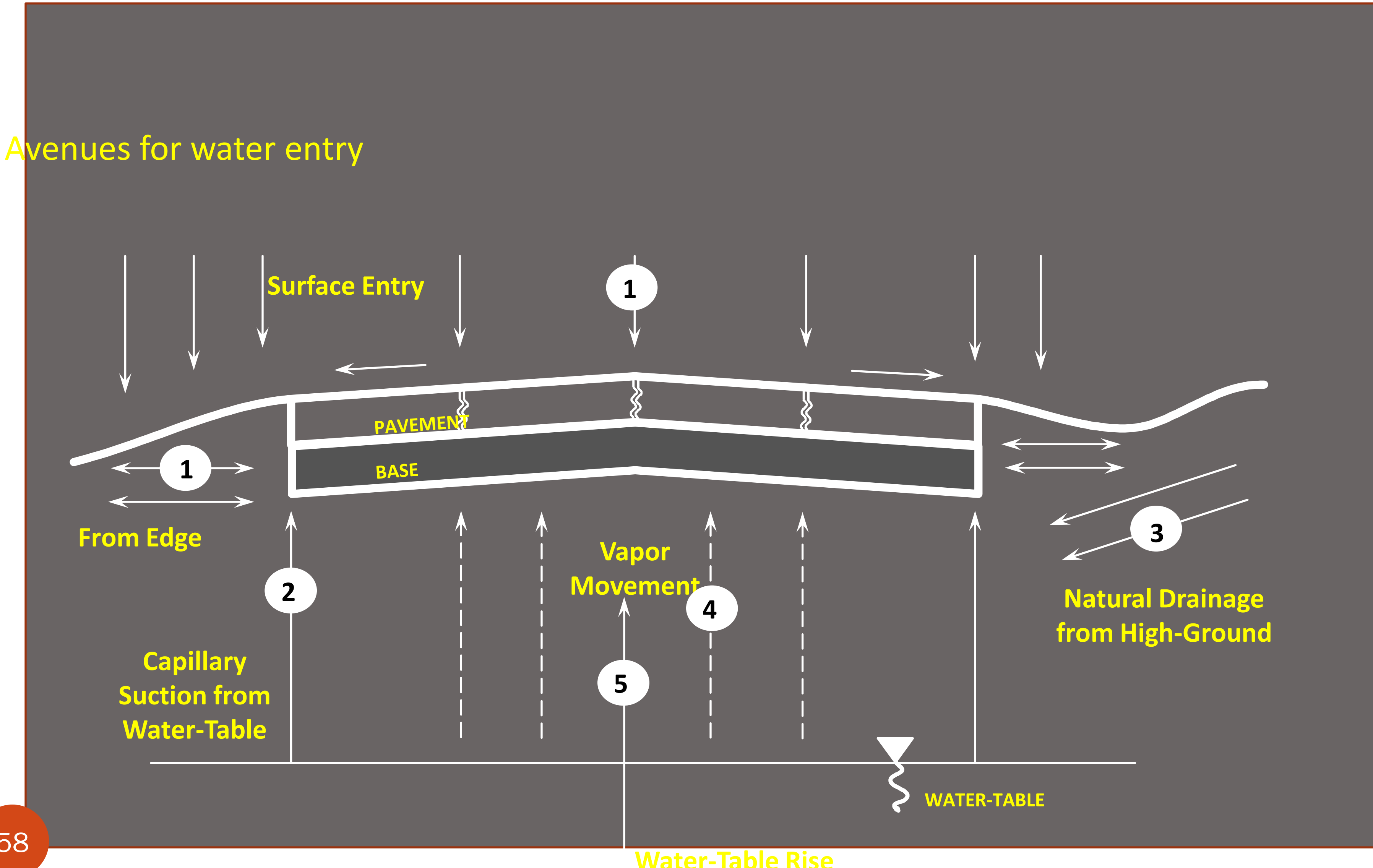
$$a_{granular} = 0.249[\log (30{,}000)] - 0.977 = 0.138$$

$$a_{granular} = 0.0045 \sqrt[3]{30{,}000} = 0.139$$

AASHTO Design Drainage , C_d

- Effects of Water Trapped within the Pavement Structure
    1. Reduced Strength of Unbound Granular Materials
    2. Reduced Strength of Subgrade Soils
    3. Pumping of fines
    4. Differential Heaving of Swelling Soils
    5. Frost Heave

AASHTO Design Drainage



AASHTO Design Drainage

Recommended Values for Drainage Coefficient

Quality of Drainage	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
	Less than 1%	1 - 5%	5 - 25%	Greater than 25%
Excellent	1.25 - 1.20	1.20 - 1.15	1.15 - 1.10	1.10
Good	1.20 - 1.15	1.15 - 1.10	1.10 - 1.00	1.00
Fair	1.15 - 1.10	1.10 - 1.00	1.00 - 0.90	0.90
Poor	1.10 - 1.00	1.00 - 0.90	0.90 - 0.80	0.80
Very Poor	1.00 - 0.90	0.90 - 0.80	0.80 - 0.70	0.70

AASHTO Design Reliability

- The statistical factors that influence pavement performance are:
  - RELIABILITY, R - The statistical probability that a pavement will meet its design life.
  - STANDARD DEVIATION, s_o -The amount of statistical error present in the design equations resulting from variability in materials, construction, traffic, etc.

AASHTO Design Reliability

Recommended Reliability Values for Design

	Recommended Level of Reliability	
Functional Classification	*Urban*	*Rural*
Interstate / Freeways	85-99.9	80-99.9
Principal Arteials	80-99	75-99
Collectors	80-95	75-95
Local	50-80	50-80

AASHTO Design Reliability

Recommended s_o Values for Design

	Concrete	*Asphalt*
Ranges	0.30 – 0.40	0.40 – 0.50
Use		
New Construction	0.35	0.45
Overlays	0.39	0.49

Advantages & Limitations of AASHTO Method

- Advantages
  - Straightforward
  - Inclusion of reliability and standard deviation
  - Can be applied to a variety of traffic, climate, material condition
- Limitations
  - Empirical – developed to specific condition over a short period of time
  - The use of effective resilient modulus and layer coefficient concept
  - ESAL (LEF): based on limited inspection
  - Limited materials and subgrade