Pavement Design

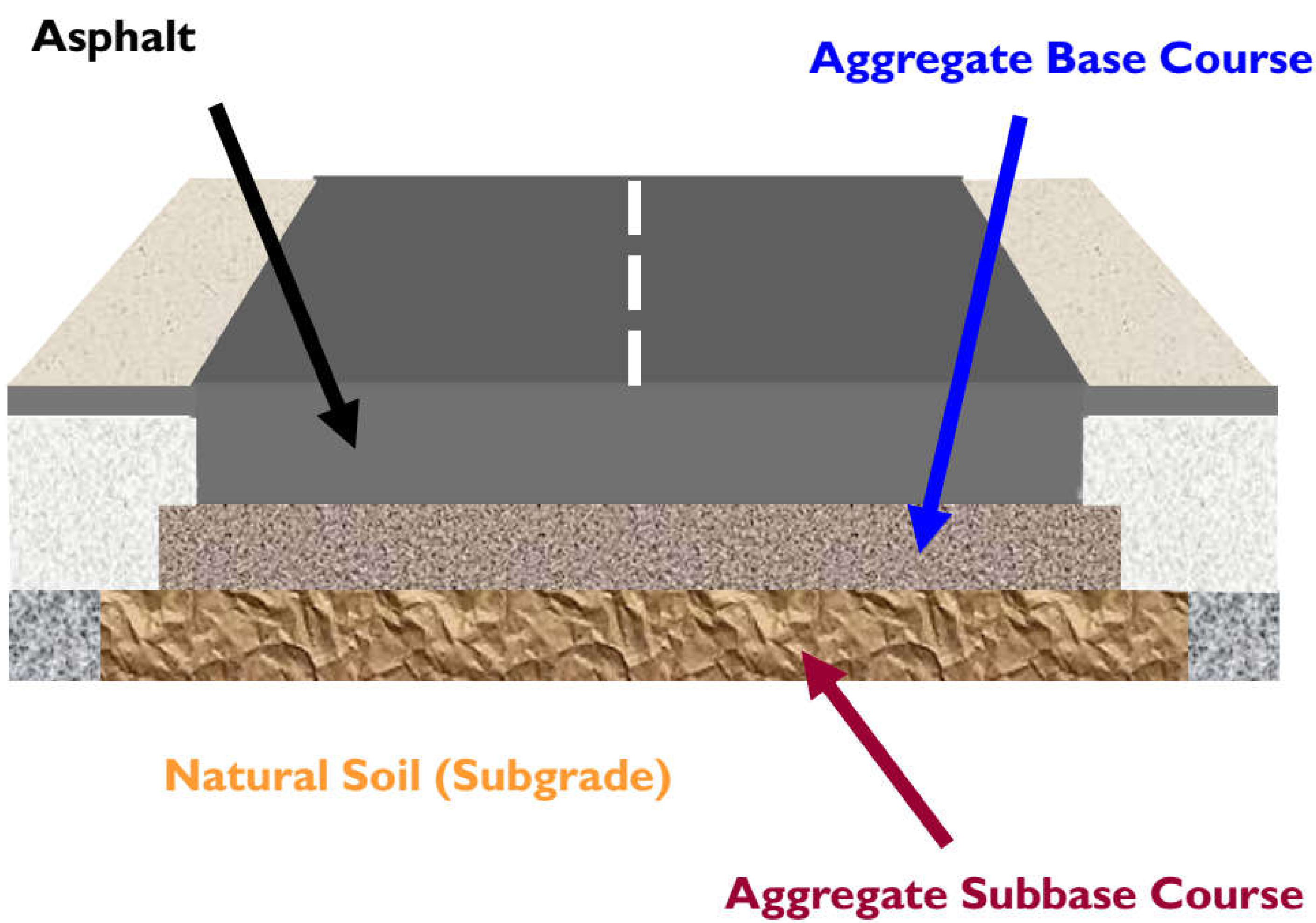
Outline

1. **Pavement**
2. **History + Material**
3. **Pavement Purpose**
4. **Pavement Significance**
5. **Pavement Condition**
6. **Pavement Types**
   a. **Flexible**
   b. **Rigid**
7. **Pavement Design**
8. **Example**

Pavement

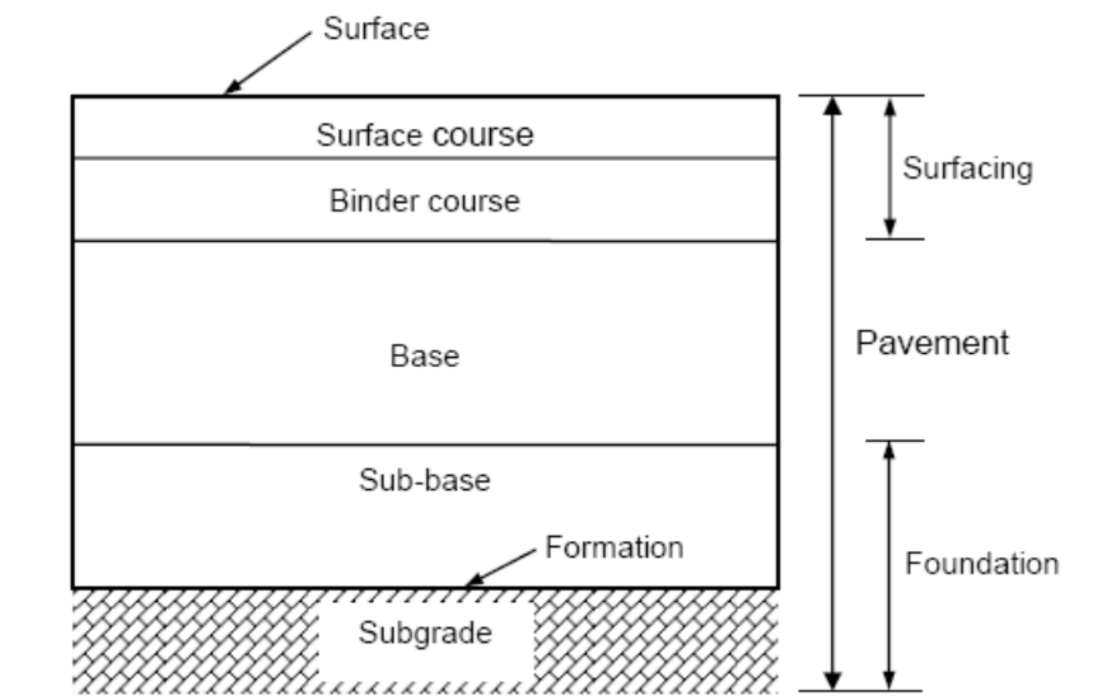
- **A pavement is a structure which separates the wheels of vehicles from the underlying foundation material.**
- **Pavements over soil are normally of multilayer construction with relatively weak materials below and progressively stronger ones above**
- **Similarly pavement layers thickness varies from top to bottom.**

A Typical Pavement



Pavement

- **Pavements can be considered to consist of three main layers, the surfacing, the base, and the foundation.**



Pavement

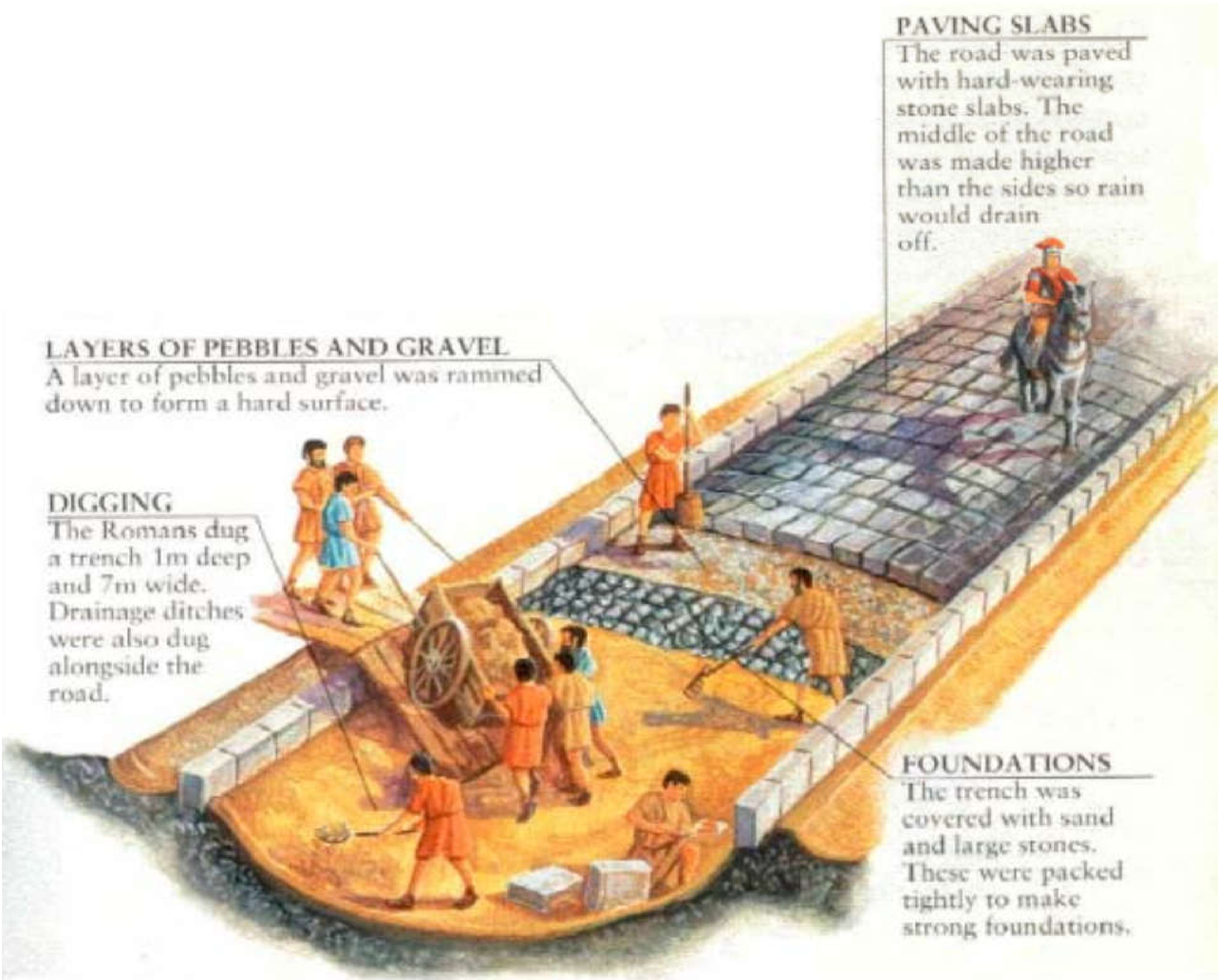
- **In the case of asphalt pavements, the surfacing is generally divided into surface course and base course which are laid separately. The base is the main structural component in the pavement.**
- **The foundation of pavement essentially comprises of two layers. The upper layer is termed as subbase and is usually formed of good quality granular material. The subbase provides a structural layer which distributes loads to the subgrade and provides a working platform for construction traffic and a compaction platform onto which bituminous materials can be laid and compacted.**

Pavement

- **The lower section, the subgrade is the natural soil or fill material which provides the surface upon which the pavement is constructed.**
- **Where the soil is considered to be very weak, a capping layer may also be introduced additionally between the subbase and the soil foundation.**

History

- **The modern concept of pavement construction was pioneered by the Romans.**
- **The concept used by the Romans is not very different to the typical multi-layer flexible pavement layout.**

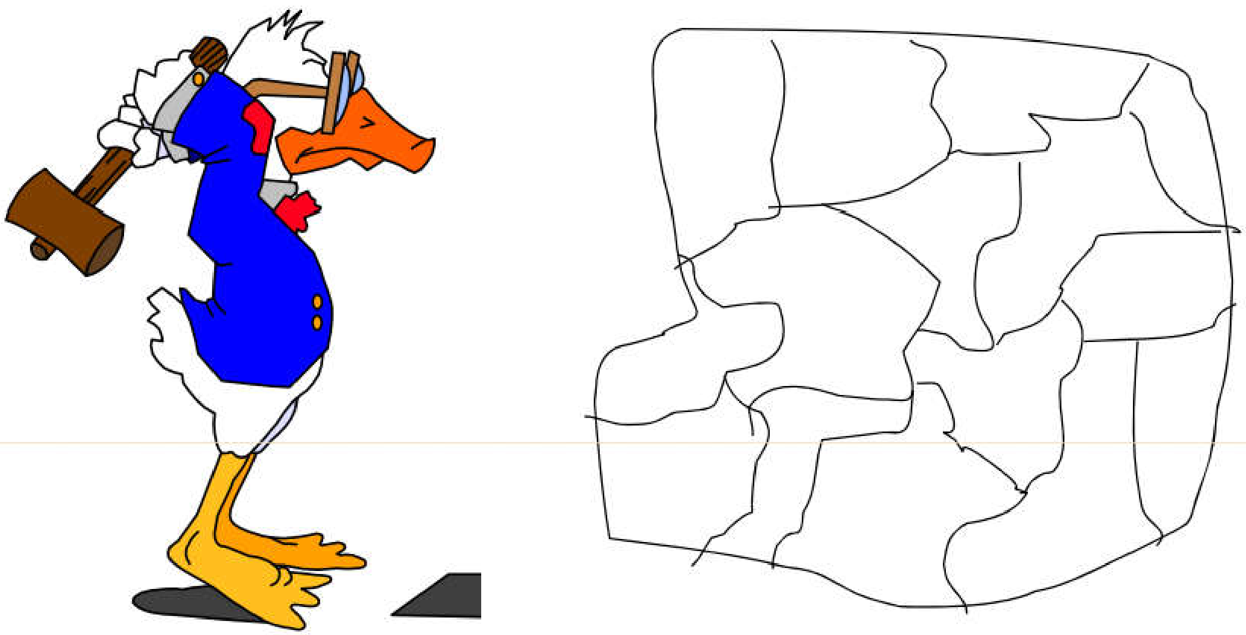

PAVING SLABS
The road was paved with hard-wearing stone slabs. The middle of the road was made higher than the sides so rain would drain off.
LAYERS OF PEBBLES AND GRAVEL
A layer of pebbles and gravel was rammed down to form a hard surface.
DIGGING
The Romans dug a trench 1m deep and 7m wide. Drainage ditches were also dug alongside the road.
FOUNDATIONS
The trench was covered with sand and large stones. These were packed tightly to make strong foundations.

Material

- **Bitumen**
- **Viscoelastic organic liquid comprised predominantly of hydrocarbon molecules**

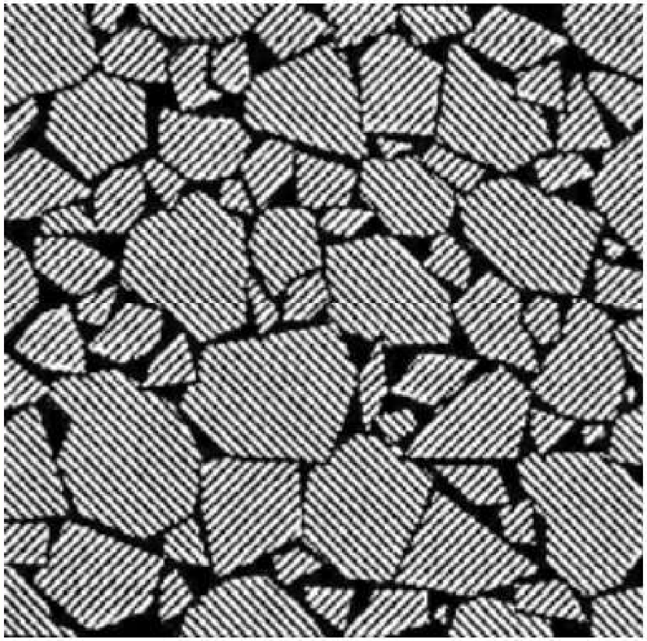
- **Asphalt**
- **Combination of bitumen, aggregate (stone), and air with visco-elasto-plastic properties**

Rock



Crushed Rock

Glue it together again!



Pavement Purpose

- **Load support**
- **Smoothness**
- **Drainage**

DC to Richmond Road in 1919 – from the Asphalt Institute

Pavement Significance

- **How much pavement?**
  - **3.97 million centerline miles in U.S.**
  - **2.5 million miles (63%) are paved**
  - **8.30 million lane-miles total**
  - **Largest single use of HMA and PCC**
- **Costs**
  - **$20 to $30 billion spent annually on pavements**

Pavement Condition

Pavement Condition

Pavement Condition

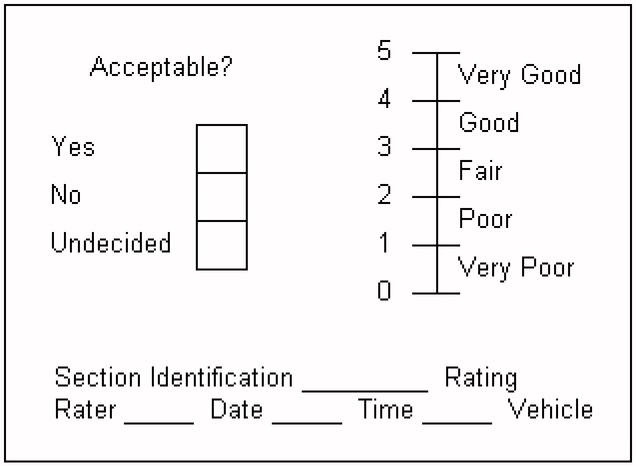
Pavement Condition

From WSDOT
I – 90 “fat driver” syndrome

Pavement Condition

- **Defined by users (drivers)**
- **Develop methods to relate physical attributes to driver ratings**
- **Result is usually a numerical scale**

From the AASHO Road Test (1956 – 1961)



Present Serviceability Rating (PSR)

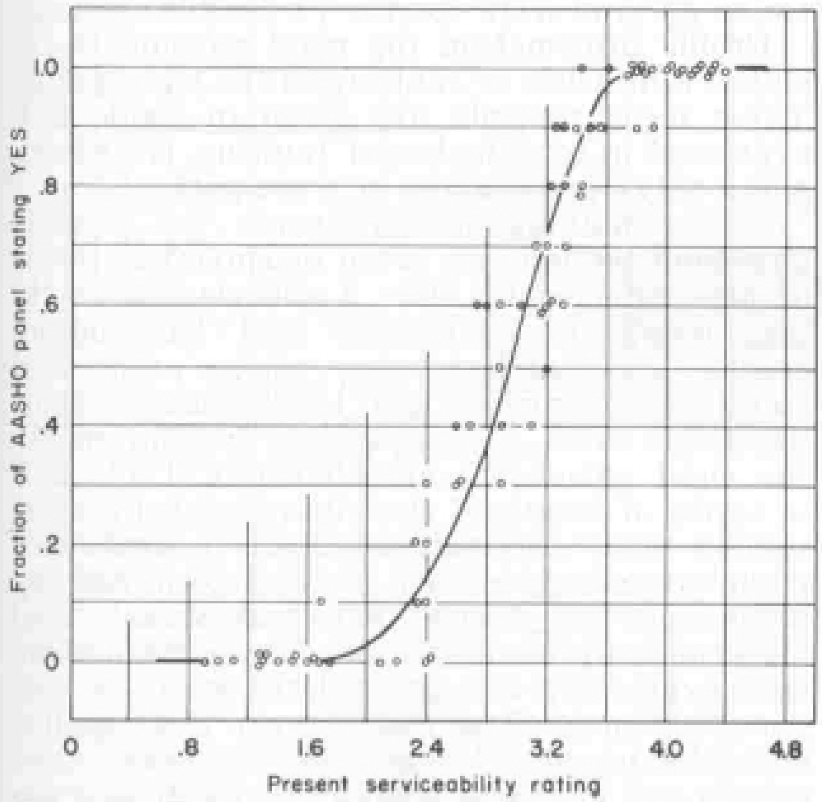


Figure 2–F. Acceptability vs present serviceability rating; 74 flexible pavements.

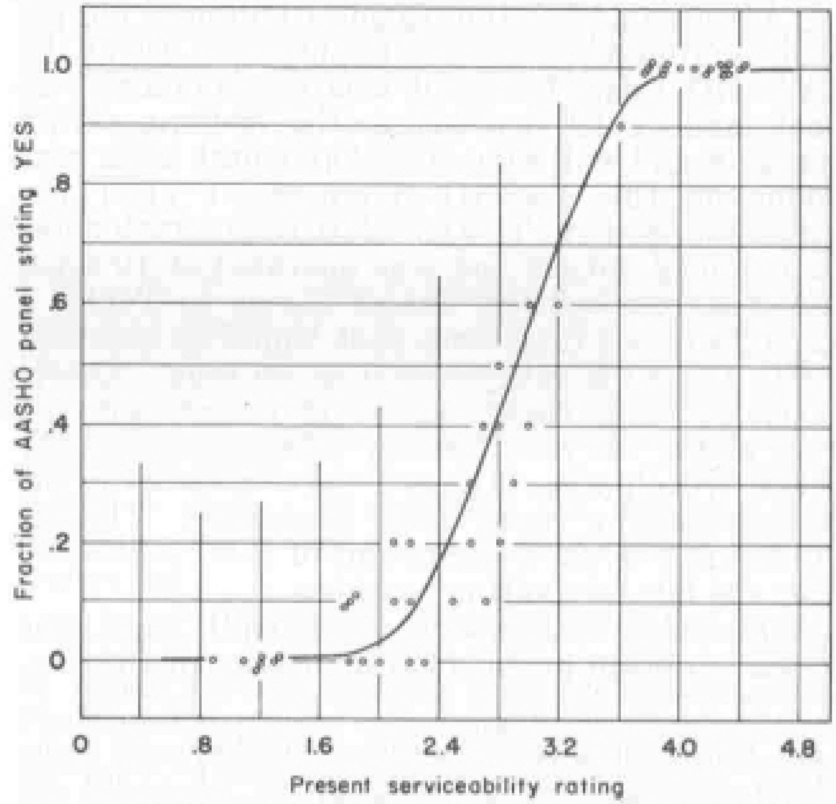


Figure 3–F. Acceptability vs present serviceability rating; 49 rigid pavements.

Picture from: Highway Research Board Special Report 61A-G

FYI – NOT TESTABLE

Present Serviceability Index (PSI)

- **Values from 0 through 5**
- **Calculated value to match PSR**

$$PSI = 5.41 - 1.80\log\left(1 + \overline{SV}\right) - 0.9\sqrt{C + P}$$

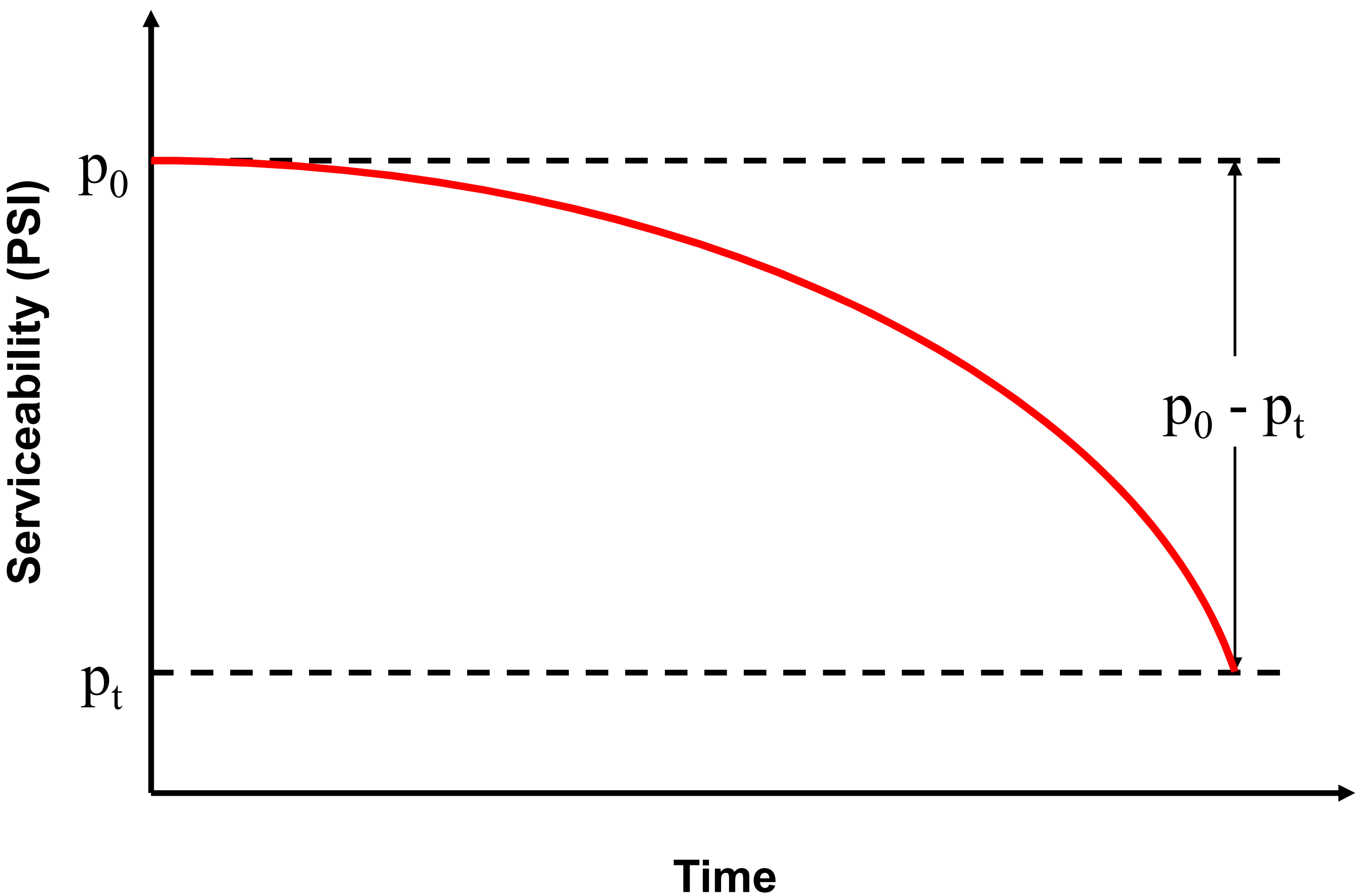
SV = mean of the slope variance in the two wheelpaths (measured with the CHLOE profilometer or BPR Roughometer)

C, P = measures of cracking and patching in the pavement surface

C = total linear feet of Class 3 and Class 4 cracks per 1000 ft^2 of pavement area. A Class 3 crack is defined as opened or spalled (at the surface) to a width of 0.25 in. or more over a distance equal to at least one-half the crack length. A Class 4 is defined as any crack which has been sealed.

P = expressed in terms of ft^2 per 1000 ft^2 of pavement surfacing.

Typical PSI vs. Time

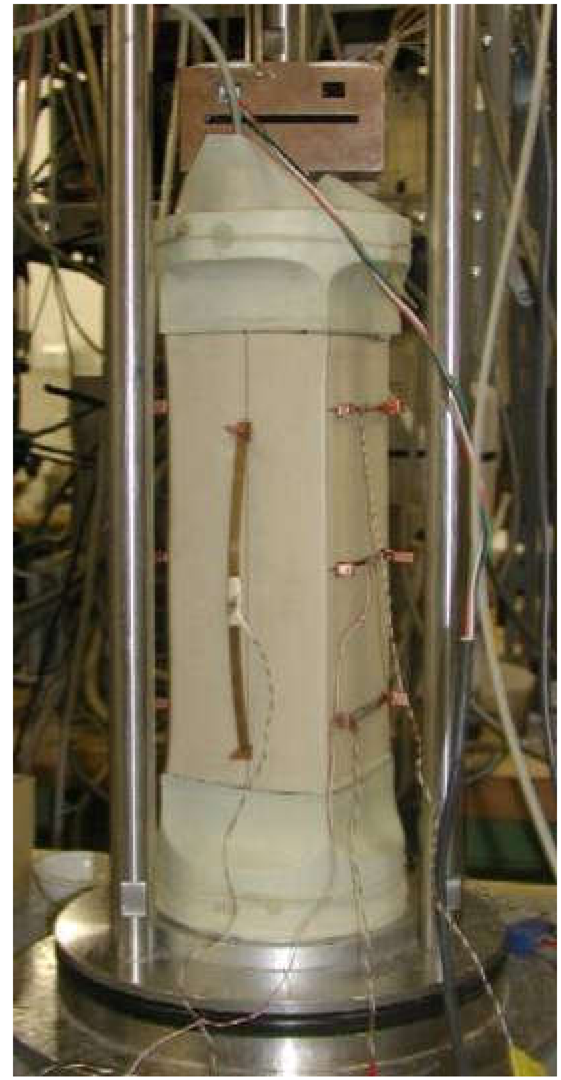


Design Parameters

- **Subgrade**
- **Loads**
- **Environment**

Subgrade

- **Characterized by strength and/or stiffness**
  - **California Bearing Ratio (CBR)**
    - **Measures shearing resistance**
    - **Units: percent**
    - **Typical values: 0 to 20**
  - **Resilient Modulus (M_R)**
    - **Measures stress-strain relationship**
    - **Units: psi or MPa**
    - **Typical values: 3,000 to 40,000 psi**



Picture from University of Tokyo Geotechnical Engineering Lab

Subgrade

Some Typical Values

Classification	CBR	M_R (psi)	Typical Description
Good	≥ 10	20,000	Gravels, crushed stone and sandy soils. GW, GP, GM, SW, SP, SM soils are often in this category.
Fair	5 – 9	10,000	Clayey gravel and clayey sand, fine silt soils. GM, GC, SM, SC soils are often in this category.
Poor	3 – 5	5,000	Fine silty sands, clays, silts, organic soils. CL, CH, ML, MH, CM, OL, OH soils are often in this category.

Loads

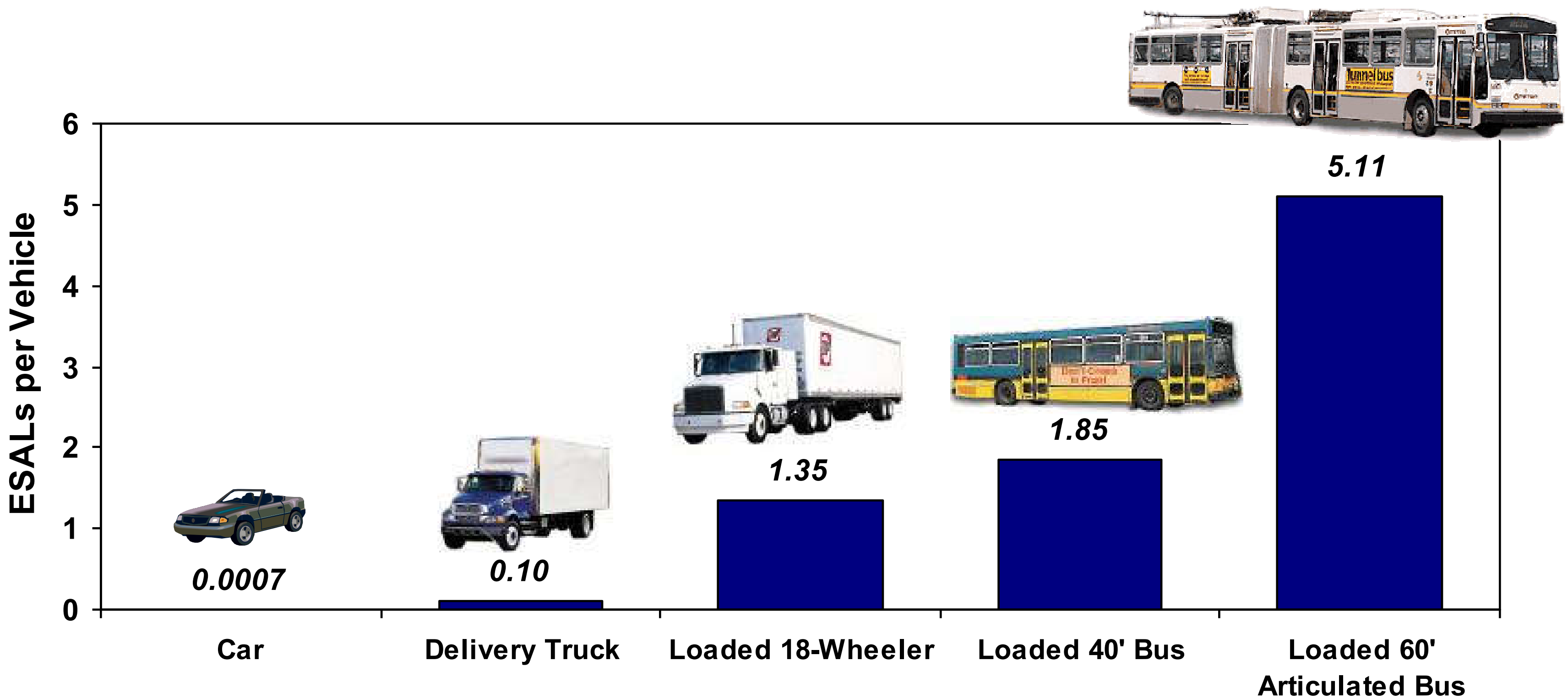
- **Load characterization**
  - **Tire loads**
  - **Axle and tire configurations**
  - **Load repetition**
  - **Traffic distribution**
  - **Vehicle speed**

Load Quantification

- **Equivalent Single Axle Load (ESAL)**
  - **Converts wheel loads of various magnitudes and repetitions ("mixed traffic") to an equivalent number of "standard" or "equivalent" loads**
  - **Based on the amount of damage they do to the pavement**
  - **Commonly used standard load is the 18,000 lb. equivalent single axle load**
- **Load Equivalency**
  - **Generalized fourth power approximation**

$$\left(\frac{\text{load}}{18{,}000\ \text{lb.}}\right)^4 = \text{relative damage factor}$$

Typical LEFs



Notice that cars are insignificant and thus usually ignored in pavement design.

LEF Example

The standard axle weights for a standing-room-only loaded Metro articulated bus (60 ft. Flyer) are:

Axle	Empty	Full
Steering	13,000 lb.	17,000 lb.
Middle	15,000 lb.	20,000 lb.
Rear	9,000 lb.	14,000 lb.

Using the 4^{th} power approximation, determine the total equivalent damage caused by this bus in terms of ESALs when it is empty. How about when it is full?

Solution

- **Empty**
- **$(13,000/18,000)^4 = 0.272$**
- **$(15,000/18,000)^4 = 0.482$**
- **$(9,000/18,000)^4 = 0.063$**
- **Total = 0.817 ESALs**
- **Full**
- **$(17,000/18,000)^4 = 0.795$**
- **$(20,000/18,000)^4 = 1.524$**
- **$(14,000/18,000)^4 = 0.366$**
- **Total = 2.685 ESALs**

- **Increase in total weight = 14,000 lb. (about 80 people) or 39%**
- **Increase in ESALs is 1.868 (229%)**

Environment

- **Temperature extremes**
- **Frost action**
  - **Frost heave**
  - **Thaw weakening**

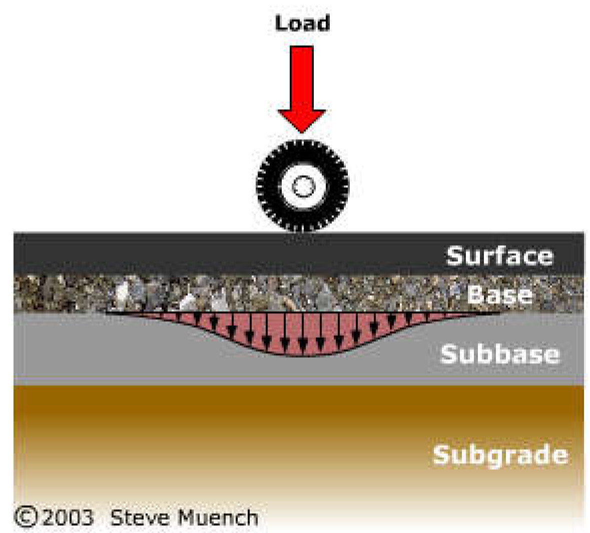
Pavement Types

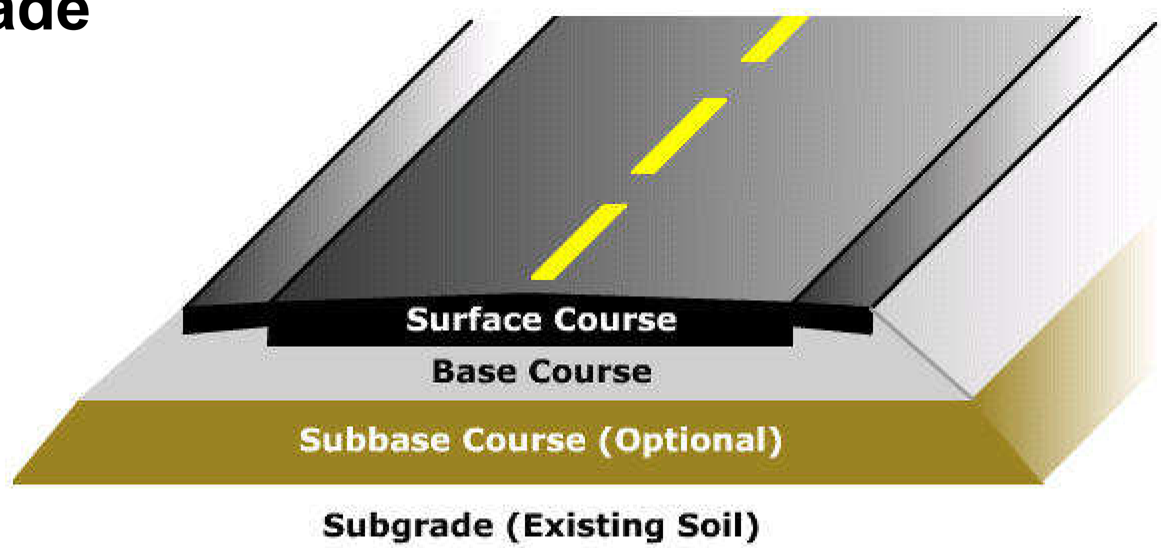
- **Flexible Pavement**
  - **Hot mix asphalt (HMA) pavements**
  - **Called "flexible" since the total pavement structure bends (or flexes) to accommodate traffic loads**
  - **About 82.2% of paved U.S. roads use flexible pavement**
  - **About 95.7% of paved U.S. roads are *surfaced* with HMA**

- **Rigid Pavement**
  - **Portland cement concrete (PCC) pavements**
  - **Called “rigid” since PCC’s high modulus of elasticity does not allow them to flex appreciably**
  - **About 6.5% of paved U.S. roads use rigid pavement**

Flexible Pavement

- **Structure**
  - **Surface course**
  - **Base course**
  - **Subbase course**
  - **Subgrade**





Types of Flexible Pavement

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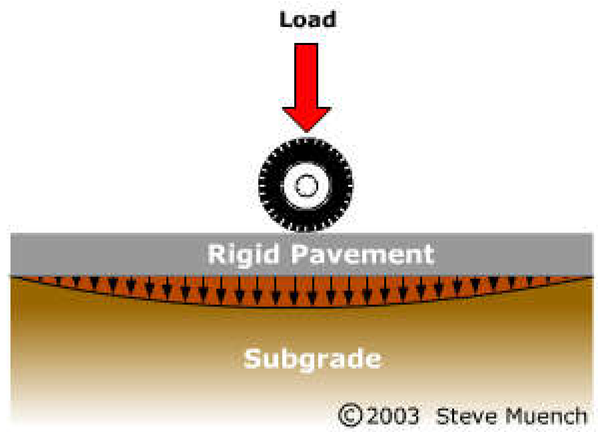
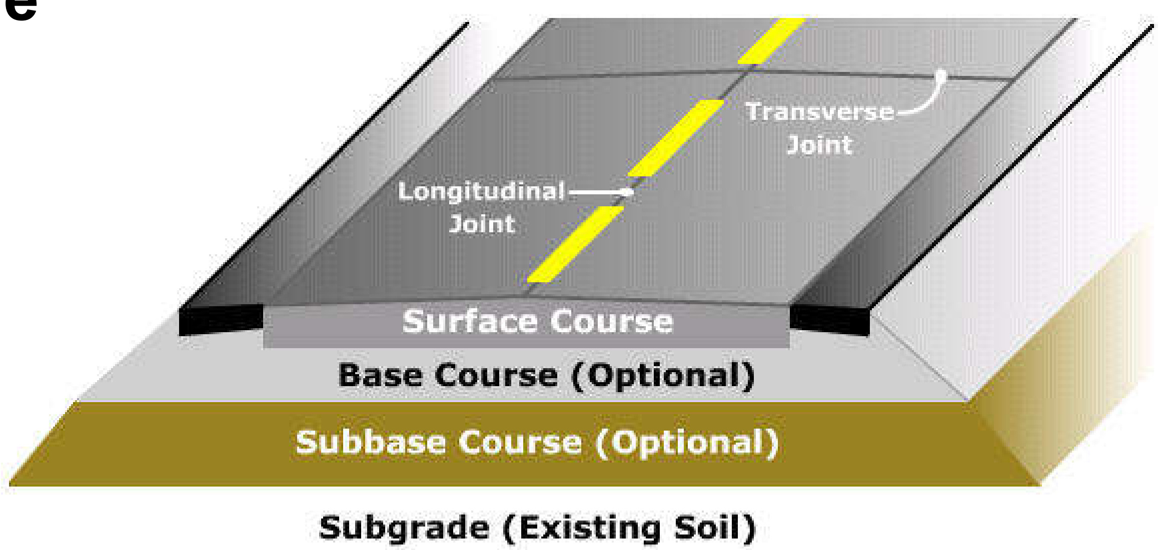
Flexible Pavement − Construction

Rigid Pavement

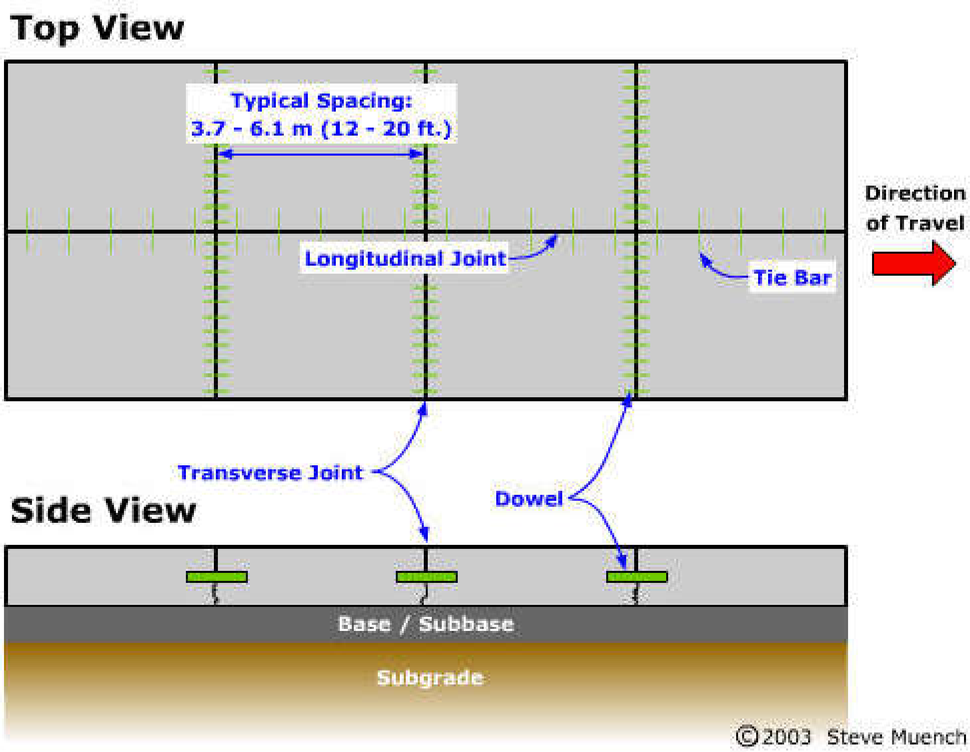
- **Structure**
  - **Surface course**
  - **Base course**
  - **Subbase course**
  - **Subgrade**





Types of Rigid Pavement

- **Jointed Plain Concrete Pavement (JPCP)**



Types of Rigid Pavement

- **Continuously Reinforced Concrete Pavement (CRCP)**

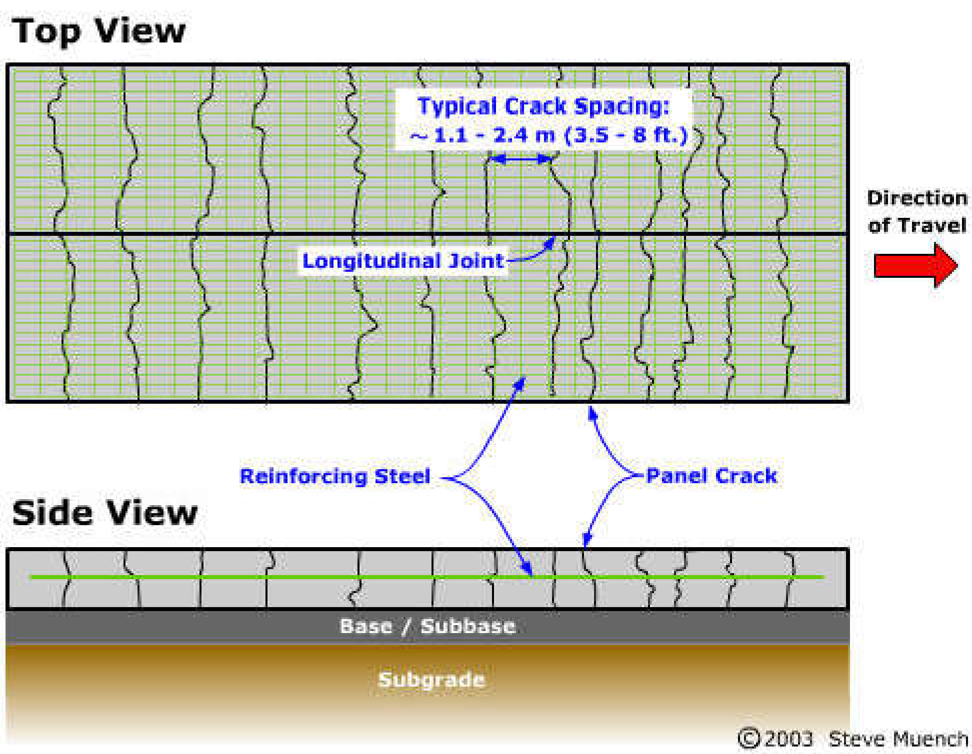


Photo from the Concrete Reinforcing Steel Institute

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Rigid Pavement – Construction

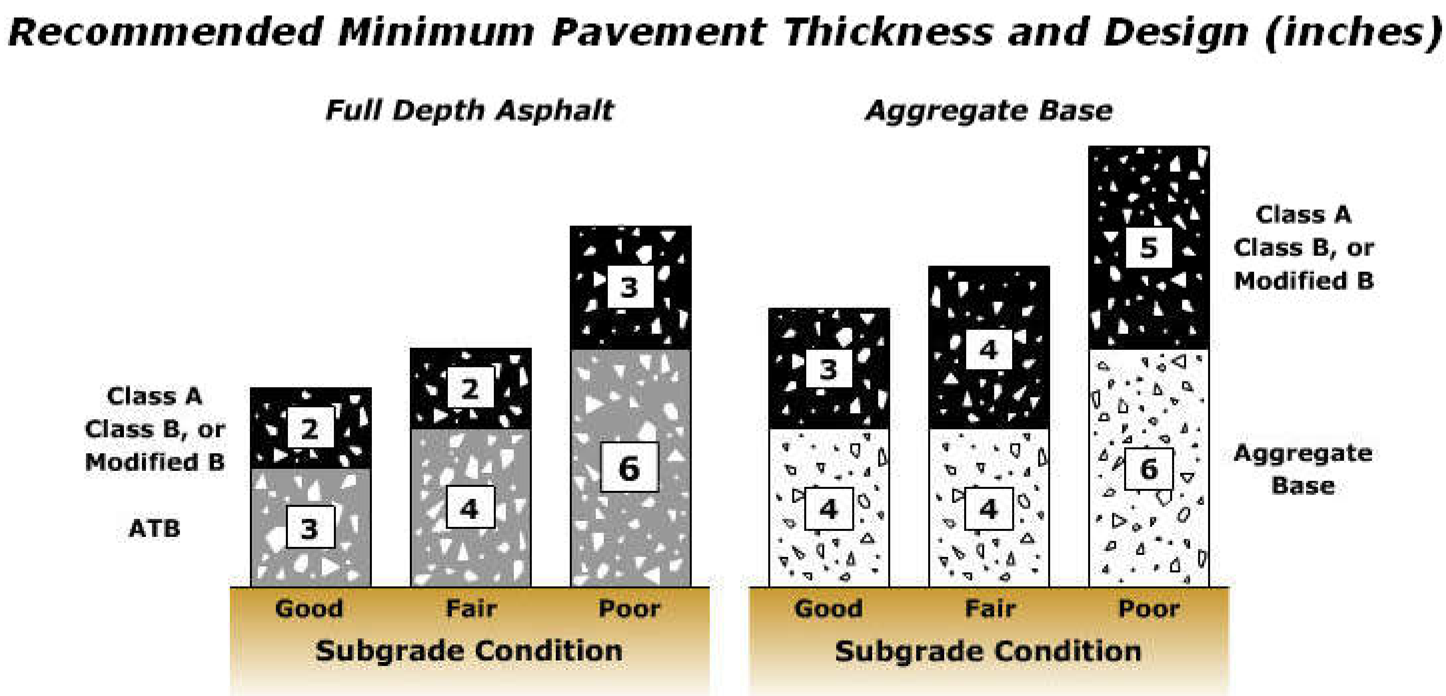
Fixed form

Slipform

Pavement Design

- **Several typical methods**
  - **Design catalog**
  - **Empirical**
    - **1993 AASHTO method**
  - **Mechanistic-empirical**
    - **New AASHTO method (as yet unreleased)**

Design Catalog



Example design catalog from the Washington Asphalt Pavement Association (WAPA) for residential streets

Empirical

- **1993 AASHTO Flexible Equation**

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

- **1993 AASHTO Rigid Equation**

$$\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{(S_c')(C_d)(D^{0.75}) - 1.132}{215.63(J)\left(D^{0.75} - \frac{18.42}{\left(E_c/k\right)^{0.25}}\right)}\right]$$

Terms – Flexible

- **W_{18} (loading)**
  - **Predicted number of ESALs over the pavement's life.**
- **SN (structural number)**
  - **Abstract number expressing structural strength**
  - **$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 + \ldots$**
  - a=a layer coefficient that represents the relative strength of the material
  - D= layer thickness in inches
  - M= a drainage coefficient
- **ΔPSI (change in present serviceability index)**
  - **Change in serviceability index over the useful pavement life**
  - **Typically from 1.5 to 3.0**
- **M_R (subgrade resilient modulus)**
  - **Typically from 3,000 to 30,000 psi (10,000 psi is pretty good)**

Terms – Rigid

- **D (slab depth)**
  - **Abstract number expressing structural strength**
- **S'_c (PCC modulus of rupture)**
  - **A measure of PCC flexural strength**
  - **Usually between 600 and 850 psi**
- **C_d (drainage coefficient)**
  - **Relative loss of strength due to drainage characteristics and the total time it is exposed to near-saturated conditions**
  - **Usually taken as 1.0**

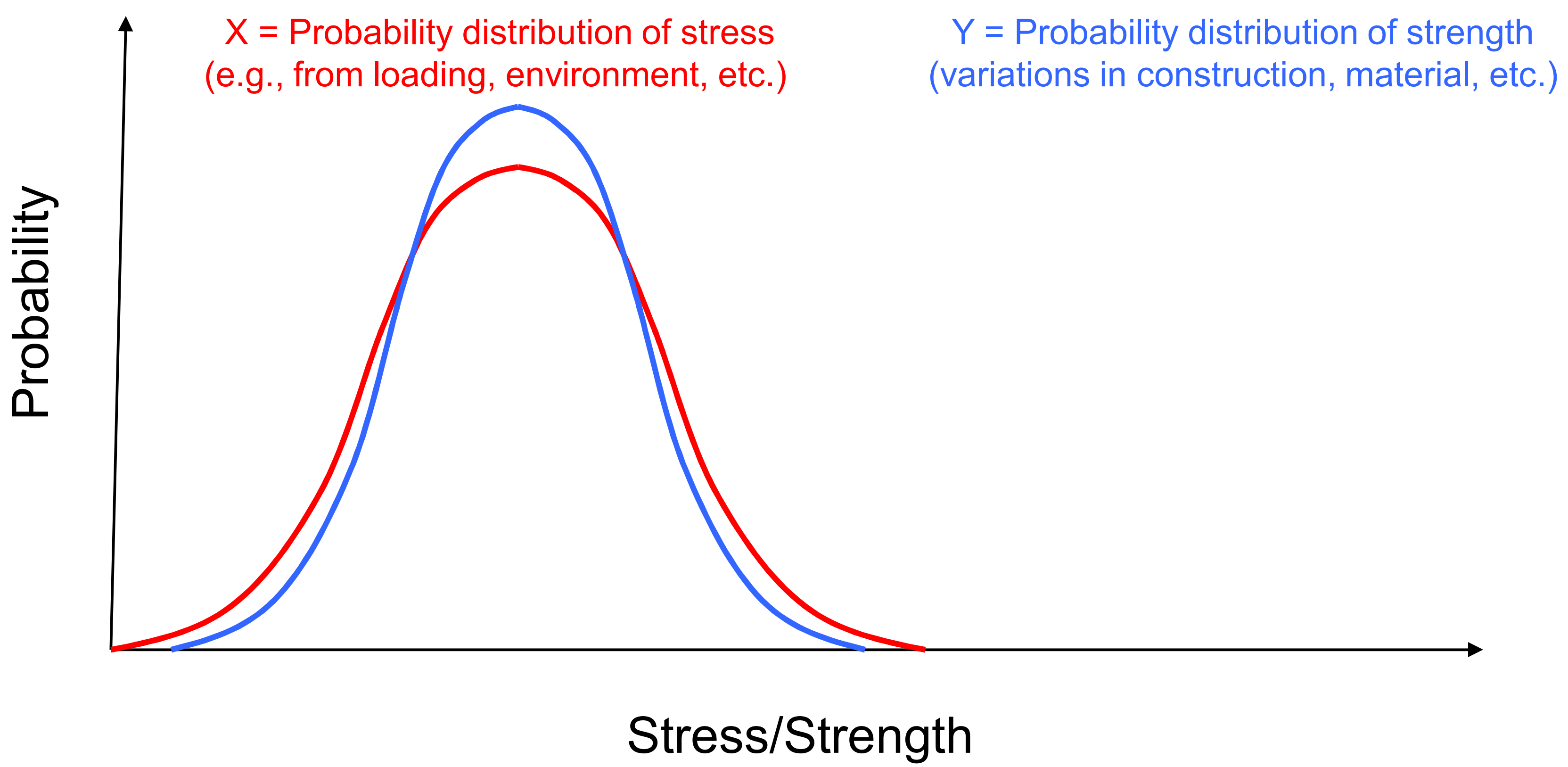
Terms − Rigid

- **J (load transfer coefficient)**
  - **Accounts for load transfer efficiency**
  - **Lower J-factors = better load transfer**
  - **Between 3.8 (undoweled JPCP) and 2.3 (CRCP with tied shoulders)**
- **E_c (PCC elastic modulus)**
  - **4,000,000 psi is a good estimate**
- **k (modulus of subgrade reaction)**
  - **Estimates the support of the PCC slab by the underlying layers**
  - **Usually between 50 and 1000 psi/inch**

Reliability

Reliability = P [Y > X]

$$P[Y > X] = \int_{-\infty}^{\infty} f_x(x)\left[\int_{x}^{\infty} f_y(y)\,dy\right]dx$$



WSDOT Flexible Table

Design Period ESALs	Subgrade Condition	Layer Thickness[1] (feet)											
		Reliability = 75%				Reliability = 85%				Reliability = 95%			
		HMA Surface Course	HMA Base Course	ATB	Crushed Stone[2]	HMA Surface Course	HMA Base Course	ATB	Crushed Stone[2]	HMA Surface Course	HMA Base Course	ATB	Crushed Stone[2]
0.5 - 1 million	Poor	0.35	-	-	1.25	0.40	-	-	1.30	0.45	-	-	1.45
	Average	0.35	-	-	0.65	0.40	-	-	0.70	0.45	-	-	0.75
	Good	0.35	-	-	0.25	0.40	-	-	0.25	0.45	-	-	0.25
1 - 5 million	Poor	0.35	0.30	0.30	0.30	0.35	0.35	0.30	0.30	0.35	0.45	0.30	0.30
	Average	0.35	0.30	-	0.30	0.35	0.35	-	0.30	0.35	0.45	-	0.30
	Good	0.25	0.35	-	0.30	0.25	0.25	-	0.30	0.35	0.25	-	0.30
5 - 10 million	Poor	0.25	0.40	0.30	0.35	0.35	0.30	0.30	0.35	0.35	0.55	0.30	0.35
	Average	0.35	0.40	-	0.35	0.35	0.45	-	0.35	0.35	0.50	-	0.35
	Good	0.25	0.30	-	0.35	0.35	0.25	-	0.35	0.35	0.30	-	0.35
10 - 25 million	Poor	0.35	0.50	0.30	0.45	0.35	0.55	0.30	0.45	0.35	0.70	0.30	0.45
	Average	0.35	0.45	-	0.45	0.35	0.50	-	0.45	0.35	0.60	-	0.45
	Good	0.35	0.25	-	0.45	0.35	0.30	-	0.45	0.35	0.40	-	0.45
25 - 50 million	Poor	0.35	0.60	0.30	0.45	0.35	0.70	0.30	0.45	0.35	0.80	0.30	0.45
	Average	0.35	0.55	-	0.45	0.35	0.60	-	0.45	0.35	0.75	-	0.45
	Good	0.35	0.35	-	0.45	0.35	0.40	-	0.45	0.35	0.50	-	0.45
50 - 75 million	Poor	0.35	0.70	0.30	0.45	0.35	0.75	0.30	0.45	0.35	0.85	0.30	0.45
	Average	0.35	0.60	-	0.45	0.35	0.70	-	0.45	0.35	0.80	-	0.45
	Good	0.35	0.40	-	0.45	0.35	0.45	-	0.45	0.35	0.55	-	0.45

1. Based on the 1993 AASHTO *Guide for Design of Pavement Structures* for flexible pavements with the following inputs:

   $\Delta PSI = 1.5$ | $a_{surface\ HMA} = 0.44$ | Subgrade condition (effective modulus):

   $S_0 = 0.50$ | $a_{base\ HMA} = 0.44$ | Poor: M_R = 35 MPa (5,000 psi)

   $m = 1.0$ | $a_{ATB} = 0.30$ | Average: M_R = 70 MPa (10,000 psi)

   $a_{crushed\ stone} = 0.13$ | Good: M_R = 140 MPa (20,000 psi)

2. Gravel borrow may be substituted for a portion of crushed stone when the required thickness of the crushed stone is at least 0.70 ft.. The minimum thickness of crushed stone is 0.35 ft. when such a substitution is made.
3. Shaded areas indicate unlikely combinations of ESALs and reliability for mainline roadways.

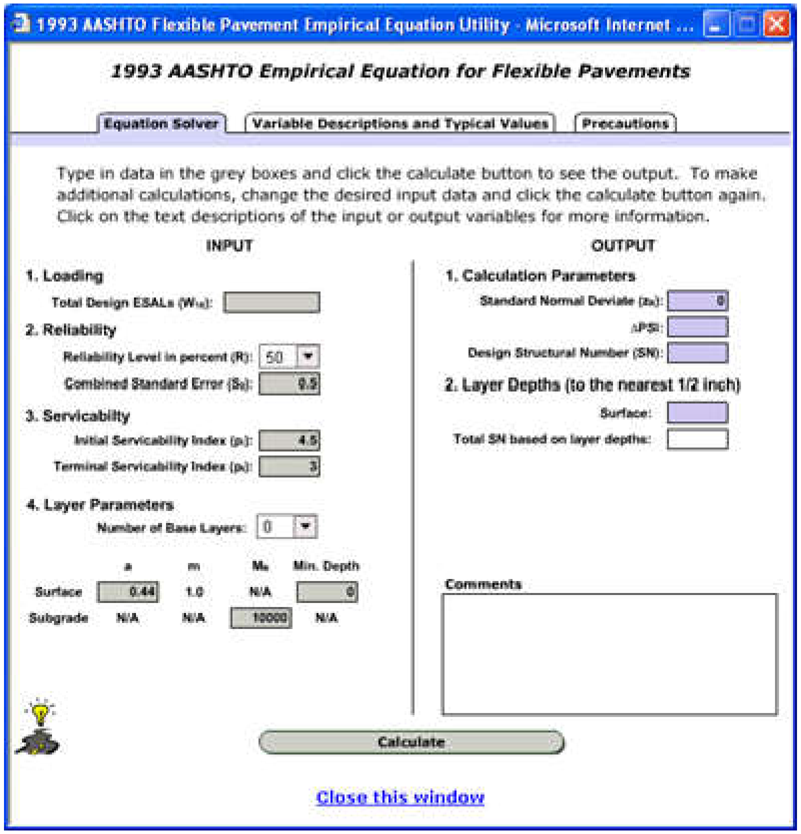
WSDOT Rigid Table

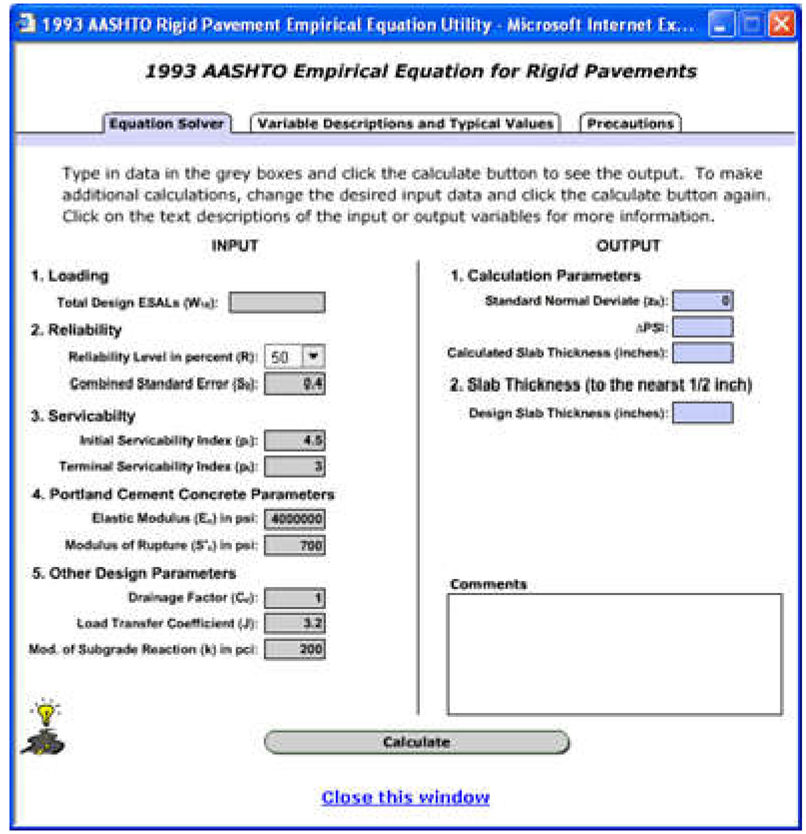
Design Period ESALs	Slab Thickness[1] (feet)		
	Reliability = 75%	Reliability = 85%	Reliability = 95%
Undoweled Joints, Crushed Stone Base Material			
< 5 million	0.74	0.79	0.85
5 - 10 million	0.82	0.87	0.95
10 - 15 million	0.89	0.94	1.02
Undoweled Joints, HMA Base Material			
< 5 million	0.71	0.75	0.84
5 - 10 million	0.80	0.85	0.94
10 - 25 million	0.94	0.98	1.08
Doweled Joints, Crushed Stone Base Material			
< 25 million	0.85	0.90	0.98
25 - 50 million	1.28	1.00	1.02
> 50 million	1.02	1.07	1.16
Doweled Joints, HMA Base Material			
< 25 million	0.75	0.79	0.87
25 - 50 million	0.84	0.90	0.97
> 50 million	0.90	0.95	1.03

1. Based on the 1993 AASHTO *Guide for Design of Pavement Structures* for rigid pavements with the following inputs:

$\Delta PSI = 1.5$	E_c = 26,700 MPa (4,000,000 psi)	Modulus of subgrade reaction (k):
$S_0 = 0.40$	S'_c = 4,480 kPa (650 psi)	k = 54 MPa/m (200 pci) for stone base
$C_d = 1.0$	J = 3.4 for undoweled pavement	k = 108 MPa/m (400 pci) for HMA base
	J = 2.7 for doweled pavement	assumes unyielding subgrade conditions

Design Utilities





From the WSDOT *Pavement Guide Interactive*

http://guides.ce.washington.edu/uw/wsdot

://www.pavementinteractive.org/1993-aashto-rigid-pavement-structural-design-ap

New AASHTO Method

- **Mechanistic-empirical**
- **Can use load spectra (instead of ESALs)**
- **Computationally intensive**
  - **Rigid design takes about 10 to 20 minutes**
  - **Flexible design can take several hours**

Design Example − Part 1

A WSDOT traffic count on Interstate 82 in Yakima gives the following numbers:

Parameter	Data	WSDOT Assumptions
AADT	18,674 vehicles	
Singles	971 vehicles	0.40 ESALs/truck
Doubles	1,176 vehicles	1.00 ESALs/truck
Trains	280 vehicles	1.75 ESALs/truck

Assume a 40-year pavement design life with a 1% growth rate compounded annually. How many ESALs do you predict this pavement will by subjected to over its lifetime if its lifetime were to start in the same year as the traffic count?

$$Total = \frac{P\left(\left(1+i\right)^n - 1\right)}{i}$$

Solution

- **First year ESALs**
- **ESALs in traffic count year = 0.40(971) + 1.00(1176) + 1.75(280) = 2,054.4 ESALs/day**
- **Total ESALs = 2,054.4 × 365 = 749,856**

- **In 40 years**
- **Total ESALs = 749,856($(1+0.01)^{40}$-1)/0.01 = 36,657,740 ESALs**

Design Example − Part 2

Design a flexible pavement for this number of ESALs using (1) the WSDOT table, and (2) the design equation utility in the WSDOT *Pavement Guide Interactive*. Assume the following:

- Reliability = 95% (Z_R = -1.645 , S_0 = 0.50)
- ΔPSI = 1.5 (p_0 = 4.5, p_t = 3.0)
- 2 layers (HMA surface and crushed stone base)
  - HMA coefficient = 0.44, minimum depth = 4 inches
  - Base coefficient = 0.13, minimum depth = 6 inches
  - Base M_R = 28,000 psi
- Subgrade M_R = 9,000 psi

Design Example – Part 3

Design a doweled JPCP rigid pavement for this number of ESALs using (1) the WSDOT table, and (2) the design equation utility in the WSDOT *Pavement Guide Interactive*. Assume the following:

- Reliability = 95% (Z_R = -1.645 , S_0 = 0.40)
- ΔPSI = 1.5 (p_0 = 4.5, p_t = 3.0)
- E_{PCC} = 4,000,000 psi
- S'_C = 700 psi
- Drainage factor (C_d) = 1.0
- Load transfer coefficient (J) = 2.7
- Modulus of subgrade reaction (k) = 400 psi/in
  HMA base material

Primary References

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