The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Structural Design of Porous Asphalt Pavements

Tuesday, July 17, 2018
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss the composition and use of porous asphalt pavements.

Learning Objectives

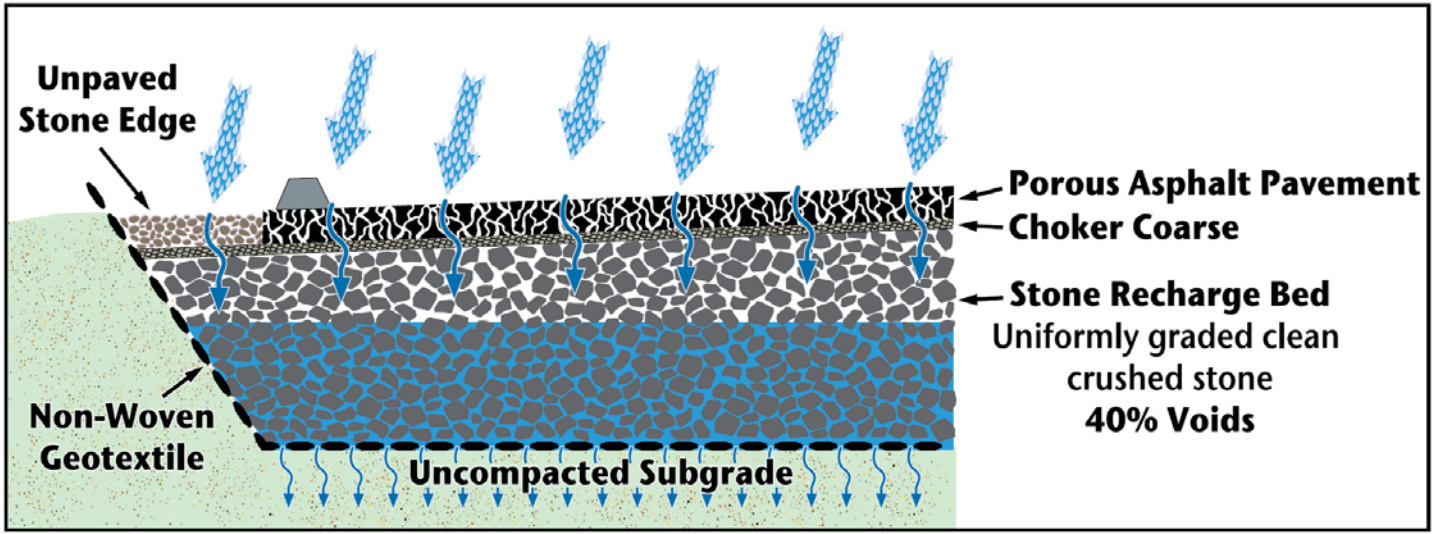
At the end of this webinar, you will be able to:

- Define structural design-related properties for materials used in porous flexible pavements
- Estimate the stiffness of a composite foundation (base and subgrade), which is equivalent to a given layered system
- Design and select the thickness of a porous asphalt pavement suitable to carry projected traffic loads

Structural Design of Porous Asphalt Pavements

Background

Porous Pavements



National Asphalt Pavement Association, IS-131

Hydrologic Characteristics:

- Subgrade infiltration rate: 0.1 to 10 inches/hour
- Time to drain, stone recharge bed: 12 to 72 hours

} Stone Recharge Bed typical thickness: 12 to 36 inches

Scope

✓ **Structural Design of Porous Asphalt Pavements**

Ensuring the Pavement Structure Can Carry the Design Traffic Loads

✗ Site Selection

✗ Hydrologic Design

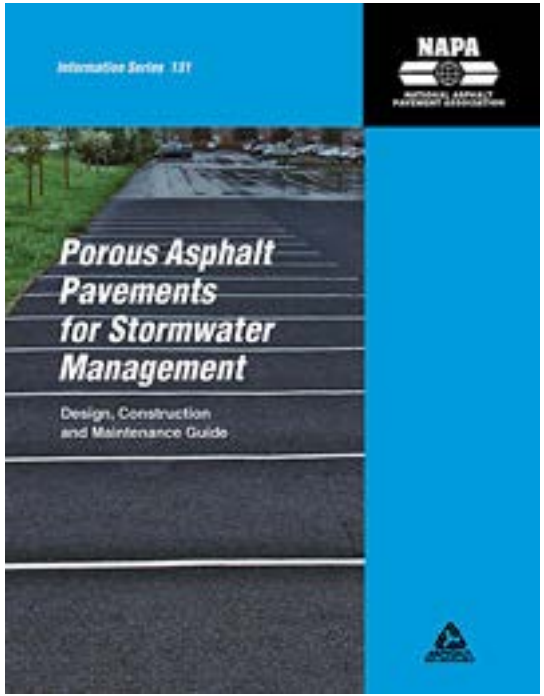
✗ Mixture design

✗ Construction

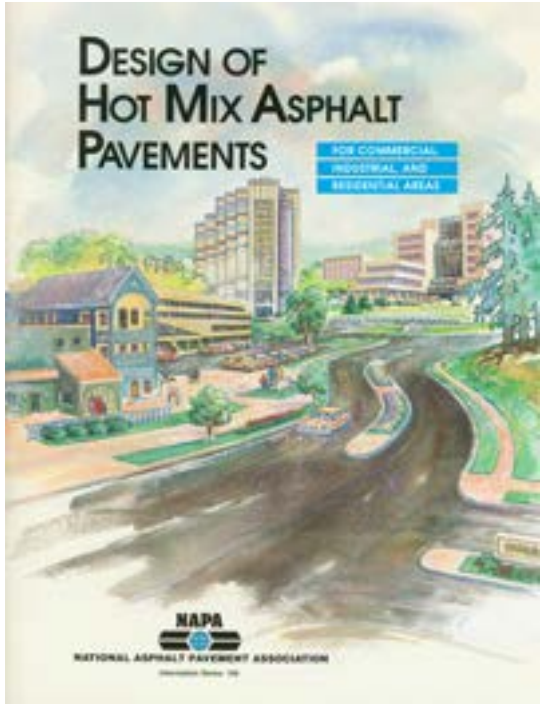
✗ Maintenance


http://theasphaltpro.com/when-it-rains-it-porous/

Additional Information Sources

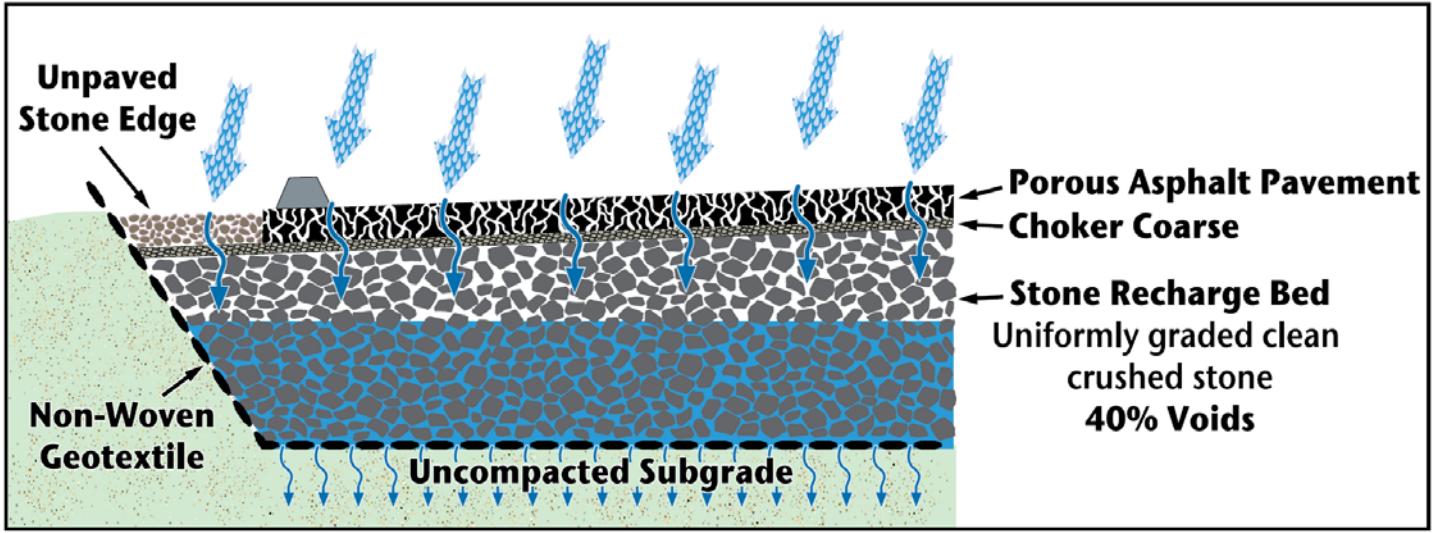


NAPA Information Series 131



NAPA Information Series 109

Porous Pavements



National Asphalt Pavement Association, IS-131

Porous vs. Conventional Pavements (1)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Asphalt Surface	Provide stable wearing surface; allows infiltration of water to stone recharge bed	Open-graded asphalt concrete; minimal compaction; interconnected voids; high air voids (typically 15 to 20% or more); permeable	Provide stable wearing surface; maintain ride quality; prevent water infiltration into the underlying layers; reduce traffic-induced stress/strain to underlying layers	Dense-graded asphalt concrete; low air voids (typically <8%); relatively impermeable; may have 1, 2, or 3 lifts of varying aggregate size.

Porous vs. Conventional Pavements (2)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Base Layer(s)	“Choker Course” - stable surface for subsequent paving	Clean, single-sized crushed stone	Provide structural capacity to pavement system; reduce traffic-induced stress/strain on subgrade	Dense-graded crushed stone
	“Stone Recharge Bed” - stormwater storage	Clean, single-sized large crushed stone with high void ratio (typically ~40%)		
	“Separation Layer” - prevents migration of fine subgrade material to recharge bed	Geotextile fabric		

Porous vs. Conventional Pavements (3)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Subgrade	Provide infiltration of stormwater	Natural or select material (ideally, low fines content); typically uncompacted or only lightly-compacted to promote infiltration	Provide stable platform for pavement structure	Natural or select material; typically compacted to high percentage of maximum density

Structural Design

Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

$$\log_{10} w_{18} = z_R * s_o + 9.36 * \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$

***SN* = required Structural Number (structural capacity) of the pavement**

w_{18} = number of 18-kip equivalent single axle loads (ESALs) expected over design life
z_R = standard normal deviate (level of design reliability)
s_o = standard deviation
ΔPSI = allowable change in the Present Serviceability Index (PSI) over design life
M_R = subgrade resilient modulus (psi)

Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

$$\log_{10} w_{18} = z_R * s_o + 9.36 * \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$

SN* = design Structural Number of the pavement = *DESIGN OUTPUT

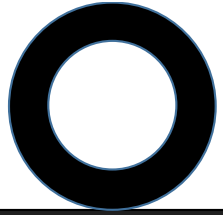
$$SN = d_1 a_1 + d_2 a_2 m_2$$

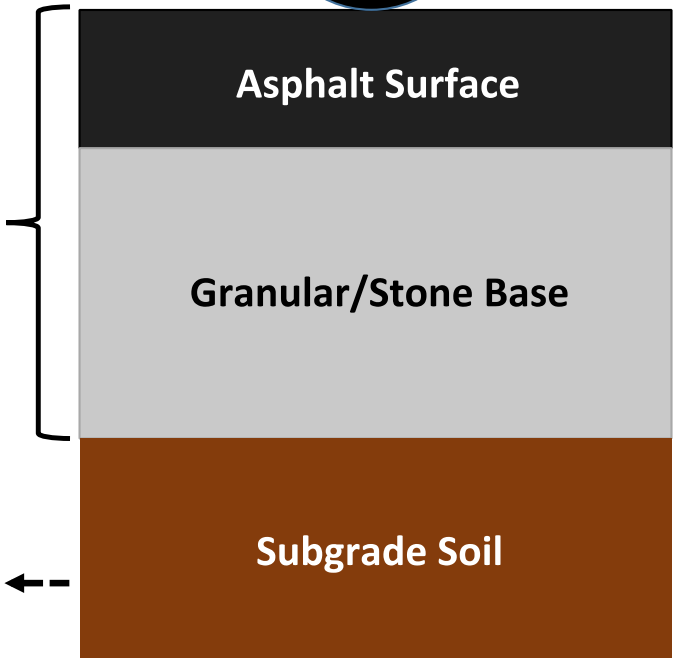
d_1 = thickness of asphalt layer
a_1 = structural layer coefficient for asphalt
d_2 = thickness of granular base (stone recharge bed)
a_2 = structural layer coefficient for granular base
m_2 = moisture/drainage coefficient for unbound granular base

Design Traffic
W_{18}
(ESAL)

AASHTO Design Equation:
$\mathbf{SN_{design}}$
of Pavement Structure

Subgrade Resilient Modulus
M_R
(psi)





a_i = structural coefficient
d_i = thickness (in)
m_i = drainage coefficient

$$a_1 * d_1 = SN_1$$

$$+$$

$$a_1 * d_1 * m_2 = SN_2$$

$$SN_1 + SN_2 = SN_{pvmt}$$

$$\mathbf{SN_{design} \leq SN_{pvmt}}$$

Structural Design Inputs

Structural Design Inputs (1)

AASHTO Design Equation: Design Traffic w_{18} (ESALs)

Use existing agency procedure for estimating design traffic or the NAPA Traffic Classifications:

Type of facility and vehicle types	Maximum trucks per month (one lane)	Traffic class	Design period (years)	Design ESALs
Residential driveways, parking stalls, parking lots for autos and pickup trucks.	<1	Class I	5 10 15 20	3,000 3,000 5,000 7,000
Residential streets without regular truck traffic or city buses; traffic consisting of autos, home delivery trucks, trash pickup, occasional moving vans, etc.	60	Class II	5 10 15 20	7,000 14,000 20,000 27,000
Collector streets, shopping center delivery lanes; up to 10 single-unit or 3-axle semi-trailer trucks per day or equivalents; average gross weights should be less than the legal limit.	250	Class III	5 10 15 20	27,000 54,000 82,000 110,000
Heavy trucks; up to 75 fully loaded 5-axle semi-trailer trucks per day; equivalent trucks in this class may included loaded 3-axle and 4-axle dump trucks, gross weights over 40,000 lbs.	2200	Class IV	5 10 15 20	270,000 540,000 820,000 1,100,00

NAPA Information Series 109, Design of Hot-Mix Asphalt Pavements for Commercial, Industrial, and Residential Areas

Structural Design Inputs (2)

AASHTO Design Equation: Reliability, Standard Deviation, ΔPSI

Design Reliability

Reliability (%)	Std Normal Deviate, Z_R
50	0.000
75	-0.674
80	-0.842
90	-1.282
95	-1.645
99.99	-3.719

Standard Deviation

Typical values for the AASHTO flexible pavement equation:

0.42 – 0.49

For Reliability, Standard Deviation, and ΔPSI, use typical values and policies of local/state agencies.

ΔPSI

$$\Delta PSI = p_0 - p_t$$

p_0 Initial serviceability index; typical values: 4.2 – 4.5

p_t Terminal serviceability index; typical values: 2.0 – 2.5

Typical Values for ΔPSI:

2.0 – 2.5

Structural Design Inputs (3)

AASHTO Design Equation: Subgrade Resilient Modulus -- M_R

- Resilient modulus for existing subgrade soil
  - NAPA Subgrade Classification Guide (next slide)
- Reduce typical modulus values in NAPA table by 25 to 50%
  - Subgrades typically uncompacted/lightly compacted
  - Subgrades typically at higher moisture contents
- Composite subgrade modulus for structural pavement design
  - Accounts better for thick stone recharge bed
  - Procedure described later

Subgrade Classification Guide w/ Typical Resilient Modulus (M_R) Values

NAPA Information Series 109, Design of Hot-Mix Asphalt Pavements for Commercial, Industrial, and Residential Areas (2002)

Soil Type	Unified Soil Class	Percent Finer Than 0.02mm	Permeability	Frost Potential[1]	Typical CBR[2]	Design Class	Typ. Flexible Pavement M_R (psi)[2]	Porous Pavement M_R (psi)[2]
Sands, sand-gravel mix Little or no fines <0.02mm	SW,SP	0 – 3	Excellent	NFS	17	Very Good	20,000	20,000
Sands, sand-gravel mix Some fines <0.02mm	SW,SP	1.5 – 3	Good	PFS	17	Very Good	20,000	20,000
Sandy soils Medium fines <0.02mm	SW,SP,SM	3 – 6	Fair	Low	8	Good	12,000	9,000
Silty gravel soils High fines <0.02mm	GM, GW-GM,GP-GM	6 – 10 10 - 20	Fair to Low	Medium	8	Good	12,000	9,000
Silty sand soils High fines <0.02mm	SM, SW-SM,SP-SM	6-15	Fair to Low	Medium	8	Good	12,000	9,000
Clayey sand soils High fines <0.02mm	SM,SC	Over 20	Low to Very Low	Medium to High	5	Medium	7,500	3,750
Clays, PI>12	CL,CH		Very Low	High[3]	3	Poor	4,500	2,250
All silt soils	ML,MH		Very Low	High to V.High[3]	3	Poor	4,500	2,250
Clays, PI<12	CL,CL-CM		Very Low	High to V.High[3]	3	Poor	4,500	2,250

[1]NFS = not frost susceptible; PFS = possible frost susceptible

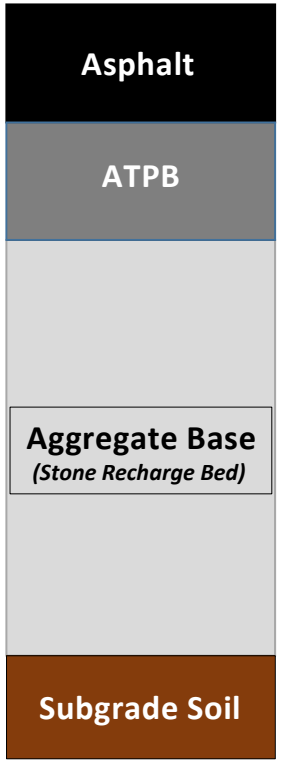
[2]CBR = California Bearing Ratio and Mr = Resilient Modulus values are minimum values expected for each subgrade class

[3]Replace in severe frost areas

(Excerpts)

Structural Design Inputs (4)

AASHTO Design Equation: Layer coefficients a_i



Porous Asphalt: a_1 **= 0.40**

- Typically placed at low densities
- Typically features open gradations

Asphalt-Treated Permeable Base (ATPB): a_2 **= 0.30 to 0.33**
(if present)

Coarse Aggregate Base (Stone Recharge Bed): a_2 **= 0.07 to 0.10**

- Typically placed at high void contents (lower stiffness, e.g. 15 ksi)
- AASHTO stiffness relationship for granular base:

$$a_2 = 0.247(\log_{10} E_{base}) - 0.977$$

Structural Design Inputs (5)

AASHTO Design Equation: Drainage coefficient m_2

Aggregate Base
(Stone Recharge Bed)

Applies to unbound materials only

(Coarse Aggregate Base [Stone Recharge Bed])

- AASHTO relationship based on "quality" of drainage (time to drain) and percent time near saturation

For Porous Asphalt pavements:

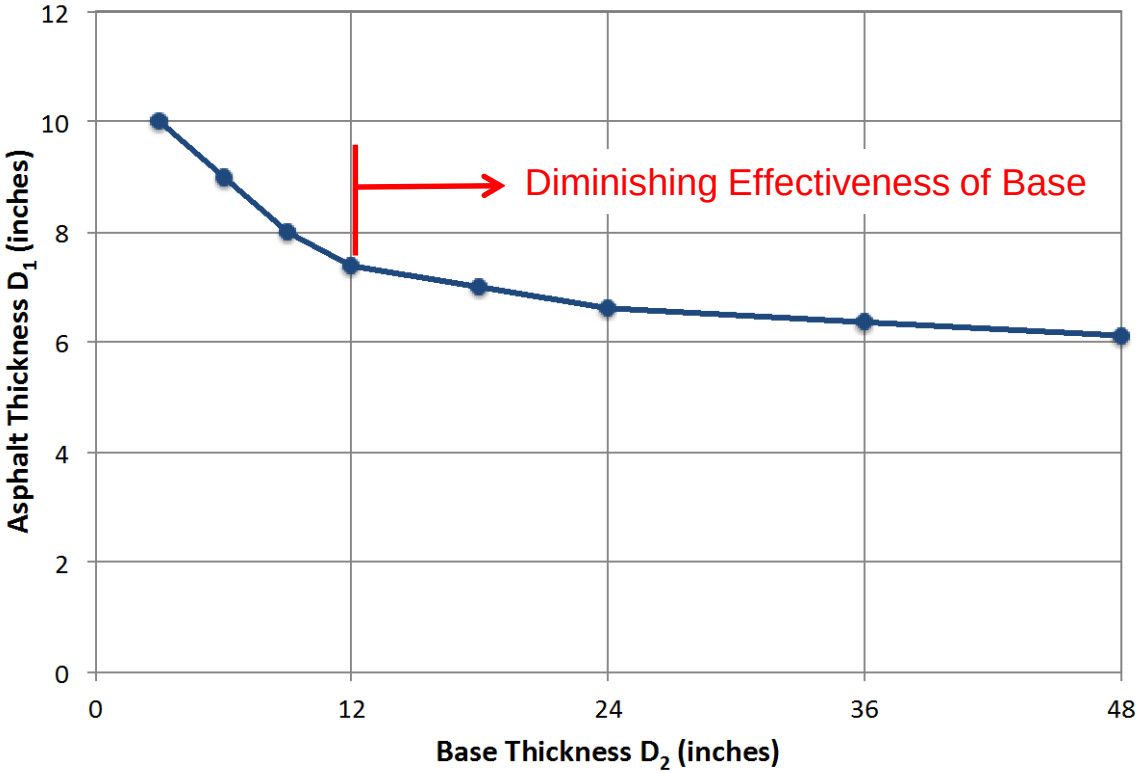
- Assumed drainage quality is GOOD (water removed in ~1 day)
- Assumed time near saturation is 5-25%

Quality of Drainage	Water Removed Within	Percent of Time Pavement is Exposed to Moisture Levels Approaching Saturation			
		<1%	1-5%	5-25%	>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	1.05-0.80	1.05-0.80	0.80-0.60	0.60
Very Poor	> 1 month	0.95-0.75	0.95-0.75	0.75-0.40	0.40

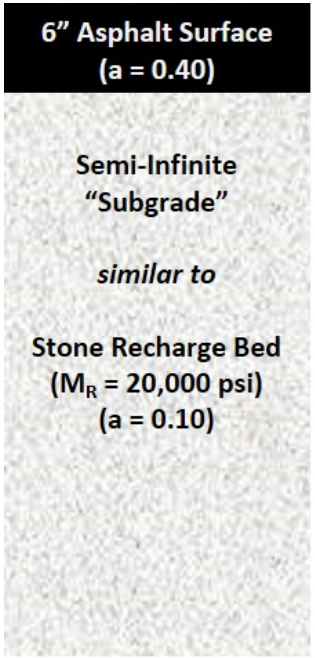
For porous pavement design, use m_2 = 1.0 for all situations

Base Effective Thickness and Composite Subgrade

Effective Thickness of Base Layer
(1993 AASHTO Design Approach)



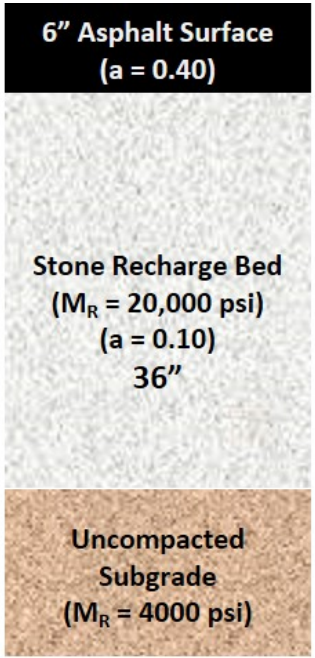
Maximum base thickness at AASHO Road Test was 9 inches!



SN_1= 2.4

From the AASHTO Design Equation:
Reliability = 75% (z_R = -0.674)
Std. Deviation (So) = 0.45
Change in PSI (ΔPSI) = 2.5 (p_0=4.5; p_t=2.0)
Subgrade Modulus (M_R) = 20,000 psi
Structural Number (SN) = 2.40

→ Allowable Traffic: **2.3M ESALs**



SN_1= 2.4

SN_2= 3.6

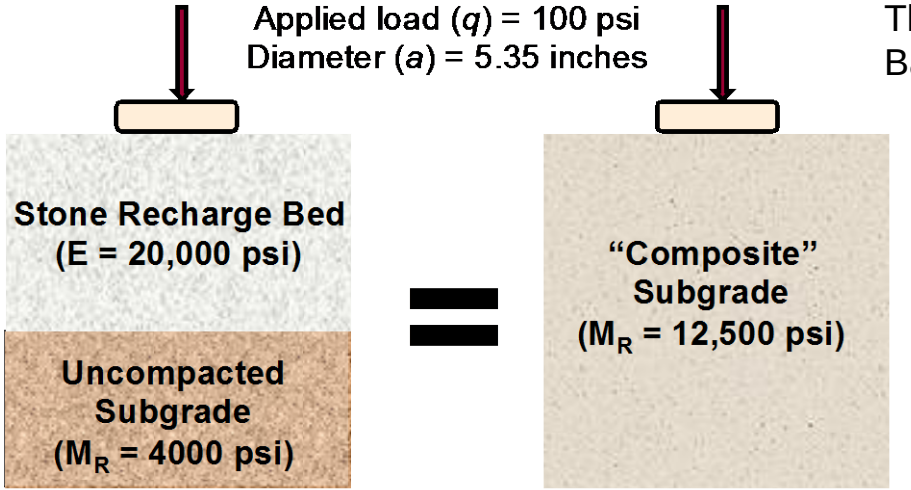
From the AASHTO Design Equation:
Reliability = 75% (z_R = -0.674)
Std. Deviation (So) = 0.45
Change in PSI (ΔPSI) = 2.5 (p_0=4.5; p_t=2.0)
Subgrade Modulus (M_R) = 4000 psi
Structural Number (SN) = 6.0

→ Allowable Traffic: **41.5M ESALs!!**

A Problem…

How can a weaker pavement section carry **20x** more traffic??

Composite Subgrade Concept



These two cross-sections are ***structurally equivalent***
Based on equal surface deflections from an applied load.

The analysis is based on elastic layer theory; the two-layer (stone over subgrade) system is converted to a one-layer ('composite' subgrade) system.

Burmister's Equation
For 2-layer systems:

$$w_o = \frac{1.5qa}{E_2} F_2$$

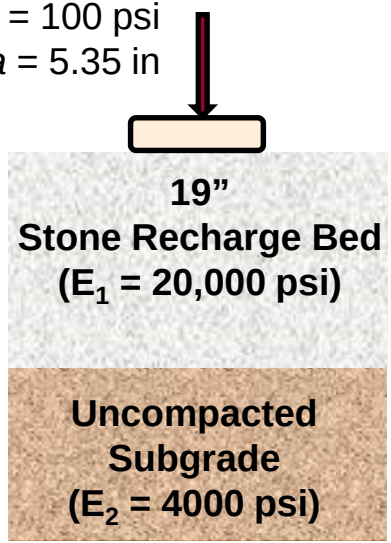
Burmister's Equation
For 1-layer systems:

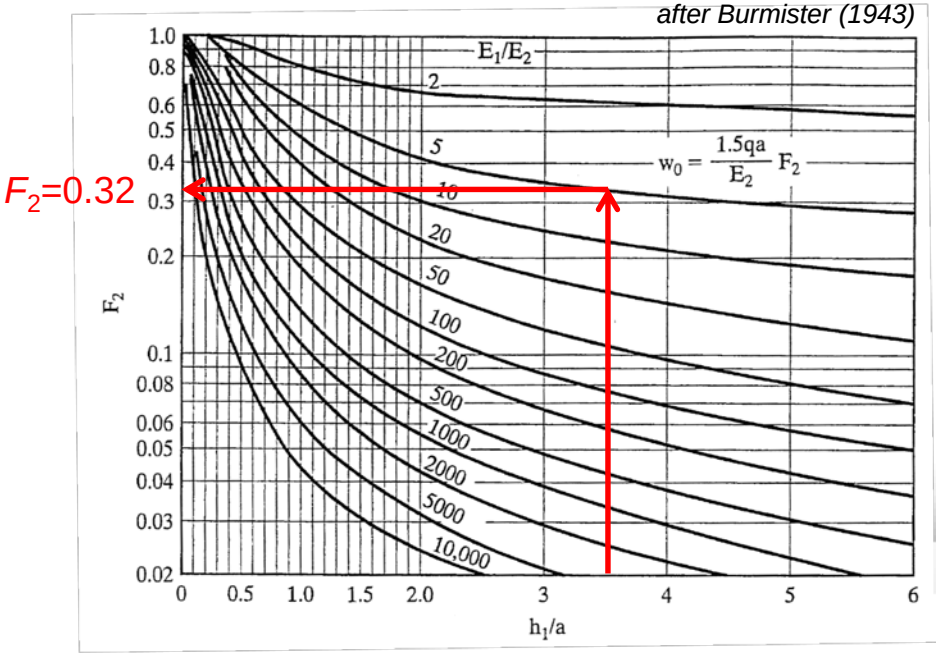
$$w_o = \frac{1.5qa}{E}$$

where:
w_0 = surface deflection (in)
q = applied load (psi)
a = load diameter (in)
E = single-layer modulus
E_2 = 'layer 2' modulus in 2-layer system (uncompacted subgrade)
F_2 = Burmister's 2-layer deflection factor

Deflection of Two-Layer System

q = 100 psi
a = 5.35 in





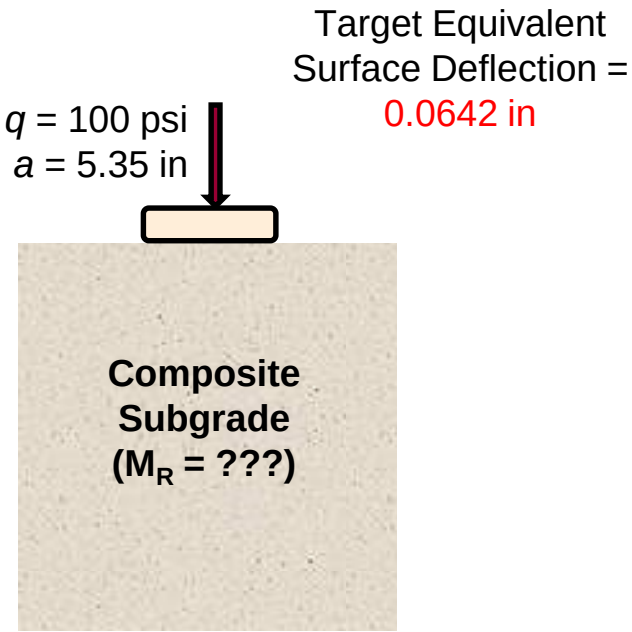
Surface Deflection:

$$w_o = \frac{1.5qa}{E_2} F_2 = \frac{(1.5)(100\ \text{psi})(5.35\ \text{in})}{4000\ \text{psi}}(0.32) = 0.0642\ \text{in}$$

E_1/E_2 = 20,000 psi / 4,000 psi = 5.0

h_1/a = 19 in / 5.35 in = 3.55

Composite Subgrade Stiffness of Equivalent One-Layer System



Surface Deflection for One-Layer System:

$$w_0 = \frac{1.5qa}{E}$$

Equivalent Composite Subgrade for One-Layer System:

$$E = \frac{1.5qa}{w_0} = \frac{1.5(100\text{ psi})(5.35\text{ in})}{0.0642\text{ in}} = 12{,}500\text{ psi}$$

Design Example

Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

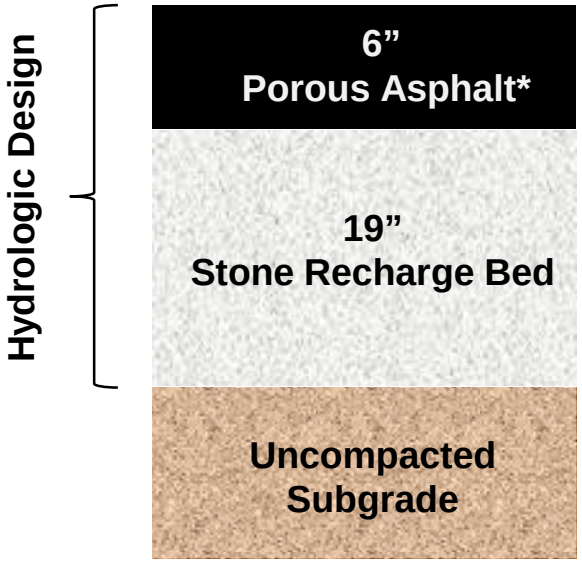
$$\log_{10} w_{18} = z_R * s_o + 9.36 * \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$

***SN* = design Structural Number of the pavement = $D_1a_1 + D_2a_2m_2$**

w_{18} = number of 18-kip equivalent single axle loads (ESALs) expected over design life
z_R = standard normal deviate (level of design reliability)
s_o = standard deviation
ΔPSI = allowable change in the Present Serviceability Index (PSI) over design life
M_R = subgrade resilient modulus (psi)

Step 1: Define the Problem (1)

- **Obtain Hydrologic Design** ***(not covered here)***
- **Determine Structural Parameters**



*Maximum for hydrologic design

Structural Coefficient, a_i	Resilient Modulus, M_R (psi)
0.40 (see Slide 19)	
0.10 (see Slide 19)	**20,000** (see Slide 19)
	4,000 (see Slides 30/18)

Step 1: Define the Problem (2)

- **Determine Design Parameters**

***Given*:**

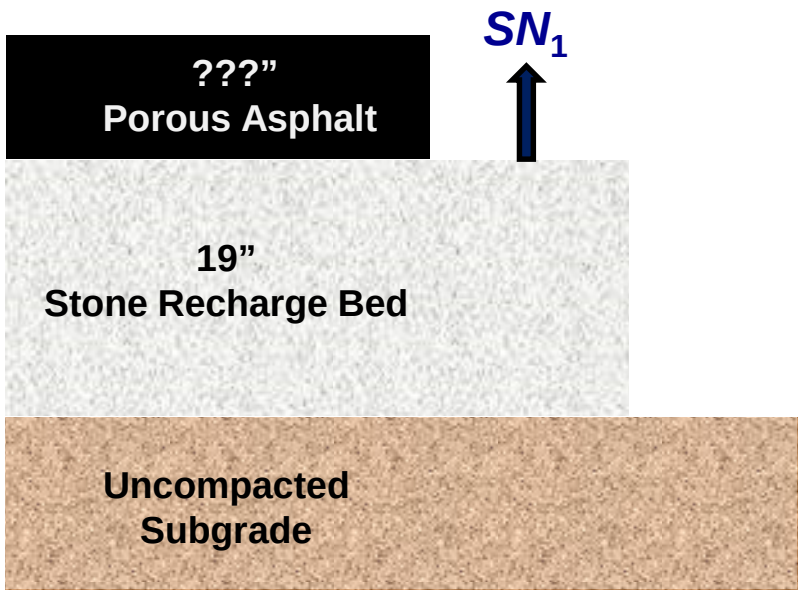
- Design traffic : **3M** ESALs (Heavy Trucks)
  (project specific)

- Subgrade soil: clayey sand with medium-high fines, classification SM, SC
  - Per Subgrade Classification Table (Slide 17), M_R = 3750+ psi
  - Subgrade Modulus for Design: Use **4000** psi

- Allowable deterioration: ΔPSI = **2.5**
  (Initial PSI p_0 = 4.5; Terminal PSI p_t = 2.0)
  (typical values and/or agency policy)

- Reliability parameters:
  (typical values and/or agency policy)
  - Reliability: **75%** (Z_R = -0.674)
  - Standard Deviation: **0.45**

Step 2: Check Minimum Porous Asphalt Thickness



See Slide 29

- w_{18} = **3M** ESALs
- ΔPSI = **2.5**
- Reliability: **75%** (Z_R = -0.674)
- Standard Deviation: **0.45**
- Asphalt layer support provided by stone recharge bed
  - M_R: **20,000** psi **See Slide 28**

***Solve AASHTO Flexible Pavement Design Equation*:**

SN_1 = 2.55

***Minimum asphalt thickness*:**

$d_1 = SN_1/a_1$ = 2.55/0.40 = 6.375 in.

Hydrologic design does NOT provide minimum structural thickness → **minimum d_1 = 6.5 inches**

Step 3: Minimum Porous Asphalt Thickness (2)

Example of a "Design Catalog"

W_{18} (ESALs)	Minimum Porous Asphalt Thickness (inches)
50,000	3.0
100,000	3.5
250,000	4.0
500,000	4.5
750,000	5.0
1,000,000	5.5
2,000,000	6.0
4,000,000	6.5

Values based on:

$a_2 = 0.1$

$E_{base} = 20{,}000$ psi

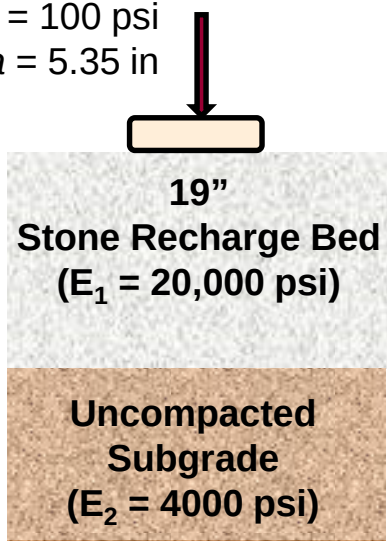
75% reliability

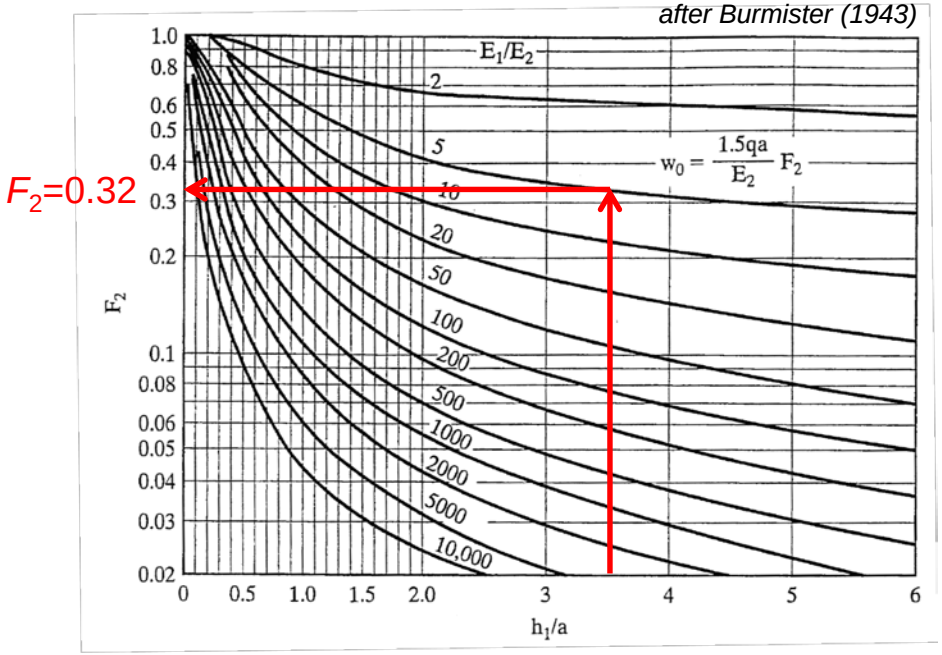
$s_0 = 0.45$

$\Delta PSI = 2.5$

Step 4: Calculate Composite Modulus of the Subgrade (1) – *see slides 24-26*

q = 100 psi
a = 5.35 in





Surface Deflection:

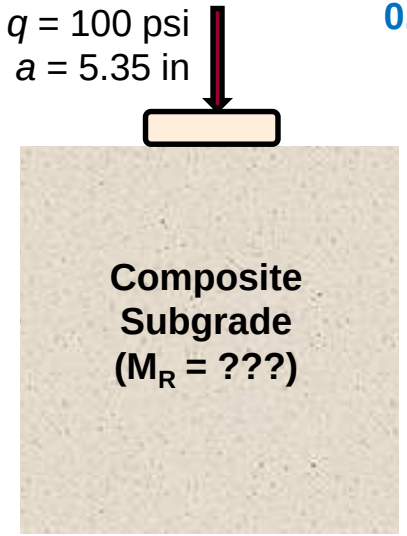
$$w_o = \frac{1.5qa}{E_2}F_2 = \frac{(1.5)(100\text{ psi})(5.35\text{ in})}{4000\text{ psi}}(0.32) = \underline{\underline{0.0642\text{ in}}}$$

E_1/E_2 = 20,000 psi / 4,000 psi = 5.0

h_1/a = 19 in / 5.35 in = 3.55

Step 4: Calculate Composite Modulus of the Subgrade (2) – *see slides 24-26*

Target Equivalent Surface Deflection = **0.0642 in**



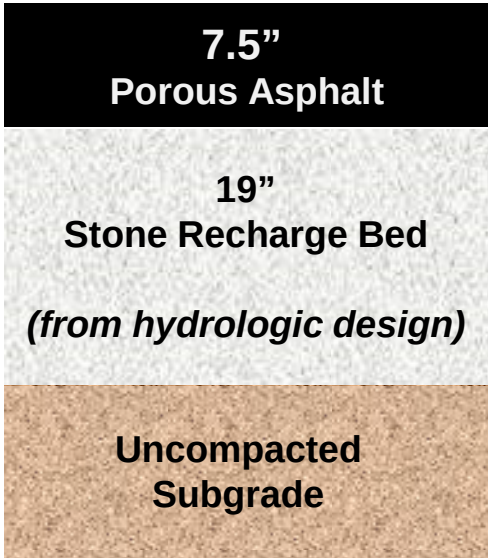
Surface Deflection for One-Layer System:

$$w_0 = \frac{1.5qa}{E}$$

Equivalent Composite Subgrade for One-Layer System:

$$E = \frac{1.5qa}{w_0} = \frac{1.5(100\text{ psi})(5.35\text{ in})}{0.0642\text{ in}} = 12{,}500\text{ psi}$$

Step 6: Establish Final Structure



Porous Asphalt Thickness:

(use maximum value)

- **Hydrologic design: 6 in.**
- **<u>Minimum</u> Structural Thickness: 6.5 in.**
- **Structural Design Thickness: 7.5 in.**

Thickness = SN_{design} / a_1

= 3.00 / 0.40 = 7.5 in

(slide 35) (slide 29)

Design Catalogs

For W_{18} = 3,000,000 ESAL

Base Thickness (inches)	Design Subgrade Resilient Modulus (psi)						
	2000	**3000**	**4000**	**6000**	**8000**	**10000**	**12000**
6	11.5	10	9	8	7.5	7.5	7
12	10	8.5	8	7.5	7	7	6.5
18	8.5	8	7.5	7	7	7	6.5
24	8	7.5	7.5	7	7	6.5	6.5
30	7.5	7.5	7	7	6.5	6.5	6.5
36	7.5	7	7	7	6.5	6.5	6.5
42	7	7	7	6.5	6.5	6.5	6.5
48	7	7	6.5	6.5	6.5	6.5	6.5

Required Porous Asphalt Thickness

(For thin bases, also use conventional AASHTO design and take most conservative case)

Design Assumption for Catalog Tables:

- a_1 = 0.40 (porous asphalt)
- a_2 = 0.10 (stone base)
- E_{base} = 20,000 psi (stone base)
- 75% reliability (Z_R = -0.674)
- s_0 = 0.45 (overall variability)
- ΔPSI = 2.5 (allowable serviceability decrease)
- a = 5.35 in (load radius)
- q = 100 psi (load pressure)

Values for composite subgrade modulus computation

pavexpressdesign.com

PAVEXpress with LCCA Module now in Beta!

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Pavement design using AASHTO 93/98

Pavement design for engineers and students

Pavement design for project scoping

Introduction

Welcome to PaveXpress, a scoping tool to help you create simplified pavement designs while taking into account key engineering inputs.

Resources

PaveXpress includes access to resources such as design guides from state DOTs and industry associations so you can build formal designs from its simple recommendations.

View Resources

Welcome Charles!

Click on the button below to launch the PaveXpress Scoping Tool and start creating your own designs, with options for both flexible and rigid pavement construction.

Enter

Discussion

Today's Speakers

- Kevin Hall, *University of Arkansas,* kdhall@uark.edu

- Chuck Schwartz, *University of Maryland,* schwartz@umd.edu

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