Development and Validation of Mechanistic-Empirical Design Method for Permeable Interlocking Concrete Pavement

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Outline

- Introduction
- Test Track Design
- Test Track Construction
- Accelerated Load Testing
- Test Results
- M-E Design Procedure
- Conclusions

Introduction

- Interest in using permeable pavements in higher traffic applications
- Previous work by UCPRC
  - Preliminary Caltrans Study (2008 – 2010) on permeable concrete and asphalt pavements
  - No validation with traffic
- Validation study funded by industry
- Study objective
  - Develop mechanistic-based design method and tables for PICP

Introduction

- Study approach
  - Literature review
  - Field testing
  - Test track design
  - Test track construction
  - Accelerated load testing
  - Data Analysis
  - Design method & tool
  - Design tables
  - Final report
    - includes interim reports

www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2014-04.pdf

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Research Report: UCPRC-RR-2014-04

Development and HVS Validation of Design Tables for Permeable Interlocking Concrete Pavement: Final Report

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Design Method

- Distress
  - Unbound layer rutting
- Approach
  - Shear stress to shear strength ratio (SSR) at top of layer
  - $0.3 \leq SSR \leq 0.7$
- Required inputs
  - Unbound layer stiffness, strength, and other mechanical properties
  - Obtained from lab and field testing

$$Shear\ Stress\ Ratio\ (SSR) = \frac{\tau_f}{\tau_{max}} \quad (1)$$

$$\tau_f = \frac{\sigma_1 - \sigma_3}{2} cos\phi = \frac{\sigma_d}{2} cos\phi \quad (2)$$

$$\tau_{max} = c + \sigma_f tan\phi \quad (3)$$

$$\sigma_f = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} sin\phi = \frac{\sigma_d + 2\sigma_3}{2} - \frac{\sigma_d}{2} sin\phi \quad (4)$$

Where: τ_{max} is applied shear stress acting on the failure plane oriented at an angle of $45° + \phi/2$

σ_f is applied normal stress acting on the failure plane oriented at an angle of $45° + \phi/2$

τ_f is shear strength of the material under a certain stress state

σ_1 and σ_3 are the major and minor principal stresses, respectively

σ_d is the deviator stress, $\sigma_d = \sigma_1 - \sigma_3$

c is the cohesion of the material

ϕ is the internal friction angle of the material ($\phi = 0$ for stress-independent materials)

Design – Subbase Thickness

Subbase Thickness	Shear Stress Ratio (SSR)	Calculated (mm)		As-Built
		Dry	Wet	
Thin	0.8	450	650	450
Medium	0.5	800	950	650
Thick	0.2	1,350	1,450	950

Surface
- 80 mm interlocking concrete paver

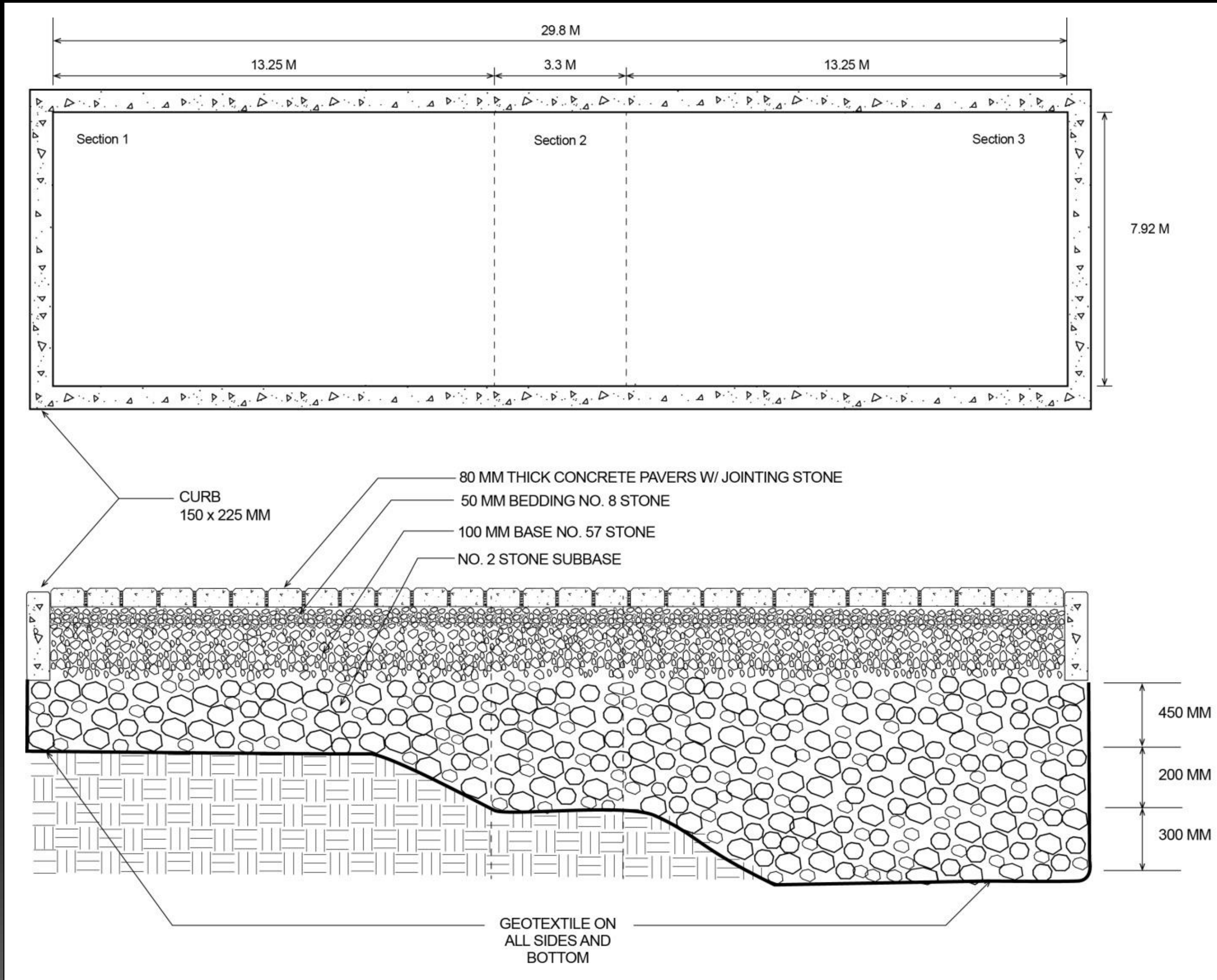
Bedding layer
- 50 mm ASTM #8 aggregate

Base layer
- 100 mm ASTM #57 aggregate

Subbase layer
- Varying thickness ASTM #2 aggregate

Subgrade soil
- Silty clay, compacted after excavation

Design



29.8 M
13.25 M
3.3 M
13.25 M
Section 1
Section 2
Section 3
7.92 M
CURB
150 x 225 MM
80 MM THICK CONCRETE PAVERS W/ JOINTING STONE
50 MM BEDDING NO. 8 STONE
100 MM BASE NO. 57 STONE
NO. 2 STONE SUBBASE
450 MM
200 MM
300 MM
GEOTEXTILE ON
ALL SIDES AND
BOTTOM

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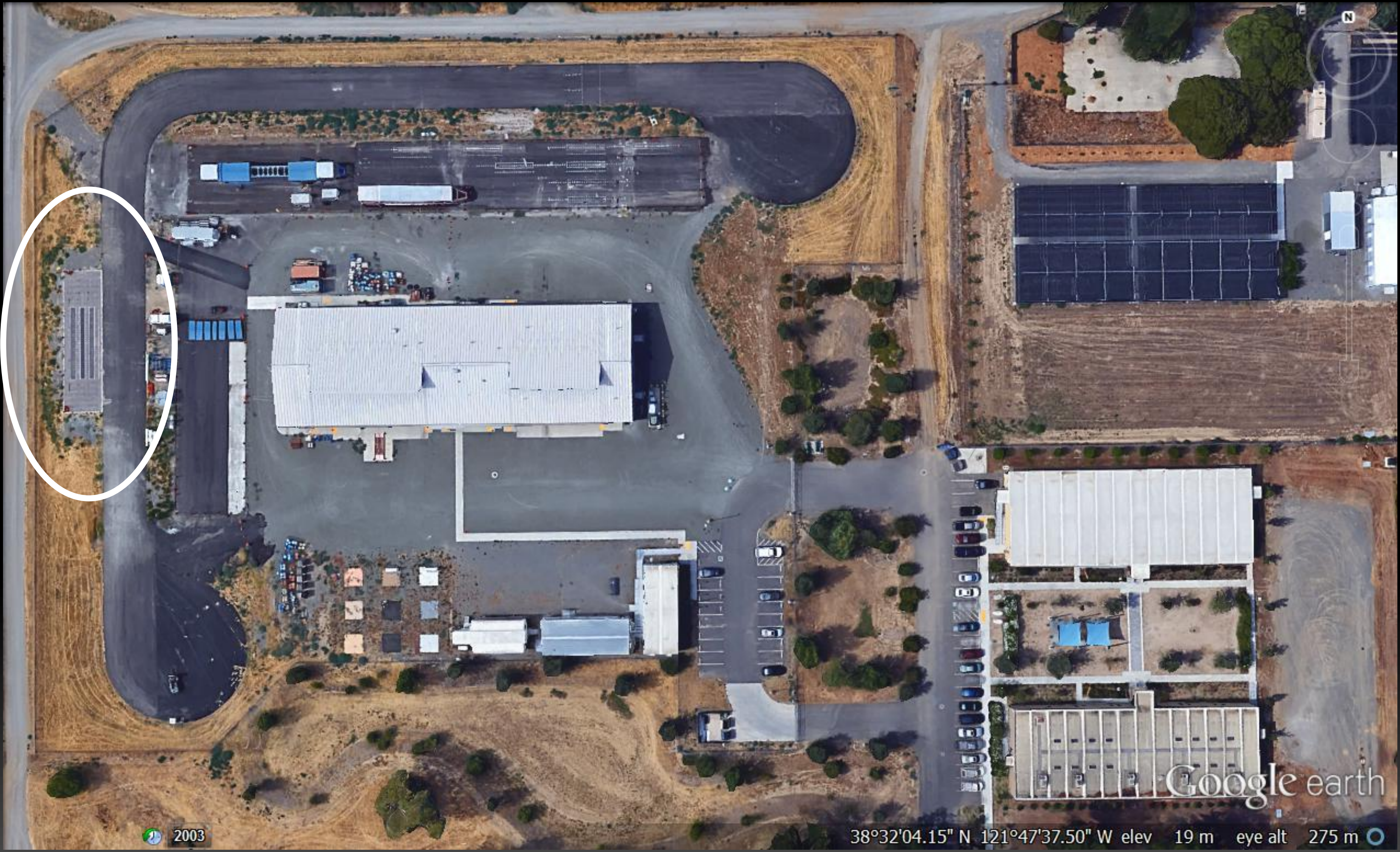
UCPRC Facility



Test Track Construction

Test Track Construction

Instrumentation

- Aggregate size limited options
- Stress (pressure cell)
  - Top of base
  - Top of subgrade
- Deformation (profiler + dipsticks)
  - Surface
  - Top of base
  - Top of subgrade
- Deflection (RSD)
- Water level
  - Manual and automated

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APT – Test Program

- Extended HVS (13m) used to test all sub sections together
  - Bidirectional trafficking with wander
  -
- Th
  -
  -
  -
  -
- Fa
  -

APT – Wet Testing

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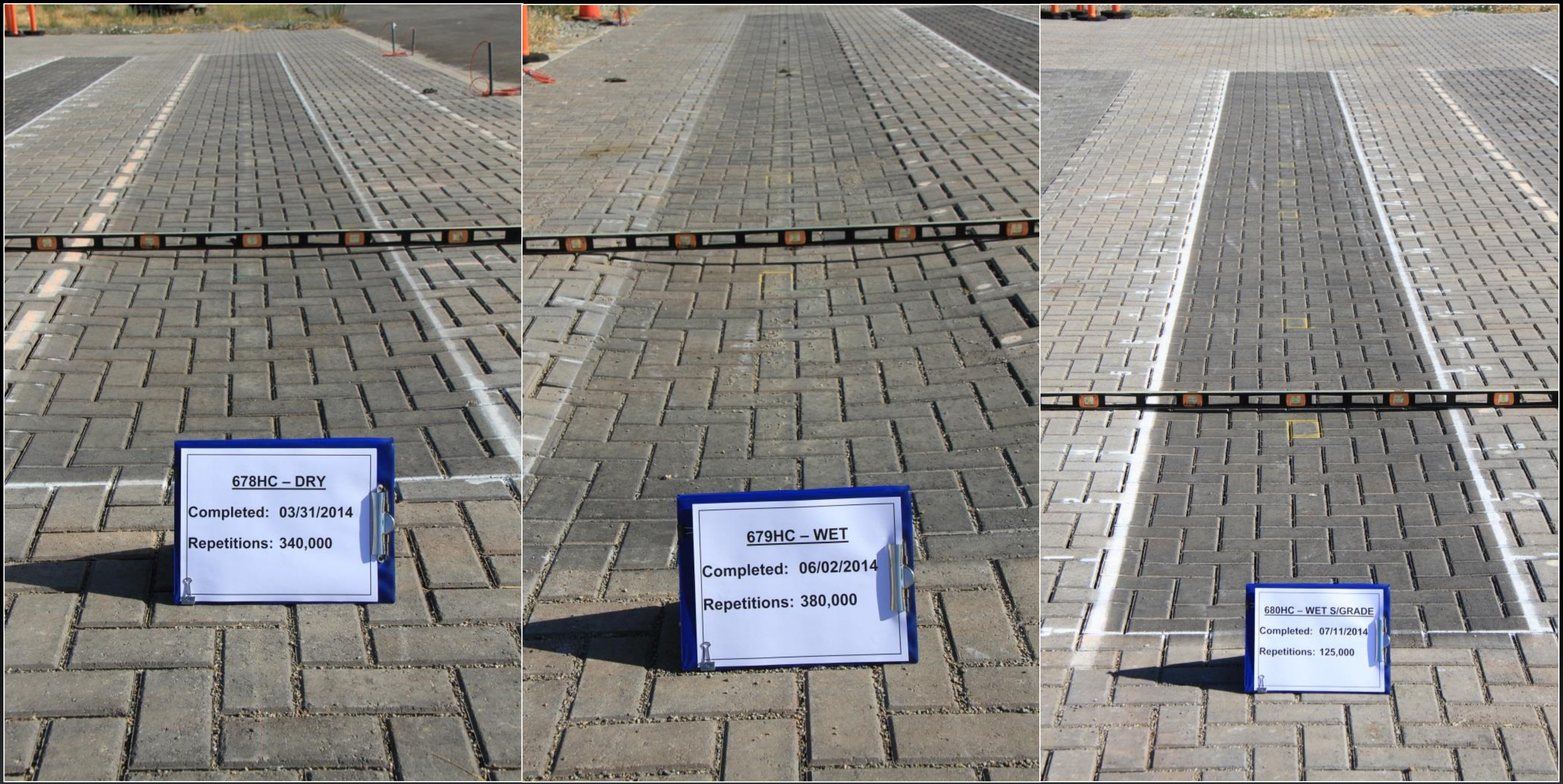
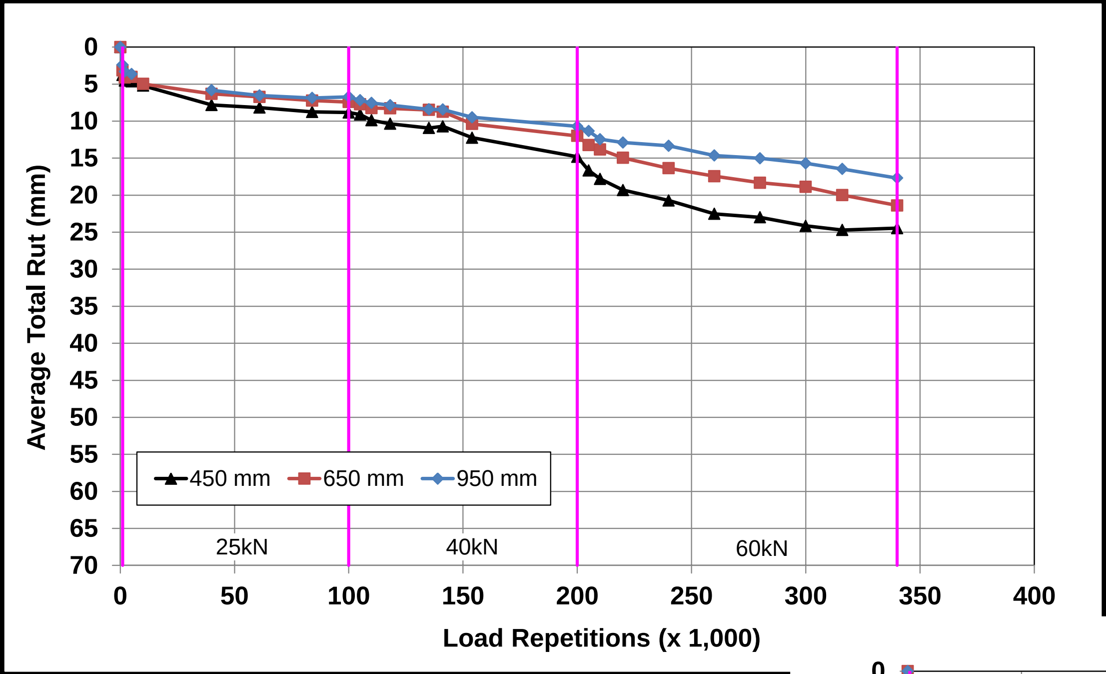
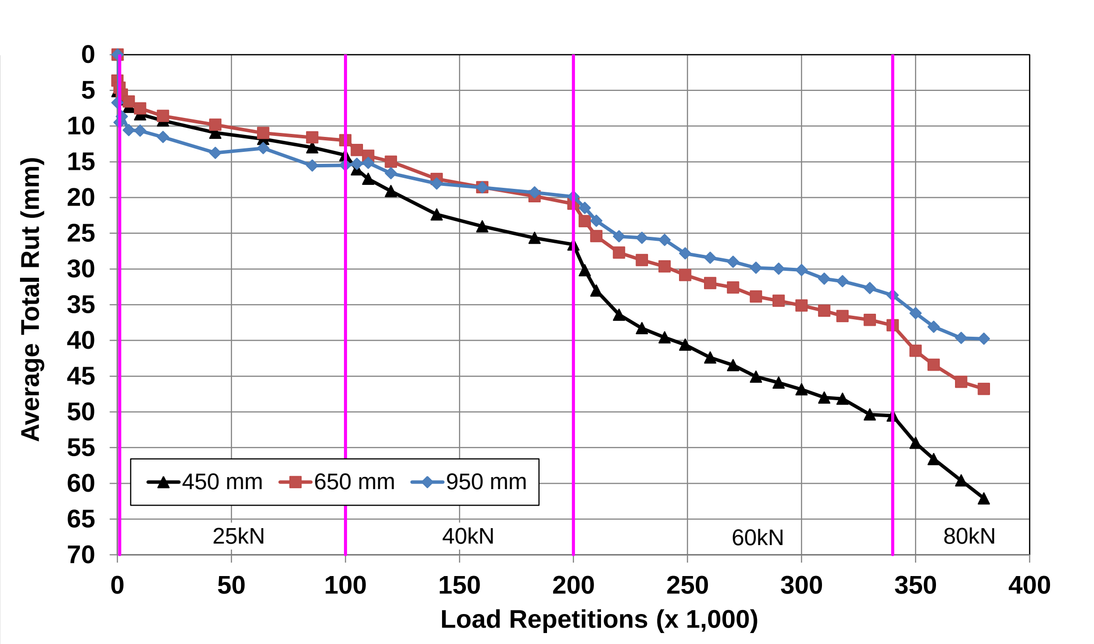
APT – Visual Assessment



APT – Total Surface Rut

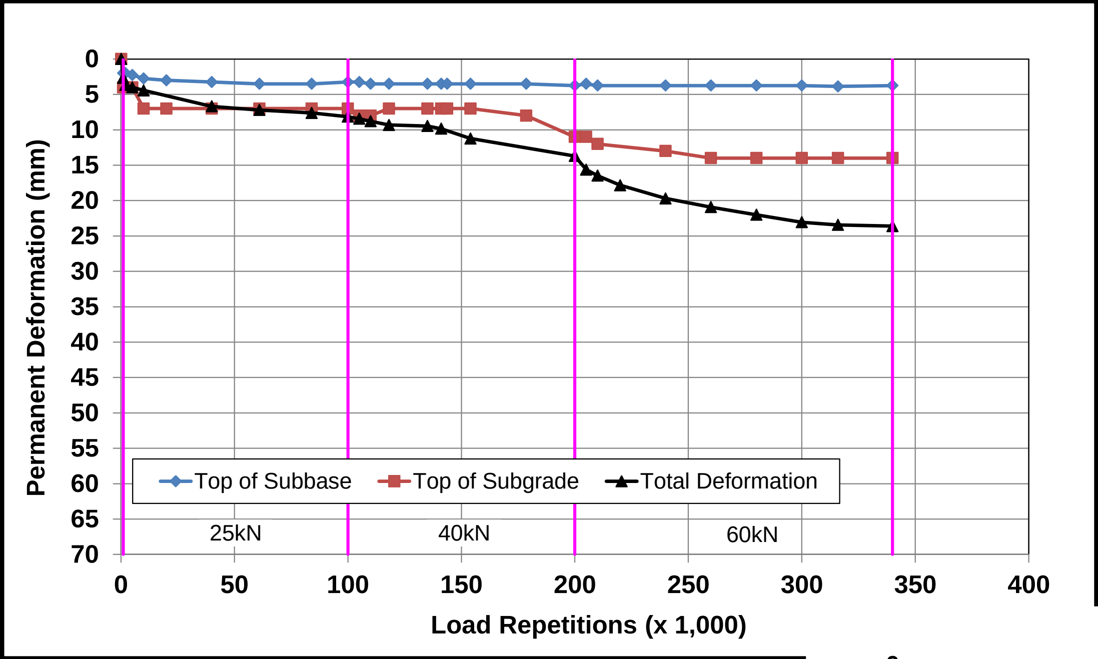


Dry

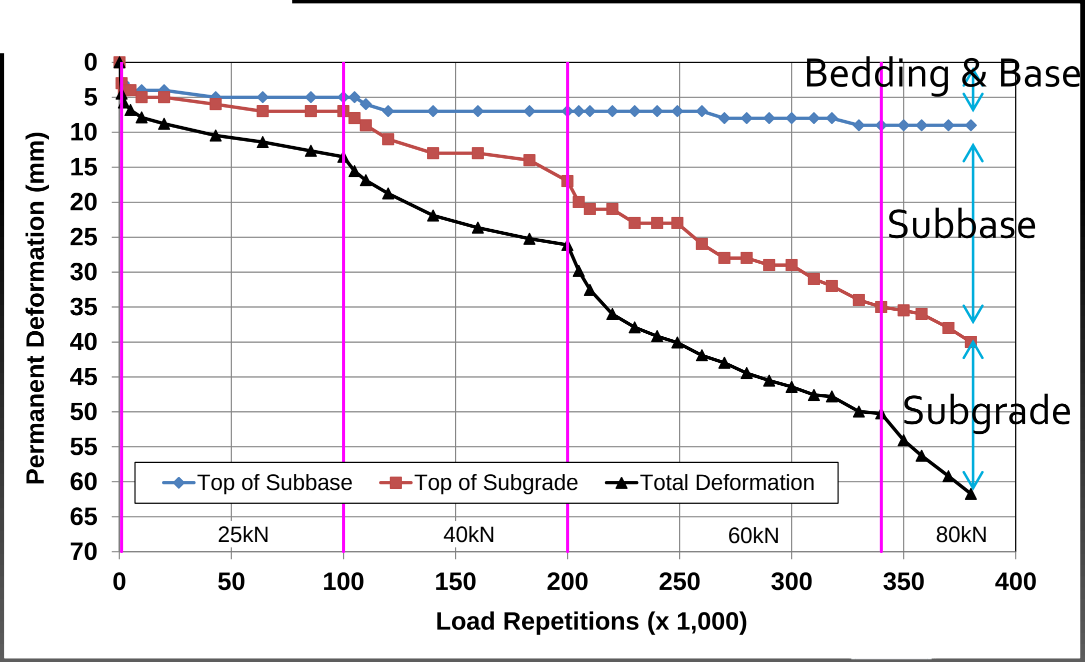


Wet

APT – Down Rut: 450mm Subbase

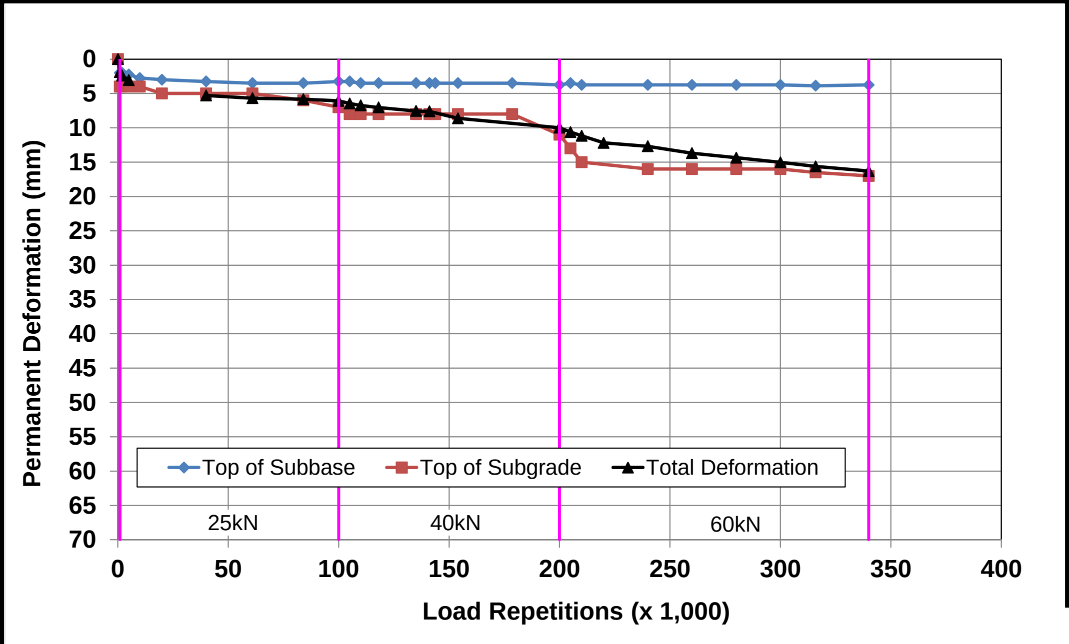


Dry

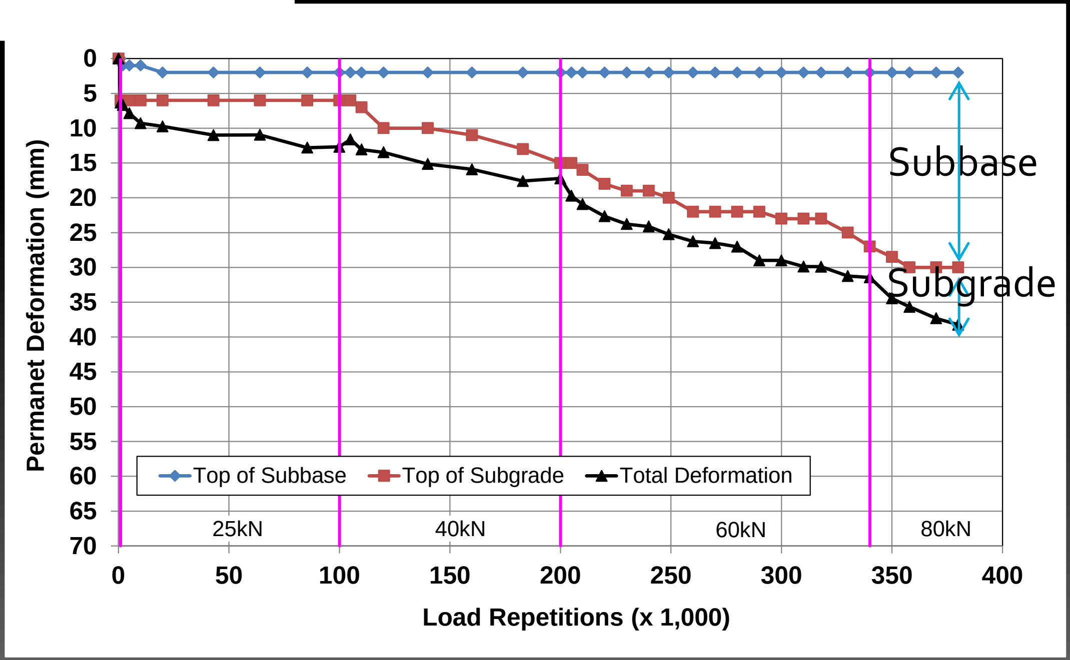


Wet

APT – Down Rut: 950mm Subbase



Dry



Wet

APT – General Observations

- Significant difference in wet and dry testing
- Wet test rutting was in both subbase and subgrade
  - Thickness design to prevent rutting in subgrade
  - Subbase aggregate properties and construction quality are critical to minimize subbase rutting

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M-E Design Procedure

- Design procedure and parameters adjusted from initial design based on actual test track values
- Rut models developed for each layer
- Partial validation of rut models using APT data
  - Analyzed with *OpenPave* software
- Design tool developed (*Excel*® spreadsheet)
  - Number of days with water in the subbase
  - Material properties
  - Traffic and load spectra
- Tool used to validate ICPI design tables
  - Less conservative than current ICPI for dry conditions
  - Slightly more conservative for very wet conditions

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Rut Models for Different Layers

TABLE 1 Summary of Rut Models Developed for Different Layers in a PICP

Layer	Rut Model[1]	Moisture Condition	Model Parameters		
			a	***b***	***c***
Combined bedding and base	$RD_{BB} = a \times h\_SB + b$	Dry	0	4.0	-
		Wet	-0.012	13.1	-
Subbase	$RD_{SB} = (a \times SSR^{b}) \times N^{c}$	Dry	3.10E-06	2.70	1
		Wet	3.10E-06	2.70	1
Subgrade (Silty clay)	$RD_{SG} = (a \times SSR + b) \times N^{c}$	Dry	0.03	-0.01	0.5
		Wet	0.03	-0.01	0.5

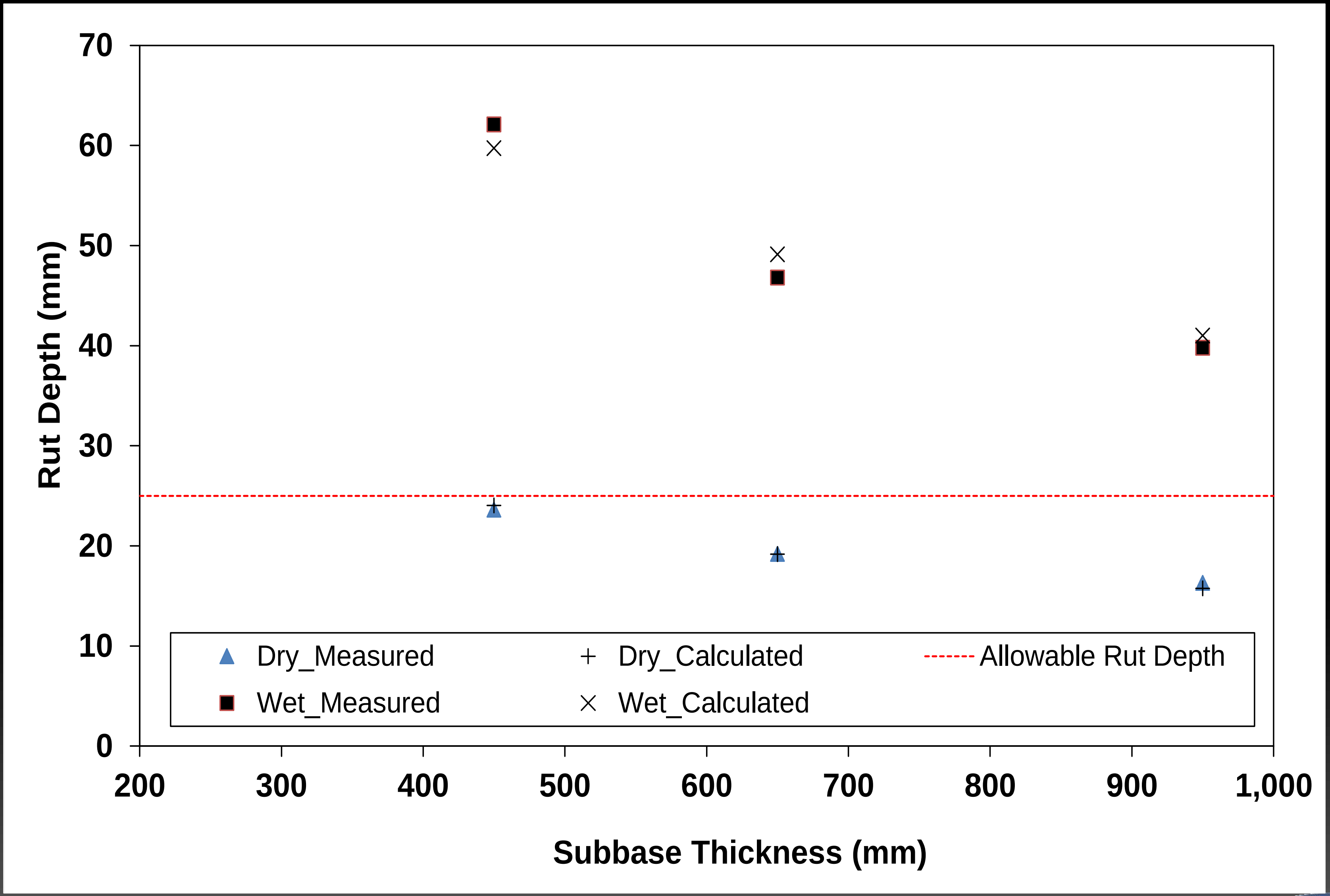
[1] RD_{xx}, rut depth of *xx* layer (BB=surface(paver, bedding and base); SB=subbase; SG=subgrade), mm;
h_SB, thickness of subbase, mm;
SSR, shear stress/strength ratio at the top of the layer;
N, load repetition;
a, *b*, *c*, model constants.

Input Parameters for M-E Design

TABLE 2 Summary of Inputs for Performance Modeling and M-E Design of PICP

Variable		Surface, Combined (Paver, bedding & base)		Subbase			Subgrade	
		Thickness (mm)	**Stiffness (MPa[1])**	**Thickness (mm)**	**Stiffness (MPa)**	**c, ϕ (kPa, °)**	**Stiffness (MPa)**	**c, ϕ (kPa, °)**
Pavement Structure and Materials	Label	h1	E1	h2	E2	c, ϕ	E3	c, ϕ
	Value	230	110 (dry) 87 (wet)	Varying (450 default)	122 (dry) 73 (wet)	0, 45 (dry) 0, 30 (wet)	60 (dry) 37 (wet)	15, 25 (dry) 9, 15 (wet)
Climate	**Variable**	**Wet Days [2]**	[2] Number of days in a calendar year when the subbase has standing water					
	Label	W						
	Value	50						
Traffic	**Variable**	**Axle Type**	**Axle Load[2] (kN[3])**	**Stress Location**	[2] The total truck traffic volume was divided into different axle loads according to an axle-load distribution factor. Group 1 WIM truck traffic data from California was used as the default axle-load distribution factor.			
	Label	AT	AL	SL				
	Value	Single (S) Tandem (T)	10 to 160 (S) 20 to 200 (T)	Under Wheel Between Wheel				
[1] 1,000 psi = 6.890 MPa			[3] 1,000 lb = 4.448 kN					

Validation of M-E Design Method



M-E Design Tool for PICP

PICP Design Tool

Input

Structure & Materials

Layer	Moisture Condition	Thickness (mm)	Stiffness (MPa) [1]	Poisson's Ratio	c (kPa)	ϕ (°)
Surface (80 mm concrete paver plus 50 mm #8 bedding and 100 mm #57 base)	Wet	230	87	0.35	-	-
	Dry		110	0.35	-	-
Subbase (ASTM #2)	Wet	150	73	0.35	*0*	*30*
	Dry		122	0.35	*0*	*45*
Subgrade (Clay)	Wet	-	37	0.35	*9*	*15*
	Dry		60	0.35	*15*	*25*

Climate

Number of Days in a Year When the Subbase has Standing Water (Wet Days) [2]
20

1. The wet stiffness to dry stiffness ratio can be assumed as 0.8, 0.6 and 0.6 for surface, subbase and subgrade layers, respectively.
2. Seasons when the subbase has standing water.

Traffic

Traffic Volume Calculation
AADT (two-way)
250
Percent Trucks, T
5.0%
Direction Distribution Factor, D
0.5
Lane Distribution Factor, L
0.9
Annual Growth Rate, r
2.0%
Design Life (years), Y
20
Traffic Days (days/year), TD
365
Traffic Safety Factor, TSF
1.0
Truck Traffic Volume, V
50,055

$$V = AADT \times T \times D \times L \times (1+r)^{Y/2} \times Y \times TD \times TSF$$

Axle Type	Axle Load (kN)	Axle-Load Distribution (%)	Lifetime Repetition: Wet Season [2]	Lifetime Repetition: Dry Season	Lifetime Repetition: Total	Lifetime Repetition: ESALs	Lifetime ESALs (Millions)
Single	10	3.25	89	1,538	1,627	0	0.01
	20	5.97	164	2,823	2,987	12	
	30	5.83	160	2,756	2,916	58	
	40	4.43	121	2,095	2,217	139	
	50	3.23	89	1,528	1,617	247	
	60	2.80	77	1,324	1,401	443	
	70	3.13	86	1,481	1,567	919	
	80	2.40	66	1,137	1,203	1,203	
	90	0.85	23	400	424	679	
	100	0.15	4	69	73	177	
	120	0.03	1	15	15	78	
	160	0.01	0	5	5	80	
Tandem	20	1.59	44	755	798	0	
	40	5.79	159	2,738	2,897	23	
	60	6.76	186	3,201	3,386	134	
	80	4.48	123	2,118	2,241	280	
	100	3.42	94	1,617	1,711	522	
	120	3.86	106	1,824	1,930	1,221	
	140	4.12	113	1,950	2,063	2,419	
	160	1.94	53	918	971	1,943	
	180	0.29	8	139	147	471	
	200	0.05	1	24	25	123	

Outcome

Rut Depth

Layer	Moisture Condition	Shift Factor	Rut Depth by Layer (mm)	Expected Total Rut Depth (mm)	Allowable Rut Depth (mm)	Satisfactory ?
Surface (80 mm concrete paver plus 50 mm #8 bedding and 100 mm #57 base)	Wet	1.30	0.8	23.0	25.0	*Y*
	Dry	1.10	4.2			
Subbase (ASTM #2)	Wet	1.30	0.8			
	Dry	1.10	9.2			
Subgrade (Clay)	Wet	1.30	2.8			
	Dry	1.10	5.2			

Calculate Rut Depth | **Design Subbase Thickness**

Example Design Tables

Number of Days in a Year When the Subbase has Standing Water (Wet Days)		0				10				30			
Resilient Modulus of Subgrade (ksi)	Dry	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5
	Wet	3.5	5.2	6.7	8.7	3.5	5.2	6.7	8.7	3.5	5.2	6.7	8.7
Cohesion (psi), Internal Friction Angle of Subgrade (°)[1]	Dry	1.5, 20	2.2, 25	2.9, 30	3.6, 35	1.5, 20	2.2, 25	2.9, 30	3.6, 35	1.5, 20	2.2, 25	2.9, 30	3.6, 35
	Wet	0.9, 12	1.3, 15	1.7, 22	2.2, 25	0.9, 12	1.3, 15	1.7, 22	2.2, 25	0.9, 12	1.3, 15	1.7, 22	2.2, 25
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in inches[2] ASTM #2 for 1 in. Allowable Rut Depth (All designs have 3.2 in. Paver, 2 in. ASTM #8 Bedding Layer, & 4 in. ASTM #57 Base Layer)											
50,000 (6.3)		6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
100,000 (6.8)		6.0	6.0	6.0	6.0	8.5	6.0	6.0	6.0	10.5	6.0	6.0	6.0
200,000 (7.4)		9.0	6.0	6.0	6.0	12.5	8.5	6.0	6.0	14.5	10.0	6.5	6.0
300,000 (7.8)		11.5	7.0	6.0	6.0	15.0	10.5	7.0	6.0	17.0	12.5	8.5	6.0
400,000 (8.1)		13.0	9.0	6.0	6.0	17.0	12.0	8.5	6.0	19.0	14.0	10.0	7.0
500,000 (8.3)		14.5	10.0	6.5	6.0	18.0	13.5	9.5	6.5	20.0	15.0	11.0	8.0
600,000 (8.5)		15.5	11.0	7.5	6.0	19.0	14.5	10.5	7.0	21.0	16.0	12.0	9.0
700,000 (8.6)		16.5	12.0	8.0	6.0	20.0	15.0	11.0	8.0	22.0	17.0	13.0	10.0
800,000 (8.8)		17.0	12.5	9.0	6.0	20.5	16.0	12.0	8.5	22.5	17.5	13.5	10.5
900,000 (8.9)		17.5	13.0	9.5	6.0	21.0	16.5	12.5	9.0	23.5	18.0	14.0	11.0
1,000,000 (9.0)		18.0	13.5	10.0	6.5	22.0	17.0	13.0	9.5	24.0	19.0	14.5	11.5

[1] Default values based on testing cited in the literature *(10,12)*

[2] Subbase thickness calculated by dividing metric thickness by 25 and then rounding to nearest 0.5 in.

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Conclusions

- Shear stress to shear strength ratio (SSR) approach is appropriate for permeable pavement design
- Subgrade rutting dependent on subbase thickness
  - Design for wet conditions
- Subbase thickness does not prevent subbase rutting
  - Rutting depends on aggregate properties and construction quality
  - Pervious concrete subbase below aggregate subbase can be considered to compensate for this
- Mechanistic-Empirical design tool and revised design catalogue has been developed and partially validated.

Thank-you

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