DEPARTMENT OF TRANSPORTATION
THE STATE OF NEW JERSEY

RowanUniversity
CENTER FOR RESEARCH & EDUCATION IN
ADVANCED TRANSPORTATION ENGINEERING SYSTEMS

Structural Design of Porous Asphalt Pavement Systems (PAPS) for High Traffic Volume Roadways

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Outline of presentation

- Introduction
- Objectives
- Methodology
- Development of design framework
- Collection of inputs for the design
- Validation of the developed framework
- Summary for findings
- Conclusions
- References


Source: hawaiiasphalt.org

Porous asphalt mixture

Source: https://www.forconstructionpros.com/

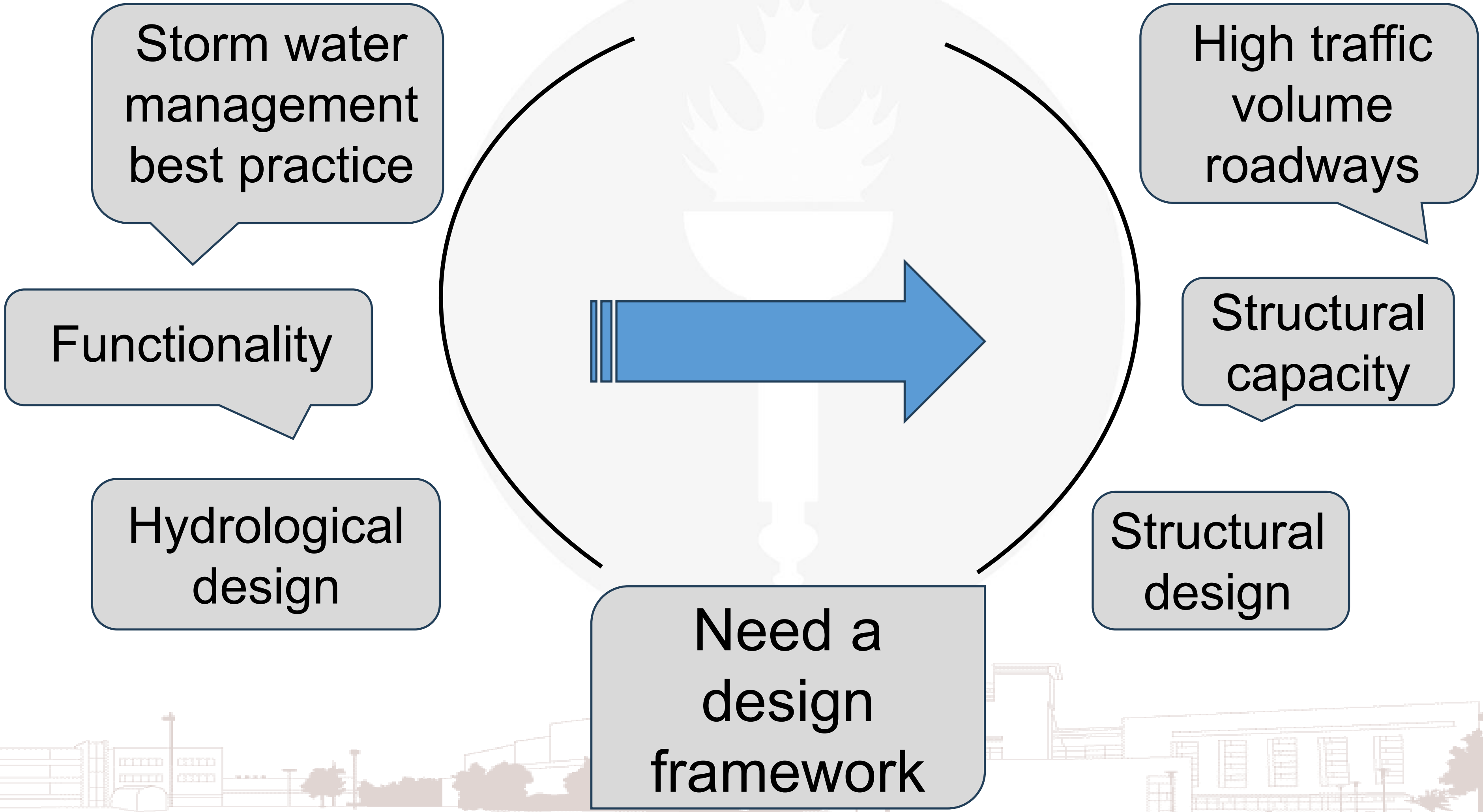
Introduction

- Best practices for stormwater management on parking lots, walkways, shoulder lanes, and low volume roads across the world
- Design is focused on the hydrological aspects
- Example:
  - New York Beach Road parking lot,
  - State Route 87 in Arizona,
  - low-volume roads in Minnesota,
  - Maine Mall road
- Over the years these structures showed better performance

New York beach road

Maine Mall Road (Portland, Maine)
Photo Credit: Maine DOT

Significance of the study



Storm water management best practice

Functionality

Hydrological design

High traffic volume roadways

Structural capacity

Structural design

Need a design framework

Significance of this study

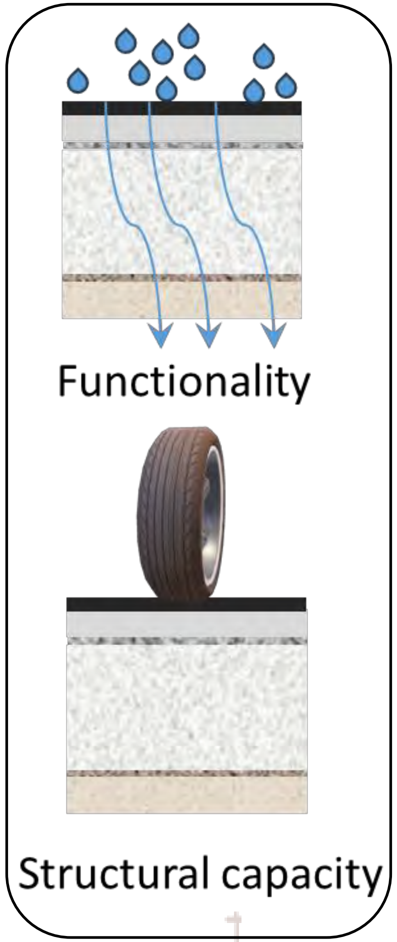
- PAPS has been used extensively for low volume roads
- Need to evaluate the PAPS technology on roadways with high traffic.
- Need to develop a design framework for porous asphalt pavement for high traffic volume roadways using both, AASHTO 93 and AASHTOWare ME.

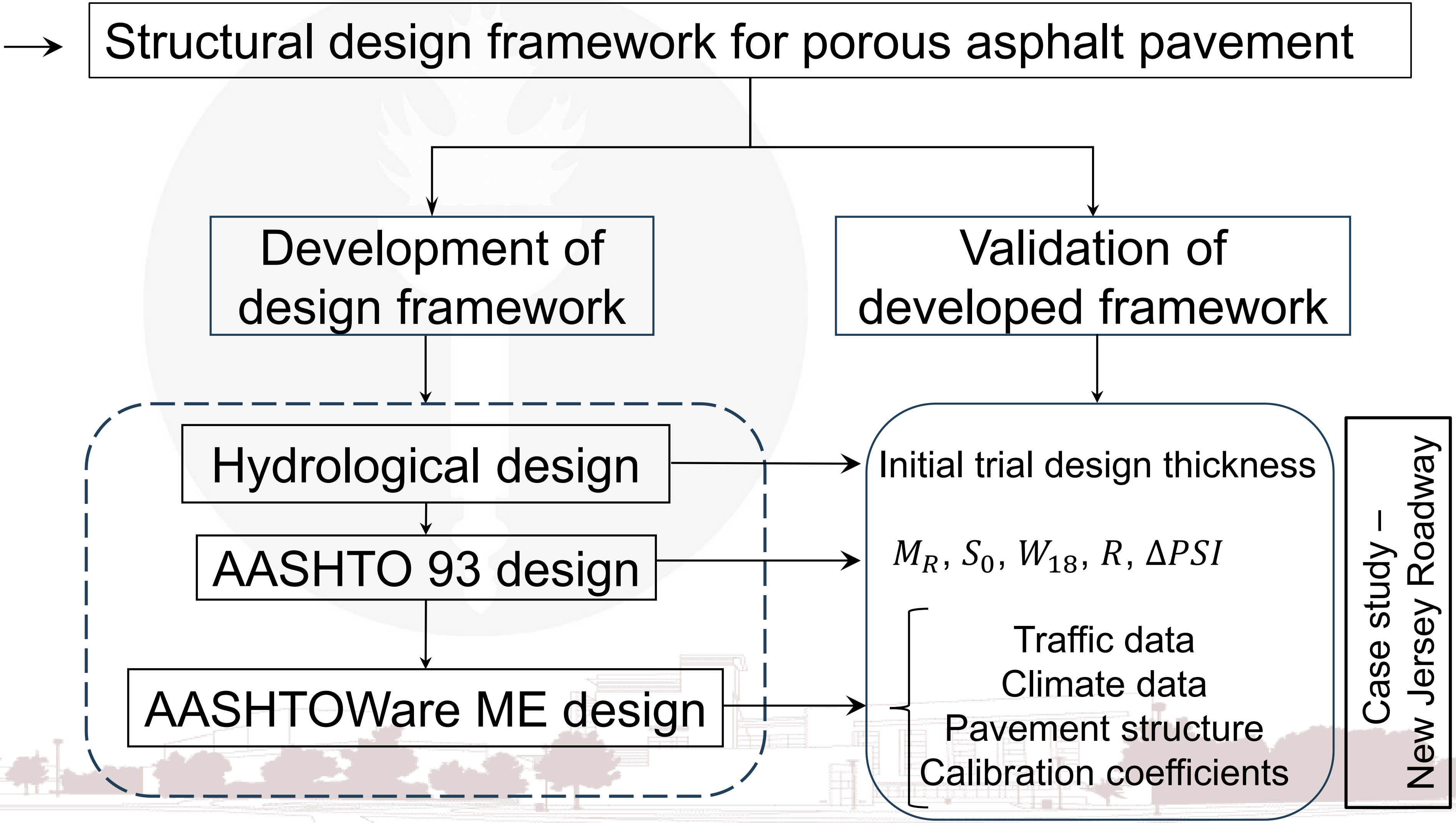
Study Objectives

- Develop a framework for the design of porous asphalt pavement structure for high traffic volume roadways (>10M ESALS) for using in AASHTO 93 design method and AASHTOWare ME method.

- Validate the framework by designing a long-lasting porous asphalt pavement structure for a high traffic volume road in New Jersey.

Methodology adopted in this study





Structural design framework for porous asphalt pavement

Development of design framework

Validation of developed framework

Hydrological design

AASHTO 93 design

AASHTOWare ME design

Initial trial design thickness

$M_R, S_0, W_{18}, R, \Delta PSI$

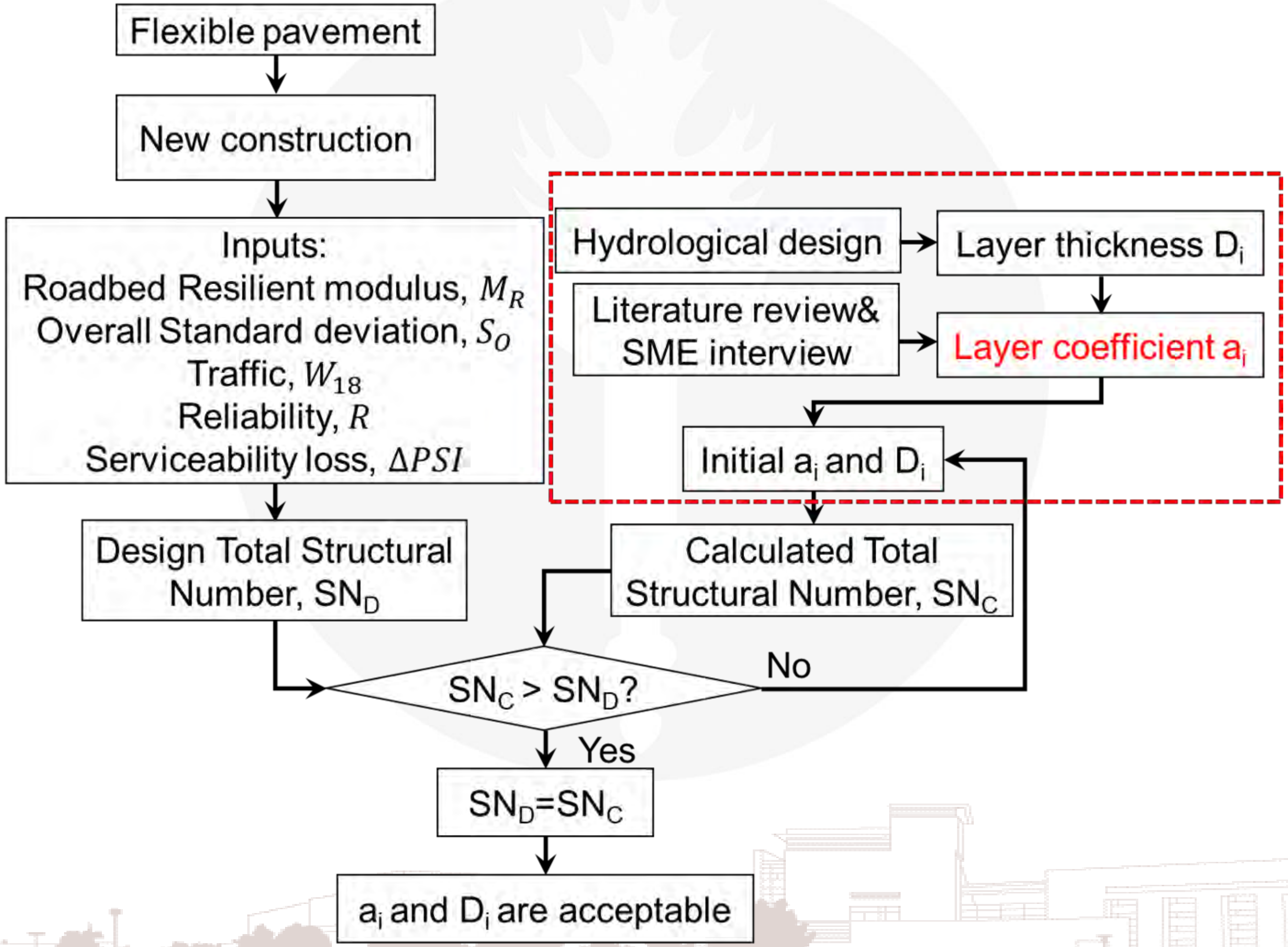
Traffic data
Climate data
Pavement structure
Calibration coefficients

Case study – New Jersey Roadway

Hydrological design of porous asphalt pavement

- Provide sufficient storage capacity for the gradual release of collected storm water into the stormwater system or natural soil
- Infiltration rate, capacity of the subgrade soil and the volume of anticipated stormwater runoff are the design elements
- Minimum thickness (combined thickness of all asphalt layers) of 6-inch is recommended for PA layer
- Stone recharge bed thickness 12 to 36-inch

AASHTO 93 Design Framework for PAPS



Flexible pavement

New construction

Inputs:
Roadbed Resilient modulus, M_R
Overall Standard deviation, S_O
Traffic, W_{18}
Reliability, R
Serviceability loss, ΔPSI

Hydrological design

Layer thickness D_i

Literature review&
SME interview

Layer coefficient a_i

Initial a_i and D_i

Design Total Structural Number, SN_D

Calculated Total Structural Number, SN_C

$SN_C > SN_D$?

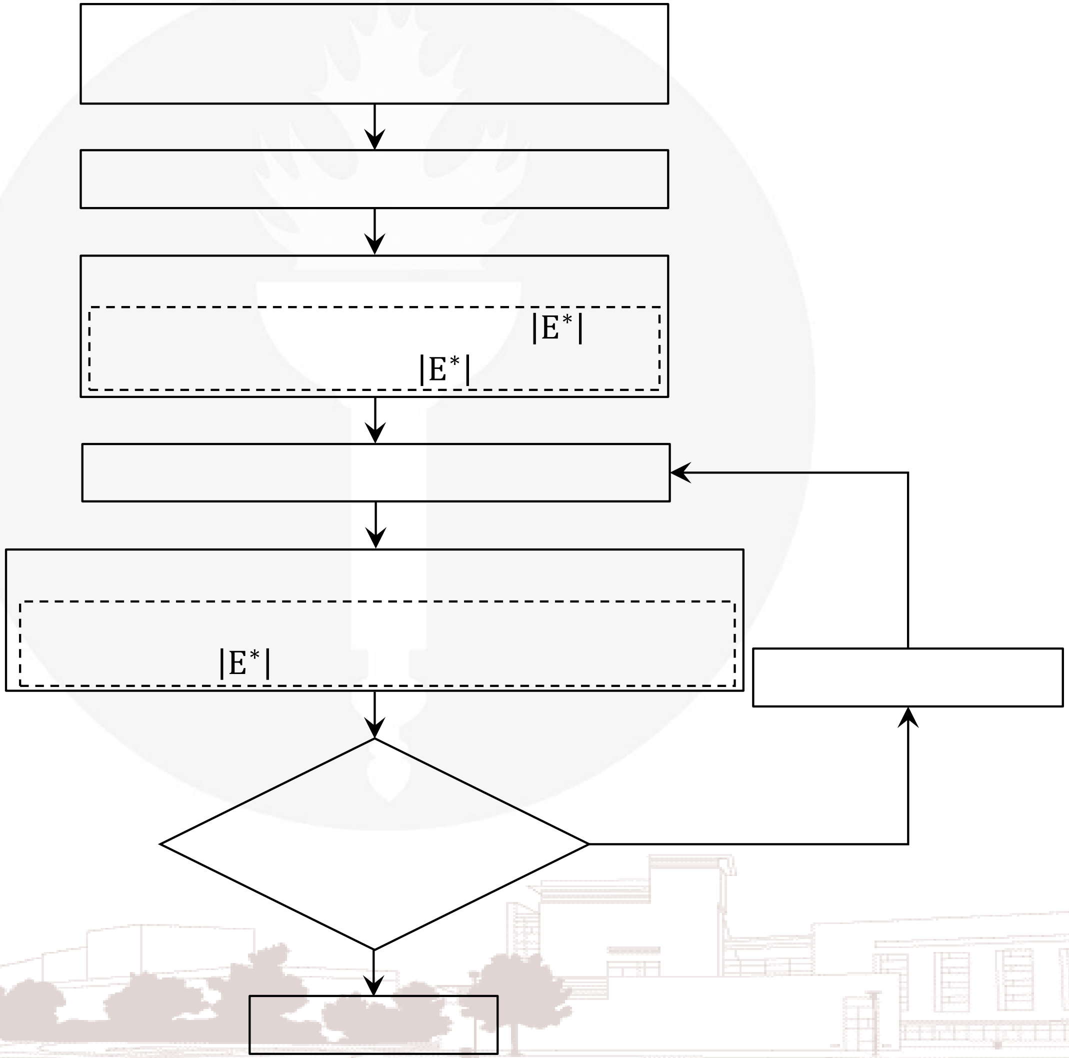
No

Yes

$SN_D = SN_C$

a_i and D_i are acceptable

Analysis of AASHTO 93 Design for PAPS in AASHTOWare ME



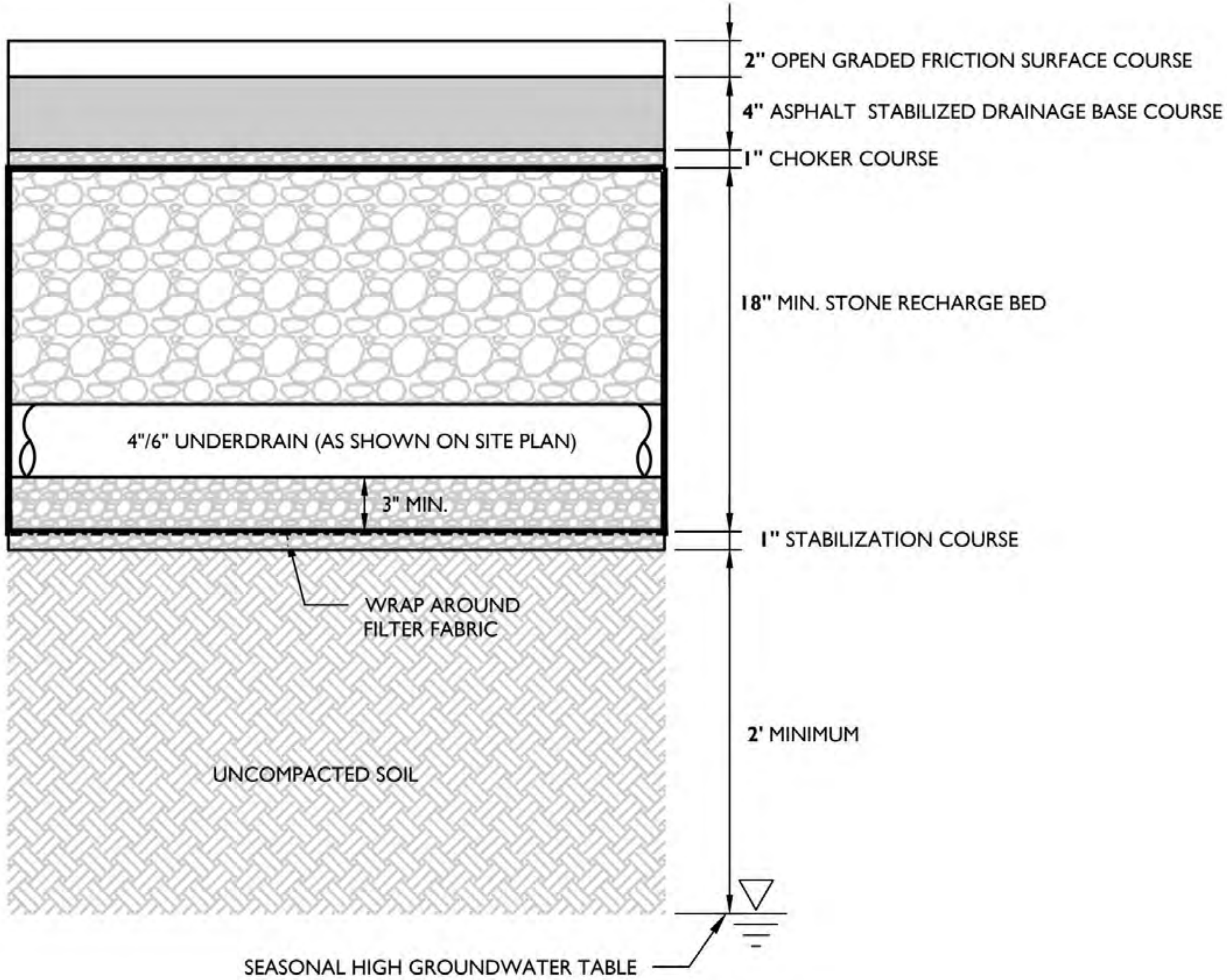
Validation of the Developed Framework

Case study of New Jersey roadway

- Hydrological design based on NJDEP BMP Manual 2021
- Porous asphalt layer properties are from the laboratory test at Rowan CREATES
- Traffic data, climatic data, and subgrade soil properties from Rt.34 details
- Design life 50 years, new flexible pavement
- Design ESAL= $13{,}140{,}618\ (13\ Million)$

Hydrological Design of Porous Asphalt Pavement

Franklin Township, NJ

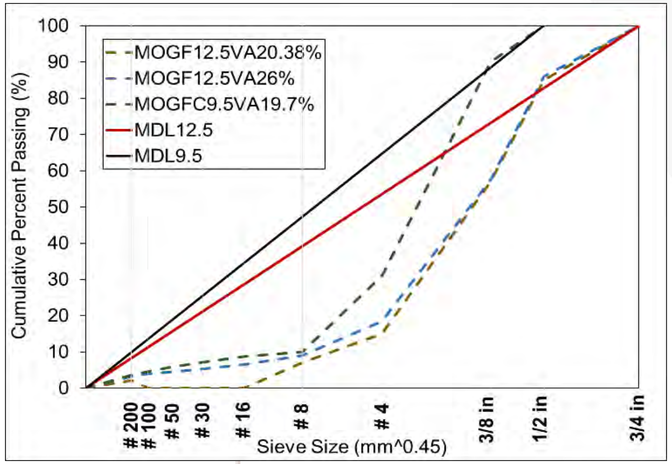


Testing for collecting the design inputs

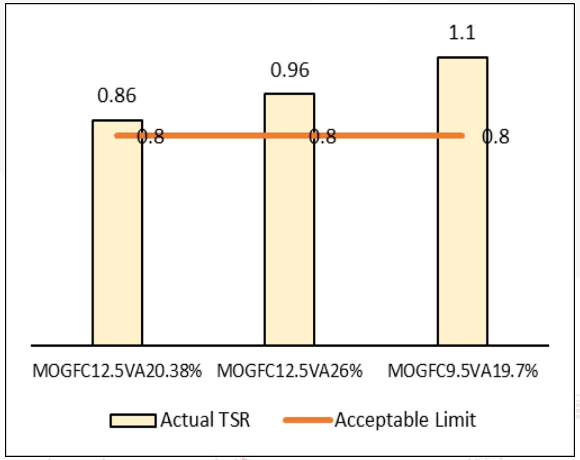
- Air voids (AASHTO T209& AASHTO T331)
- TSR (AASHTO T283)
- Durability (AASHTO TP108)
- Drain down test (ASTM D6390)
- *Permeability (FM 5-565)*
- Binder $|G^*|$ and δ (AASHTO T 315)
- *Mixture* $|E^*|$ *(AASHTO T378)*

Mix Design Verification

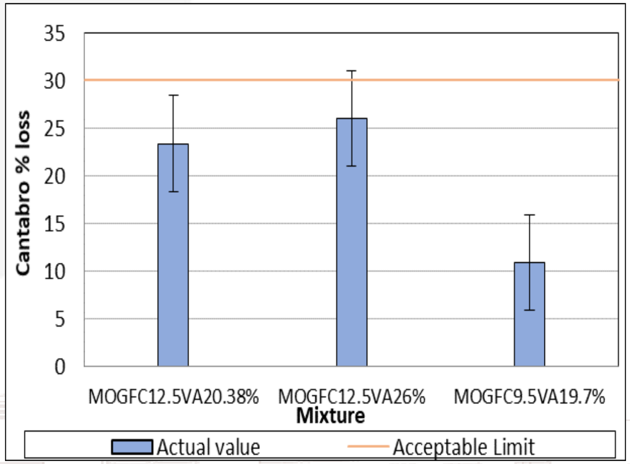
PA Mixtures	Binder PG	Air voids (%)	AC (%)	NMAS (mm)	Additive	Filler
MOGFC12.5VA20.38%	76–22	20.38	5.8	12.5	Cellulose fiber	Mineral filler
MOGFC12.5VA26%		26.00	6.2	12.5		
MOGFC9.5VA19.7%		19.70	5.7	09.5		



Gradation curve



Tensile strength ratio



Durability

No drain down
(AASHTO T305/ ASTM D6390)

Level 1 inputs for PAPS design

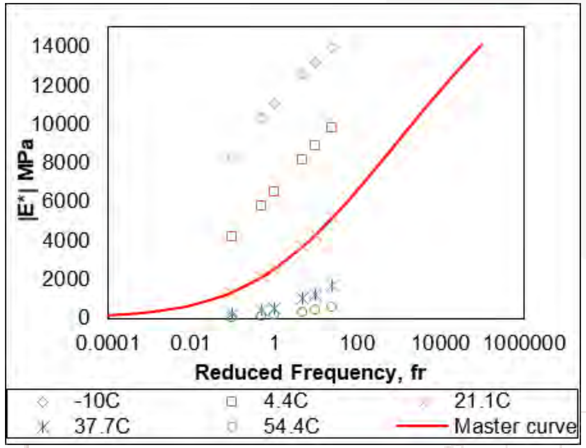
Falling head Permeability test results

PA Mixtures	Avg. Permeability (m/day)
MOGFC12.5VA20.38%	127.87 (419.52 ft/day)
MOGFC12.5VA26%	121.66 (399.15 ft/day)
MOGFC9.5VA19.7%	128.12 (420.34 ft/day)

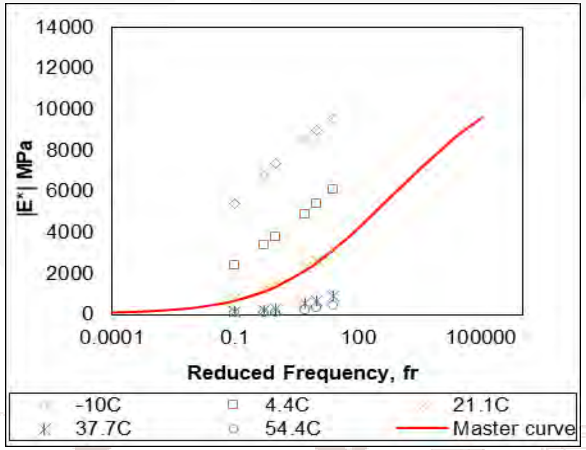
Rheological properties of PG 76-22 Binder

Angular frequency 10rad/sec		
T (C)	G^* (Pa)	δ (degree)
131	25897	62.3
158	5178	62.9
185	1226	68.1

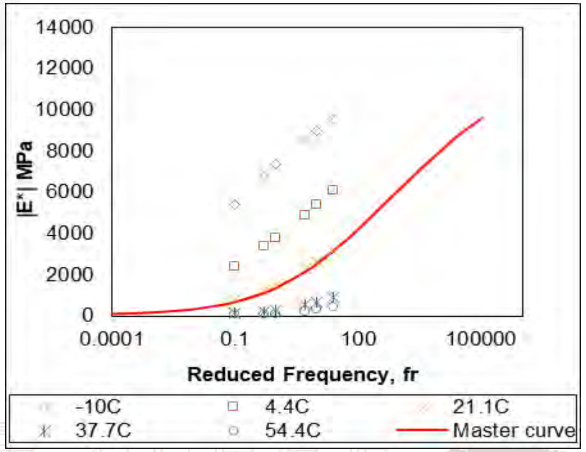
Dynamic Modulus Master Curve for the PA Mixtures



MOGFC12.5VA20.38%

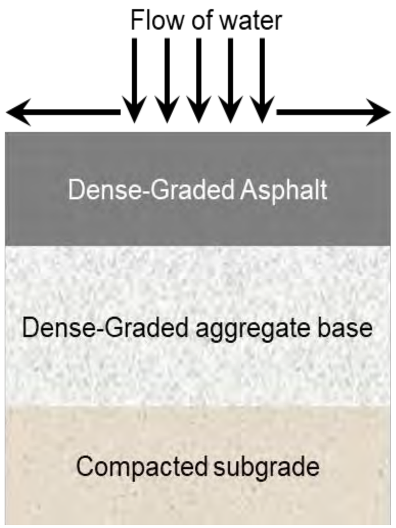


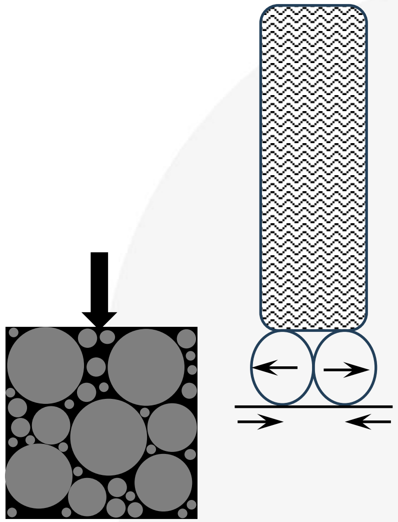
MOGFC 12.5VA26%



MOGFC9.5VA19.7%

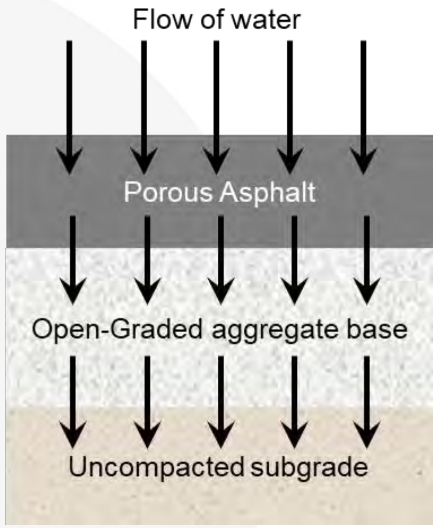
Effect of confinement

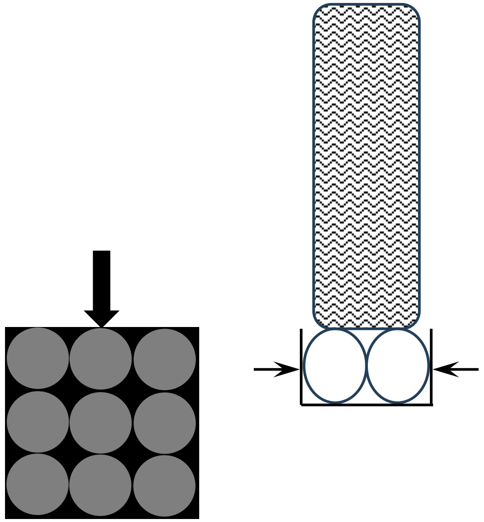




Packing concept

- Some voids
- Densest stone packing
- Friction between stones dominant





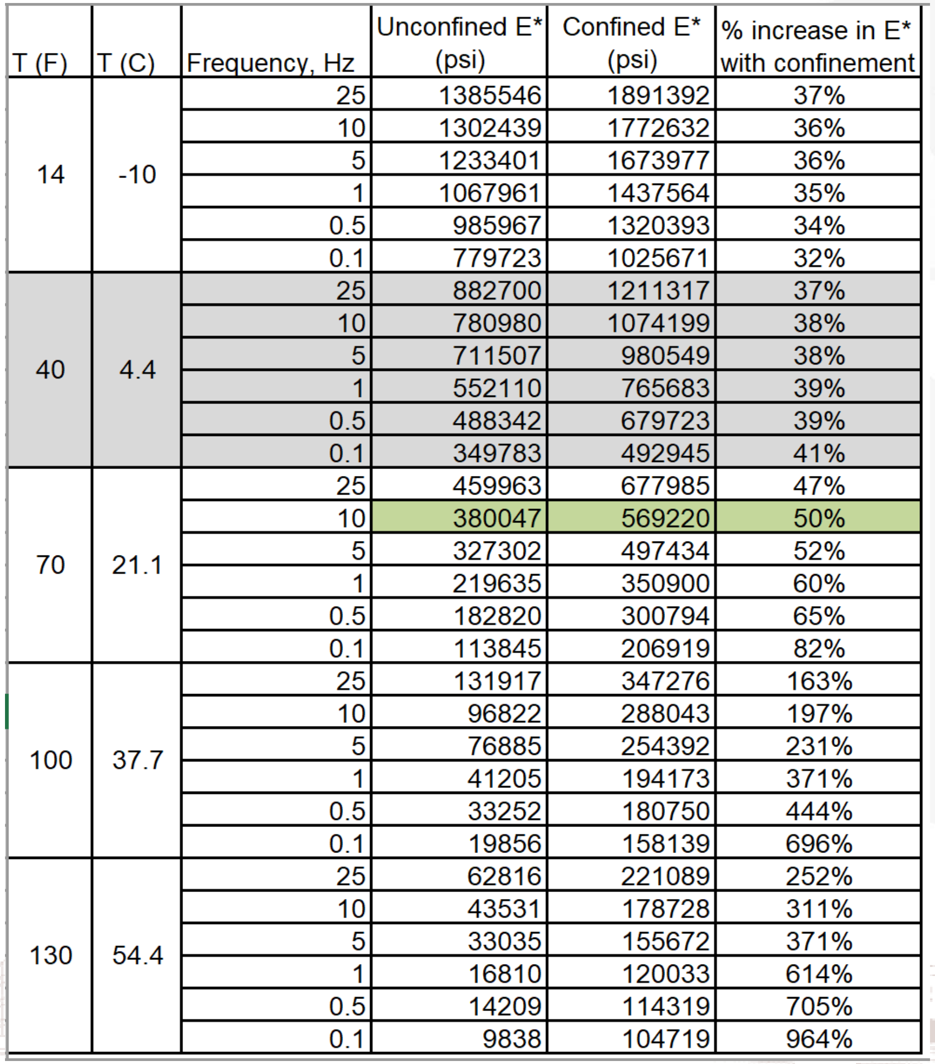
Skeleton concept

- High voids
- Open graded stone skeleton
- Lateral confinement dominant

Open-graded structure

Dense-graded structure

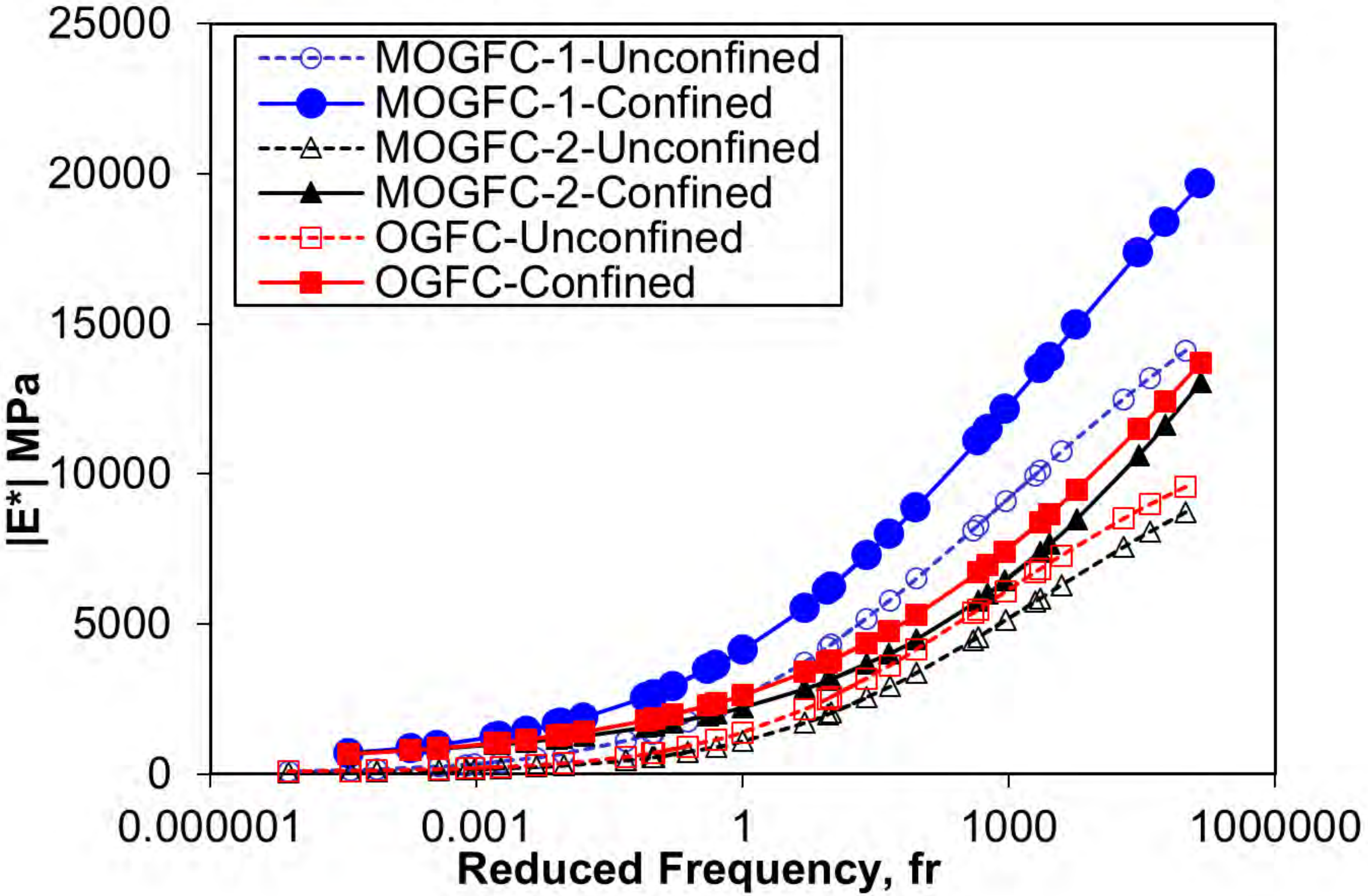
Effect of confinement on E*



T (F)	T (C)	Frequency, Hz	Unconfined E* (psi)	Confined E* (psi)	% increase in E* with confinement
14	-10	25	1385546	1891392	37%
		10	1302439	1772632	36%
		5	1233401	1673977	36%
		1	1067961	1437564	35%
		0.5	985967	1320393	34%
		0.1	779723	1025671	32%
40	4.4	25	882700	1211317	37%
		10	780980	1074199	38%
		5	711507	980549	38%
		1	552110	765683	39%
		0.5	488342	679723	39%
		0.1	349783	492945	41%
70	21.1	25	459963	677985	47%
		10	380047	569220	50%
		5	327302	497434	52%
		1	219635	350900	60%
		0.5	182820	300794	65%
		0.1	113845	206919	82%
100	37.7	25	131917	347276	163%
		10	96822	288043	197%
		5	76885	254392	231%
		1	41205	194173	371%
		0.5	33252	180750	444%
		0.1	19856	158139	696%
130	54.4	25	62816	221089	252%
		10	43531	178728	311%
		5	33035	155672	371%
		1	16810	120033	614%
		0.5	14209	114319	705%
		0.1	9838	104719	964%

- Unlike dense-graded mixtures, Open-graded mixture E* values are influenced by confinement (Zeiada et al. 2011)
- Significant increase in E* values with confinement especially at higher temperature

Dynamic modulus of PA mixtures



AASHTO 93 design inputs

Backcalculated layer coefficients

a_i from laboratory E^* values of three different MOGFC/PA mixtures

	Unconfined		Confined	
PA Mixtures	E^* (psi) at 70°F, 10 Hz	a_i	E^* (psi) at 70°F, 10 Hz	a_i
MOGFC12.5VA20.38%	629754	0.39	909071	0.43
MOGFC12.5VA26.00%	321694	0.31	489801	0.36
OGFC9.5VA19.70%	380047	0.33	569220	0.37

$$M_R(psi) = 30{,}000 \times \left(\frac{a_i}{0.14}\right)^3$$

Source: AASHTO 93 design guide

AASHTO 93 Design inputs

Project Name and Location:
New Jersey Route 34, MP 13.45 – 21.00

General Information

Input Parameter	Symbol	Value	Reference
Initial Serviceability	p_0	4.2	II-10 & NJ serviceability loss
Terminal Serviceability	p_t	2.5	II-10 & NJ serviceability loss
Reliability Level	R	90%	I-53 to I-64 or II-9 & NJ Reliability
Standard Normal Deviate	Z_R	-1.282	
Overall Standard Deviation	S_0	0.45	I-62 or II-9 & NJ Standard Deviation
Performance Period	50 years		II-5 to II-8 & NJ Performance Period

Traffic Data and Analysis

Input Parameter	Symbol	Reference
Initial AADT ($\mathrm{AADT_i}$)	8872 vpd 1-way	Based on data supplied by the NJDOT Project Manager
Final AADT ($\mathrm{AADT_f}$)	12,390 vpd 1-way	
$Car\%$	93.00	
$Carf$	0.010	
$LT\%$	5.00	
LTf	0.453	
$HT\%$	2.00	
HTf	1.789	
$\mathrm{D_D}\%$	100	II-7 & NJ Directional Distribution
$D_L\%$	100	II-7, 8 & NJ Lane Distribution

AASHTO 93 Design for PA pavement

Design structure $m_i = 1.00$

Layer	Material	a_i	D_i (in)	SN_C
1	Porous asphalt (MOGFC)	**0.31**[B]	6	1.86
2	ASDC	0.23	13	2.99
3[A]	Stone reservoir		18	
		Total	37	4.85

[A] *Not a structural layer*

[B] *Backcalculated value from E^* at 70°F, 10 Hz*

$$\searrow M_R(psi) = 30{,}000 \times \left(\frac{a_i}{0.14}\right)^3$$

Source: AASHTO 93 design guide

Design ESAL=13,140,618

$SN_C > SN_D$(4.57), Acceptable design

Sensitivity of thickness to a_i

a_i	PA thickness
0.31	6-in
0.43	4.5-in

Subgrade soil $M_R = 4186\,psi$ (50% of 8372psi; A-5 Soil) *(NAPA IS 140)*

Composite subgrade $M_R = 10734\,psi$ *(NAPA IS 140, Hall and Schwartz 2018)*

MEPDG inputs

- Climate data - retrieved from the nearest weather station (MERRA-2 station ID 14476, Edison, NJ

- Traffic data-

Age (year)	Heavy Trucks (cumulative)
2027 (initial)	1,650
2052 (25 years)	8,510,560
2077 (50 years)	19,424,800

- Default calibration factors

Porous asphalt layer (MOGFC-1, MOGFC-2, OGFC mixtures)		
Mixture volumetrics		Level 1
Mechanical properties	Dynamic modulus	Level 1
	Binder properties	Level 1
	Creep Compliance	Level 3
	Indirect Tensile Strength	Level 3
	Unit weight (120 lb/ft^3)	Level 3
AC thermal properties		Level 3
Asphalt Stabilized Drainage Course (ASDC)		
Unbound base Layer Properties		Level 3
Resilient Modulus, (135,000 psi)		
Gradation and other Engineering Properties		
Non-Stabilized Permeable Aggregate Base Layer		
Unbound base Layer Properties		Level 3
Resilient Modulus, (20,000 psi)		
Gradation and other Engineering Properties		
Uncompacted Subgrade		
Unbound base Layer Properties		Level 3
Resilient Modulus, (10743 psi)		
Gradation and other Engineering Properties		

AASHTOWare Pavement ME analysis

Design structure

Layer Type	**Material Type**	**Thickness (in)**
Flexible	Porous asphalt	6
Non-Stabilized	ASDC	13
Non-Stabilized	Stone reservoir	18
Subgrade	A-5	Semi-infinite

Distress prediction summary

Distress Type	Distress @ Specified Reliability		Criterion Satisfied?	Distress @ Specified Reliability	Criterion Satisfied?
	Target	Predicted Unconfined		Predicted Confined	
Terminal IRI (in/mile)	172.00	309.00	Fail	299.40	Fail
Permanent deformation – total (in)	1.00	0.75	Pass	0.54	Pass
AC bottom-up fatigue cracking (%)	25.00	7.14	Pass	6.41	Pass
AC thermal cracking (ft/mile)	1000.00	2892.45	Fail	2863.51	Fail
AC top-down fatigue cracking (%)	25.00	60.32	Fail	56.42	Fail
Permanent deformation - AC only (in)	0.50	0.34	Pass	0.14	Pass

AASHTOWare limitations for PAP

- AASHTOWare is developed for <u>dense-graded pavements</u>
- Lack of distress prediction models specific to PA mixtures
  - Min. 16% air voids > 10% (in software)
  - Aggregate gradation parameter (β) $>$ 0.55

$$N_{f-AC} = k_{f1}(C)(C_H)\beta_{f1}(\varepsilon_t)^{k_{f2}\beta_{f2}(E_{AC})^{k_{f3}\beta_{f3}}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_{be}}{V_a + V_b} - 0.69\right)$$

Fatigue cracking model

$$L(t) = L_{Max}\, e^{-\left(\frac{C_1 \rho}{t - C_3 t_0}\right)^{C_2 \boxed{\beta}}}$$

Top-down cracking model

- Lack of local calibration factors for NJ specific materials

Potential impact of the identified limitations

- **Limitations in the upper and lower limits of air voids** and other mixture volumetrics will directly affect the AC rutting prediction model in the AASHTOWare ME software Version 3.0

- **Aggregate gradation parameter** represents the shape parameter of the power law approximation of the gradation curve.
  - Predicted AC top-down cracking is directly influenced by aggregate gradation parameter.
  - Aggregate gradation will influence the $|E^*|$and rutting prediction

- **Default calibration coefficients** are for hot mix asphalt mixtures with a neat binder.
  - This will influence all the predicted distress values when used with open-graded porous asphalt mixtures.
  - Need to develop local calibration coefficients

Summary

- Hydrological design thickness and layer coefficient from literature will serve as the initial trial design in the AASHTO 93 method.

- Final structure from the AASHTO 93 method needs to be analyzed in AASHTOWare ME to ensure the performance of PAPS for a longer design life with high traffic volume.

- Framework validated using a case study in New Jersey resulted in a structure with 6-inch porous asphalt layer, 13-inch ASDC and 18-inch stone reservoir layer to carry 13 million ESALs over 50 years.

Summary

Variation in $|E^*|$ and layer coefficient with confinement

	MOGFC-1	MOGFC-2	OGFC
Average unconfined $|E^*|$ (at 70°F (21.1°C))	4,342 MPa (629,754 psi)	2,218 MPa, (321,694 psi)	2,620 MPa (380,047 psi)
Layer coefficient	0.39	0.31	0.33
Average confined $|E^*|$ (at Confinement level-138 kPa (20 psi)	6268 MPa (909,071 psi)	3377 MPa (489,801 psi)	3925 MPa (569,220 psi)
Layer coefficient	0.43	0.36	0.37
Increase in $|E^*|$ with confinement	44%	52%	50%

Sensitivity of thickness to layer coefficient

Layer coefficient (a_i)	PA layer thickness
0.31	6-in
0.43	4.5-in

Summary

- Analysis of AASHTO 93 design in AASHTOWare ME revealed the limitations in analyzing PAPS in the current version of the AASHTOWare ME

- AASHTOWare ME software predicted rut depth of 0.75-inch, and 0.54-inch for the PA pavement structures with OGFC mixtures.
  - These values were less than New Jersey rut criteria of maximum 1-inch.
  - This demonstrates that the design has the potential to withstand a 50-year traffic load of 13 million ESALs

Conclusions and recommendations

- Framework proposed in this study, include:
  - Step 1: Hydrological design,
  - Step 2: Design based on AASHTO 93, hen
  - Steps 3: Revaluate design using Level 1 AASHTO Pavement ME to design durable porous asphalt pavement for heavy traffic volume (>10M ESALs).
  - Collect the Level 1 input using the confined dynamic modulus test
- Equation provided in this study can be used to calculate the confined E* if the confined E* test cannot be performed.

Conclusions and Recommendations

- Level 1 inputs are required for the analysis and distress
  - Prediction models need to be calibrated for conditions specific to the proposed location
- AASHTOWare ME predicted rut depth shows that the framework will result in a PAP structure that can withstand heavy traffic (ESALS=15M)
- With some modifications in the current version (Version 3.0), AASHTOWare ME analysis will provide a more accurate and economical thickness design for the open-graded porous asphalt pavement

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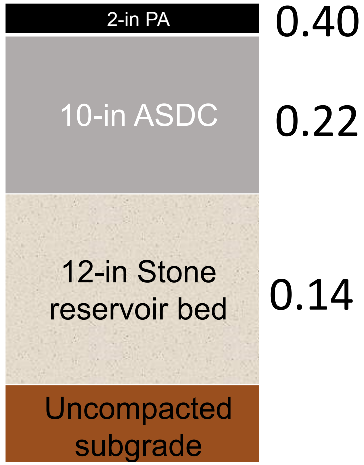
Next Step of this study

Construction of Full-scale Test Sections of Porous Asphalt Pavement

Proposed APT sections

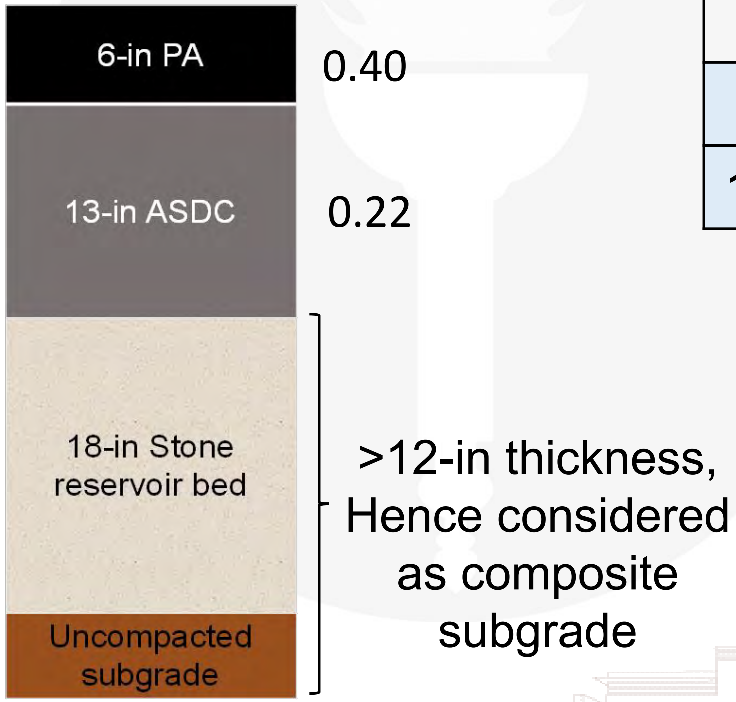
1 million ESALS
(20 years design life)



Test strip 1

Section from an existing shoulder lane in NJ

13 million ESALS
(50 years design life)



>12-in thickness, Hence considered as composite subgrade

Test strip 2

Section from validated design framework

HVS loading

ESAL	Axle load (kN/kip)	HVS Passes
1,000,000	80kN/18kip	62,500
13,000,000		812,500

KENLAYER Analysis of Proposed Sections

6 in, 13 in, 18 in- section from AASHTO 93 Phase I **(Analysis is done for 13 million ESALs (13,140,618 ESALs)**

Critical location	Sum of Damage Ratio		Tensile strain		Compressive strain		Max damage ratio	
	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined
At Bottom of Layer 1	0.93	1.03	111 μ	103 μ			2.32	1.59
At Bottom of Layer 2	0.49	0.39	120 μ	111 μ				
At Top of Layer 3	2.32	1.59			566 μ	325 μ		

2 in, 10 in, 12 in - section from existing shoulder lane in NJ **(Analysis is done for 1 million ESALs)**

Critical location	Sum of Damage Ratio		Tensile strain		Compressive strain		Max damage ratio	
	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined
At Bottom of Layer 1	0.0013	0.0060	16 μ	48 μ			2.4850	2.0610
At Bottom of Layer 2	0.4846	0.4429	261 μ	254 μ				
At Top of Layer 3	2.4850	2.0610			586 μ	562 μ		
At Top of Layer 4	1.2610	1.0110			504 μ	479 μ		

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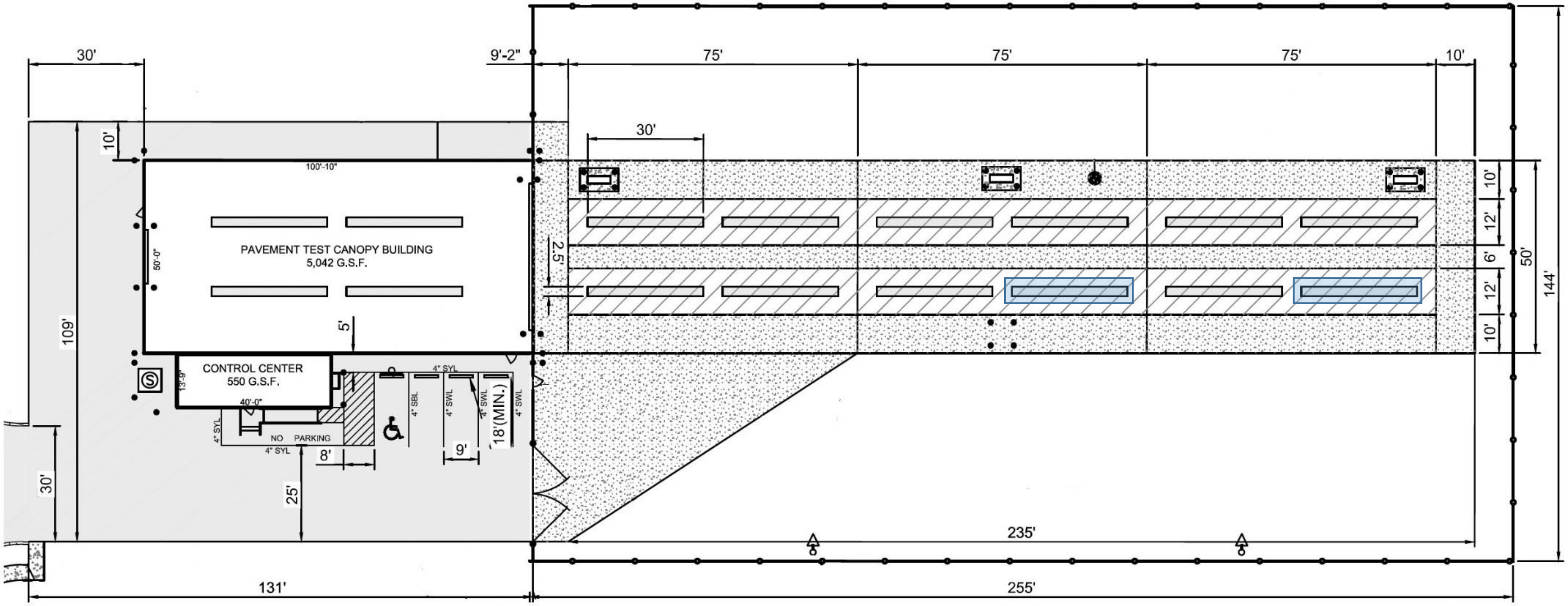
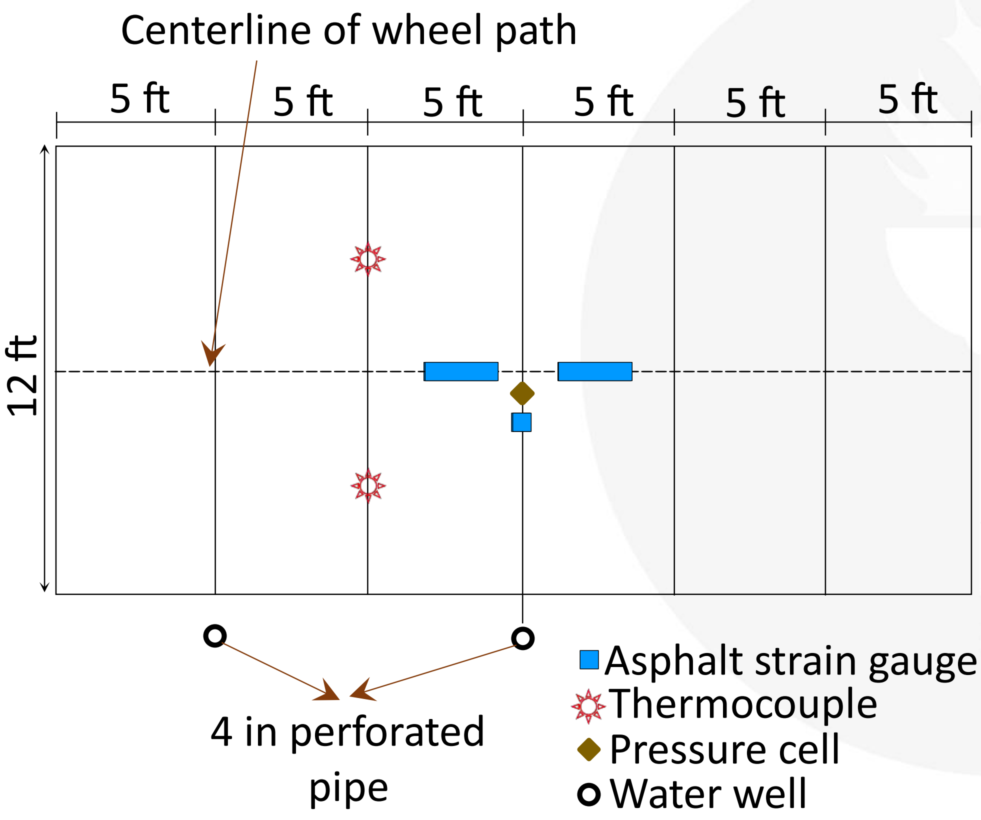
Layout of HVS facility with porous asphalt pavement sections

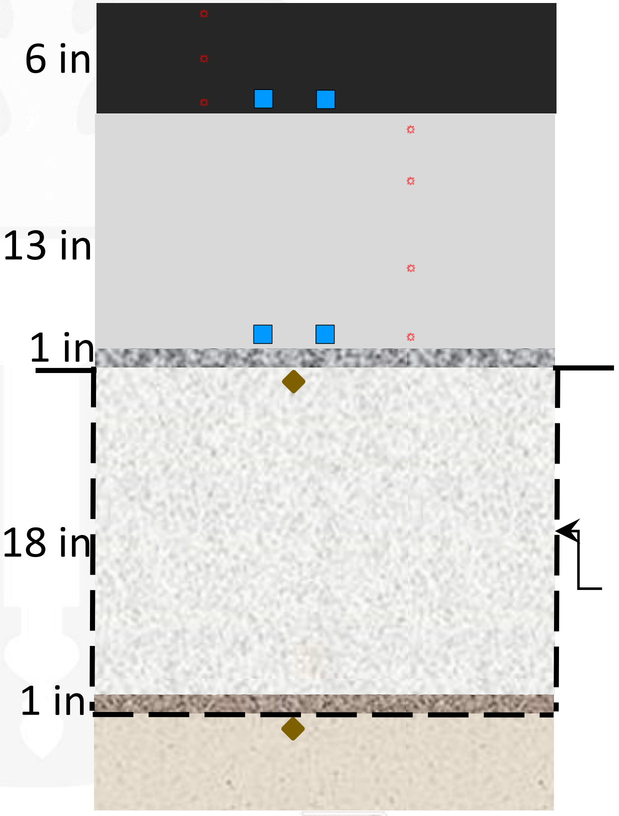


Porous asphalt pavement test section



■ Asphalt strain gauge
✲ Thermocouple
◆ Pressure cell
○ Water well

Plan



Cross Section

HVS Testing conditions

- **Testing Condition: Dry**
  - First half of HVS passes (31,250 passes- Test strip I& 406,250 passes-Test Strip II)
  - Sensor data (1,613 data points per pass from each sensor) will be used to calibrate fatigue and rutting models
  - If the section fails, HVS testing will be terminated. (Failure criteriaRutting-1 in, fatigue 25%)

If the section survives dry testing

- **Testing Condition: Partially Saturated**
  - Reservoir layer will be filled with water up to 50% of its full capacity
  - Apply the remaining passes (31,250 passes- Test strip I& 406,250 passes-Test Strip II)

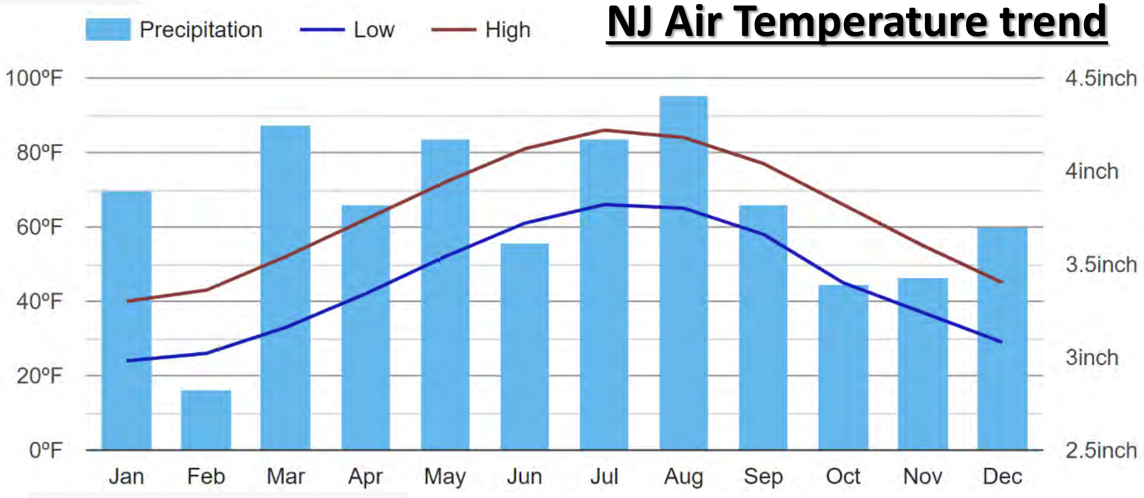
If the section survives partially saturated testing

- **Testing Condition: Fully Saturated**
  - Reservoir layer will be filled with water up to 100% of its full capacity
  - Start applying HVS passes (62,500 passes-Test strip I& 812,500 passes-Test Strip II)

HVS Loading and Laser Profilometer Measurements

- Wide-base tire, 80 kN
- Bi-directional
- Four-inch Wander
- Average air temperature in NJ around the pavement section
- High temperature test for rutting

NJ Air Temperature trend



Laser profilometer

- Every day, during the application of HVS loading, at three different locations (spaced 6 ft away from the middle of a section).

Benefits from this study

- Validated design approach for PA pavement for high-traffic volume
- Performance under high traffic volume for 50 years will be available in as less as 3 months from HVS loading
- MEPDG calibration coefficients
- New rutting and fatigue prediction models
- Periodic report on the performance history
- Systematic record of the construction problems/challenges
- Porous asphalt layer coefficient as an input in the AASHTO 93 design

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Thank You!

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