NATIONAL ACADEMIES *Sciences Engineering Medicine*

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Implementation of Inverted Pavements

September 18, 2023

2:00 – 3:30 PM

PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Andie Pitchford at TRBwebinar@nas.edu

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

ENGINEERING RCEP REGISTERED CONTINUING EDUCATION PROGRAM

Purpose Statement

This webinar will present the structural mechanics and effective uses of inverted pavements. Presenters will provide a summary of the state-of-technology. Presenters will also share case studies that discuss agency experiences during the design and construction of inverted pavements and the performance of inverted pavements compared with control sections.

Learning Objectives

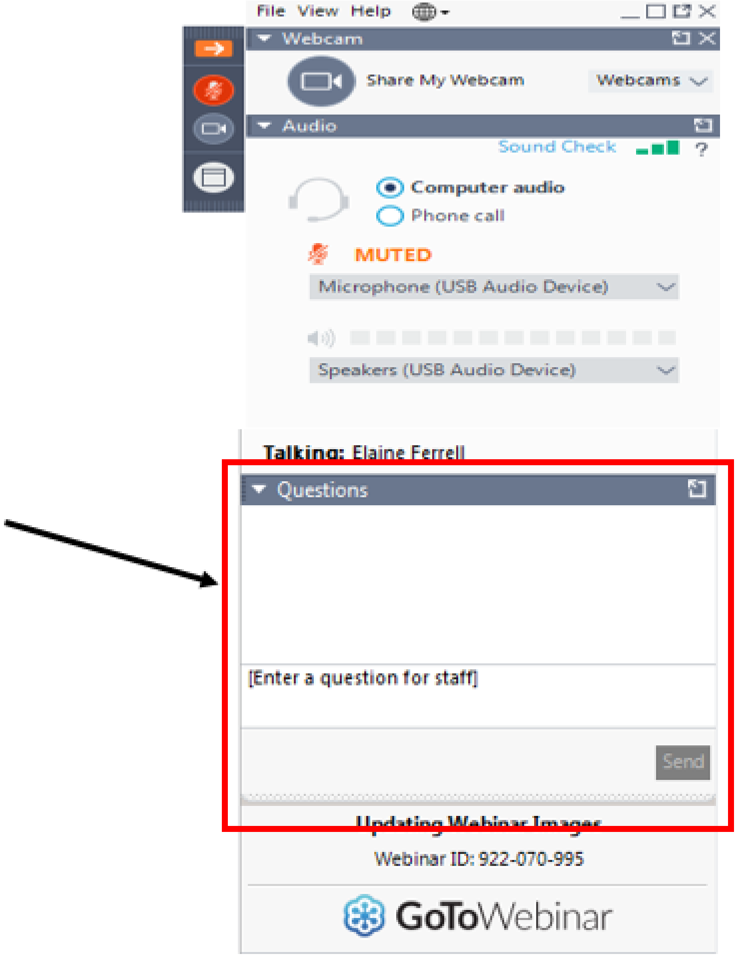
At the end of this webinar, you will be able to:

(1) Explain inverted pavements and the structural mechanics of the system

(2) Determine appropriate and effective uses of inverted pavements

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's Presenters

Imad L Al-Qadi
alqadi@testsustainability.com
University of Illinois

Erol Tutumluer
tutumlue@illinois.edu
University of Illinois

Jeff Uhlmeyer
juhlmeyer@qespavements.com
QES

Transportation Engineering Solutions & Technologies, Inc.

FHWA Task Order Request (TOR) # HIF200116PR

Inverted Pavements

TRB Webinar

Imad L. Al-Qadi and Erol Tutumluer

September 18, 2023

Acknowledgments

- FHWA sponsored 2023 TRB Workshop “Robust and Resilient Foundation Design: Inverted Pavements”
- TRB committees sponsoring this webinar:
    - AKG00 Section - Geology and Geotechnical Engineering
    - AKG40 Standing Committee on Mechanics & Drainage of Saturated and Unsaturated Geomaterials
    - AKG50 Standing Committee on Transportation Earthworks
    - AKG60 Standing Committee on Geotechnical Instrumentation and Modeling
    - AKG90 Standing Committee on Stabilization of Geomaterials and Recycled Materials
    - AKM80 Standing Committee on Aggregates
- This project is sponsored by FHWA: Task Order Request (TOR) # HIF200116PR
- FHWA (Tom Yu)
- The work was conducted by TEST, Inc (Imad Al-Qadi, Erol Tutumluer, Ester Tseng, Hasan Ozer, and Issam Qamhia)
- QES (Dennis Morian, Jeff Uhlmeyer, and Douglas Frith)

Acknowledgments

- Georgia: David Frost, Sean Donovan, James Tsai (Georgia Institute of Technology), and Peter Wu (GDOT)
- Louisiana: Xingwei Chen and Doc Zhang (LADOT)
- New Mexico: Robert Young, Rais Rizvi, Hashem Faidi, Hao Yin (NMDOT), Jeffrey Mann (WSP), Lucas Giron (Wood), and Bryce Simons (NMDOT, retired)
- North Carolina: Shane Underwood (NC State), Kevin Vaughan (Vulcan Materials)
- Virginia: Brian Diefenderfer (VDOT), Randy Weingart (formerly with Luck Stone) and Reza Ashtiani (United States Air Force Academy)
- Illinois: The research team
- Dynatest (Randall Milton)

Outline

TEST
Live Sustainably

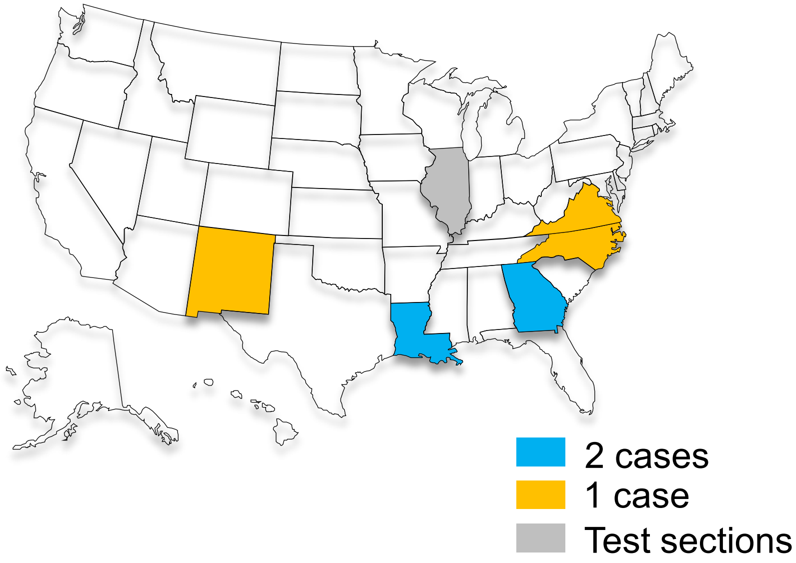
Technology

- Mechanical Behavior
- Construction
- Materials
- Performance
- Sustainability

Experience

- South Africa
- Australia
- US Early Experience

Case Studies

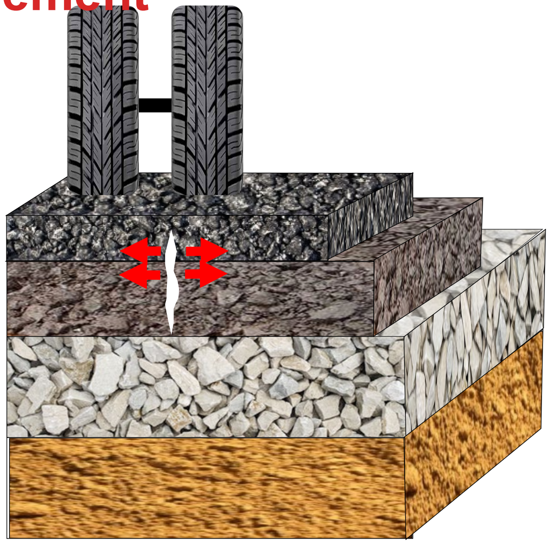


Introduction

TEST
Live Sustainably

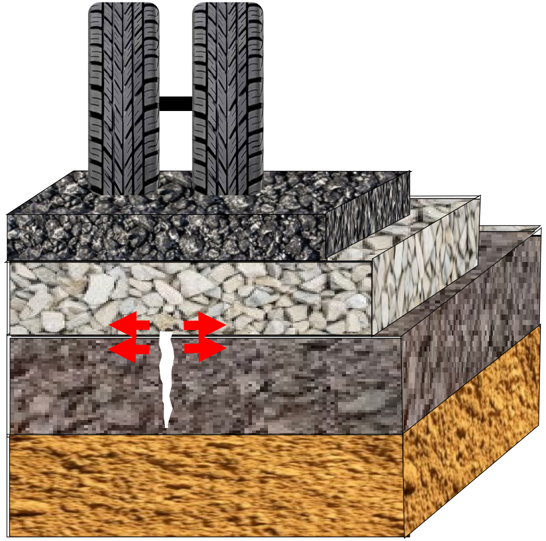
Conventional Pavement

Asphalt Concrete (AC)
AC Base
Unbound Layer
Subgrad
e



Inverted Pavement

Asphalt Concrete
Unbound Layer
Cemented
Layer
Subgrade



Inverted pavement application is limited in the US due to inadequate experience, and limited technology transfer. In addition to lack of supporting LCCA and LCA.

IP: Typical Layer Thicknesses

1.2- to 3-in-thick AC (in US up to 6in)

4- to 6-in-thick high quality crushed aggregates

4- to 16-in-thick CTB (2-5% cement, >95% mod AASHTO)

Photo courtesy: James Maina

TEST
Live Sustainably

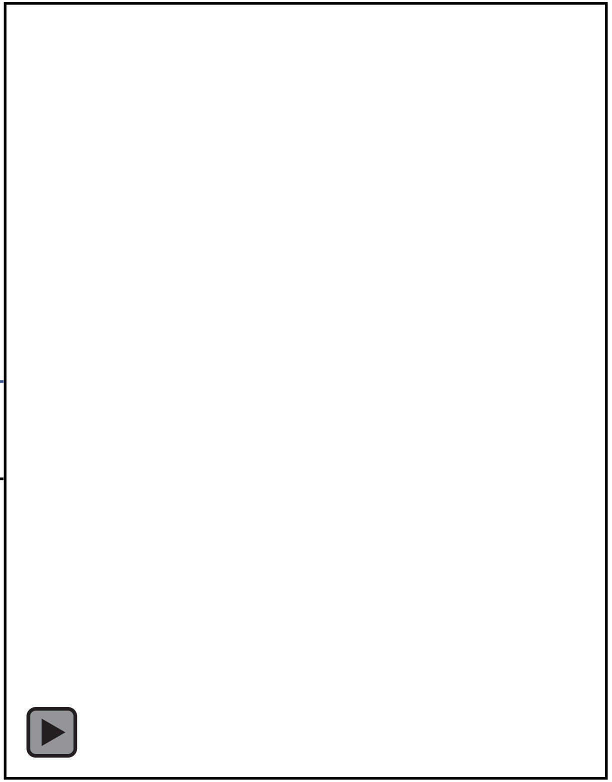
Mechanical Behavior

Lower tensile strain at bottom of AC

Anisotropic & nonlinear base

Optimum cement treated subbase
(over weak subgrade)

Lower vertical stress on subgrade

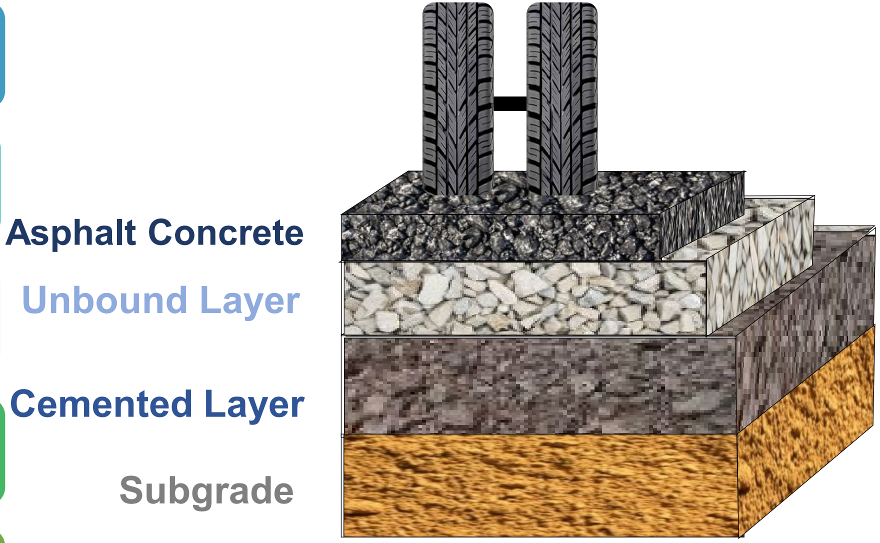


Technology - Introduction

TEST
Live Sustainably

- Moderately high-volume roads
- Cost effective
- 100% recyclable
- Reduces the use of natural resources
- Enables better compaction of unstabilized materials
- Reduces risk of reflective cracking

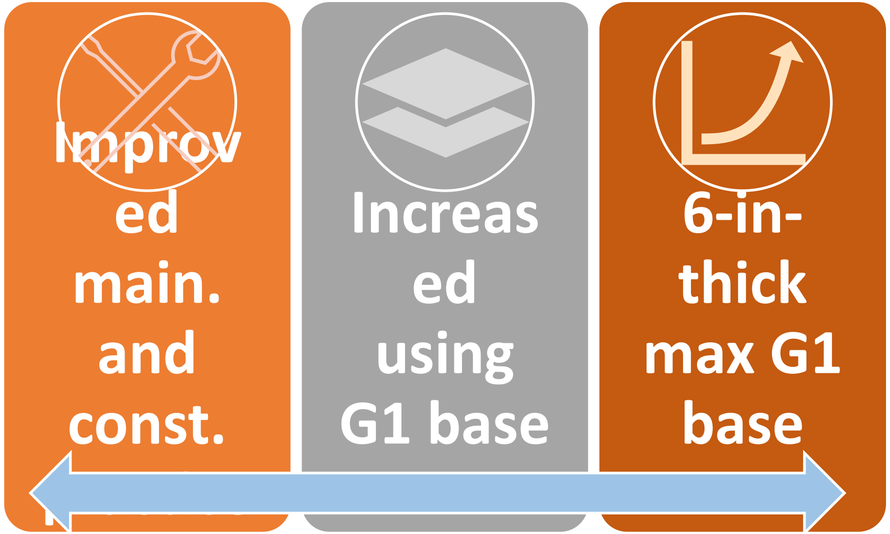
Inverted Pavement



TEST
Live Sustainably

South African Experience

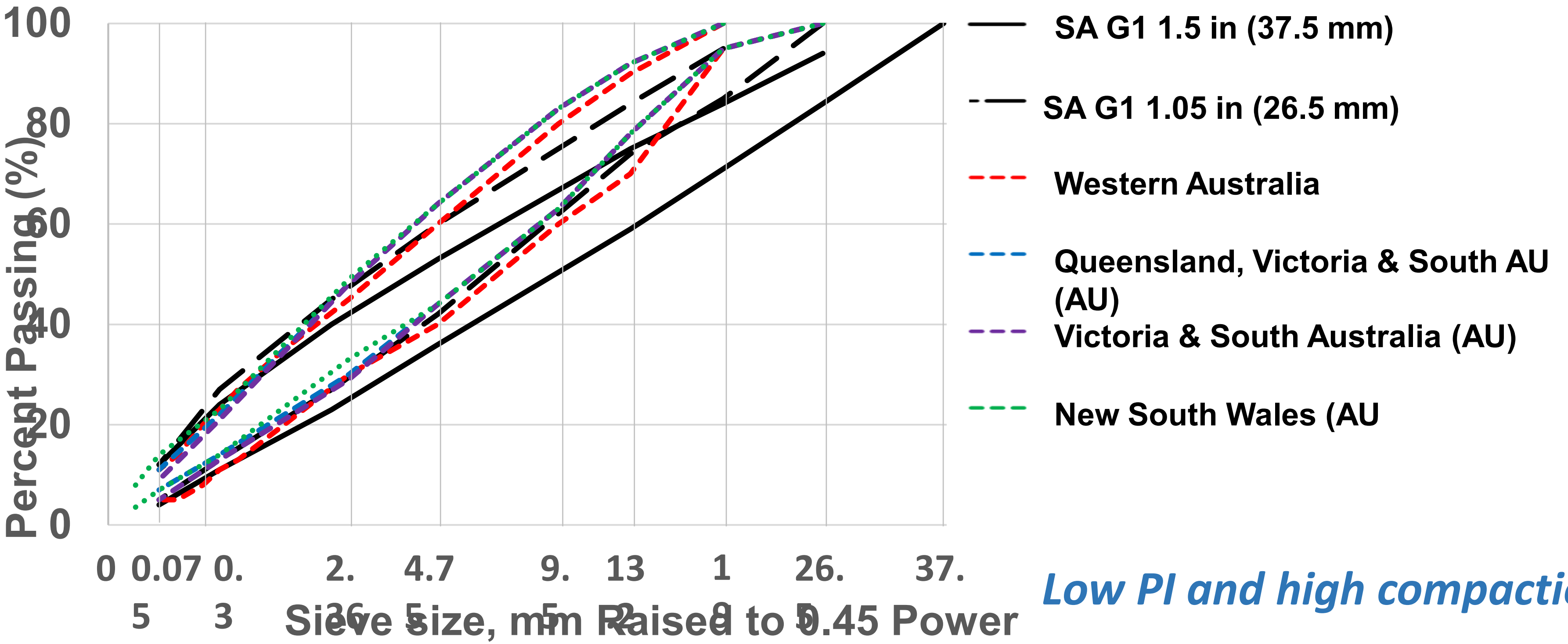
- G1 from single stage crusher-run
  - Produce tightly knit matrix by expulsion of passing #200 fines (Kleyn, 2012)
- Increased confidence in using G1 material for high traffic classes
  - A 6-in-thick G1 layer is optimal
  - 12 to 50 million ESALs
  - Feasibility of use in wet regions given that impervious surface is maintained.
  - Damage exponent (or n-value): ~3



Saving ratio from 2.6-6.2

Source: Adapted from Jooste & Sampson, 2005

Materials: Granular Base

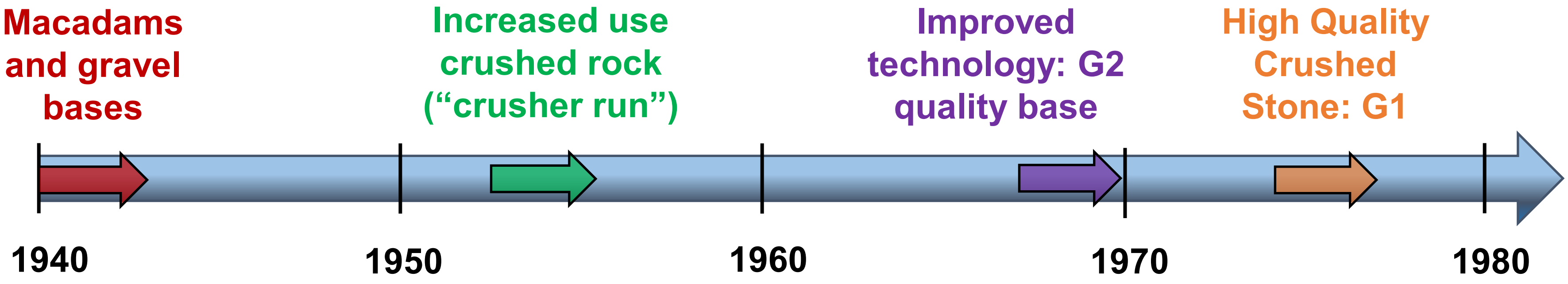


Low PI and high compaction

Sources: Adapted from TRH 14, 1985; Buchanan, 2010, DPTI (2020), MRWA (2020), TfNSW (2020a), TMR (2020), VICROADS (2017)

South African Inverted Pavement Progress

TEST
Live Sustainably



- **Crushed, hard, sound, durable, and not weathered parent rock**
- **All particle faces are fractured**
- **Can be adjusted using fines from crushing of original parent rock only**

Source: Based on Jooste & Sampson (2005)

South African Design Philosophy

Thin AC (<2 in)

AC failure not a terminal condition

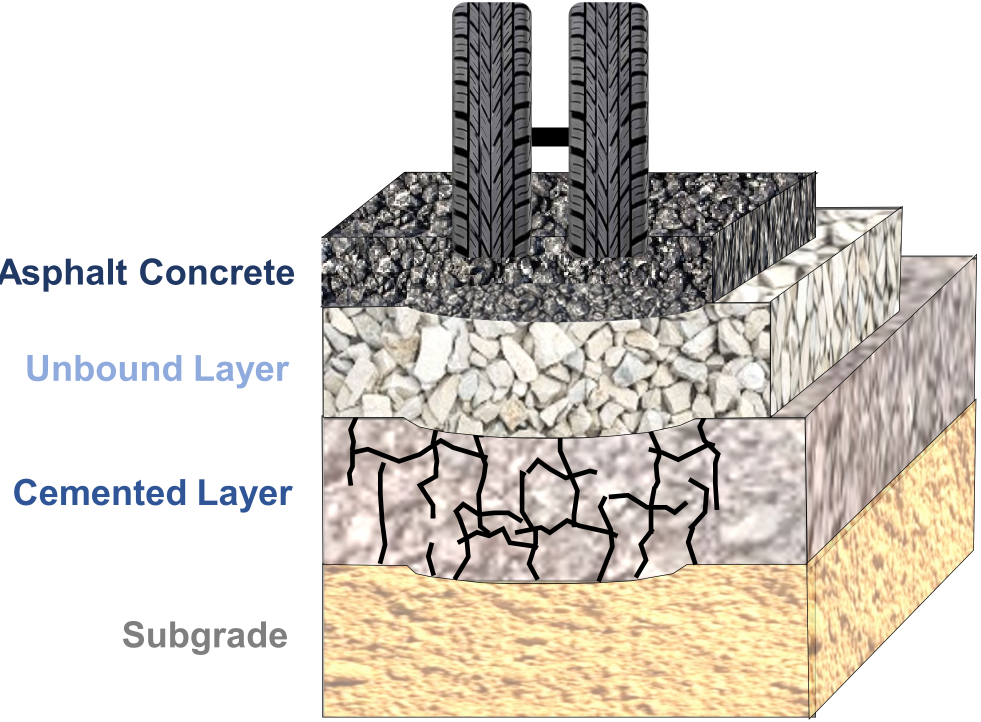
Fatigue models not considered reliable for thin AC

capacity of AC usually not considered

Crack seals, waterproof seals and/or patches

Good drainage & impervious surface

South African Design Thinking!



1
- **Pre-cracked** phase
- E > 435 ksi

2
- **Post-cracked** phase
- E = 110 to 290 ksi

3
- **Equivalent granular** phase
- E = 29 to 58 ksi

Based on South African National Roads Agency, 2014

Inverted Pavement Construction

Standard compaction → Particle interlocking or slushing

Grid roller (2 or 3 passes) → Vibratory roller → Wetting → Heavy static rollers → Brooming

Source: Simons, 2016

Construction

Standard compaction → Particle interlocking or slushing

Grid roller (2 or 3 passes) → Vibratory roller → Wetting → Heavy static rollers → Brooming

Excess Fines Expelled as Slush from Layer

Brooming and Spreading Initial Slush/Fines to Deficient Areas

Source: Steyn & Kleyn, 2016; Simons 2016, & NMDOT

Quality Control

Loose G1

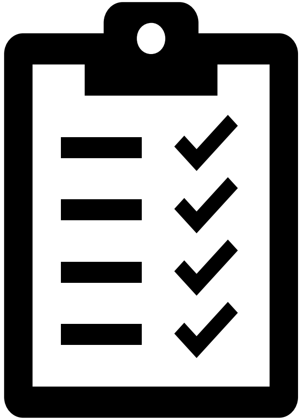
Ready for a "ping-test"

G1 stockpile

G1 base layer cut like concrete

Source: Kleyn, 2012

When to Stop Rolling?



- No more air bubbles escape during slushing
- Expelled water clearing up substantially
- Well-knit mosaic visible through surface water
- Road surface does not heave under heavy roller
- “Visual and ping” tests

(Based on Steyn and Kleyn, 2016)

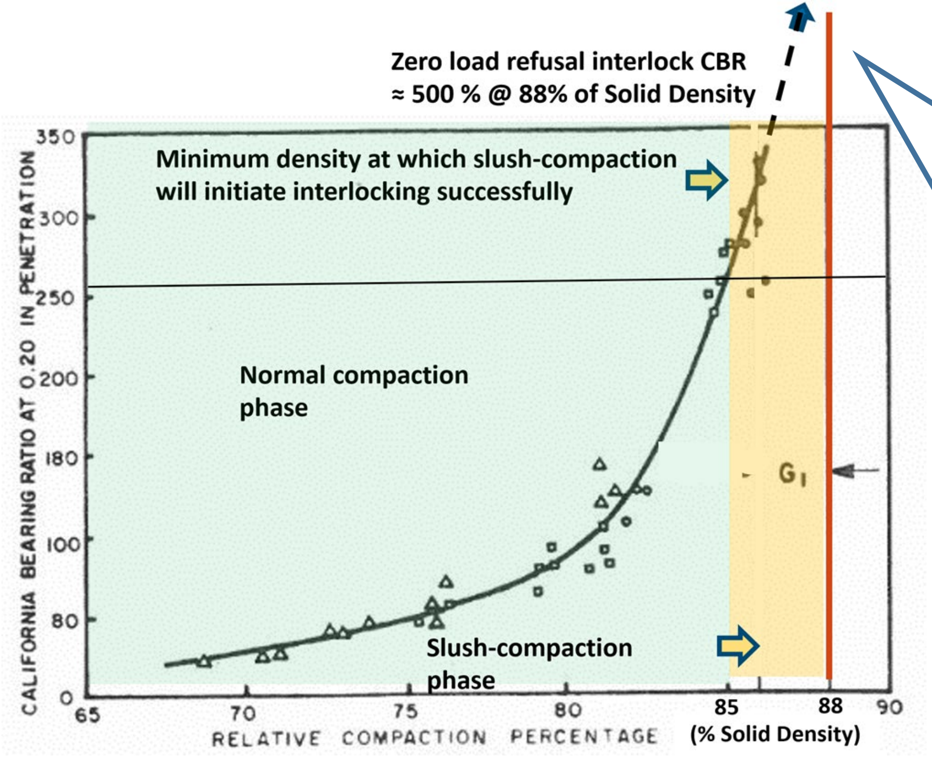
When to Place AC Surface?

- Surface broomed and cleaned
- No free water on working surface
- Moisture content of upper 2.0 in drier than 50% of OMC

Based on COTO (2020)

What Can Go Wrong?

TEST
Live Sustainably



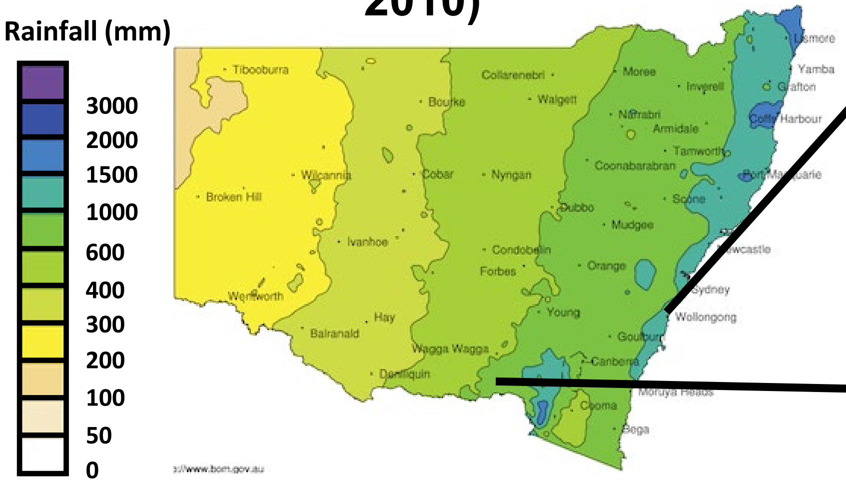
Source: Kleyn, 2016

- Insufficient subbase support
- High pavement deflection
- Aggregate gradation
- Soft aggregate
- Moisture content (not at OMC)
- Unslushed compaction
- Premature stop slush-compaction
- Roller(s) not heavy enough
- Over-vibration
- Material altered during compaction

Impact of Base Saturation on IP

NEW SOUTH WALES

Average Annual Rainfall (1981 to 2010)



Kianna Bypass, Wollongong

Failed prematurely due to base course saturation

Hume Highway, Holbrook

Good performance could be due to relatively low rainfall

Source: Adapted from Commonwealth of Australia, Australian Bureau of Meteorology (2020)

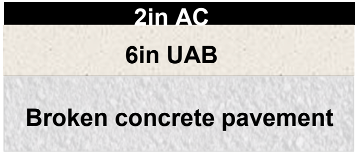
Based on RTA (2004)

Summary

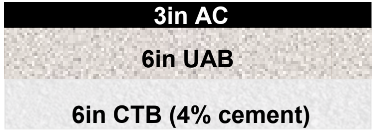
- Established in South Africa
- Granular base course:
  - High modulus (stress dependency)
  - Delays reflection cracking from cement treated subbase
  - High material quality and good construction (particle interlock)
  - Good drainage (coarse aggregate)
- Thin asphalt concrete layer
- Regular maintenance
- Well designed/built IP could perform satisfactory.

Early US Experience

- **Early Experience in New Mexico**



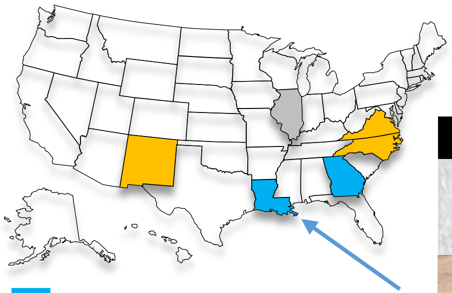
  - **1954: Overlay of badly broken concrete pavements**
    - **No reflection cracks or significant rutting after 6 years**
  - **~1960: two experimental roads**



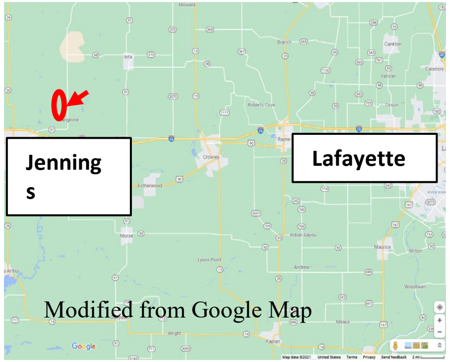
- **Army Corps of Engineers**
  - **Performance influenced by CTB stiffness and tensile strength**
  - **Laboratory tests were conducted; resulted in introducing numerical nonlinear and constitutive models**

- **Lab studies at GA Tech in 1983**

Louisiana Experience



2 cases
1 case
Test



LA 97 Control

- 1.5 + 2" AC
- 8.5" CTB
- Lime Treated Subgrade

LA 97 Inverted

- 1.5 + 2" AC
- 4" Limestone Interlayer
- 6" CTB
- Lime Treated Subgrade

US 165

- 2 + 4" AC
- 4" Limestone Interlayer
- 8" CTB
- Lime Treated Subgrade

LA 97:

- Built in 1997 near Jennings
- Design traffic 1.6×10^5 - 3.3×10^6 ESALs
- High rainfall (60.4 in/yr)
- High humidity (average 72-81%)

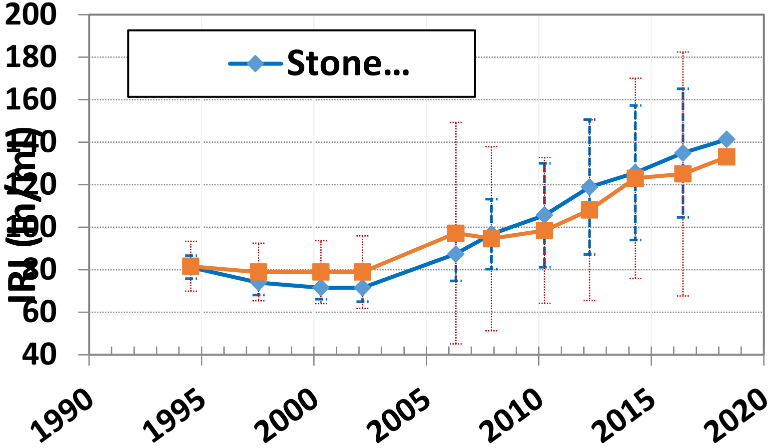
US 165:

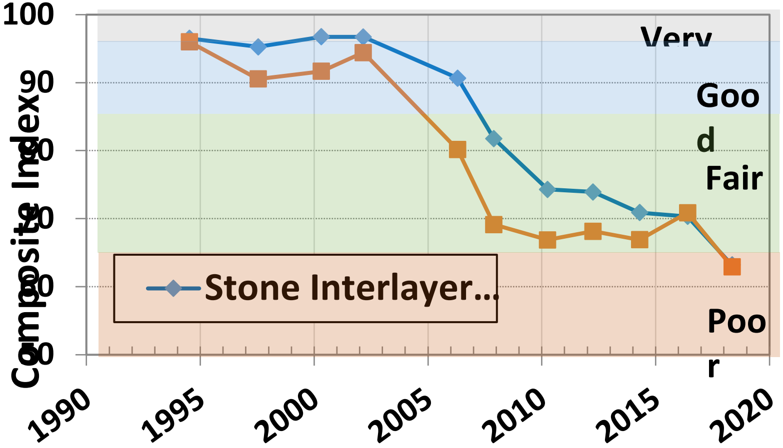
- Built in 2006 - Monroe
- 20-year design: 3.2×10^6 ESALs
- Rainfall (53.6 in/yr)
- Humidity (ave. 72-75%)

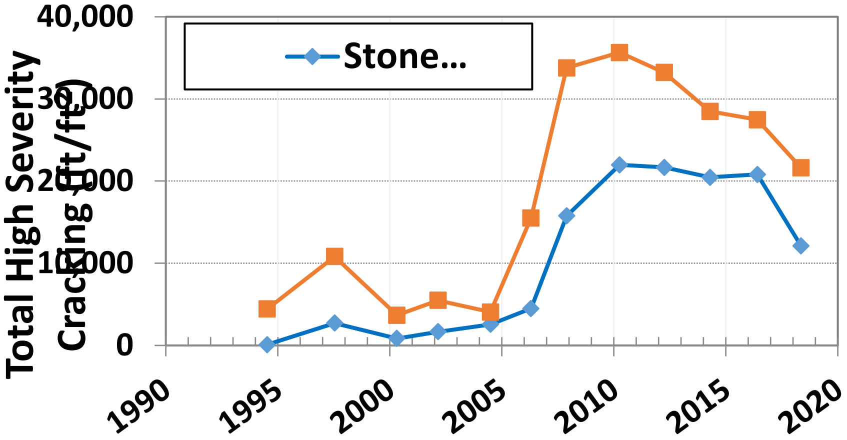
Source: Al-Qadi et al. (2015)

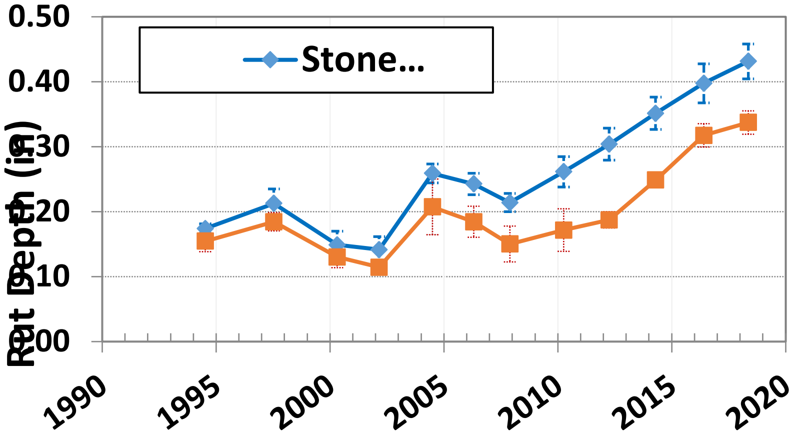
Louisiana, LA 97

LA 97 Results









Accelerated Pavement Testing: LA 97

LA 97 CONTROL

1.5 + 2” AC

8.5” CTB

Lime Treated Subgrade

LA 97 INVERTED

1.5 + 2” AC

4” Limestone Interlayer

6” CTB

Lime Treated Subgrade

ALF SOIL

3.5” AC

8.5” CTB

3.5” Select soil

Subgrade

ALF INVERTED

3.5” AC

4” Limestone Interlayer

6” CTB

2” Select soil

Subgrade

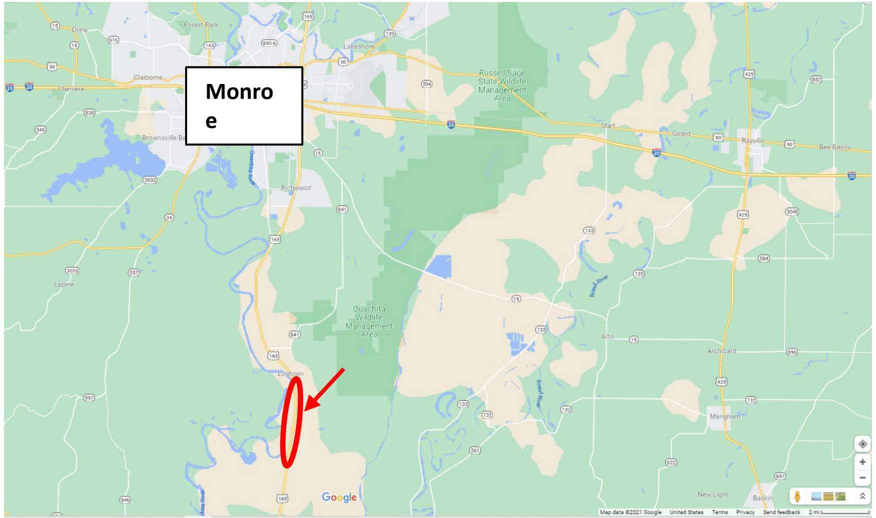
4.7 times the number of ESALs compared to the soil cement section

LA 97 Performance

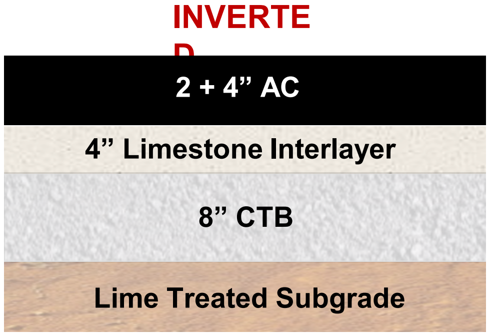
- **Inverted pavement vs. control section:**
  - **Less cracking but more rutting**
  - **Relatively similar IRI**
  - **Composite index shows slightly better pavement performance**
- **Accelerated pavement testing:**
  - **Inverted pavement showed better overall pavement performance (4.7x more ESALS to failure compared to soil-cement pavement)**

Crack initiation and progression appear to precede rut depth development. Could be related to water ingress through cracks.

US 165



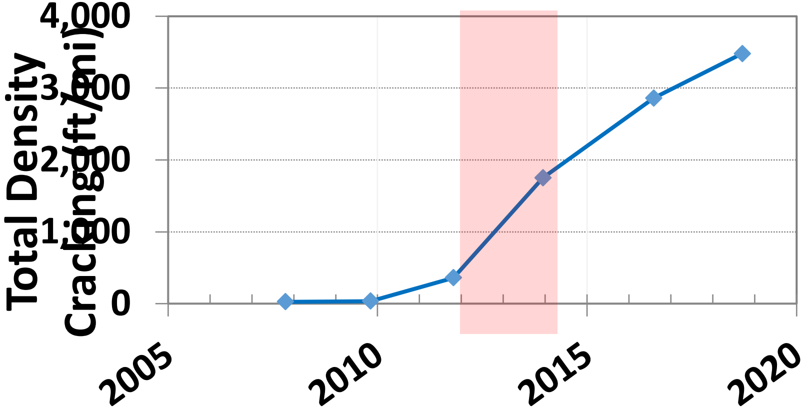
Modified from Google Map

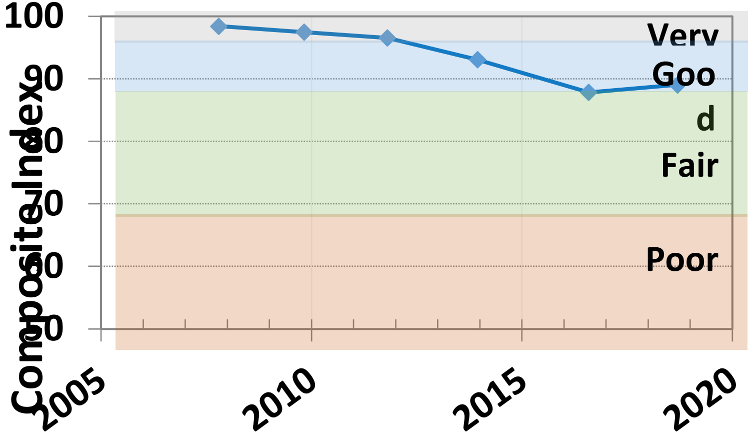


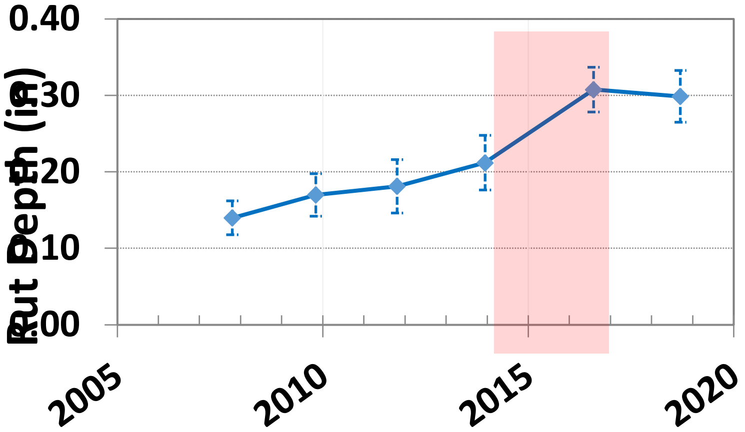
- **Built in 2006**
- **20-year design traffic 3.2×10^6 ESALs**
- **Rainfall (53.6 in/yr)**
- **Humidity (Ave. 72-75%)**

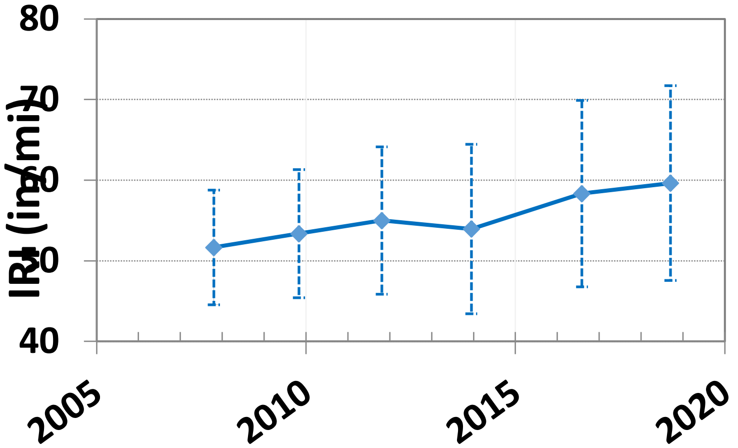
Louisiana , US 165

US 165 Results







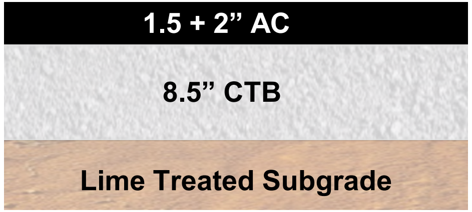


US 165 Performance

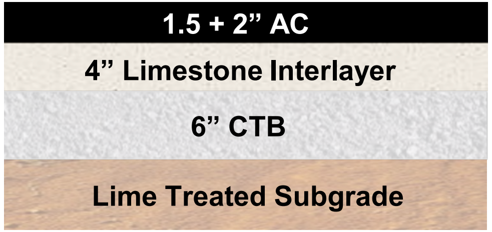
- **High cracking rate seems to precede high rut depth rate**
- **Good condition after 13 years**

LA-97 and US-165 Cost

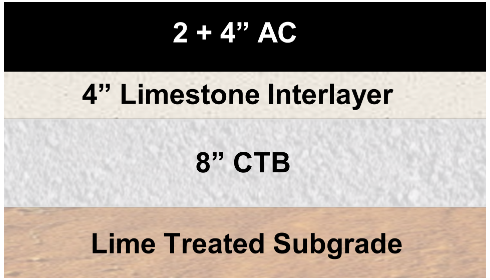
- **Costs:**
  - **LA-97[1]:**
    - **CP: $173,000/mi**
    - **IP: $208,000/mi (potentially leading to an increased capacity)**
  - **US-165[2]:**
    - **Inverted pavement: $204,208/mi**



CP



IP



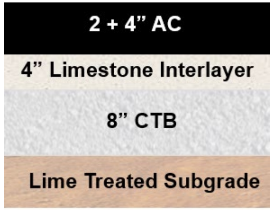
IP

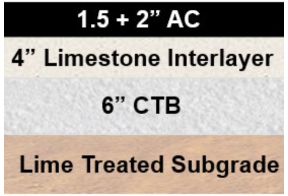
1) After Titi et al. (2003); 2) Ozer & Al-Qadi (2021)

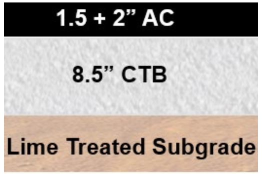
LA-97 and US-165 LCA

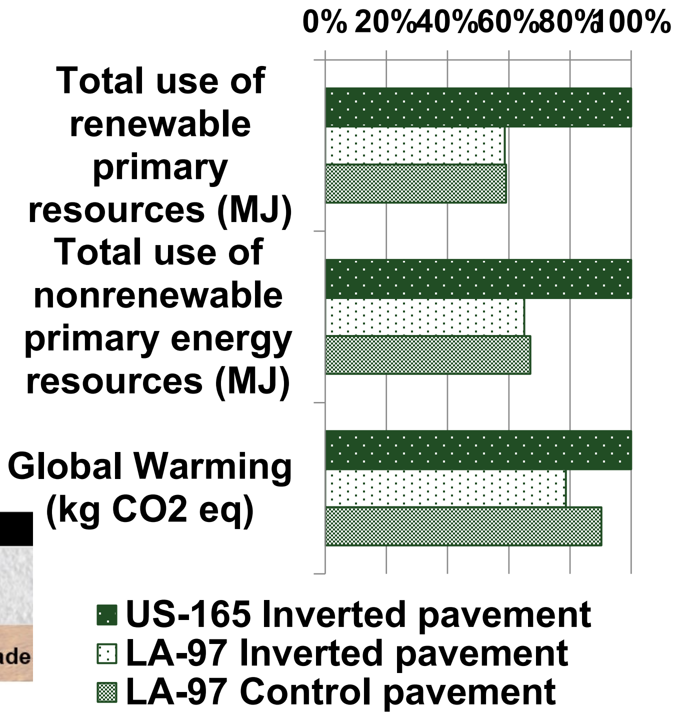
FHWA LCA Pave Tool (Materials, Construction, and Transportation)

Impact indicator	US-165	LA-97	
	IP	IP	CP
Total use of renewable primary resources (MJ/ln-mi)	2,179,377	1,279,028	1,287,936
Total use of nonrenewable primary energy resources (MJ/ln-mi)	5,786,567	3,764,955	3,880,785
Global warming (kg CO_2 eq/ln-mi)	279,694	220,068	252,227



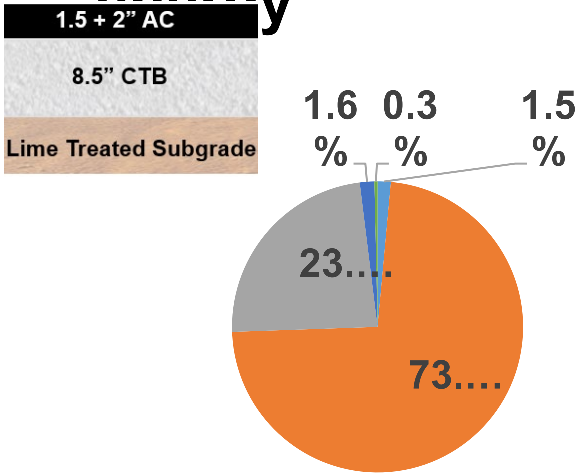




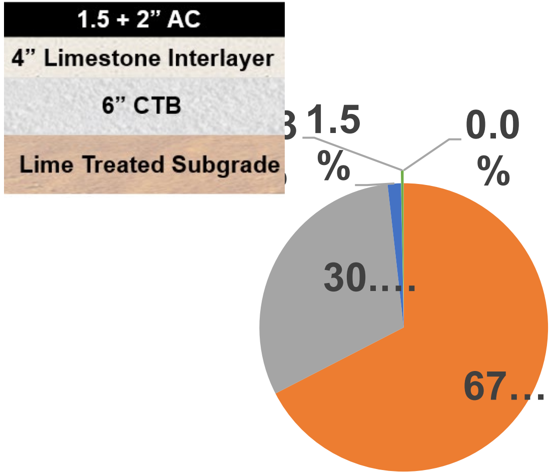


LA-97 and US-165

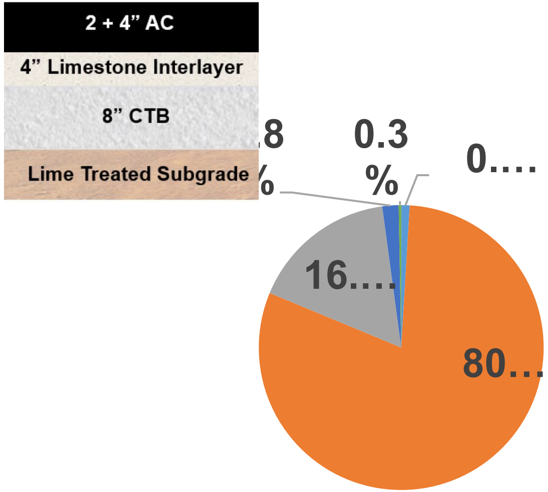
- **LCA – Contribution of material stage to total primary energy**



LA-97 CP (5,044 GJ)



LA-97 IP (5,169 GJ)

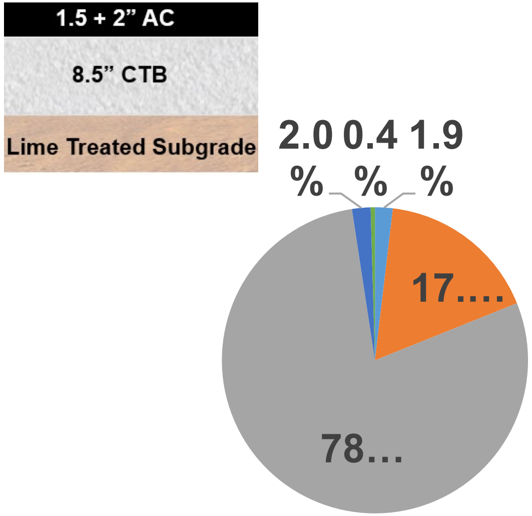


US-165 IP (7,965 GJ)

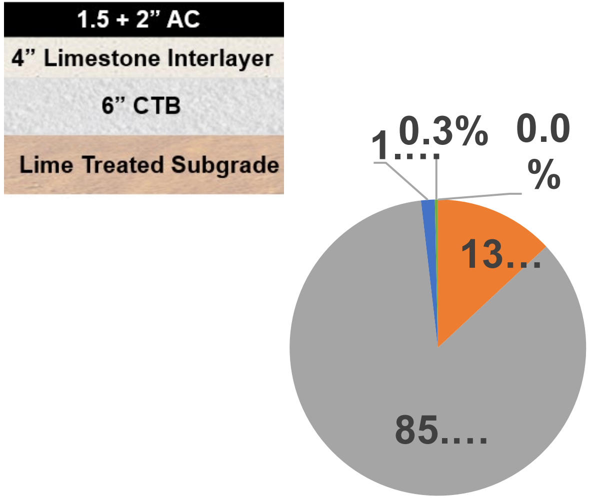
- Base and Subbase Material
- Asphalt binder, no additives, consumption mix, at terminal, from crude oil
- Cement (Blended with SCMs)
- Virgin aggregates for asphalt
- Others (lime, water, and RAP)

LA-97 and US-165

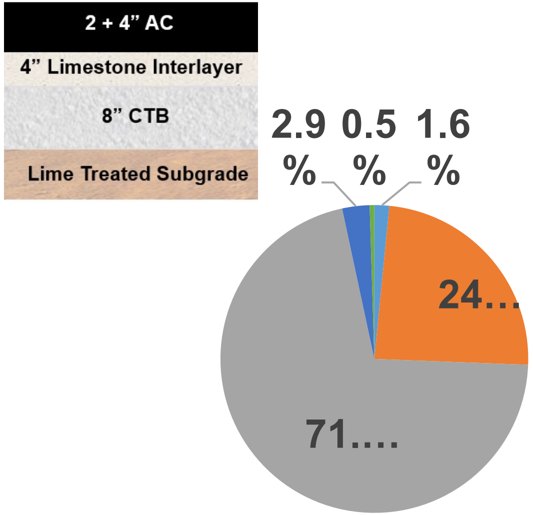
- **LCA – Contribution of material stage to global warming potential**



LA-97 IP (220t kg CO_2 eq)



LA-97 CP (252t CO_2 eq)



US-165 IP (280t CO_2 eq)

- Base and Subbase Material
- Asphalt binder, no additives, consumption mix, at terminal, from crude oil
- Cement (Blended with SCMs)
- Virgin aggregates for asphalt
- Others (lime, water, and RAP)

Louisiana

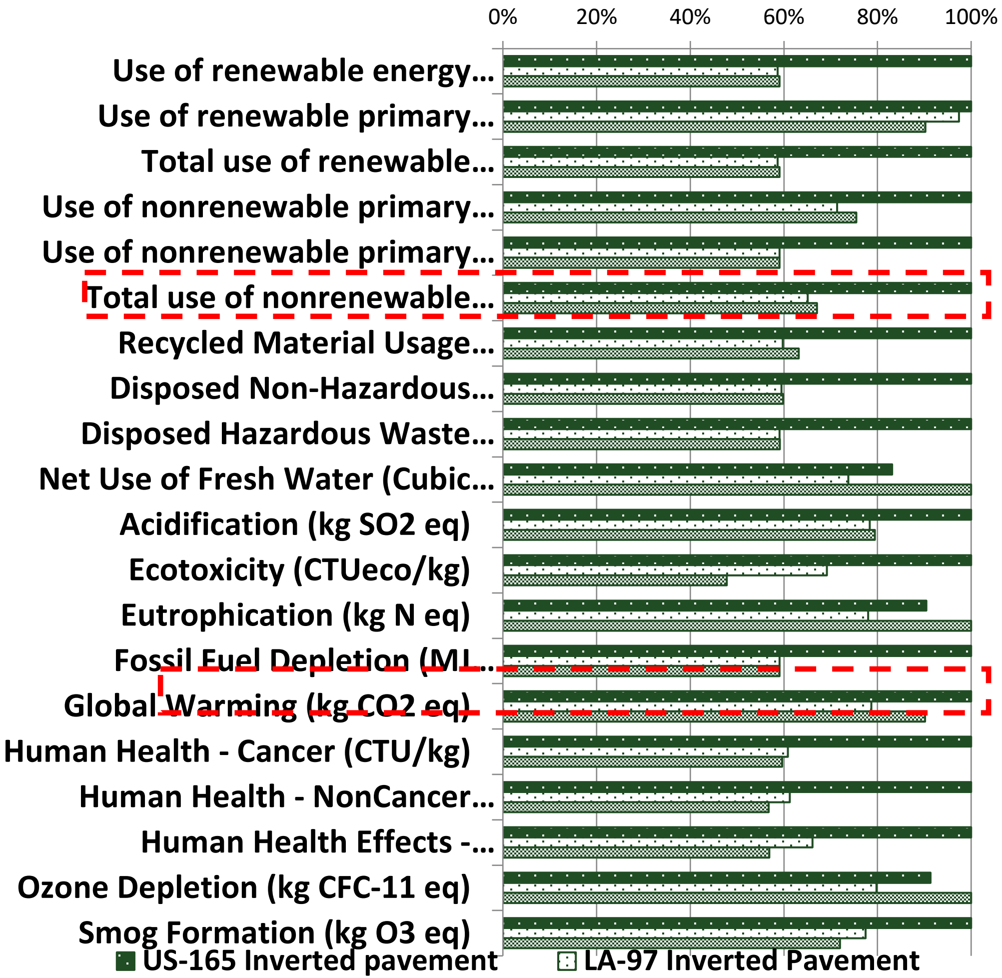
LCCA and LCA

Section	Energy Demand, MJ per lane-mile	GWP, $kgCO_2$ Per lane-mile	Initial Cost, $ per lane-mile[1]
LA 97 (control)	2.61E+06	2.90E+05	–
LA 97 (inverted)	2.63E+06	2.58E+05	–
U.S. 165 (control)[2]	3.63E+06	3.74E+05	204,599
U.S. 165 (inverted)	3.54E+06	3.23E+05	204,208
Avg. Savings	Negligible	12.3%	Negligible

[1] Cost is calculated using average bid prices for construction of CSB, crushed granular base, and AC layers obtained for specific pay items used in the U.S. 165 project.

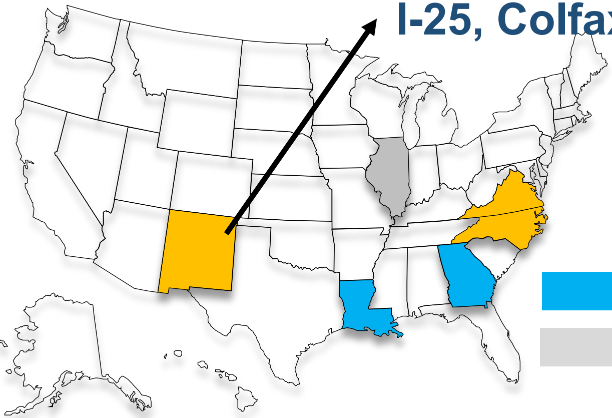
[2] Control for U.S. 165 project is hypothetical and included for comparative purposes.

Source: Al-Qadi et al. (2015)



FHWA LCA Pave Tool (materials and construction phases)

New Mexico Case: Concrete Pavement

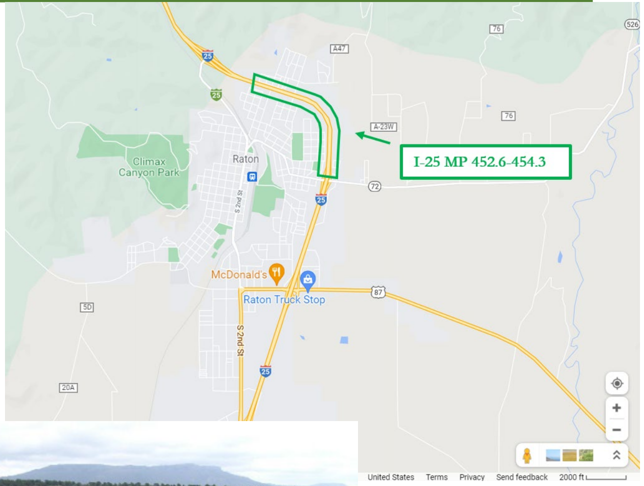


I-25, Colfax County (2012)

- Built in 2012
- 20-year ESALs: 1.0×10^7
- Slushing was used

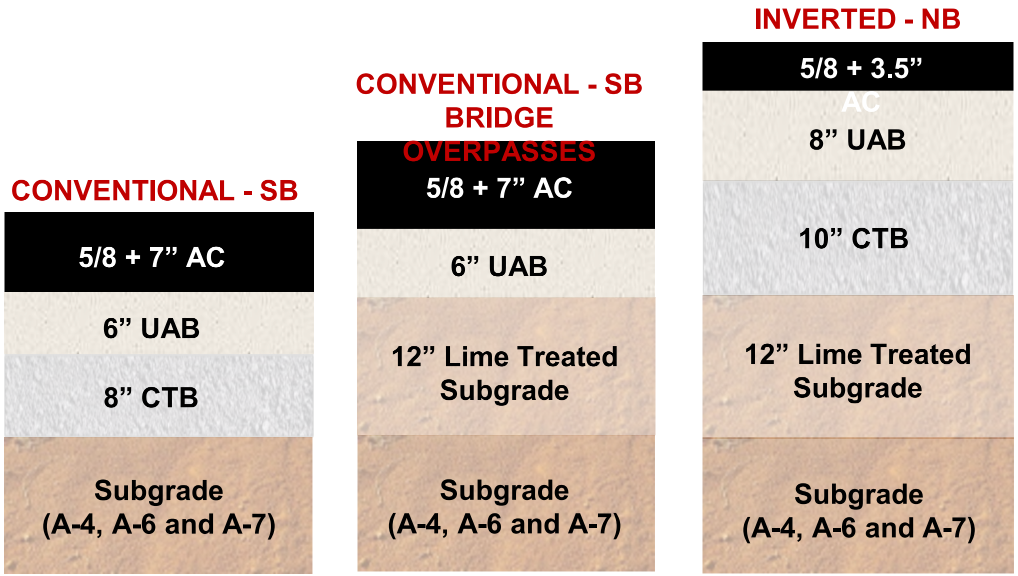
2 cases | 1 case

Test sections

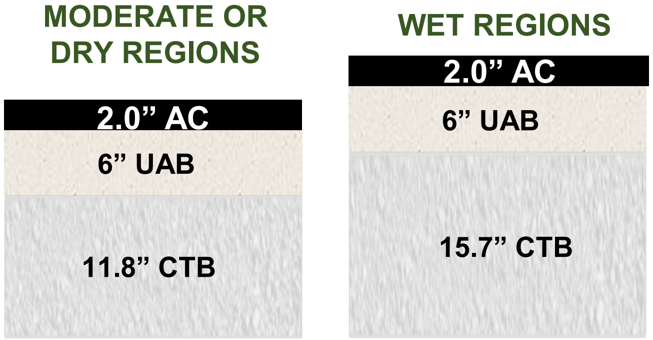


Credit: NMDOT

I-25 Design



South Africa (TRH4)



- Thinner AC
- Thicker CTB
- Coarser aggregate base
- Finer NMAS in AC
- No F/T
- Compaction level
- Controlled moisture content

Subgrade & CTB

TEST
Live Sustainably

- Subgrade: A-4, A-6 and A-7

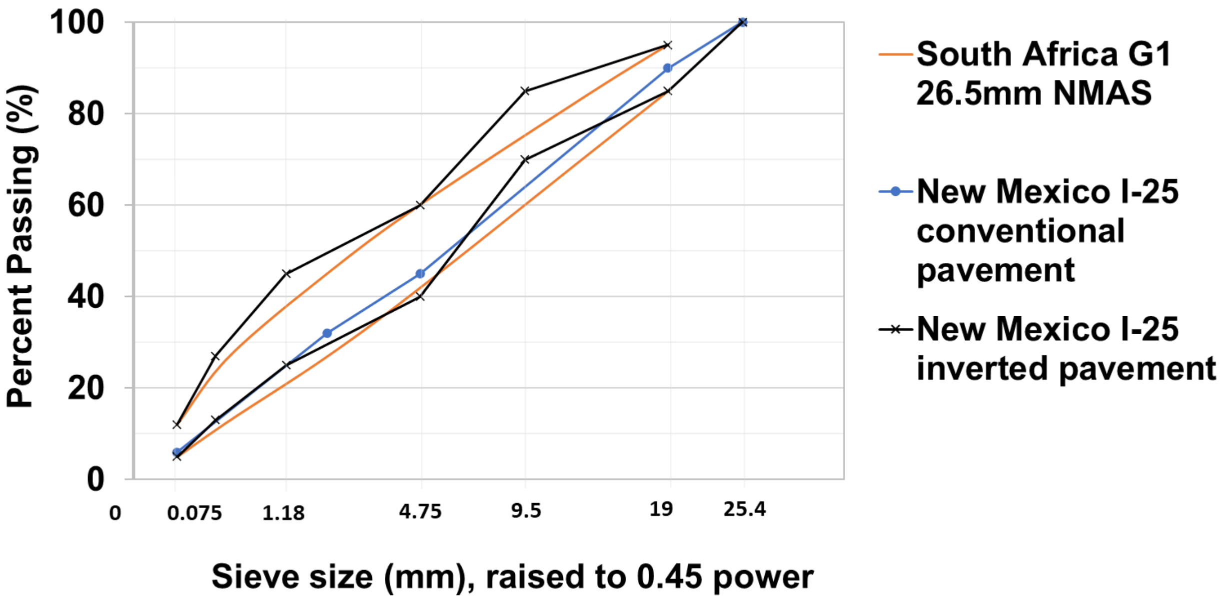
- Type III cement
- 5%
- One lift

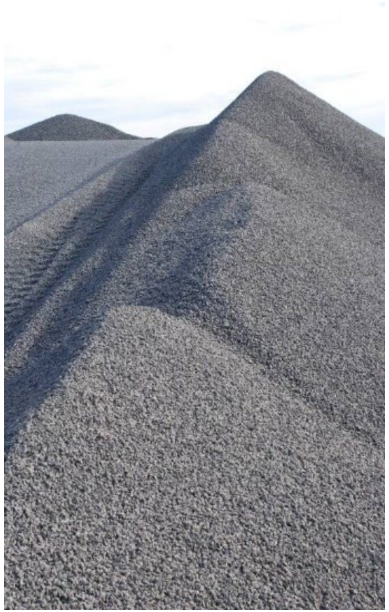
- 28-day UCS
- 850-1000psi

Source: Simons, 2016

Unbound Aggregate Base

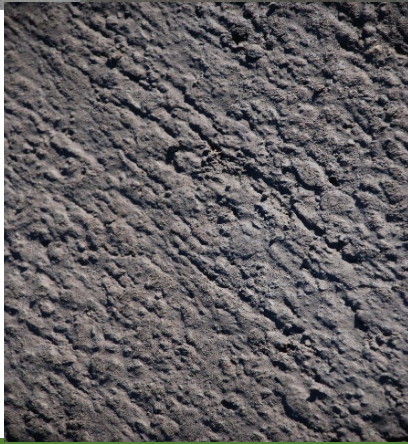
Well-graded 1-in top size crushed stone, gravel, and sand (mixed stockpiles)





Source: Simons, 2016

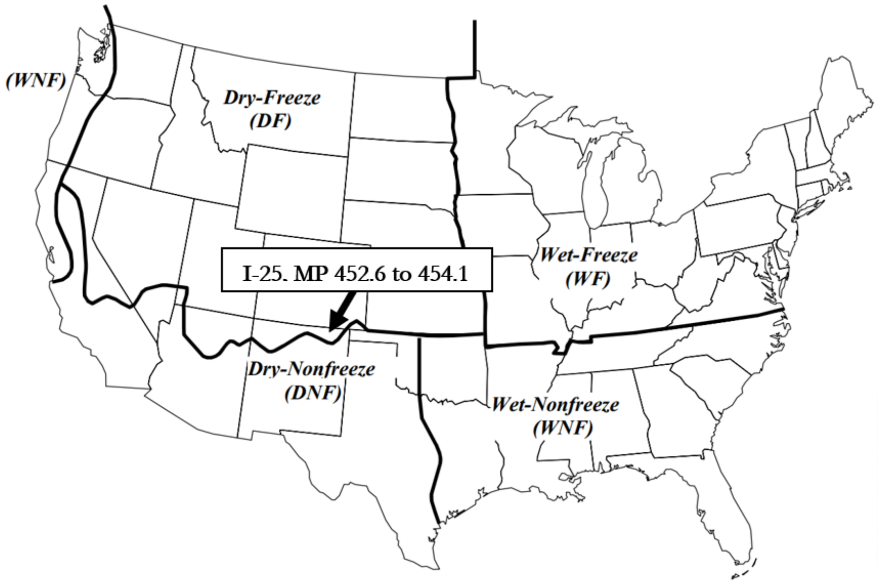
Base Construction and Slushing



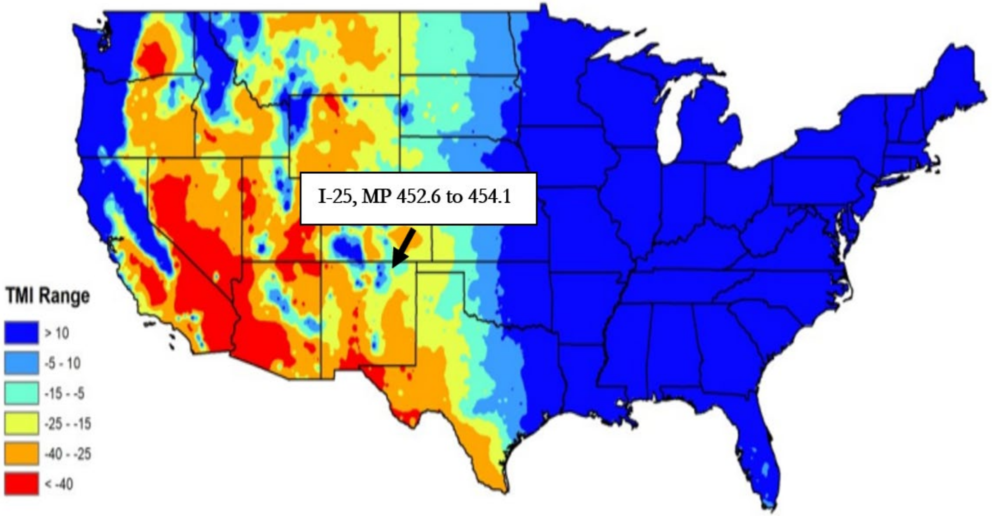
Source: Simons, 2016

Climate

Rainfall: 18.2 in/yr Snowfall: 33.0 in/yr



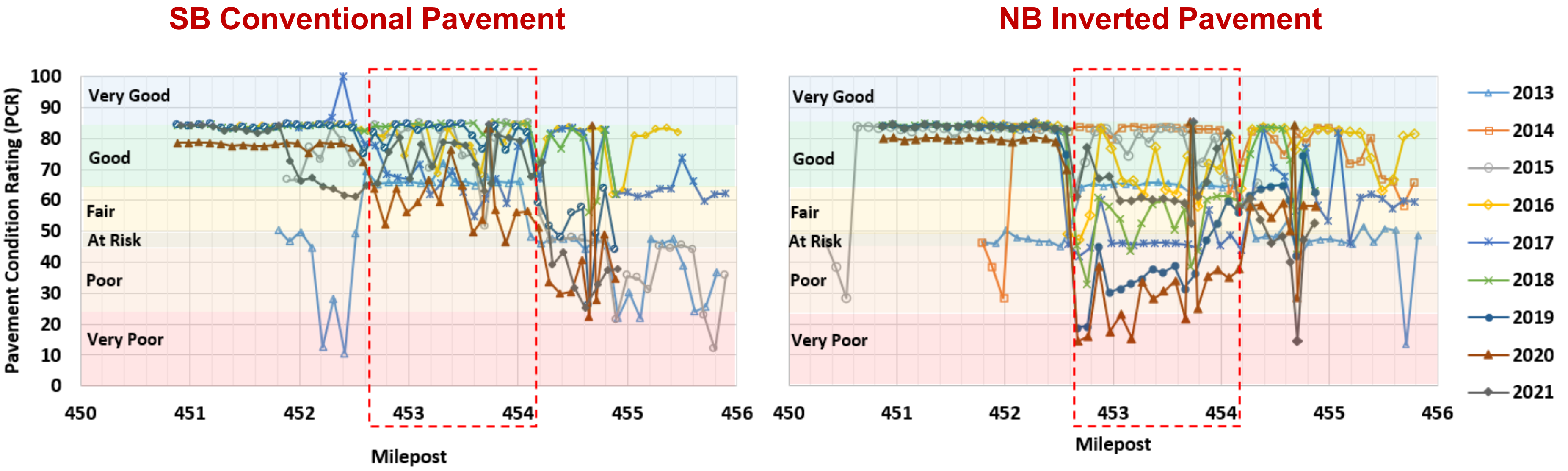
Source: ARA, 2004



Source: Singhar, 2018

Pavement Performance

- Pavement condition rating includes rutting and cracking
- Faster pavement deterioration in the NB inverted section

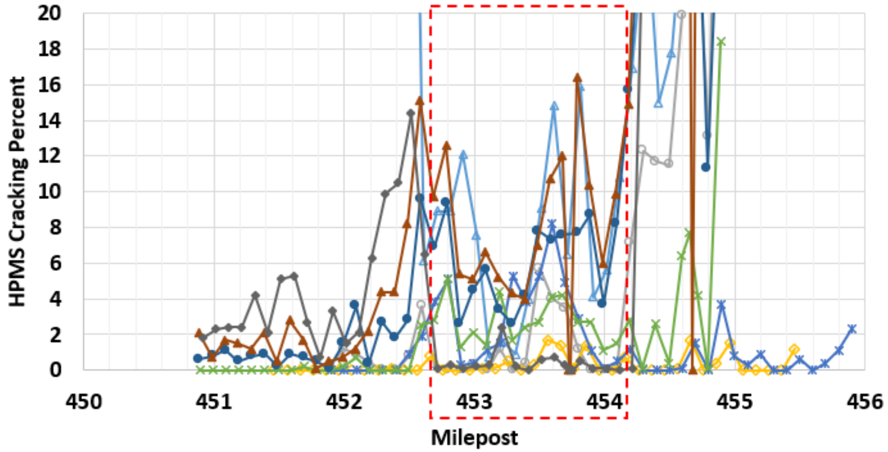


Data provided by NMDOT

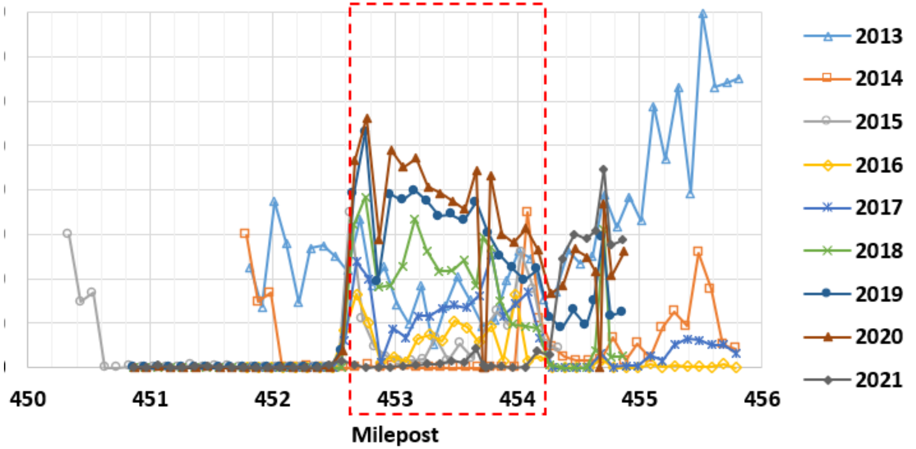
Crack Progression

- **Fatigue, transverse thermal, and longitudinal cracks were observed**

SB Conventional Pavement



NB Inverted Pavement

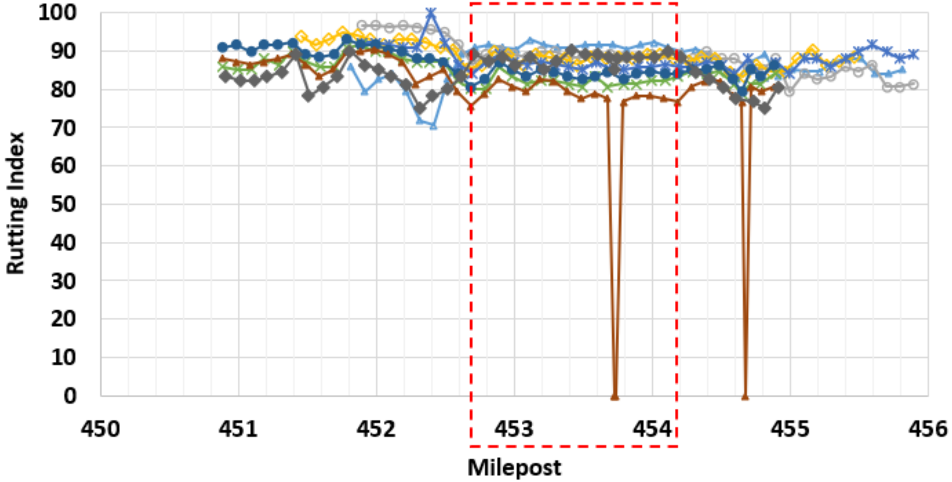


Data provided by NMDOT

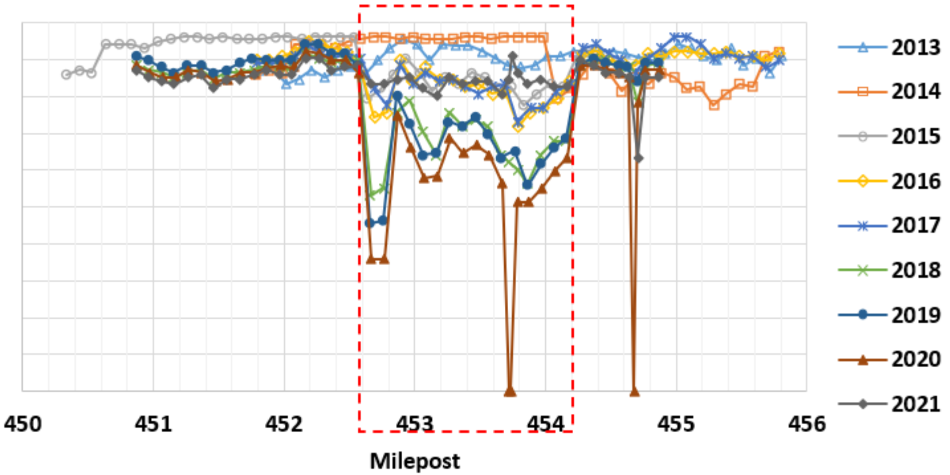
New Mexico

Rutting Development

SB Conventional Pavement

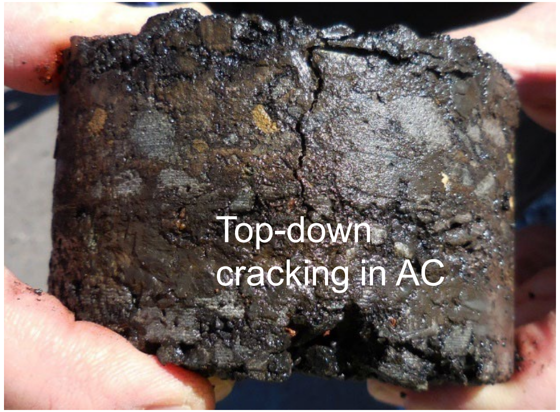


NB Inverted Pavement



Data provided by NMDOT

Pavement Performance (in 2015)



Credit: NMDOT

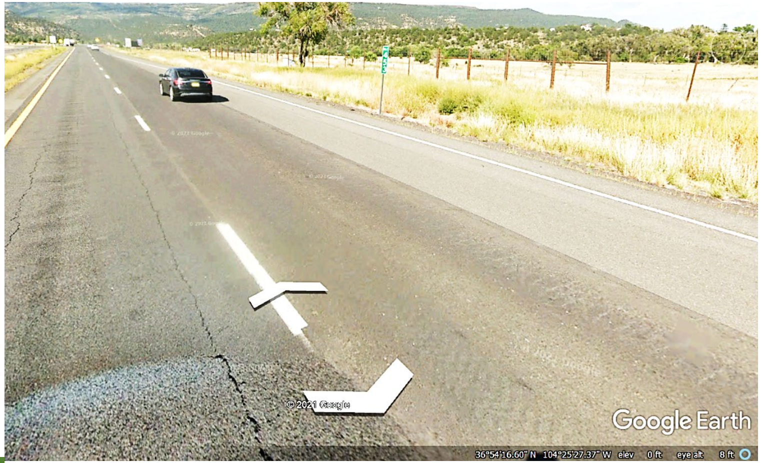
New Mexico

SB Conventional Pavement

~MP 753.0

~MP 753.5

NB Inverted Pavement

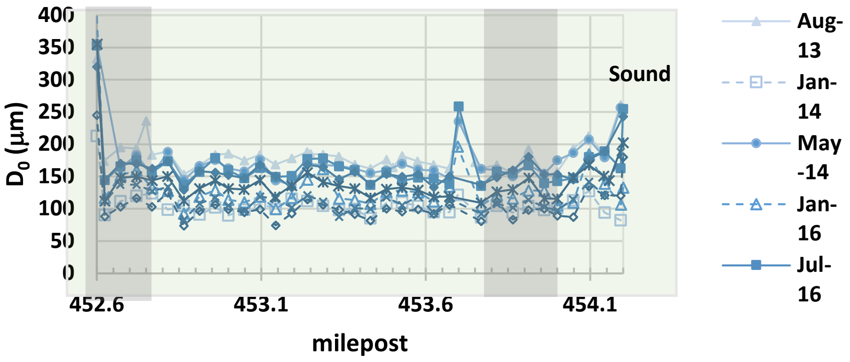


(2018)

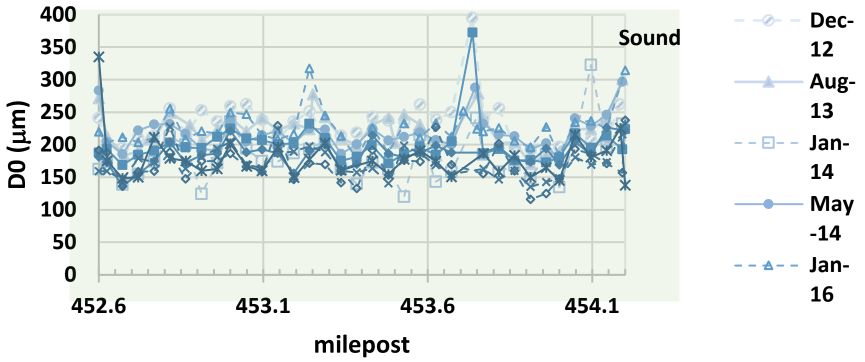
Layer Moduli Backcalculation

- FWD data were analyzed using ELMOD 6.0 software
  - Iterative procedure using Finite Element Analysis (FEA)
  - Stress dependency in the unbound layers was used

Center Deflection Data



SB Conventional Pavement

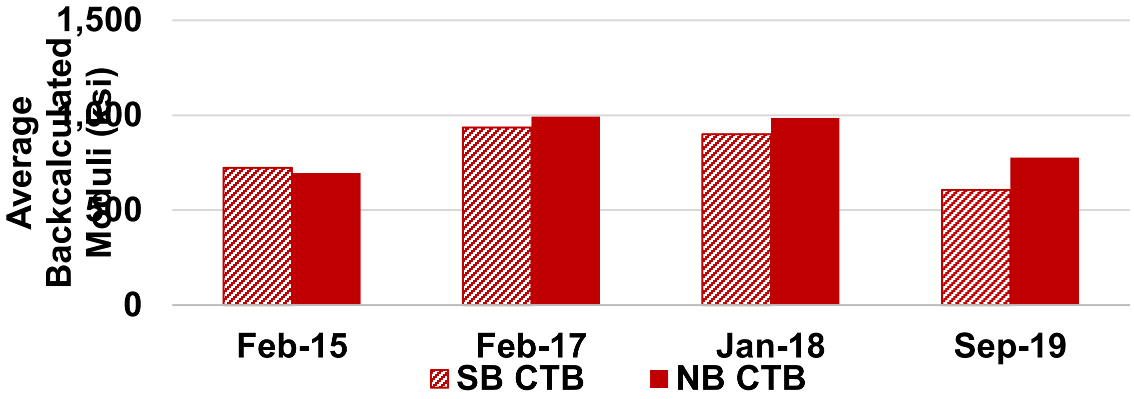


NB Inverted Pavement

FWD data provided by NMDOT

New Mexico

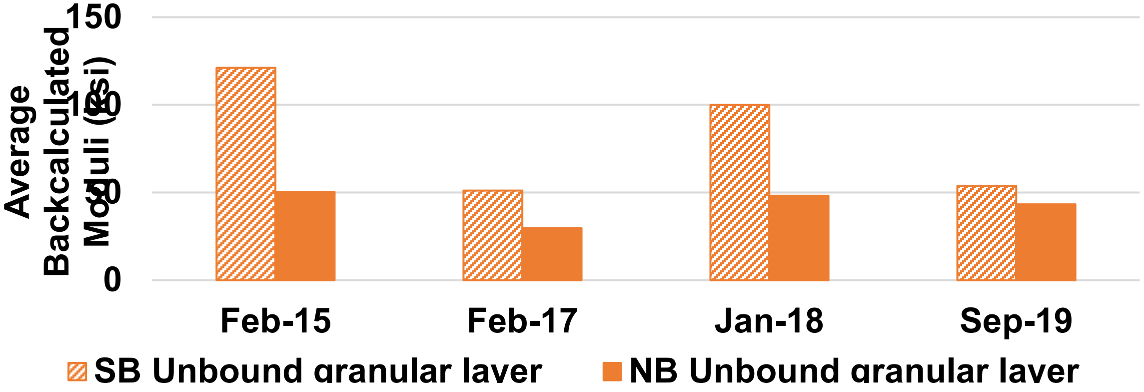
CTB and Base Layer Moduli



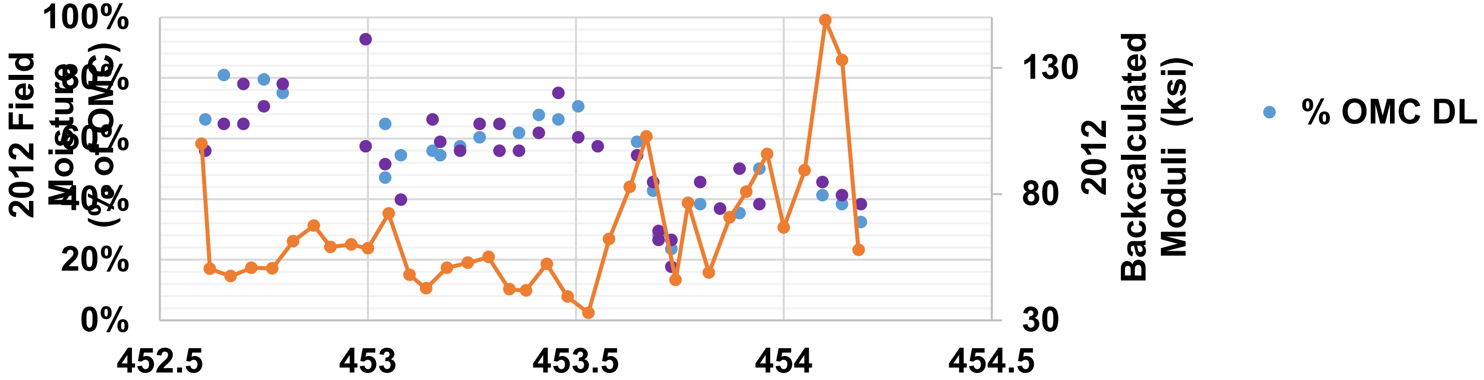
Calculated from FWD data provided by NMDOT

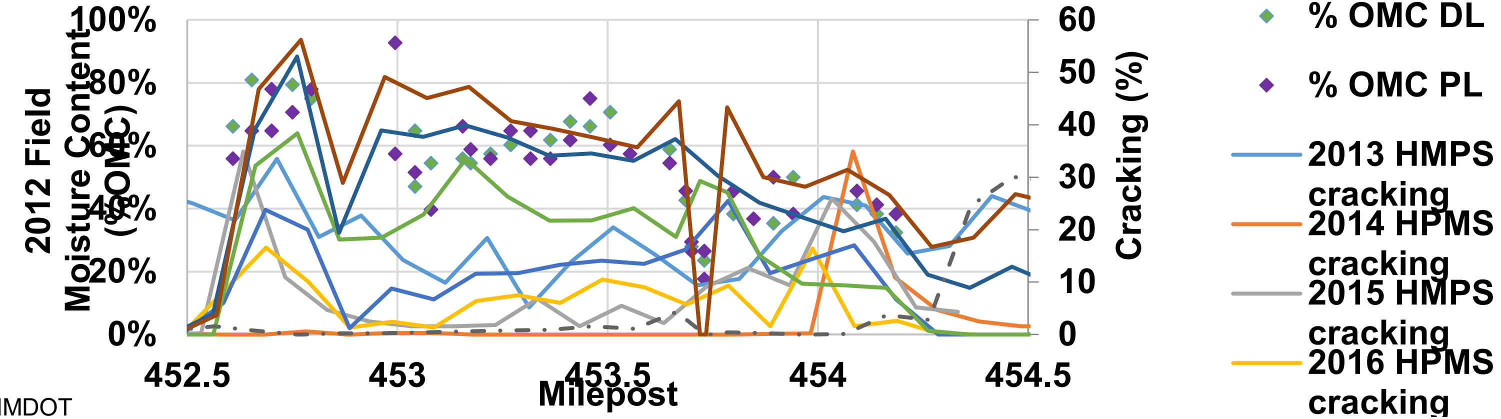
- **CTB modulus was consistent for NB and SB**

- **NB slushing did not improve layer modulus**
- **Variations in compaction level, higher moisture, etc.**



Moisture Impact on Layer Moduli and AC Cracking





Data provided by NMDOT

Field Exploration: Site Visits

- First site visit in April 2022

- Second visit in July 2022
- Core and boring samples were collected

Site Visit Observations

Two AC lifts on SB vs. a single lift of NB conventional

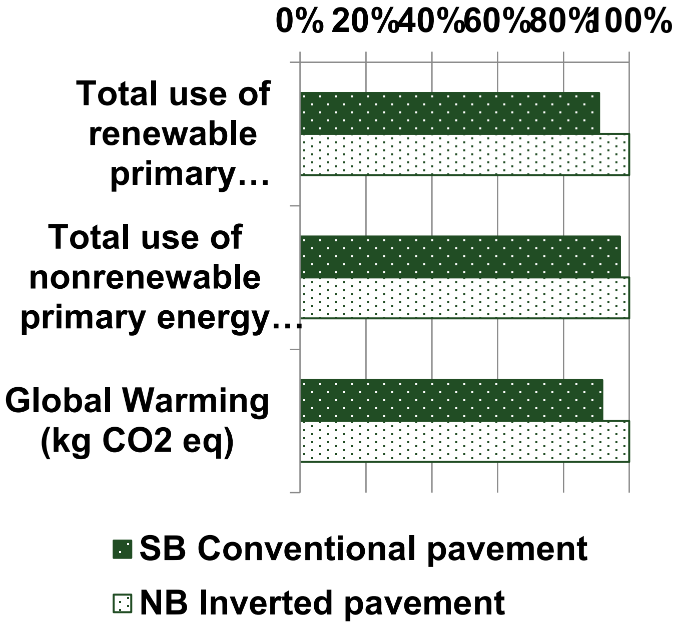
Summary

- New Mexico case study is one of the most complete and documented application of inverted pavements in the US
- Rare use of slushing in the US to construct a dense base layer
- Potential reasons for the Rapid deterioration of the inverted pavements:
  - Moisture in the granular base (from construction and ingress through unsealed cracks)
  - Thicker AC layer compared to typical South African practice (but not too thick to prevent fatigue cracking)
  - Freeze-thaw and high moisture environment

Environmental Impact: LCA

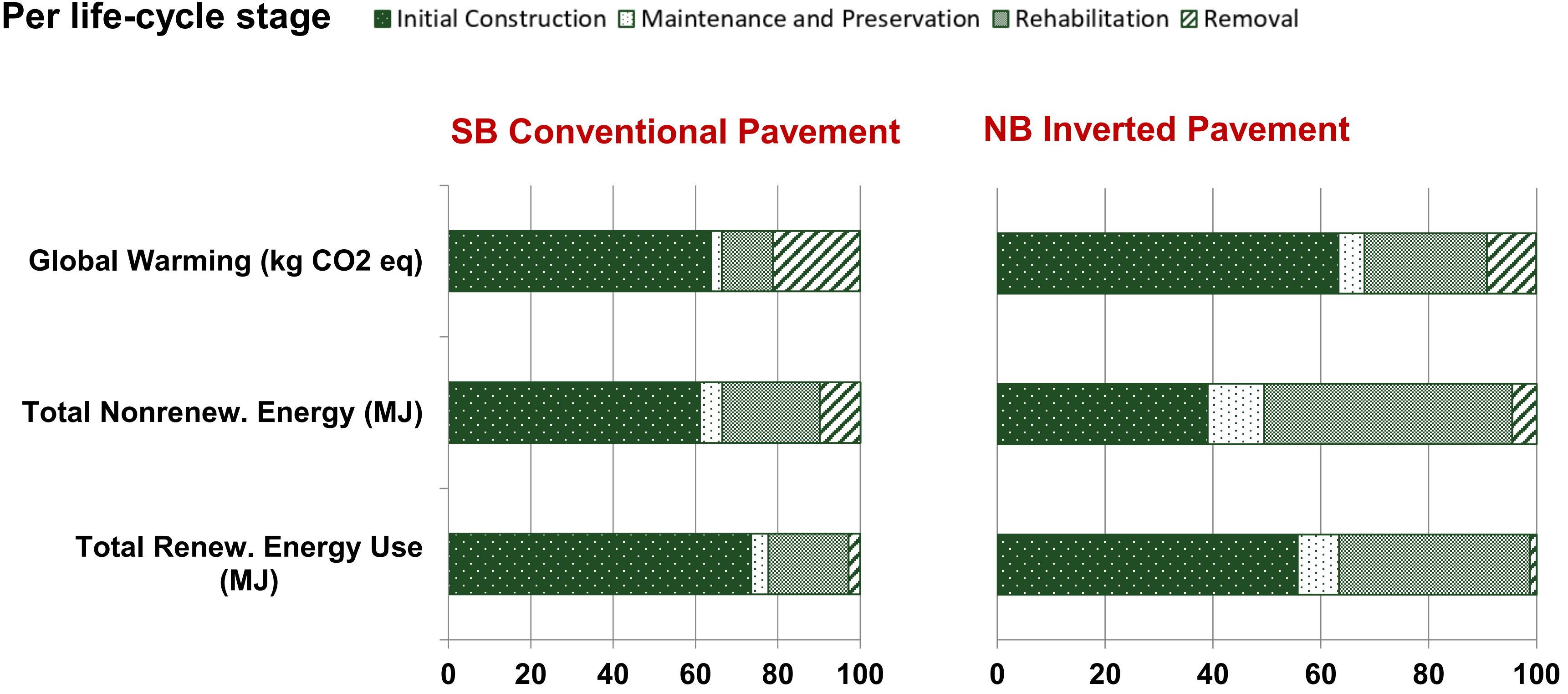
FHWA LCA Pave Tool (Materials, Construction, Transportation, Maintenance & Rehabilitation, and Disposal)

Impact indicator	CP		IP	
	Initial Construction	Total	Initial Construction	Total
Total use of renewable primary resources (MJ/ln-mi)	59,209	80,589	49,435	88,750
Total use of nonrenewable primary energy resources (MJ/ln-mi)	8,820,630	14,440,103	5,797,533	14,857,626
Global warming (kg CO_2 eq/ln-mi)	283,996	445,354	307,113	485,187

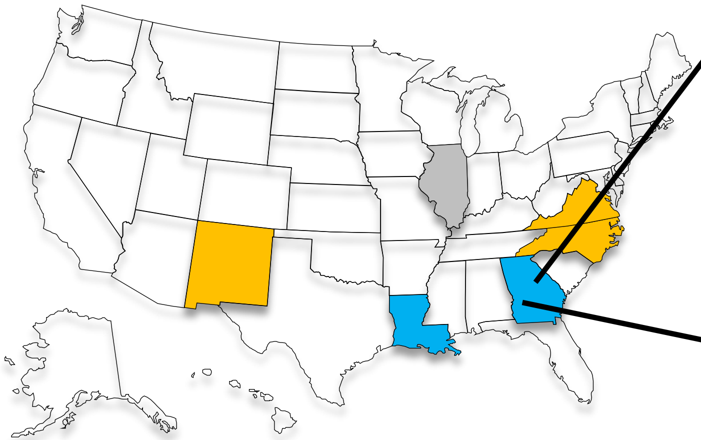


Environmental Impact per LCA Stage

Per life-cycle stage



Georgia Inverted Pavements



- 2 cases
- 1 case
- Test sections

Quarry Access Road, Morgan County (2001)

INVERTED

- 3" AC
- 6.0" Granular Base
- 8.0" CTB
- Subgrade CBR 15%

CONVENTIONAL

- 3" AC
- 8.0" Granular Base
- 6.0" compacted surge stone
- Subgrade CBR 15%

LaGrange Bypass, Pegasus Parkway (2009)

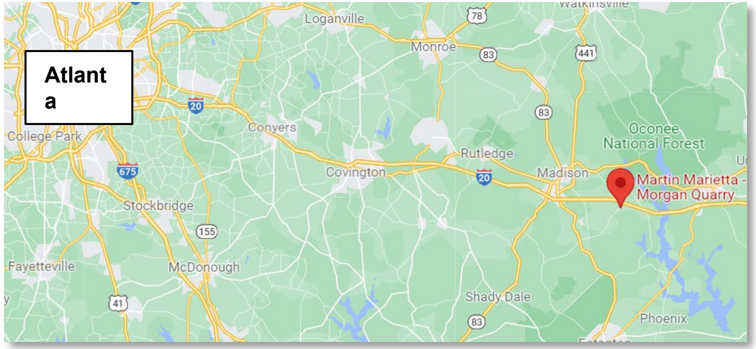
INVERTED

- 1.5 + 2" AC
- 6" GAB
- 10" CTB
- 6" Stabilized Subgrade (Min. Soil Support Value of 5)

PCC

- 9.5" PCC
- 10" GAB
- 6" Stabilized Subgrade (Min. Soil Support Value of 5)

Quarry Access Road, Morgan County



Modified from Google Map

- **Built in 2001**
- **Design EASLS: 1.3×10^6 ESALs (63.4% in 1st 5 yrs)**
- **Rainfall: 47.7 in/yr**
- **Humidity: monthly average 69-76%**

CONVENTIONAL

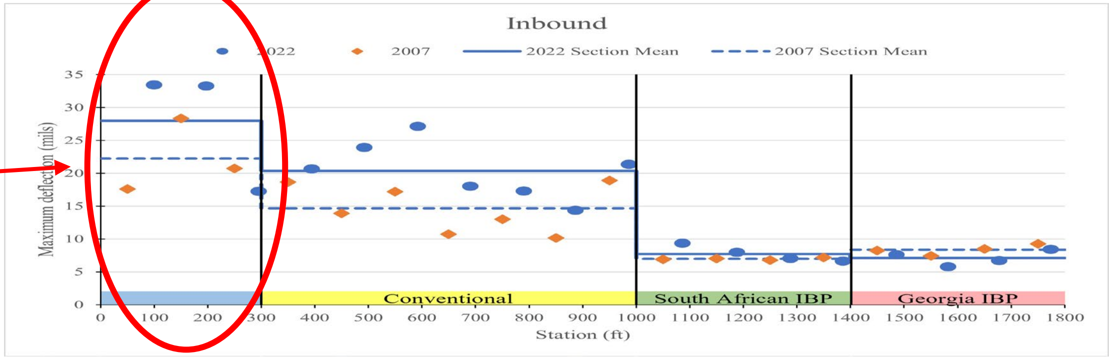
3” AC
8.0” Granular Base
6.0” compacted surge stone
Subgrade CBR 15%

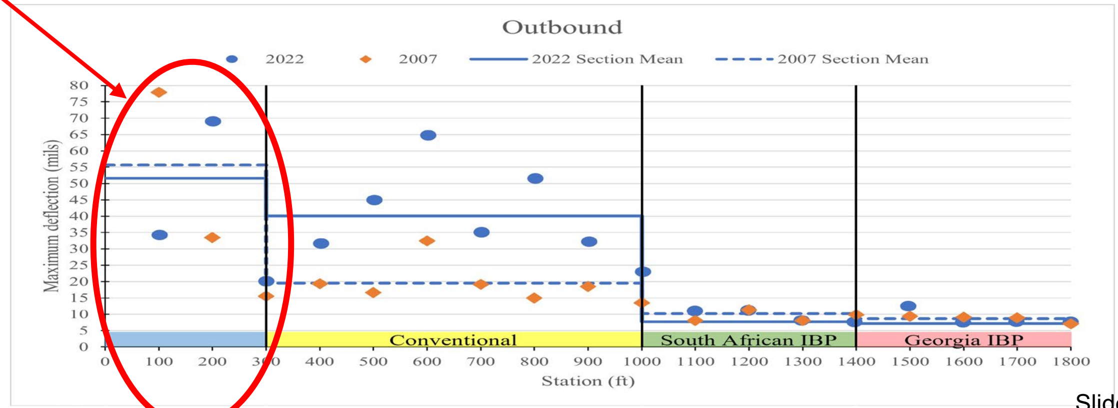
INVERTED

3” AC
6.0” Granular Base
8.0” CTB
Subgrade CBR 15%

FWD Testing & Evaluation (May 2022)

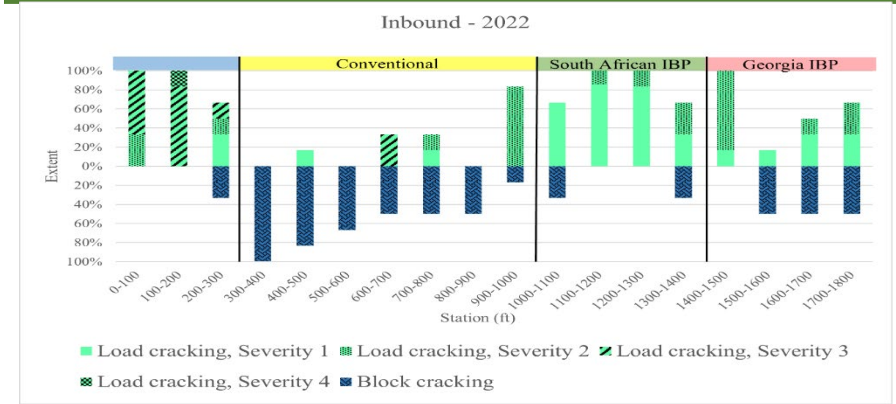
Abnormal sections due to truck braking at main exit

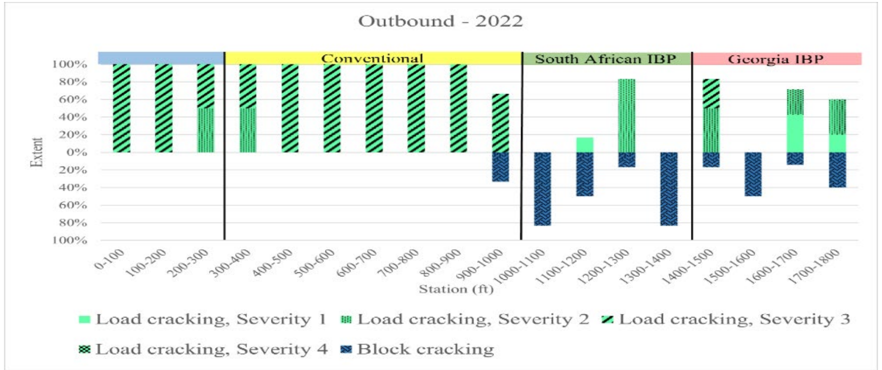




Slide from Frost (2023)

Pavement Cracking

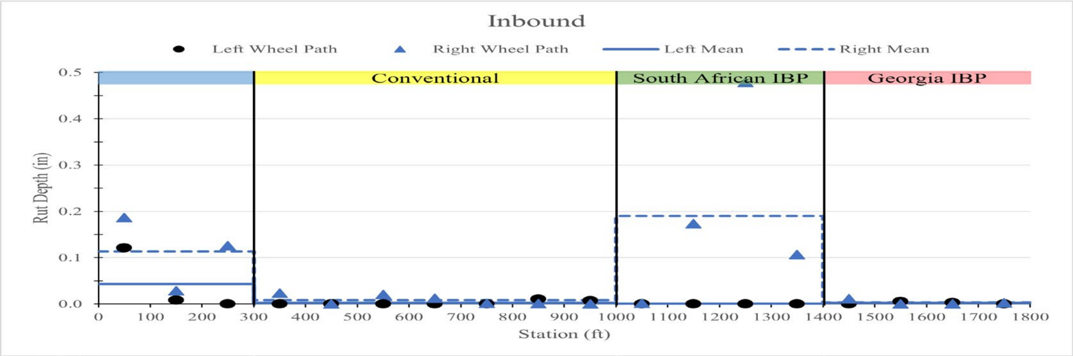


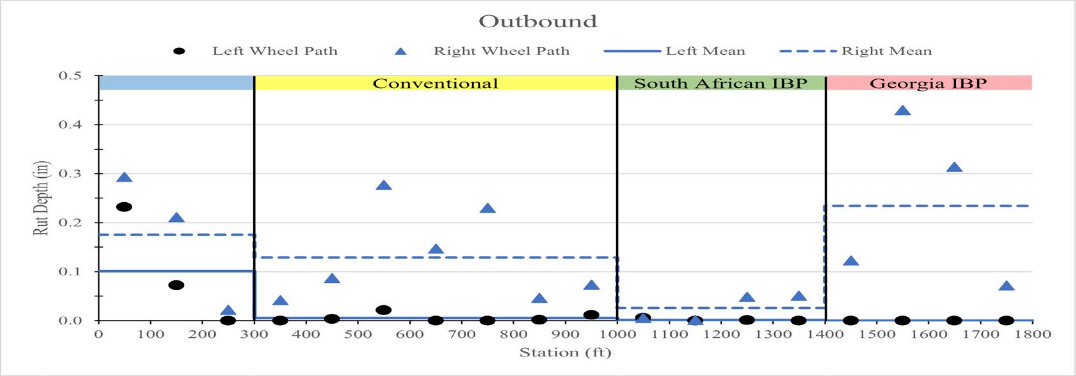


- **Low to high severity load-associated and block cracking**
- **Outbound (EB) lane showed severe and widespread load-associated cracking**
  - loaded trucks in the EB lane

Slide from Frost (2023)

Pavement Rutting





Comparison between SA and GA Inverted Pavements:

- **Both provided good performance**
- **Less rutting in SA that could be attributed to slushing!**

Slide from Frost (2023)

Performance Rating

Section	2022 PACES Rating	2016 PACES Rating (Frost 2017)	Difference
	Inbound		
Conventional	64	77	13
South African IP	69	82	13
Georgia IP	65	86	21
	Outbound		
Conventional	43	67	24
South African IP	75	81	6
Georgia IP	51	81	30

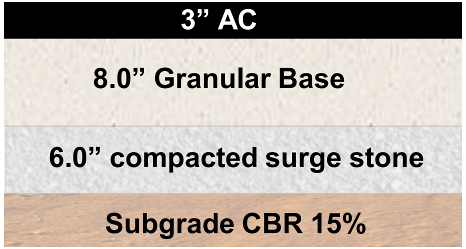
Slide from Frost (2023)

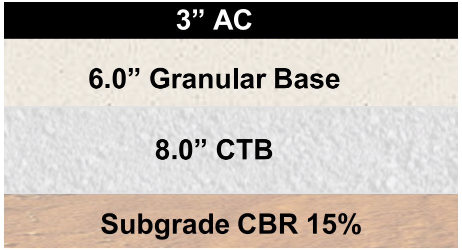
Environmental Impact: LCA

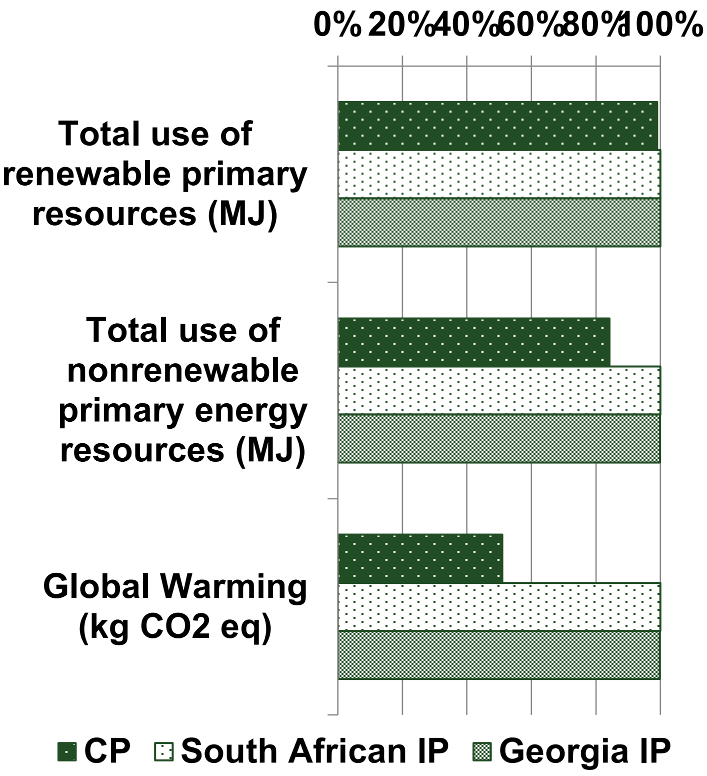
TEST
Live Sustainably

FHWA LCA Pave Tool (Materials, Construction, and Transportation)

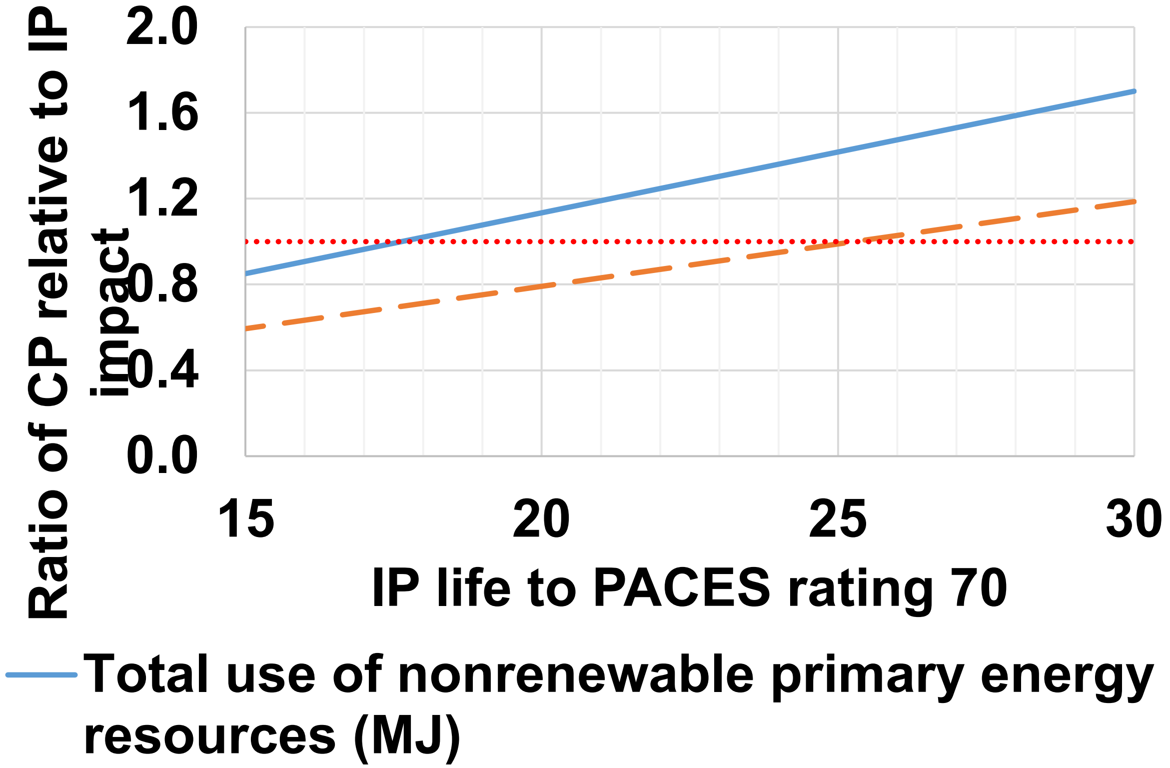
Impact indicator	CP	IP	
		South African	Georgia
Total use of renewable primary resources (MJ/ln-mi)	2,246,746	2,270,482	2,270,479
Total use of nonrenewable primary energy resources (MJ/ln-mi)	4,238,841	5,035,947	5,028,827
Global warming (kg CO_2 eq/ln-mi)	133,977	262,774	262,255





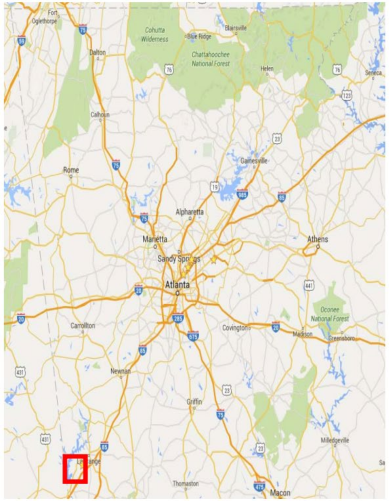


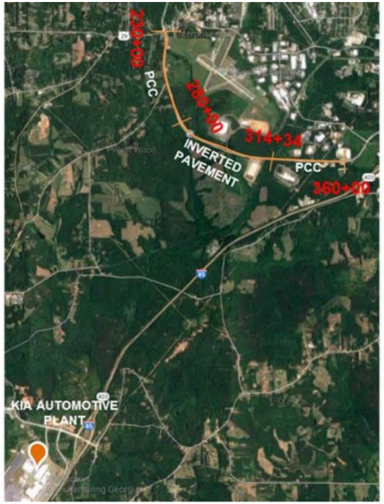
Environmental Impact: LCA



Georgia, LaGrange ByPass

LaGrange Bypass, Pegasus Parkway



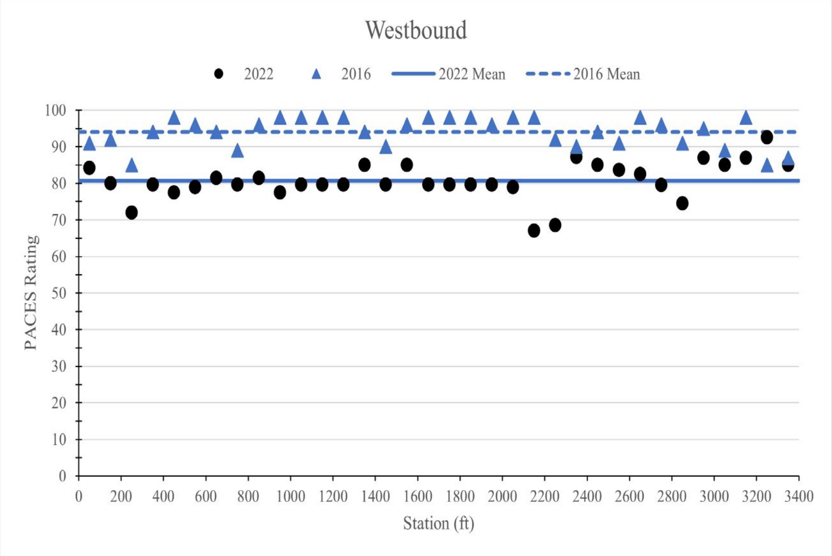


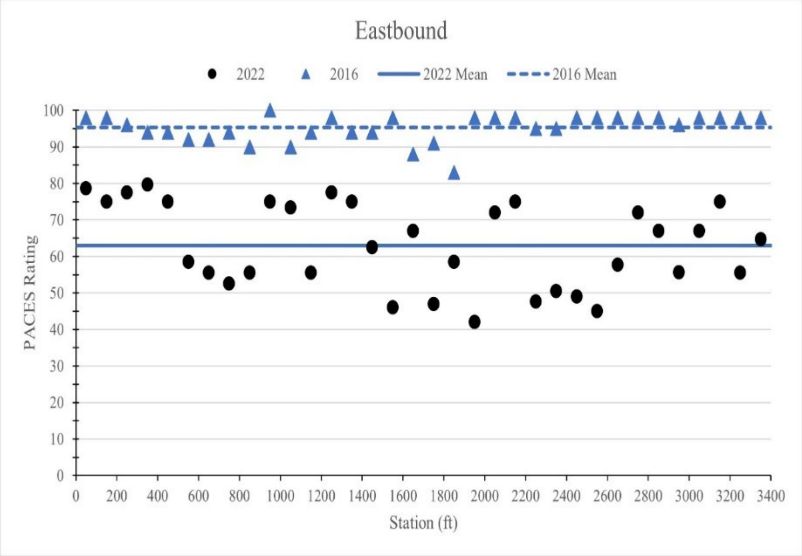
Source: Frost, 2017

- **Built in 2009**
- **20-year ESALs: 1.5 to 2 million** (Vaughan, 2018)
- **Rainfall: 51.4 in/yr**
- **Humidity: monthly average 66-73%**

INVERTE	PCC
1.5 + 2" AC	9.5" PCC
6" GAB	10" GAB
10" CTB	6" Stabilized Subgrade (Min. Soil Support Value of 5)
6" Stabilized Subgrade (Min. Soil Support Value of 5)	

Pavement Performance - PACES





Direction	2022 PACES rating	2016 PACES rating (Frost 2017)	Difference
Westbound	81	94	13
Eastbound	63	95	32

Slide from Frost (2023)

Pavement Cost Assessment

	Event	Cost ($/lane-mi)		Comparison
		Inverted pavement	PCC pavement	
Cost ($/lane-km)	Installation cost	342,000	584,000	IP net savings $139,000
	10-year maintenance	101,000		
	20-year maintenance	123,000		
	20–30-year maintenance		121,000	
	30-year life-cycle cost	566,000	705,000	

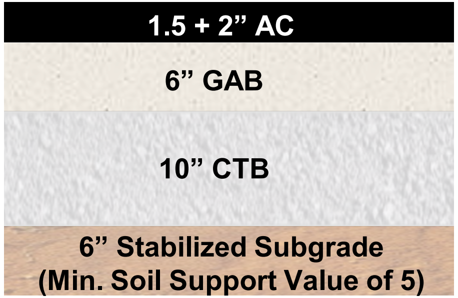
Source: cost information from Buchanan, 2010

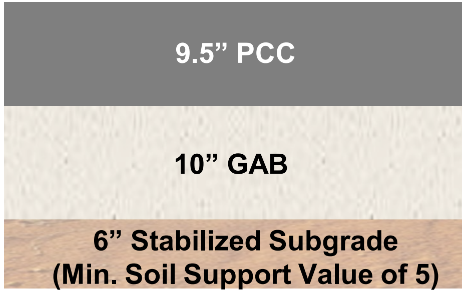
Georgia, LaGrange ByPass

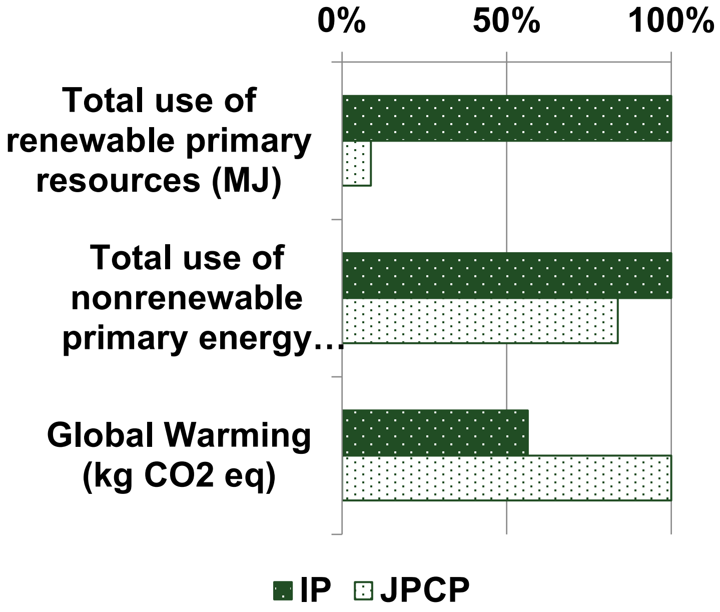
Pavement Environmental Impact: LCA

FHWA LCA Pave Tool (Materials, Construction, and Transportation)

Impact indicator	IP	JCPC
Total use of renewable primary resources (MJ/ln-mi)	1,378,434	121,481
Total use of nonrenewable primary energy resources (MJ/ln-mi)	5,608,379	4,695,499
Global warming (kg CO_2 eq/ln-mi)	316,181	560,674



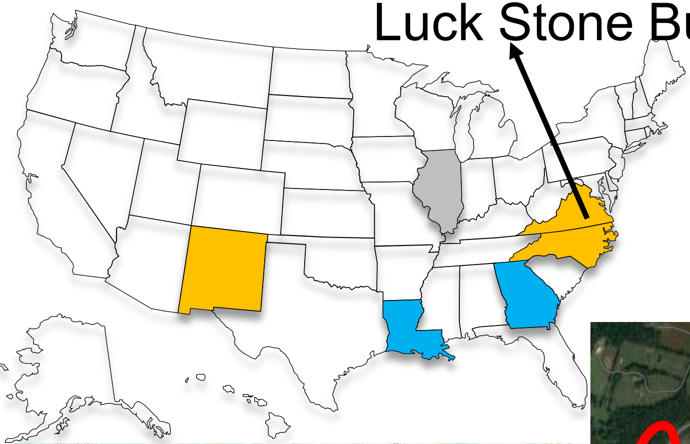


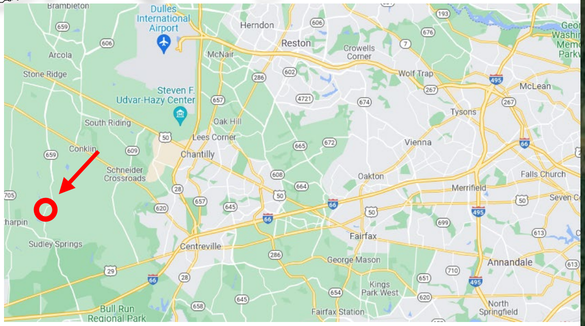


Virginia Inverted Pavement

TEST
Live Sustainably

Luck Stone Bull Run Bypass





Modified from Google Map

ORIGINAL SECTION

- 1.5 + 2 + 7.5" AC
- 3" Open Graded Drainage Layer
- 8" CTB
- Subgrade CBR 5%

INVERTED SECTION

- 2 + 3" AC
- 6" UAB
- 10" CTB
- Untreated Subgrade 10,000 psi

Built in 2011
Instrumented sections
30-year ESALs: 1.8×10^7 / 10-year ESALs: 3.4×10^6
Wet-freeze
Rainfall: 40 in/yr; Snowfall: 21.6 in/yr; humidity: monthly average 71-77%

based on Weingart, 2012

Pavement Performance

TEST
Live Sustainably

INVERTED IN 2017

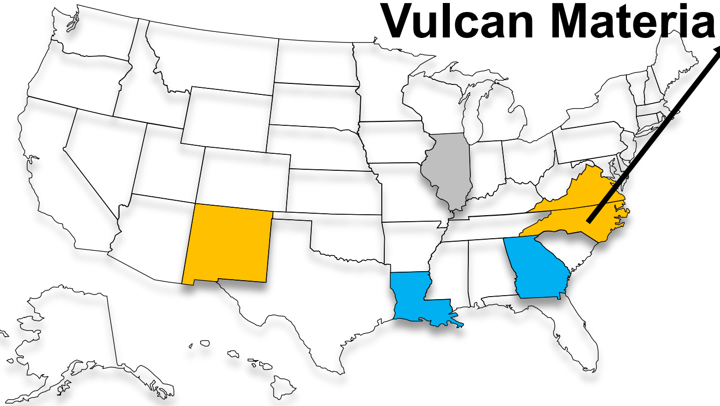
CONVENTIONAL IN 2017

Credit: VDOT

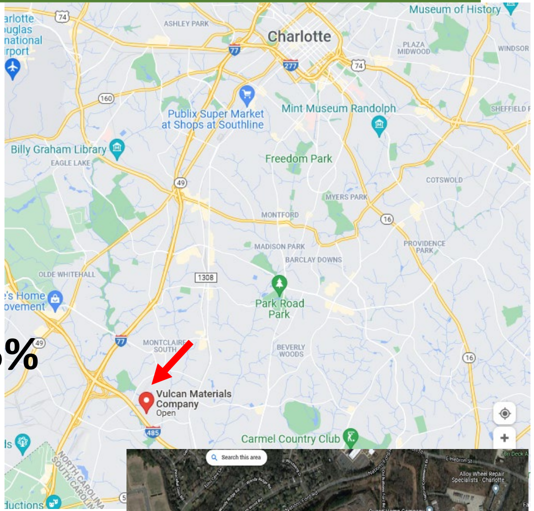
- **Both sections were opened to traffic in 2012 and showed extensive cracking in 2017, resurfaced ~2018-2019**
- **Inverted section was 14% cheaper than the original section (Weingart, 2010)**

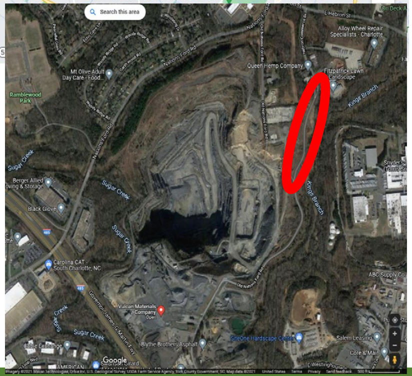
North Carolina Inverted Pavement

Vulcan Materials, Quarry Access (2015)

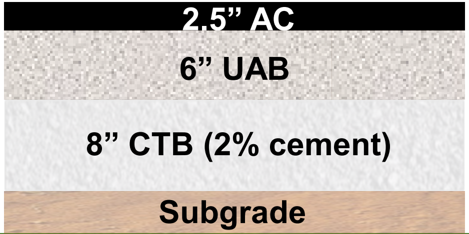


- Built in 2009
- 20-year EASLs: $1.5\text{-}2.0\times10^6$
- Rainfall: 43.3 in/yr;
- Snowfall: 4.8 in/year
- Humidity: monthly average 69-75%
- Slushing not used
- 7-day field UCS 1400 psi

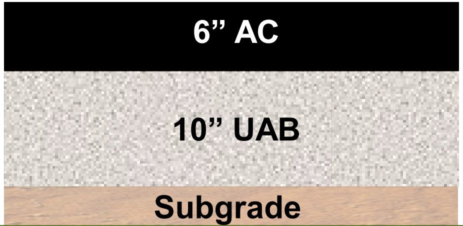




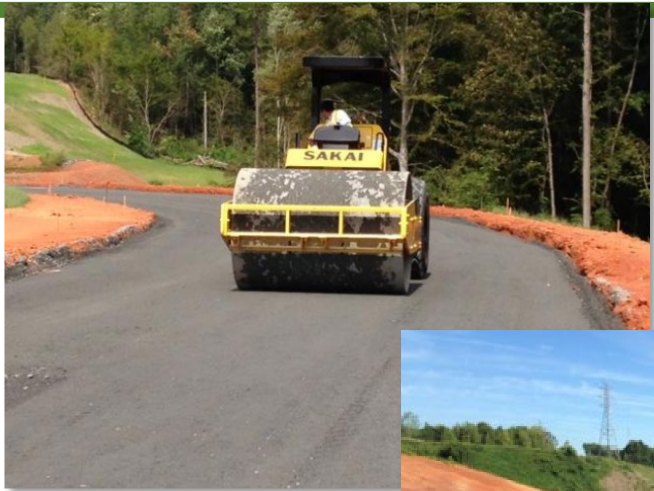
Inverted



Conventional

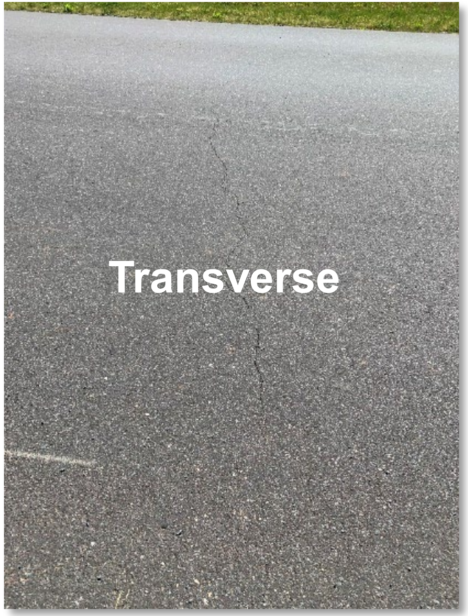


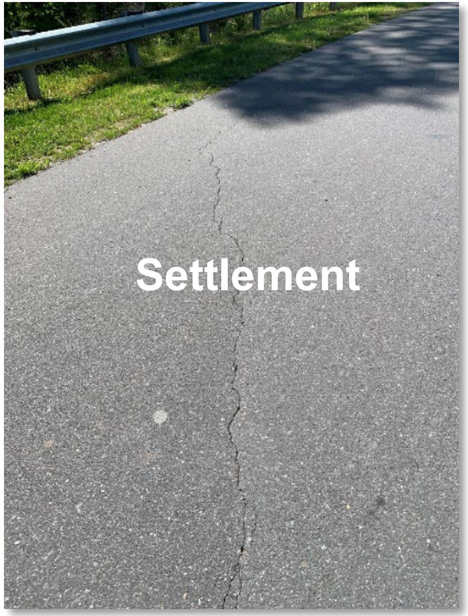
Cement Treated Base and Unbound Aggregate



Provided by Vaughan (Vulcan Materials)

Pavement Performance - 2020

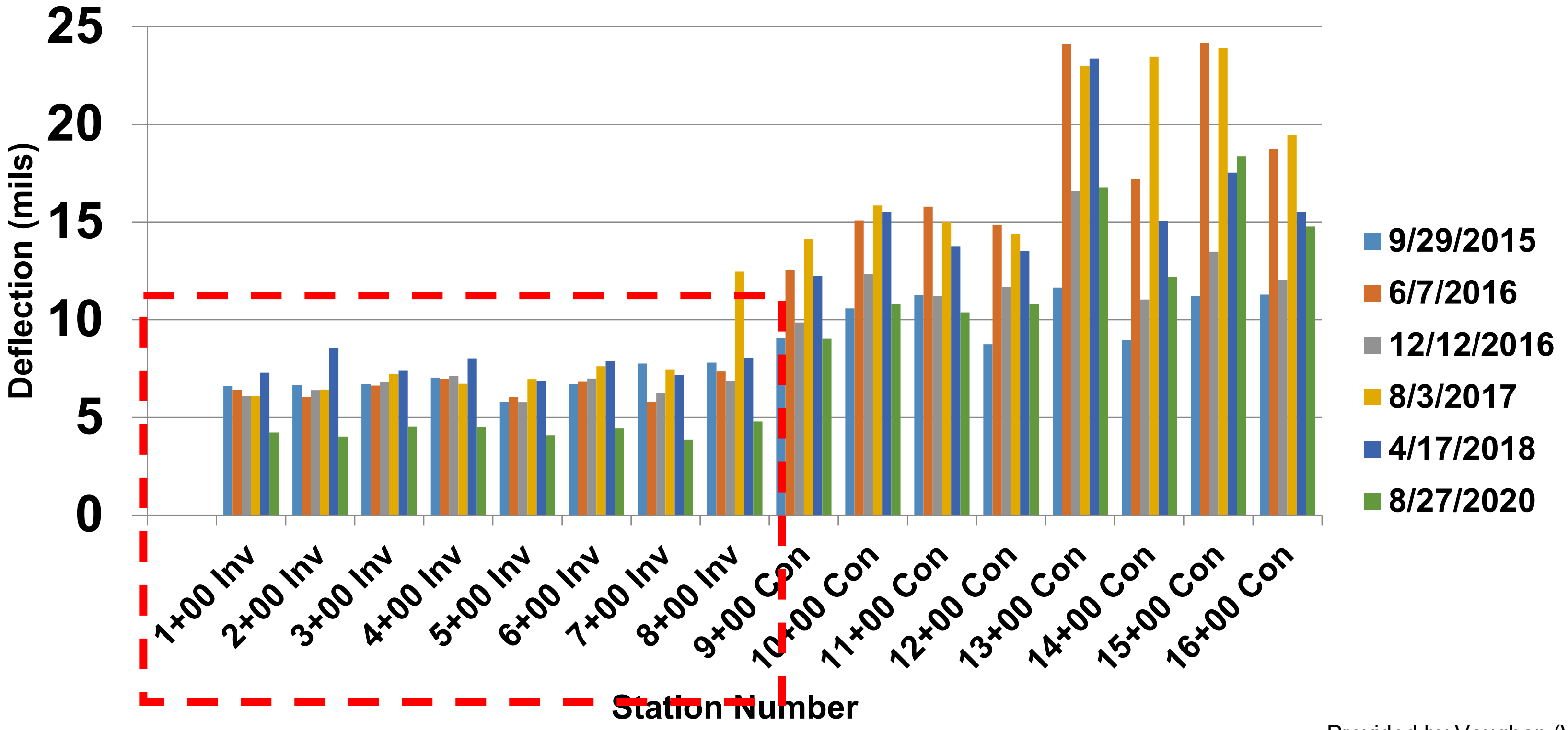




- **Performed well after 11 years of service.**
- **Limited cracks on inverted pavement section/ no cracks on conventional pavement section.**

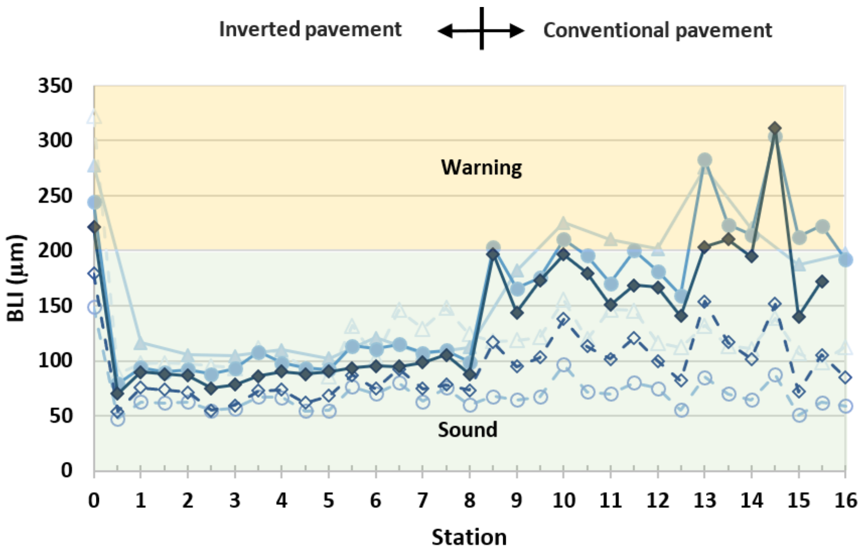
Provided by Vaughan (Vulcan Materials) and Underwood (NC State University)

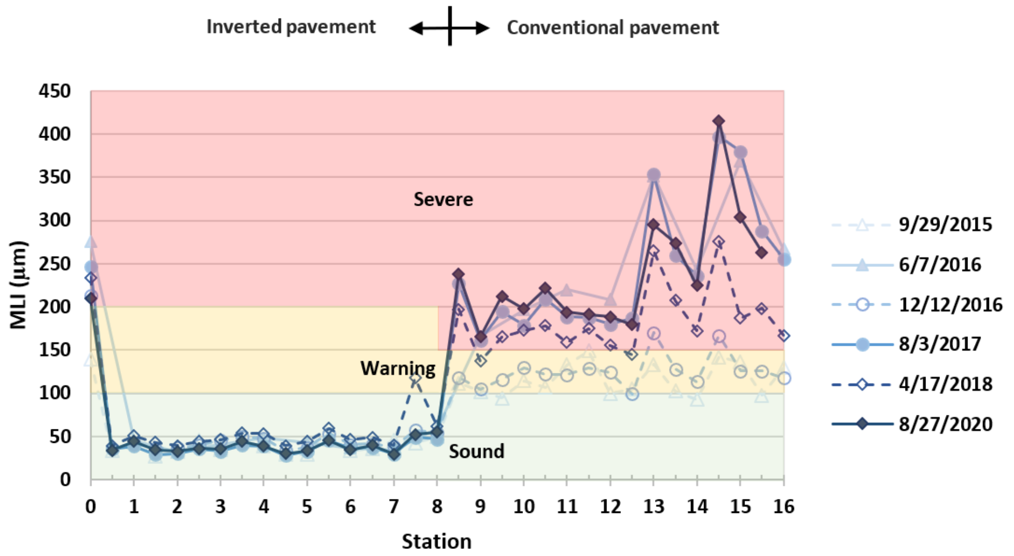
FWD Deflection Data



Provided by Vaughan (Vulcan Materials)

FWD Benchmarking Analysis





$$BLI = D_0 - D_{300}$$

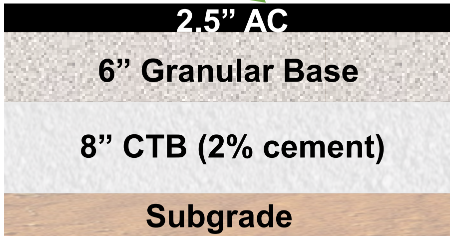
$$MLI = D_{300} - D_{600}$$

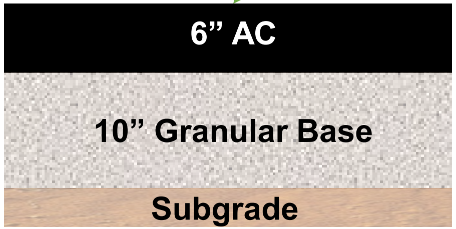
Calculated from FWD data provided by Underwood (NC State University)

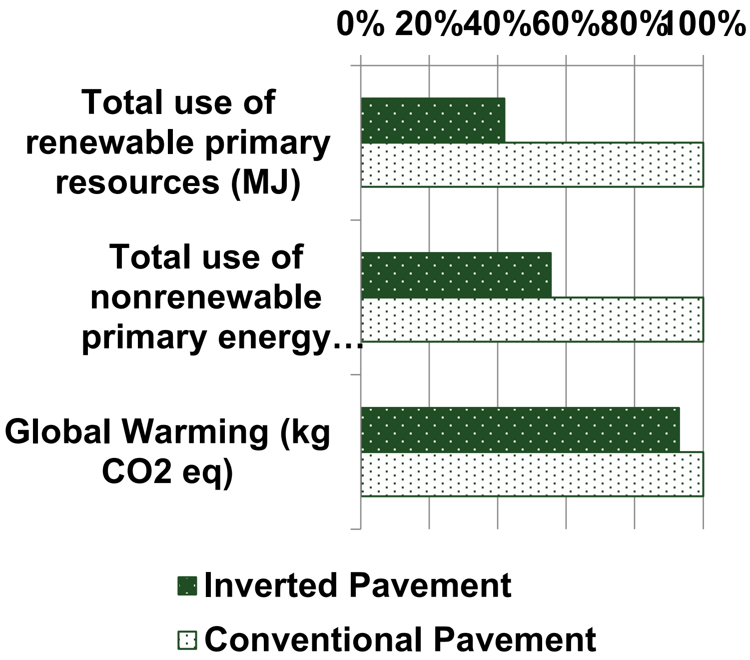
Environmental Impact: LCA

FHWA LCA Pave Tool (Materials, Construction, and Transportation)

Impact indicator	IP	CP
Total use of renewable primary resources (MJ/ln-mi)	980,657	2,337,636
Total use of nonrenewable primary energy resources (MJ/ln-mi)	4,713,914	7,785,128
Global warming (kg CO_2 eq/ln-mi)	189,902	206,264

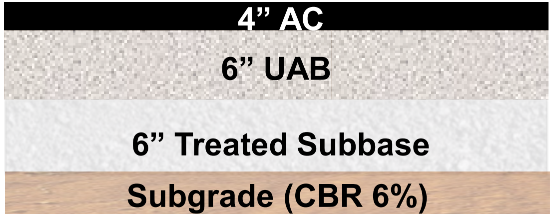






Illinois (ICT R27-168) Inverted Pavements

- Accelerated Pavement Testing study
- 2-year pavement performance data
- Traffic:
  - 1×10^5 unidirectional passes:
    - 10-kip load
    - Tire pressure 110 psi
    - 1.5×10^5 ESALs
  - 3.5×10^4 unidirectional passes:
    - 14-kip load
    - Tire pressure 125 psi
    - 1.9×10^5 ESALs
- AC surface kept at 75°F
- Slushing not used



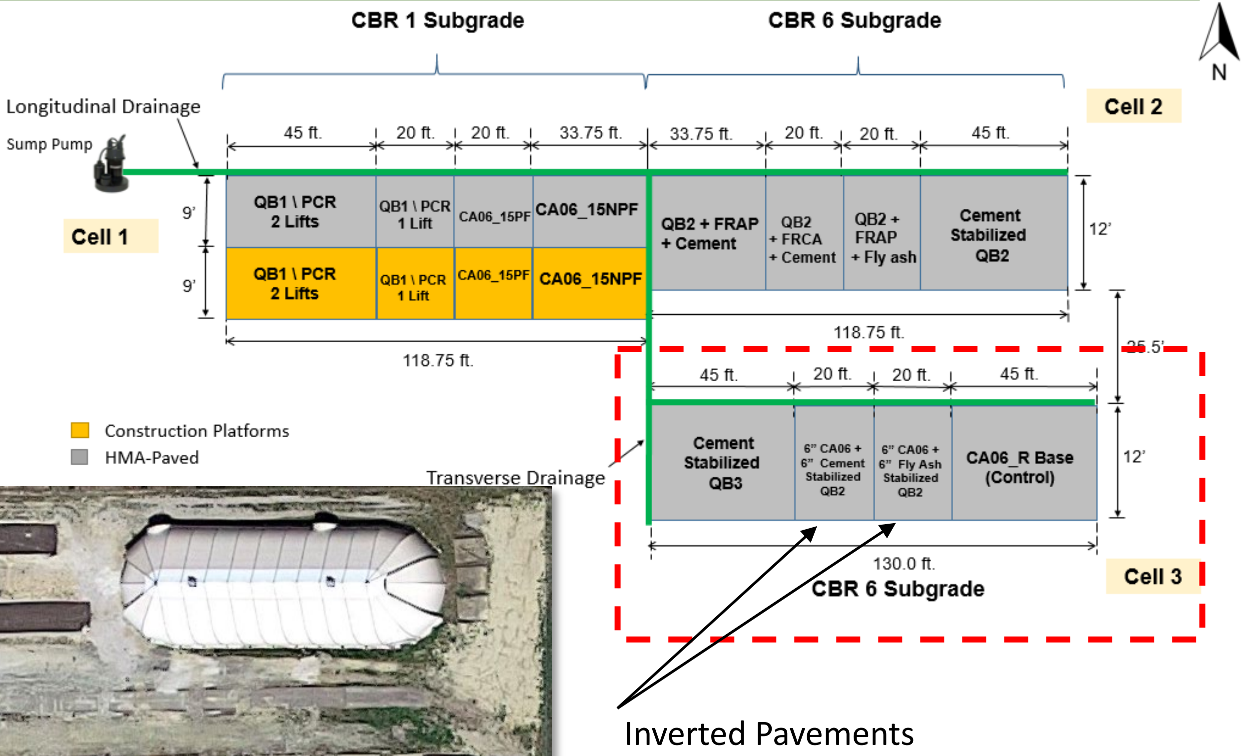
C3S1: 12” QB3* + 3% cement
C3S2: QB2** + 3% Type I cement
C3S3: QB2** + 10% Class ‘C’ fly ash
C3S4: 12” dolomite

*QB3: limestone
**QB2: dolomite

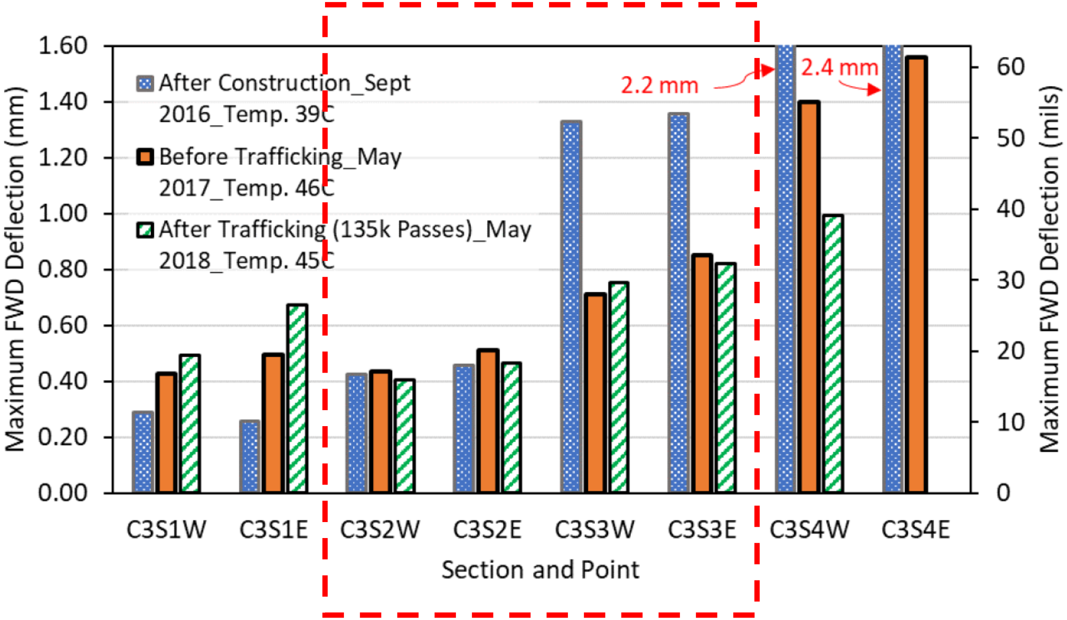
Source: Qamhia, 2019

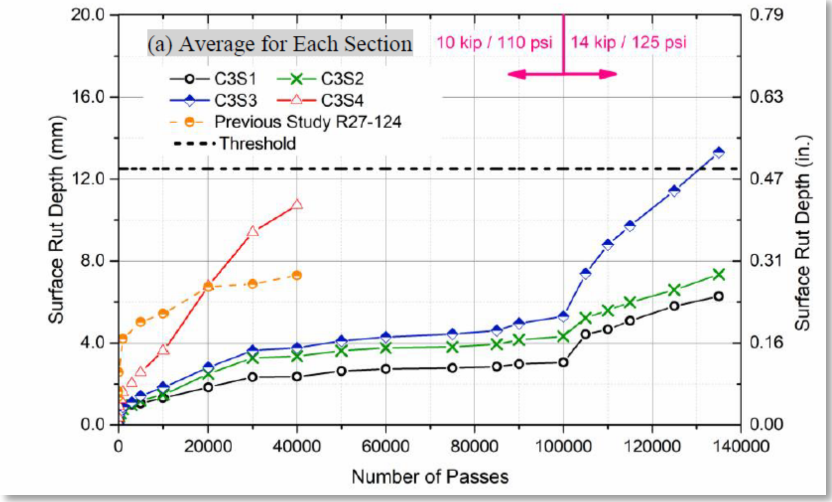
Various Sections with CTB and Inverted

- Cell 3 sections included two Inverted Pavement designs
- Stabilized the unbound layers with cement and fly ash



Pavement Performance





Source: Qamhia, 2019

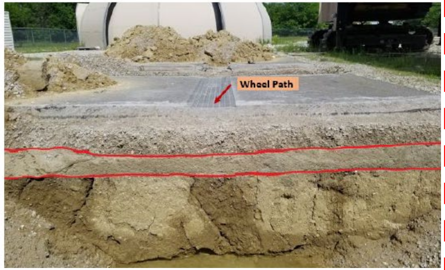
Pavement Permanence – Trenches

C3S1W – QB3 + Cement

C3S1E – QB3 + Cement

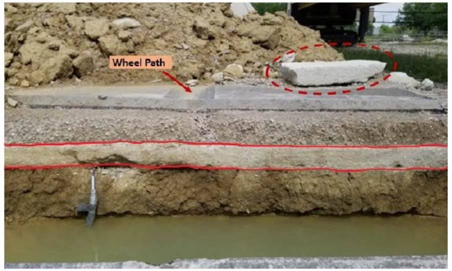
C3S3W – QB2 + Fly Ash + CA06_R

C3S3E – QB2 + Fly Ash + CA06_R



C3S2W – QB2 + Cement Subbase + CA06_R

C3S2W – QB2 + Cement Subbase + CA06_R



C3S4W – CA06_R

C3S4W – CA06_R

C3S4E – CA06_R

C3S4E – CA06_R

Source: Qamhia, 2019

Summary

TEST
Live Sustainably

- Inverted pavement was evolved in South Africa
  - It provides strong foundation through CTB
- Granular base course:
  - High quality/modulus material
  - Delays reflection cracking from CTB
- Good drainage, regular maintenance (crack sealing), and durable dense AC (low NMAS)
- **Well designed/built/maintained Inverted Pavements could adequately perform when used for the proper project**

Suggestions (to gain more experience in the US):

- **Optimum AC layer for efficient and cost-effective pavement.**
- **South African slushing technique to achieve better particle interlock.**
- **Regular crack sealing program: Prevents water infiltration.**
- **Drying granular base course prior to priming: Controls water trapping.**
- **Drier and warmer environments first.**
- **Consider stabilizing granular base course with asphalt emulsion (nontraditional inverted pavement).**

Thank you!

TEST
Live Sustainably

Questions?

alqadi@testsustainability.com

www.testsustainability.com

References

Al-Qadi, I. L., R. Yang, S. K. Kang, H. Ozer, E. Ferrebee, J. R. Roesler, A. Salinas, J. Meijer, W.V. Vavrik, and S. L. Gillen (2015). “Scenarios Developed for Improved Sustainability of Illinois Tollway.” Transportation Research Record: Journal of the Transportation Research Board, No. 2523. Transportation Research Board, Washington, DC.

ARA (Applied Research Associates), Inc., ERES Consultants Division. Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures. Final report, NCHRP Project 1-37A. Part 3. Design Analysis. Chapter 1. Drainage. Transportation Research Board of the National Academies, Washington, D.C., 2004., Figure 3.1.7, p. 3.1.17. Copyright, National Academy of Sciences. Reproduced with permission of the Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm.

Austroads (2019). “Guide to Pavement Technology Part 2: Pavement Structural Design”. Edition 4,3 published November 2019.

Barksdale, R.D., and Todres, H.A. (1983). “A Study of Factors Affecting Crushed Stone Base Performance.” School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Buchanan, S. (2010). Inverted Pavements-What, Why, and How? AFTRE Industry Education Webinar, June 1, 2010.

Commonwealth of Australia, Australian Bureau of Meteorology (2020), license:

COTO (South African Committee of Transport Officials) 2020. Standard Specifications for Road and Bridge Works for Sough African Road Authorities. Draft Standard (DS) Chapter 9: Asphalt Layers. October 2020.

Donovan, S. (2022). Performance Evaluation of Inverted Pavement Structures, Ph.D. Thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA.

DPTI – Government of South Australia Department of Planning, Transport and Infrastructure (2018a). “Supplement to the Austroads Guide to Pavement Technology Part 2 Pavement Structural Design”. Version No. 5. August 2018.

DPTI (2018b). “Specification Part R21 Construction of Unstabilised Granular Pavements”. July 2018

DPTI (2020). “Roads Master Specification RD-PV-S1 Supply of Pavement Materials”. August 2020

References

FHWA (2019). “Louisiana Experience with Inverted Pavement Systems.” FHWA-HIF-19-082.

Frost, J. D. (2017). Long-term Performance of Granular Bases Including the Effect of Wet-dry Cycles on Inverted Base Pavement Performance (No. FHWA-GA-17-1510). Georgia. Department of Transportation. Office of Research.

Jooste, F.J., and L. Sampson (2005). “The Economic Benefits of HVS Development Work on G1 Base Pavements” Department of Public Transport, Roads, and Works.

Kleyn, E.G. (2012). “Successful G1 Crushed Stone Base Course Construction” In Proceedings of the 31st Southern African Transport Conference (SATC 2012), ISBN Number: 978-1-920017-53-8, Pretoria, South Africa, 9-12 July 2012, pp. 110-118.

MRWA - Main Roads Western Australia (2013). “Engineering Road Note 9”.

MRWA (2020). “Specification 501 Pavements”. February 2020.

NOAA & NGS, N. (1978). Geodetic Bench Marks Manual. https://www.ngs.noaa.gov/PUBS_LIB/GeodeticBMs/

Accessed Dec 27, 2021.

Qamhia, I. I. (2019). Sustainable pavement applications utilizing quarry by-products and recycled/nontraditional aggregate materials (Doctoral dissertation, University of Illinois at Urbana-Champaign).

RTA – Roads and Traffic Authority (2004). “Oral History Program. Pavement Recycling & Stabilisation. Summary Report.”

Simons, B. (2016). I-25 Inverted Pavement Project – Raton, New Mexico 2013. Transportation Research Board 2016 Presentation.

Singhar, S. (2018). Evaluation of climate parameter with regards to unsaturated clay soil suction profiles (Doctoral dissertation, Arizona State University).

Steyn, WJvdM and E.G. Kleyn (2016), “Issues Around Construction of Inverted Pavements in South Africa.” PowerPoint Presentation delivered at the 95th Annual Meeting of Transportation Research Board (TRB), Workshop session 463 on Inverted Pavements, January 11, 2016.

TRH 4. 1996. (Draft) structural design of flexible pavements for Interurban and rural roads. Committee of State Road Authorities. Pretoria, South Africa. (Technical recommendations for Highways Series, TRH4)

References

TfNSW – Transport for NSW (2020a). “QA Specification 3051 Granular Pavement Base and Subbase Materials.” Ed 5, Rev 1.

TfNSW (2020b). “QA Specification R71. Construction of Unbound and Modified Pavement Course.” Ed 7, Rev 1.

VICROADS (2013). “Section 304 – Unbound Flexible Pavement Construction“. August 2013.

TMR – Queensland Department of Transport and Main Roads (2020). “Technical Specification MRTS05 Unbound Pavements.”

The South African National Roads Agency SOC Ltd.(2014). Pavement Engineering Manual. Chapter 9: Materials Utilisation and Design. Date of issue: October 2014.

The South African National Roads Agency SOC Ltd.(2014). Pavement Engineering Manual. Chapter 10: Pavement Design. Second Edition. Date of issue: October 2014.

Tutumluer, E., and R. D. Barksdale (1995). Inverted Pavement Response and Performance. Transportation Research Record, No. 1482, 1995, Figure 2, p. 108. Copyright, National Academy of Sciences. Reproduced with permission of the Transportation Research Board.

Vaughn, K.M. (2017). http://www.dot.state.pa.us/public/Bureaus/BOPD/2017_QAW/GeoTech_and_Aggregates/InvertedPavement_Vaughn.pdf (accessed February 2021).

Vaughan, K.M. (2018). “Inverted pavement.” lecture.

VICROADS (2017). “Code of Practice RC 500,02. Registration of Crushed Rock Mixes“. June 2017.

Weingart, R. (2012), “Inverted Base: The Virginia Experience,” 2012 Transportation Research Board Mineral Aggregates Committee (AFP 70) Meeting Presentation, Transportation Research Board 91st Annual Meeting, January 22-26, Washington, D.C.

Today's Presenters

Imad L Al-Qadi
alqadi@testsustainability.com
University of Illinois

Erol Tutumluer
tutumlue@illinois.edu
University of Illinois

Jeff Uhlmeyer
juhlmeyer@qespavements.com
QES

Upcoming events for you

Sept 19 - 21, 2023

TRB's Innovations in Freight Data Workshop

Nov 13 - 15, 2023

TRB's Transportation Resilience 2023

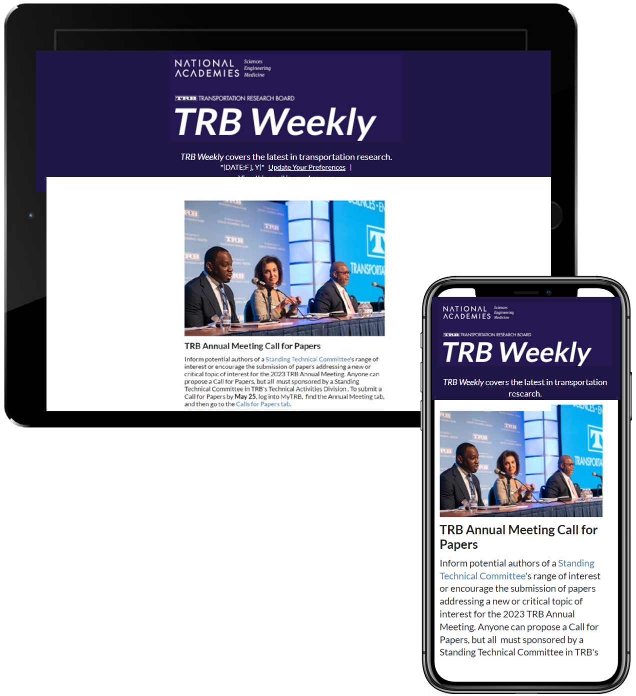
https://www.nationalacademies.org/trb/events

Subscribe to *TRB Weekly*

If your agency, university, or organization perform transportation research, you and your colleagues need the *TRB Weekly* newsletter in your inboxes!

Each Tuesday, we announce the latest:

- RFPs
- TRB's many industry-focused webinars and events
- 3-5 new TRB reports each week
- Top research across the industry



Spread the word and subscribe!
https://bit.ly/ResubscribeTRBWeekly

Discover new TRB Webinars weekly

Set your preferred topics to get the latest listed webinars and those coming up soon every Wednesday, curated especially for you!

https://mailchi.mp/nas.edu/trbwebinars

And follow #TRBwebinar on social media

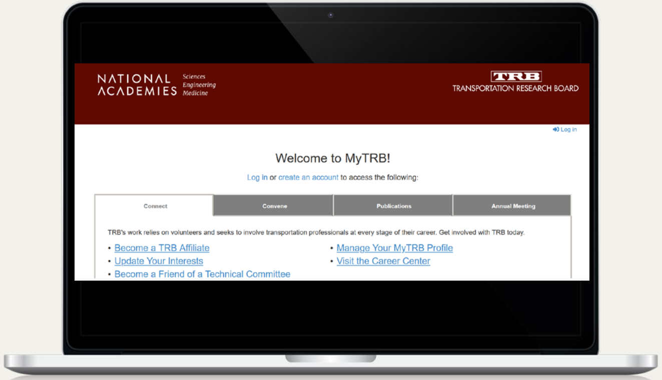
@NASEMTRB

@NASEMTRB

Transportation Research Board

Get involved

https://www.nationalacademies.org/trb/get-involved

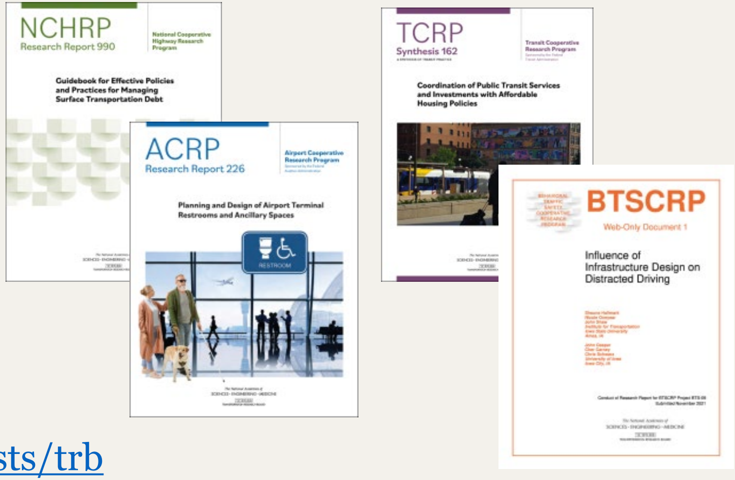


- **Become a Friend of a Standing Technical Committee**

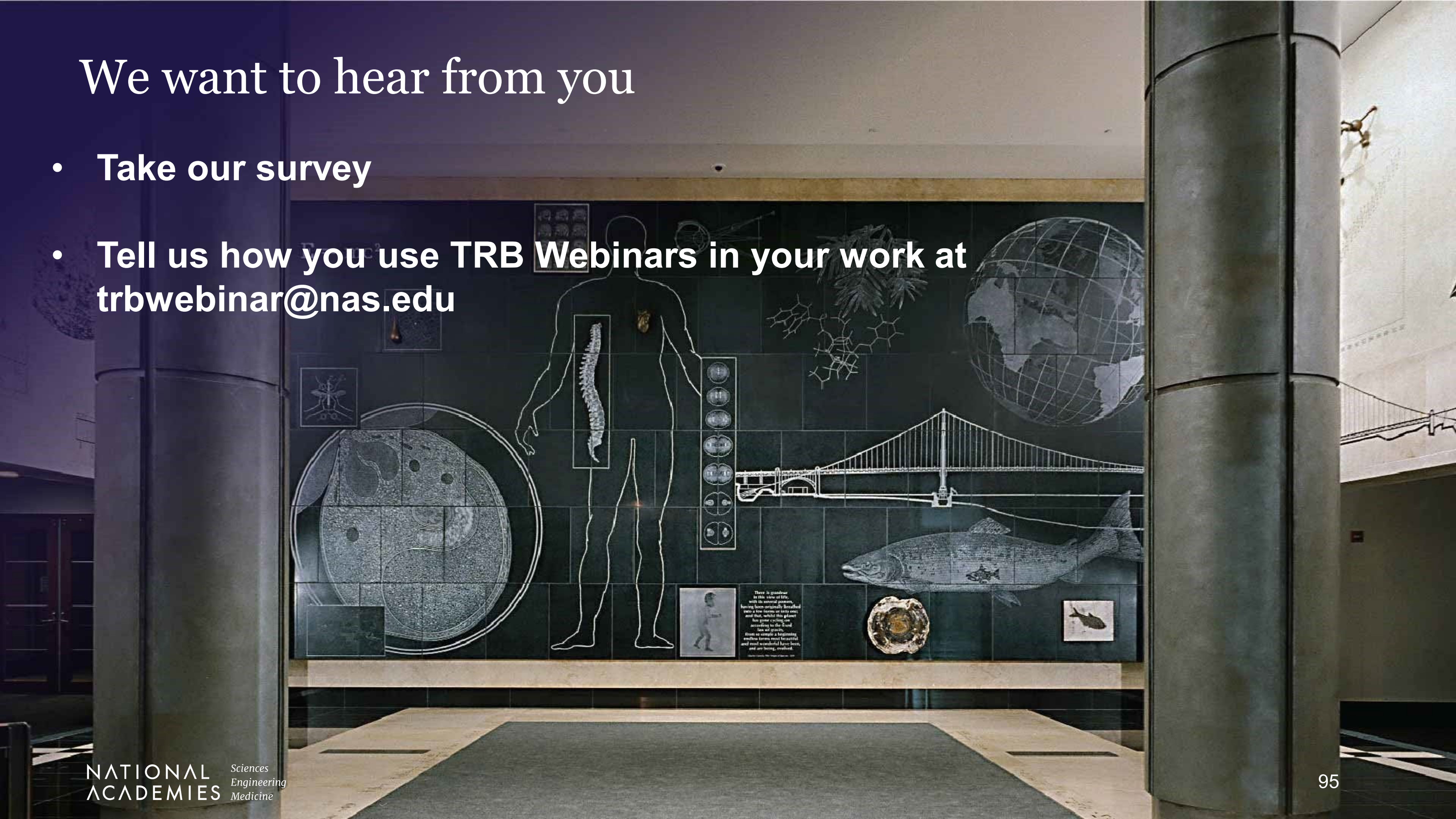
  Network and pursue a path to Standing Committee membership

- **Work with a CRP**

- **Listen to our podcast**



https://www.nationalacademies.org/podcasts/trb



We want to hear from you

- **Take our survey**
- **Tell us how you use TRB Webinars in your work at trbwebinar@nas.edu**

NATIONAL ACADEMIES *Sciences Engineering Medicine*