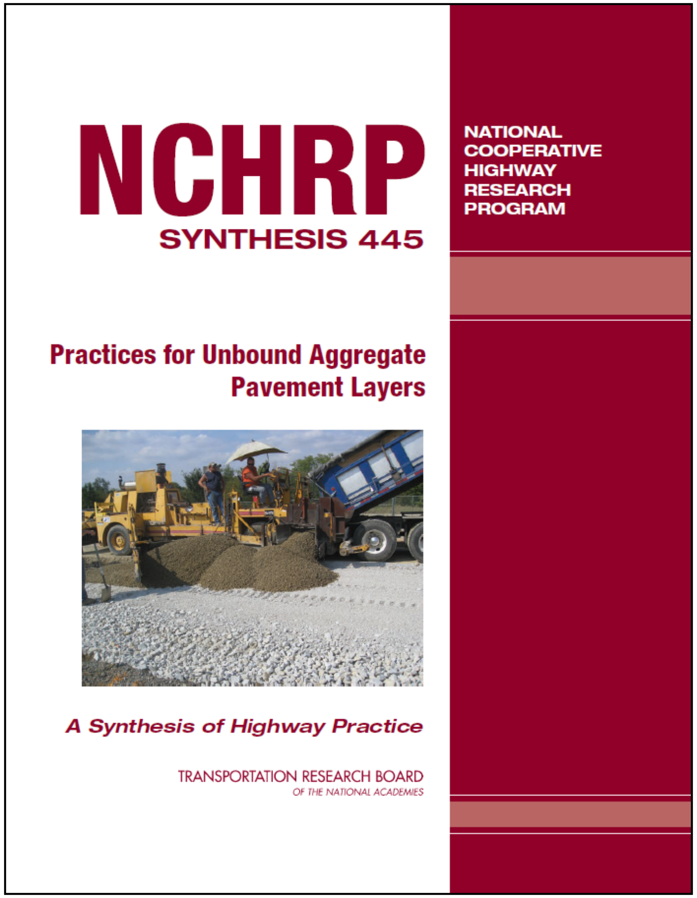
Inverted Pavements

A TRB Webinar

(AFP70 – Mineral Aggregates)

Why now?



The IP topic was briefly reviewed in **NCHRP Synthesis 445 – Practices for Unbound Aggregate Pavement Layers** (Erol Tutumluer, Deb Mishra and Rick Boudreau).

download from the TRB website:
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_445.pdf

We received tremendous audience feedback following the TRB Webinar presented June 24, 2015 (Erol Tutumluer, Andrew Dawson, Deb Mishra and Rick Boudreau).

Invited Speaker Session
TRB 95th Annual Meeting

Sponsored by AFP70 – Mineral Aggregates
(E. Tutumluer – Chair)

- Rick Boudreau (Moderator) – Boudreau Engr.
- Kevin Vaughan – Vulcan
- Wynand Steyn – South Africa
- David Frost – Georgia Tech
- Reza Ashtiani – UTEP
- Bryce Symons – N. Mexico

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Outline

- Introduction and Background *(Boudreau)*
- Design Considerations *(Frost)*
- Construction Methods *(Vaughan)*
- Performance Assessment *(Frost)*
- Summary Comments *(Boudreau)*

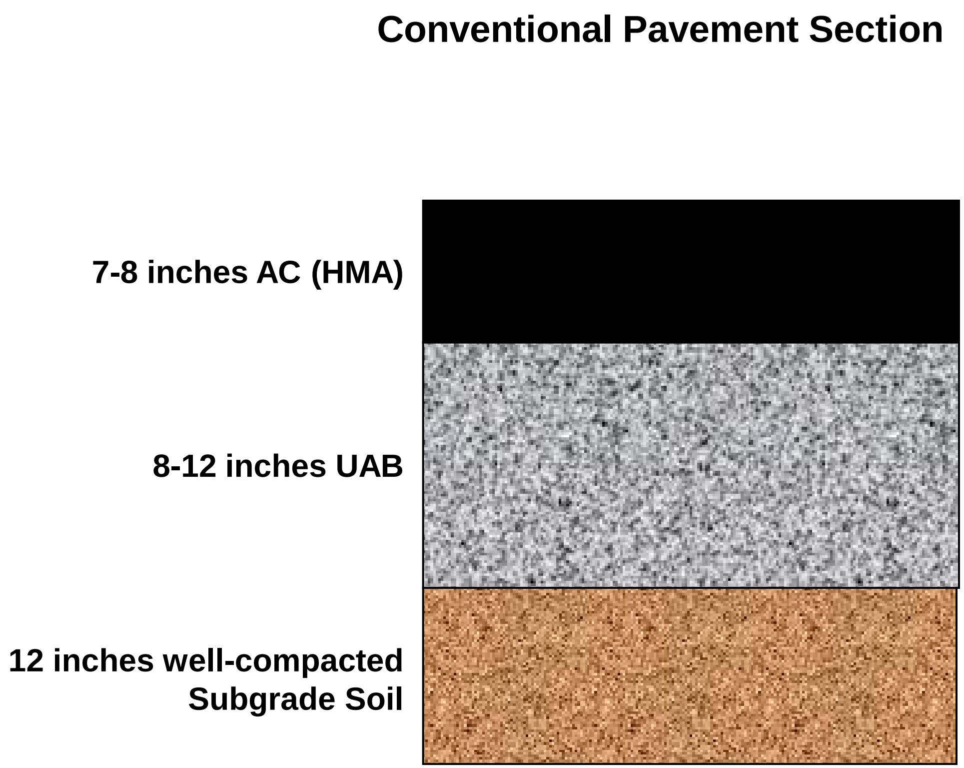
Inverted Pavement - Alias

- Inverted Base Pavement (IBP)
- Inverted G1-Base Pavement (South Africa)
- Stone Interlayer Pavement (Louisiana)
- Upside Down Pavement
- Sandwich Pavement

Inverted Pavement - Defined

- Alternative flexible pavement structure
- Relatively thin upper AC layer(s)
- Layered stiffness profile does **not** decrease with depth
- Structure typically looks like this (from bottom up):
  - Compacted Subgrade
  - Cement-Treated Base (CTB w/ 2-5% cement)
  - Unbound Aggregate Base (UAB)
  - Relatively thin Asphalt Concrete (AC)

Inverted Pavement Compared to Conventional Pavement



Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

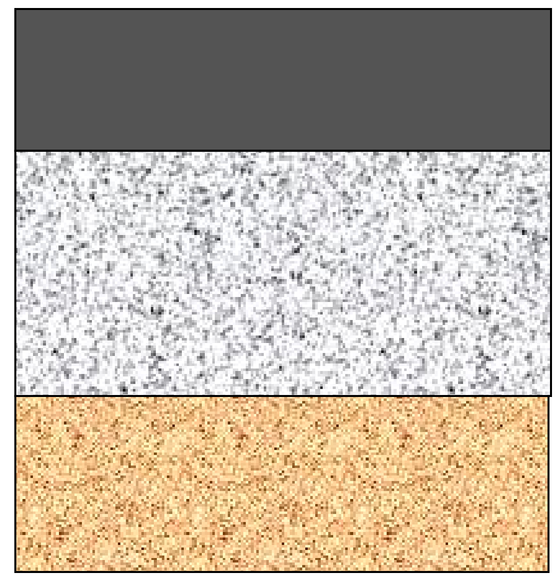
3-4 inches AC (HMA)

6-10 inches UAB

8-12 inches CTB

12 inches well-compacted Subgrade Soil

Conventional Pavement Section



7-8 inches AC (HMA)

8-12 inches UAB

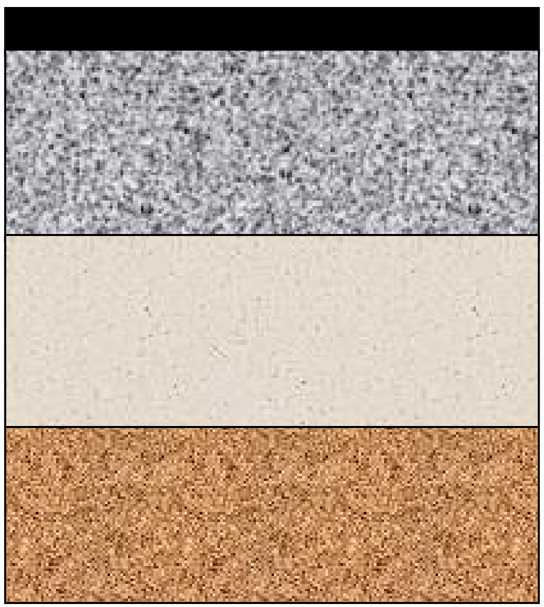
12 inches well-compacted Subgrade Soil

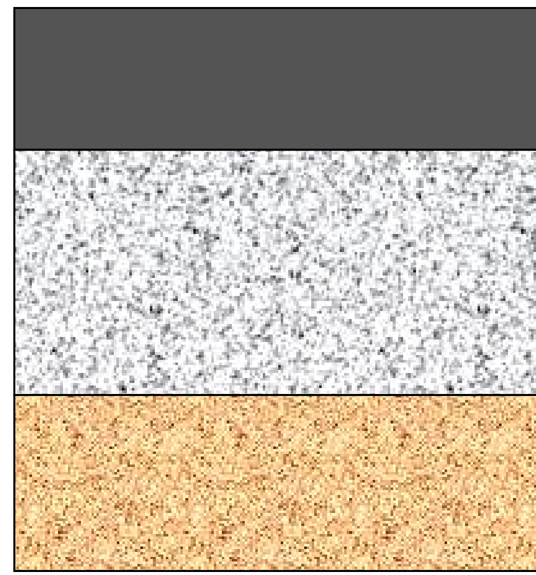
Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section

Can reach up to 25% less $ to build the inverted compared with conventional for similar performance





Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

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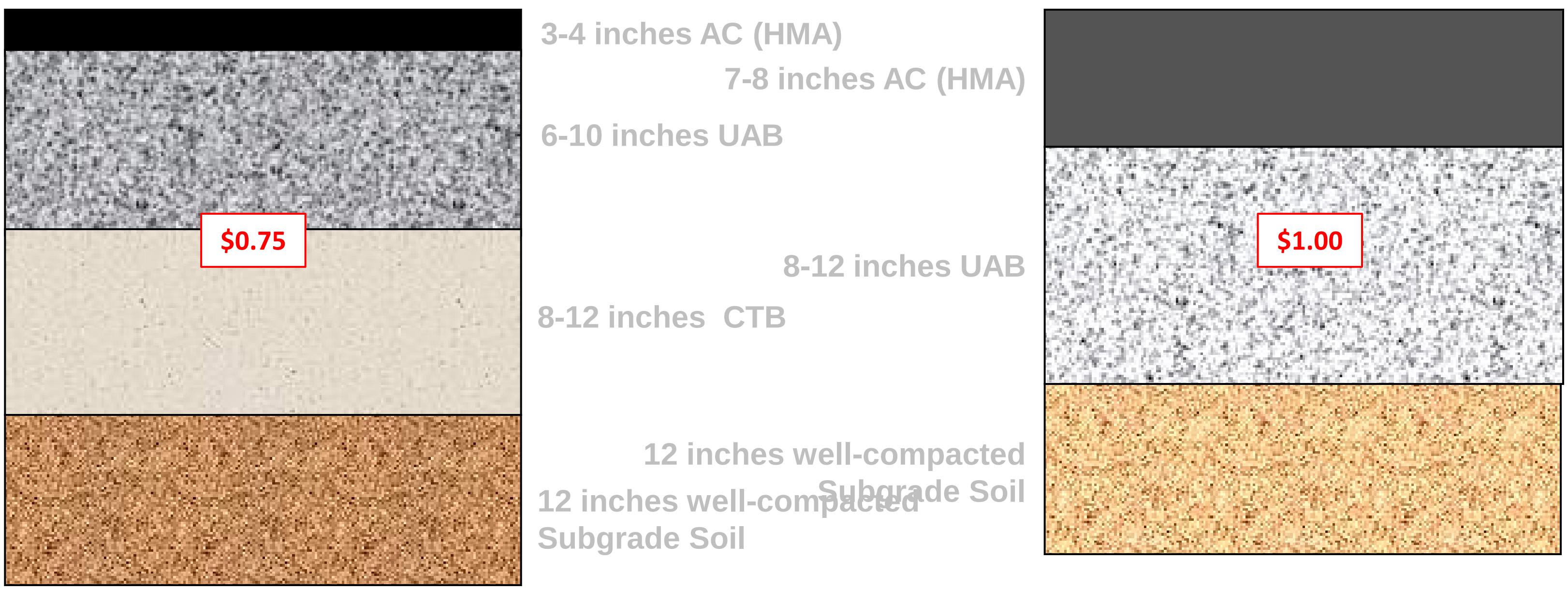

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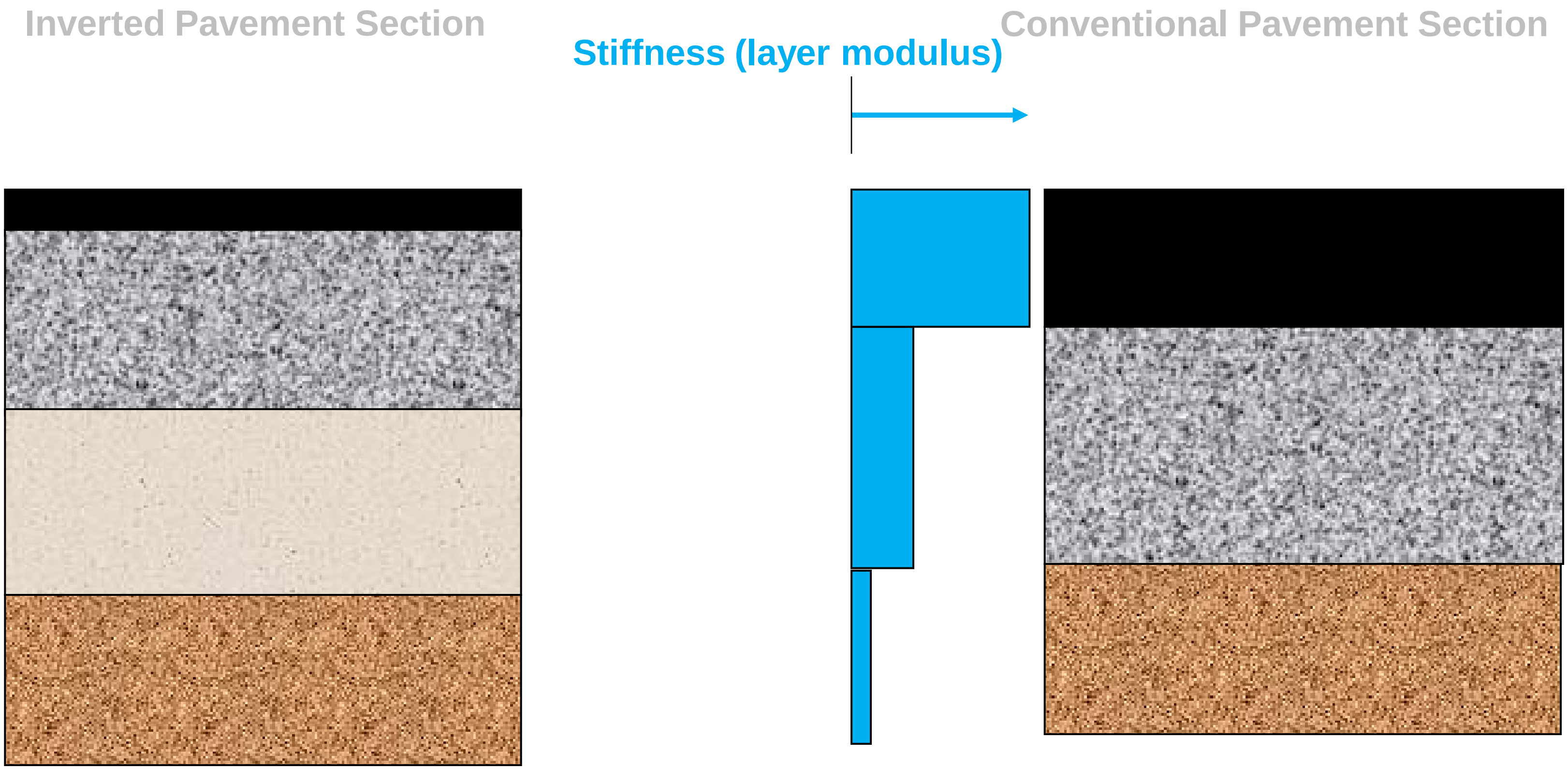

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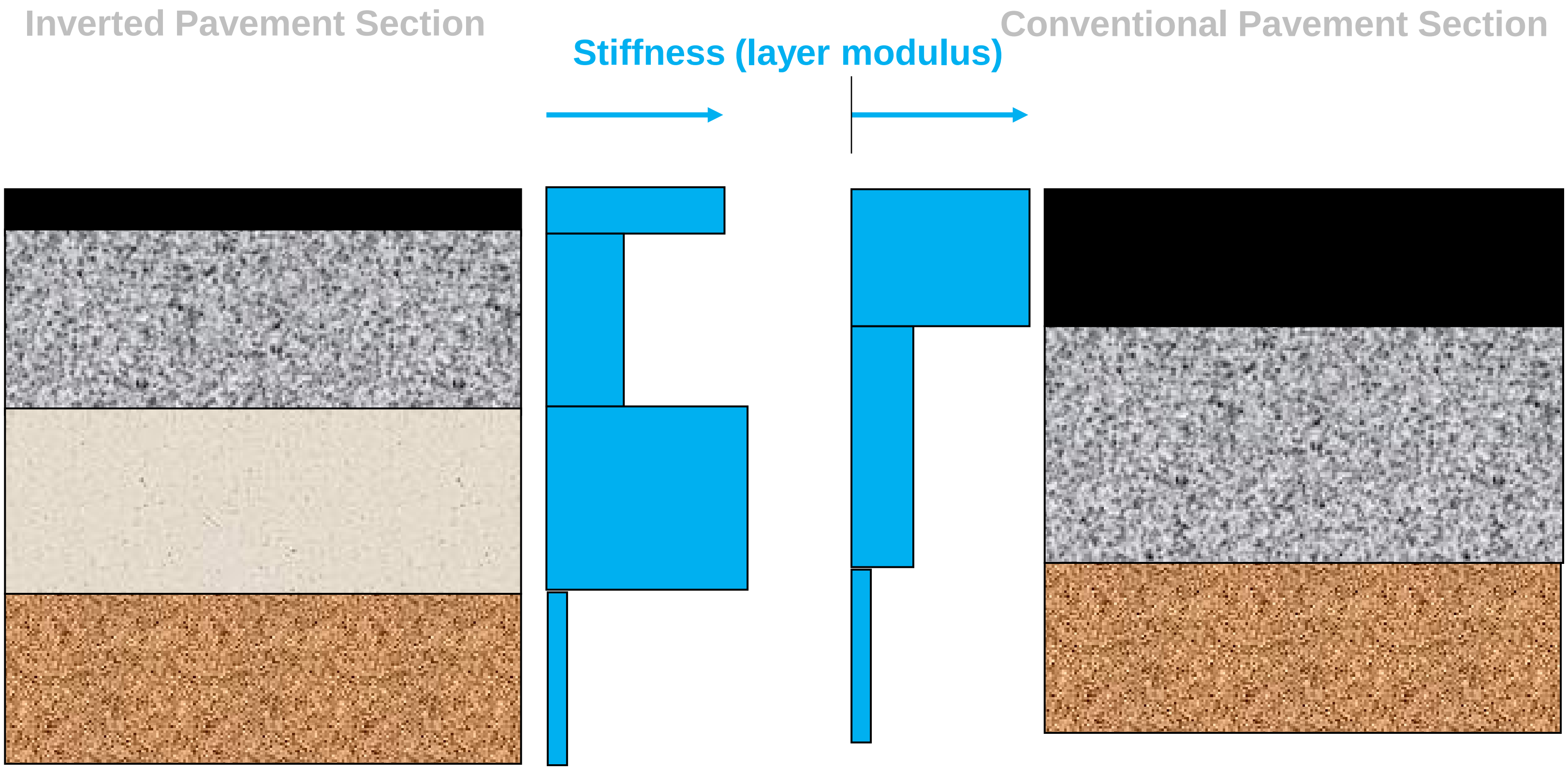

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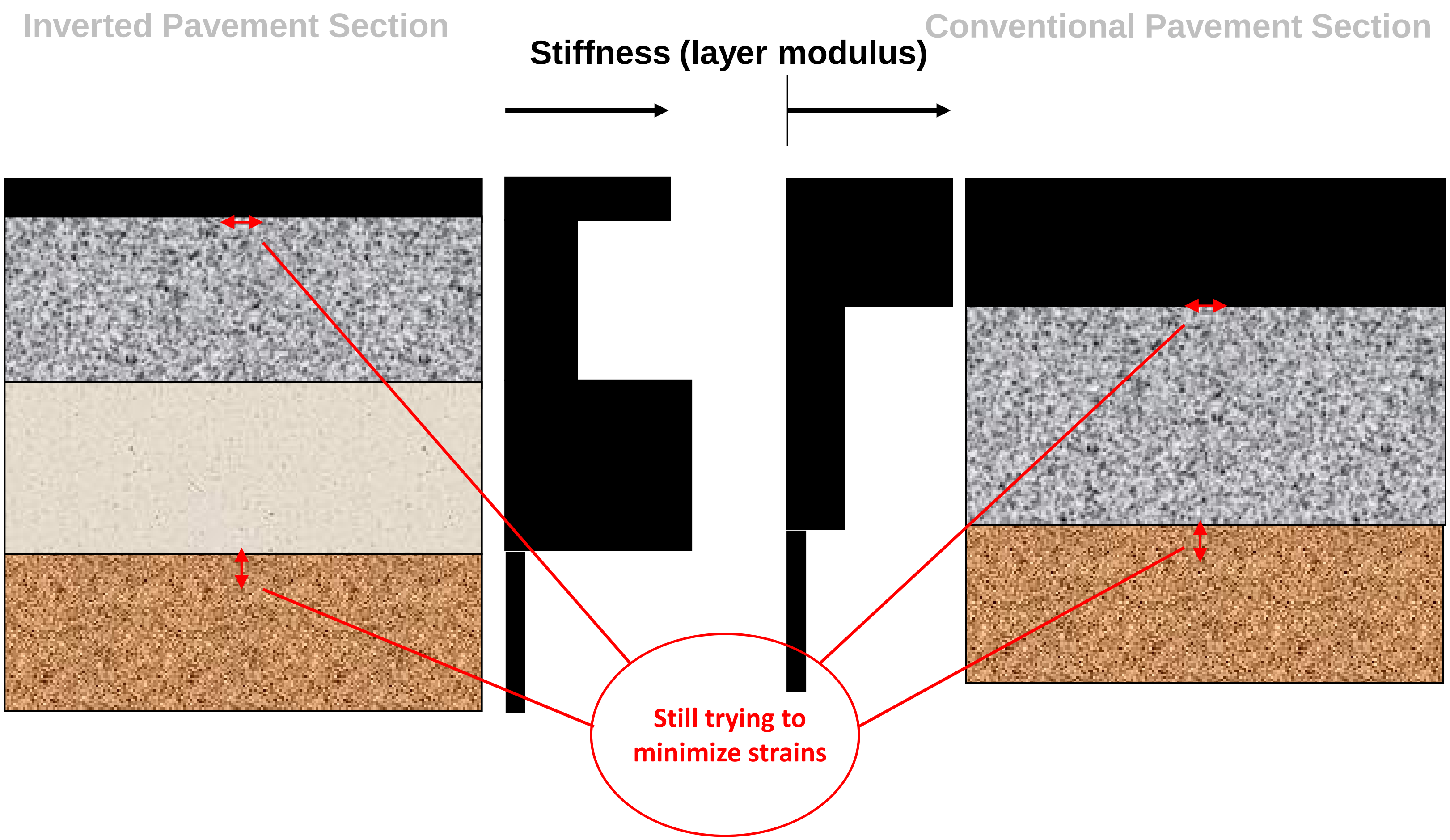
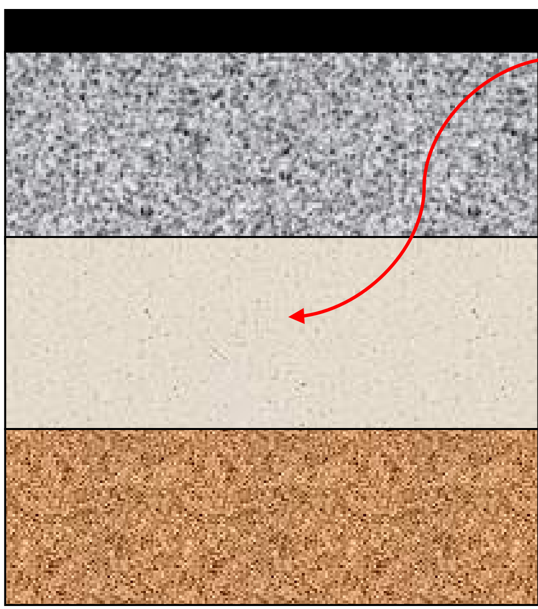


Inverted Pavement Compared to Conventional Pavement

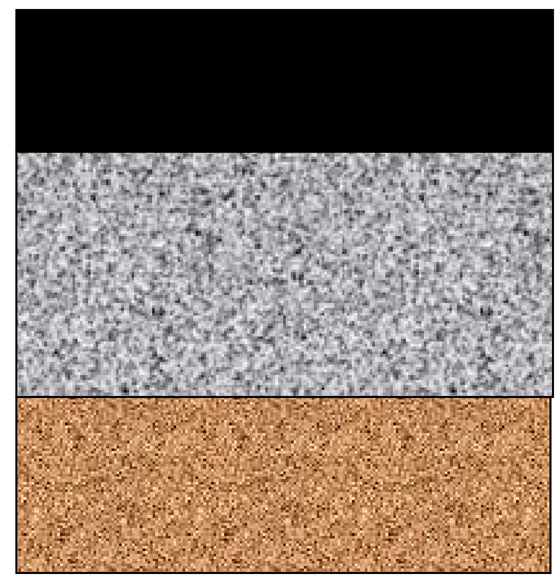
Inverted Pavement Section



As a result of the **stiff CTB layer**, higher densities can be achieved in the UAB layer during installation.

This results in higher stiffness properties, and the UAB layer remains in compression.

Conventional Pavement Section

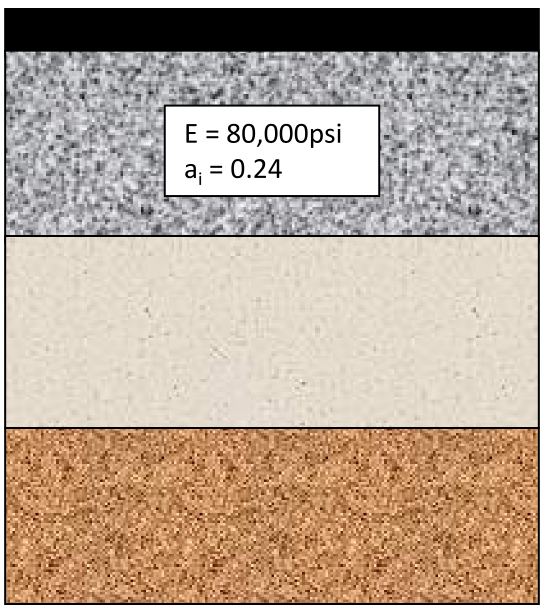


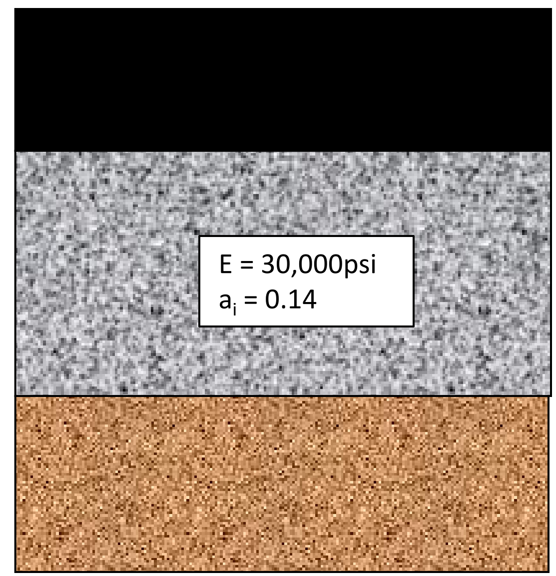
Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section

1993 AASHTO Design Guide
hypothetical ***example***





Improving the Chance of Success Unbound Aggregate Base (UAB) Layer

- **Equipment:** Mixing should be accomplished by stationary plant such as a pugmill or by road mixing using a pugmill or rotary mixer. Mechanical spreaders should be utilized to avoid segregation and to achieve grade control. Suitable vibratory compaction equipment should be employed.
- **Mixing and Transporting:** The aggregates and water should be plant mixed (stationary or roadway) to the range of optimum moisture plus 1% or minus 2% and transported to the job site so as to avoid segregation and loss of moisture.
- **Spreading:** The material should be placed at the specified moisture content to the required thickness and cross section by an approved mechanical spreader. At the engineer's discretion, the contractor may choose to construct a 500-ft long test section to demonstrate achieving adequate compaction without particle degradation for lift thicknesses in excess of 13 in. The engineer may allow thicker lifts on the basis of the test section results.

Allen, et al. ICAR 501-5 (1998)

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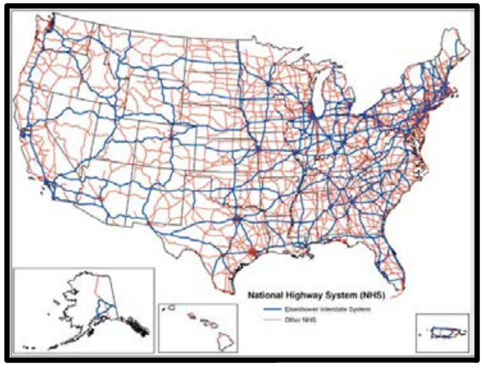
- **Slushing**: South African method to increase packing density of layer by careful over-watering during the compaction process (slush acts as a lubricant to increase density while the slush or cream exudes to the surface).

Design …………

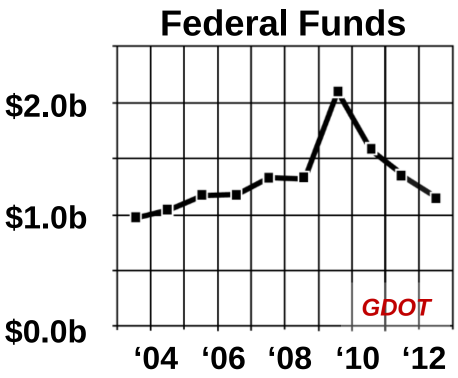
The US Road System is vast and suffers from insufficient funding.

Vast network



Wikipedia.org

Depleted funding

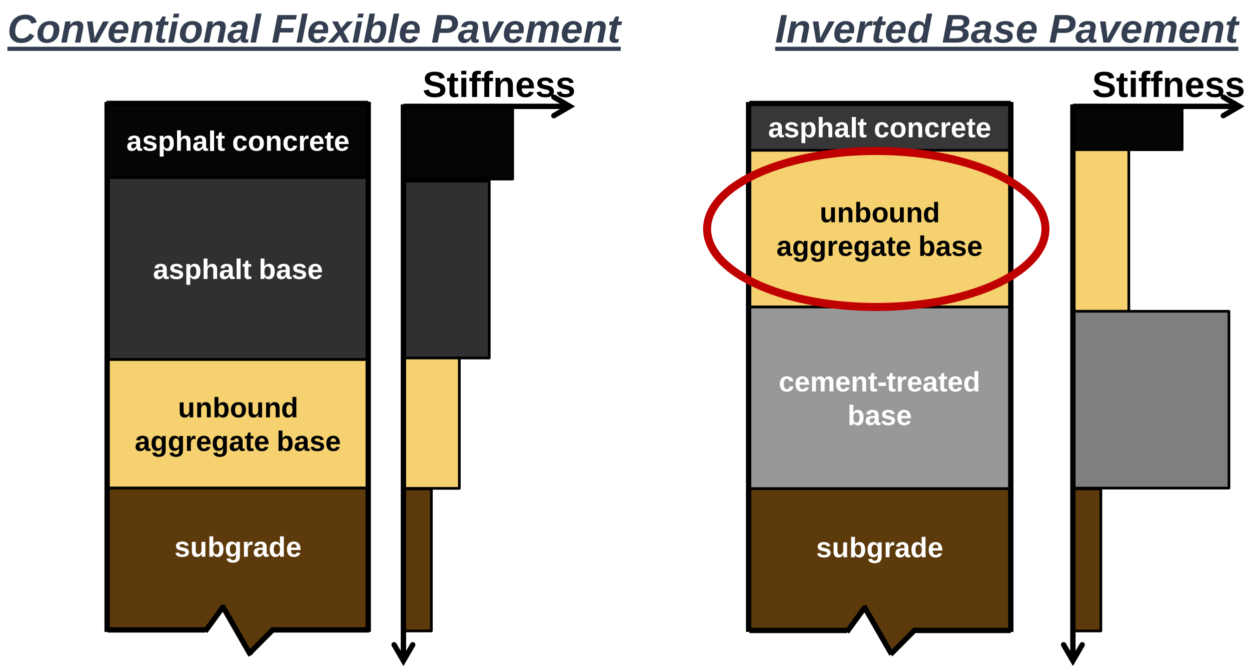


Poor condition

Solution Sources

- **Innovative designs**
- **Optimal use of materials**

An inverted base pavement (IBP) is an innovative technology that can optimize the use of materials.

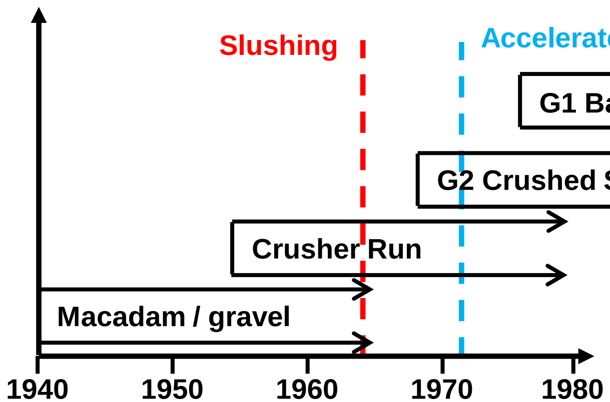


- **Stiffness contrast between layers**
- **Granular base : close to load ➔ demand for exceptional performance**

(After Papadopoulos, 2015)

South Africa has developed and utilized inverted base pavements for half a century.

Crushed stone base pavement development

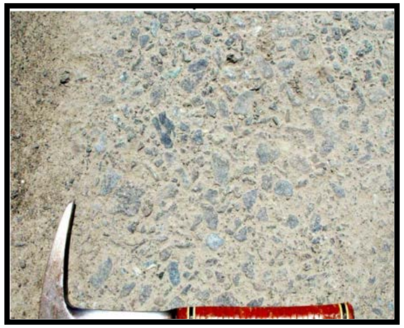


Jooste & Sampson (2005)

No Slushing

(After Papadopoulos, 2015)

Slushing after compaction

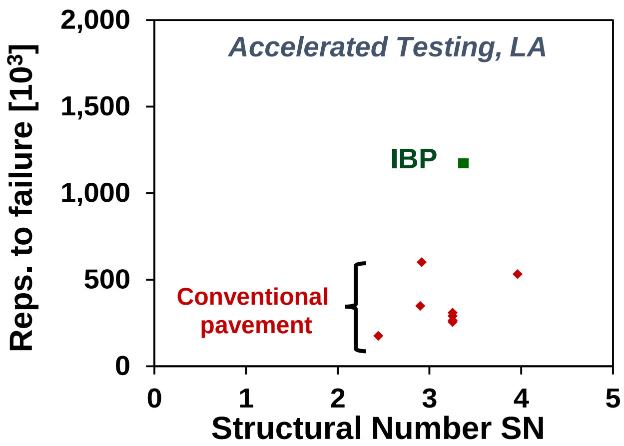


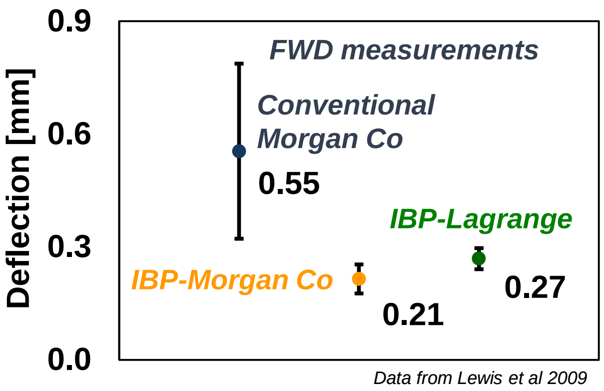
"Ping" when struck with rock hammer

Kleyn, 2012

US experience with inverted base pavements had also been long but sparse.

- New Mexico (1960s)
- USACE (1970s)
- Georgia Tech (1980s)
- Louisiana (1990s)
- Morgan County GA quarry (2000s)
- Lagrange GA bypass (2000s)
- Bull Run VA highway (2010s)
- Pineville NC quarry (2010s)

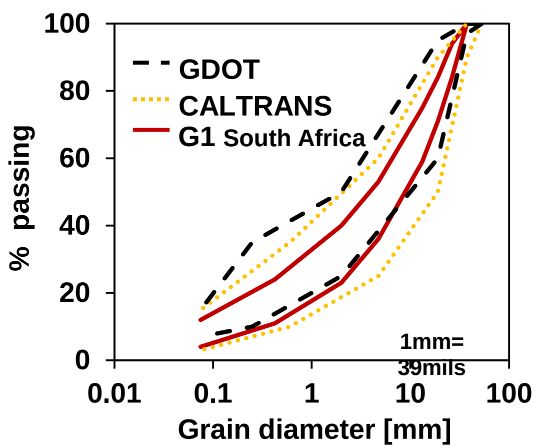


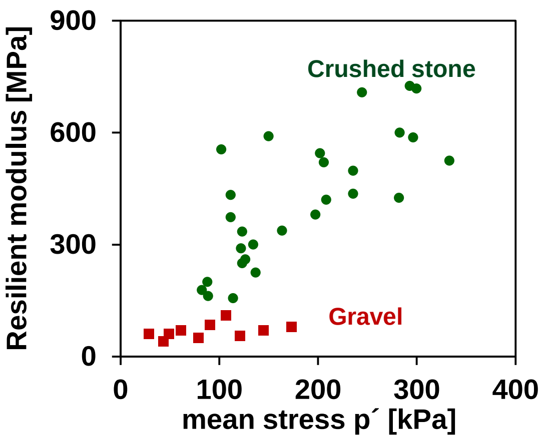


(Adapted from Papadopoulos, 2015)

Top quality unbound aggregate base is the fundamental block of IBPs.

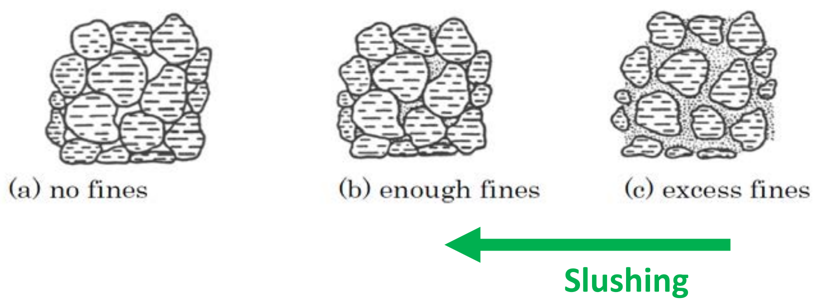
	South Africa G1 base	CALTRANS base	GDoT GAB
Fines	LL<25%, PI<4	Sand Equivalent <21	Sand Equivalent <20
Shape	flakiness (sphericity) <35%	N/A	elongated particles <10%
Density	86-88% of apparent solid density (~102% mod Proctor)	95% of CTM 231	98% mod. Proctor



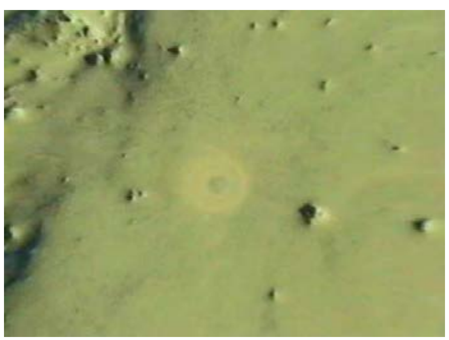


(After Papadopoulos, 2015)

Key component of Inverted Pavement construction is slushing technique



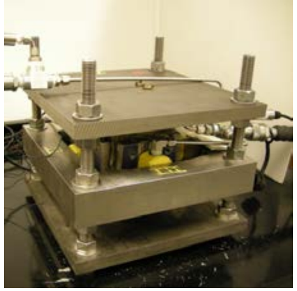
- **Process to wash away excess fines to achieve optimum fine to coarse soil matrix**
- **Water migrates to surface by capillary action carrying excess fines**



Comprehensive laboratory – field – numerical study that expanded understanding of IPB component performance.

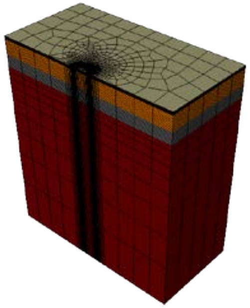
Compaction

Lab Characterization



Inverted Base Pavements

In situ testing



Mechanistic analysis

Study completed in 2014

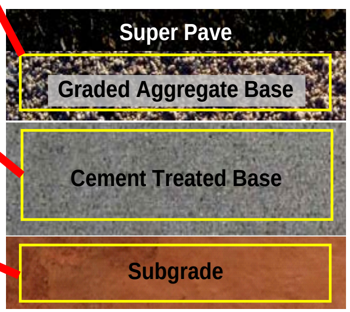
(After Papadopoulos, 2015)

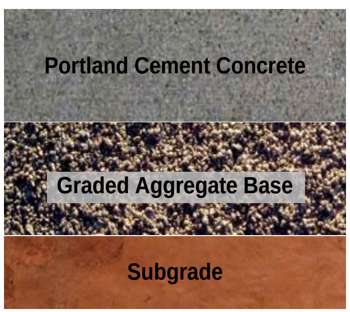
Field: fully documented construction project provides basis for long-term IBP performance assessment.

LaGrange By-Pass

Test section:
0.65 miles long
2 lanes
PCC typical section
IBP test section

Construction completed in 2009





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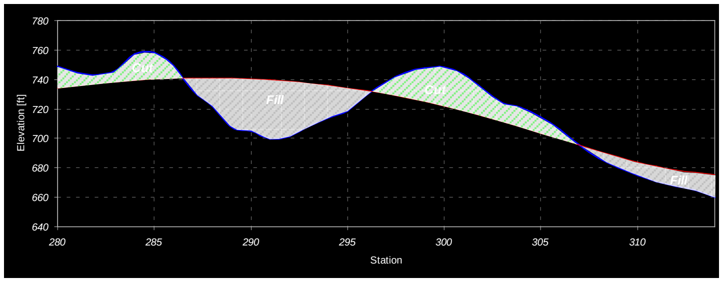
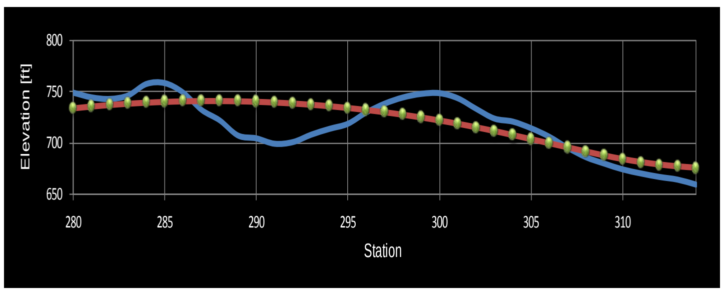
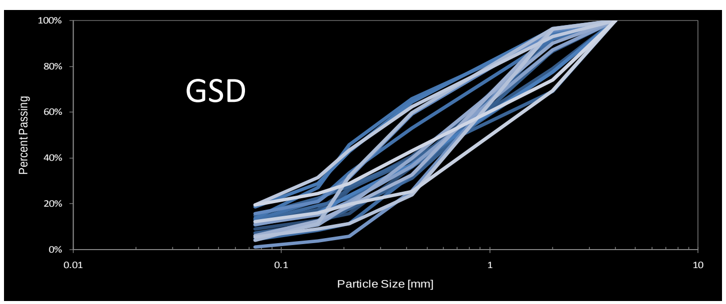
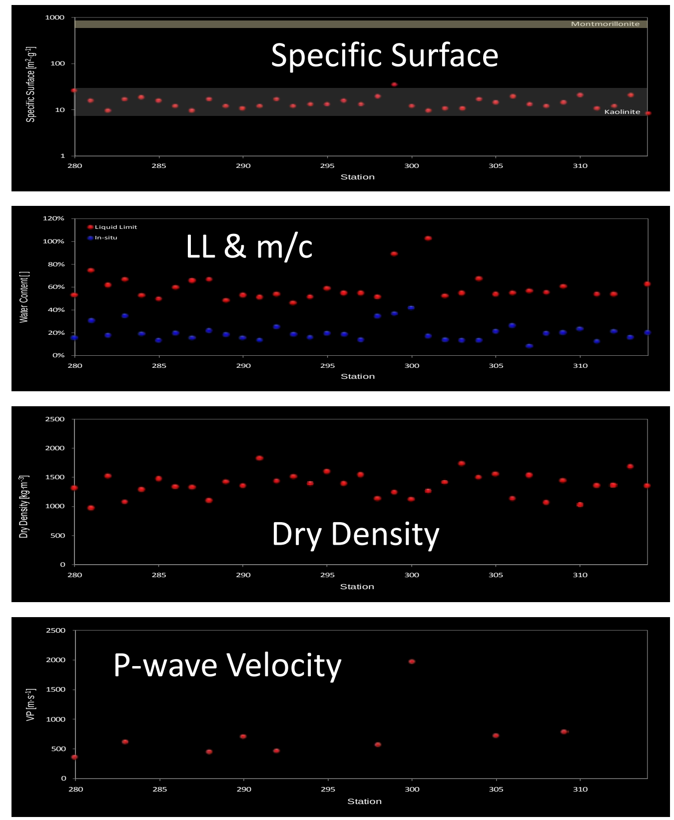




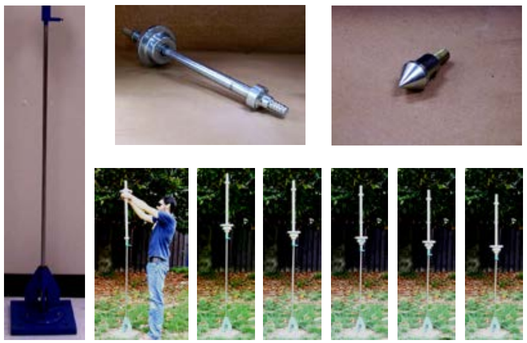


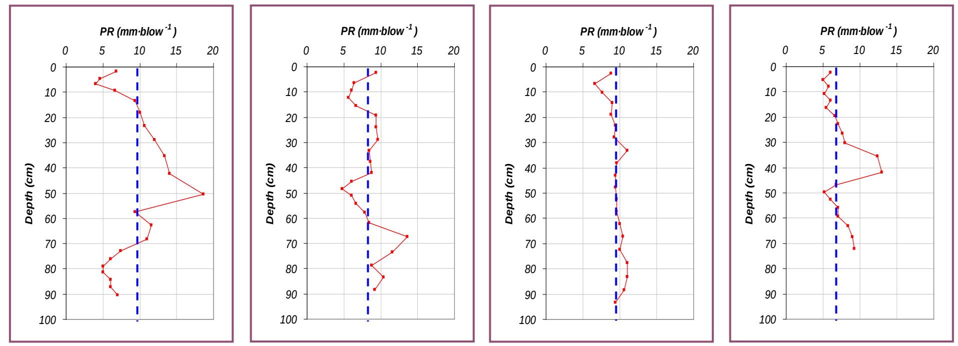


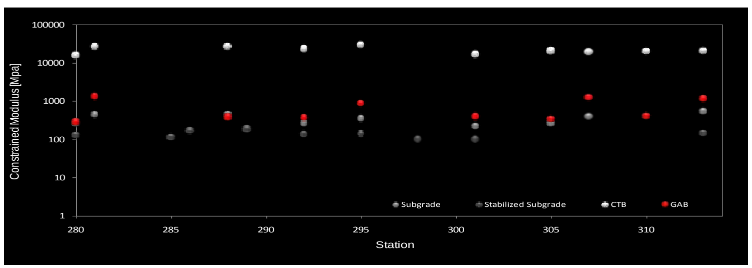
Laboratory Characterization of Subgrade

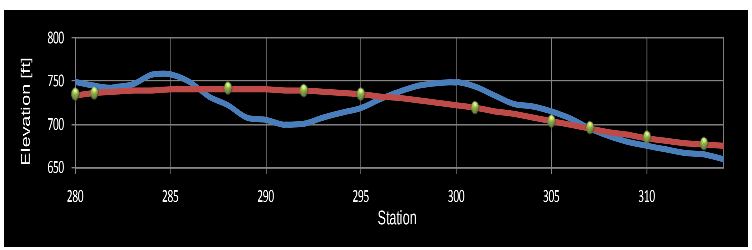
(Data from Santamarina, 2015)

Field: fully documented construction project provides basis for long-term IBP performance assessment.

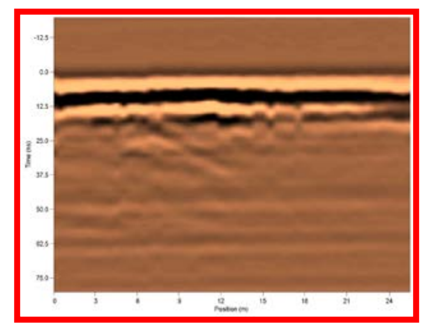








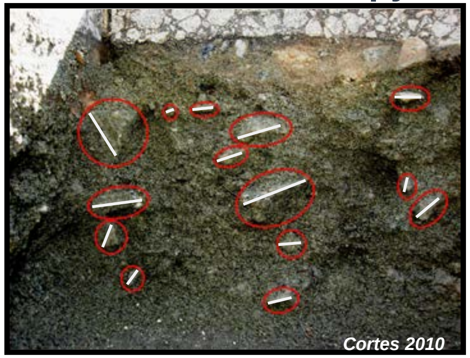
(Data from Santamarina, 2015)

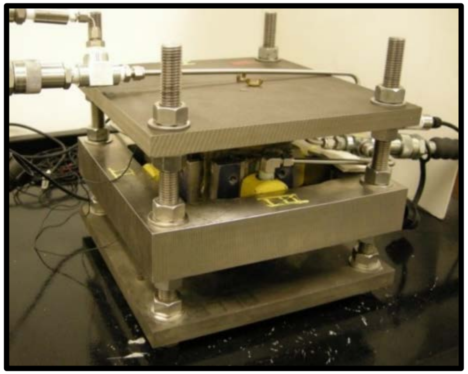


Extensive lab and field characterization studies for various layers

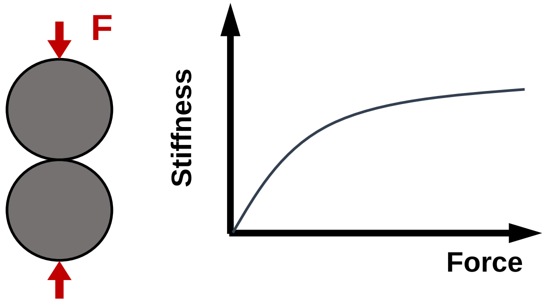
Field and Lab: current laboratory methods do not account for the complex nature of aggregate base stiffness.

Inherent Anisotropy





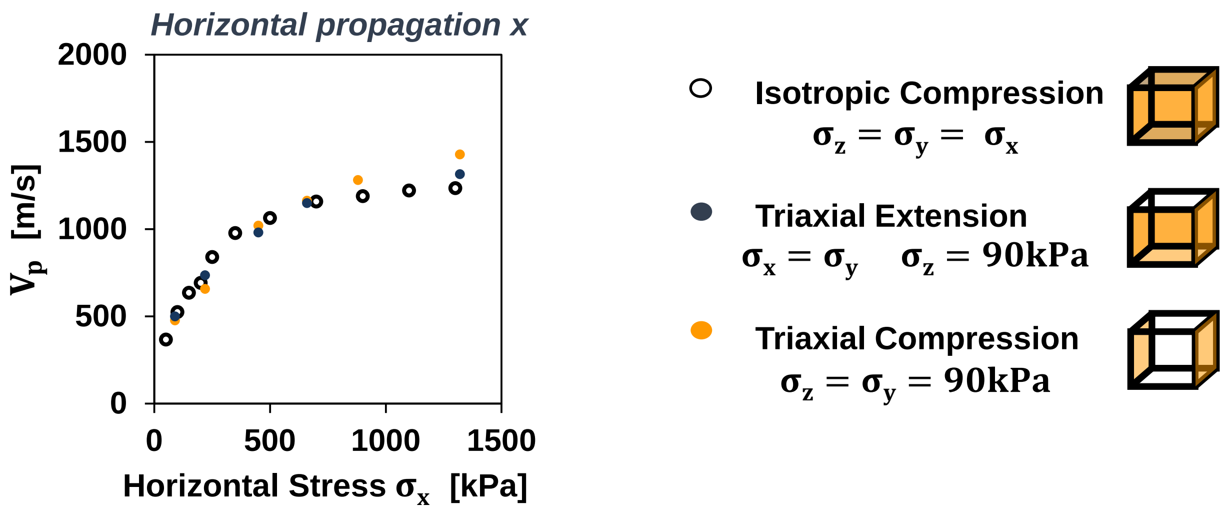
Stress-Dependent Stiffness



- **In-chamber compaction.**
- **Independent control of the 3 principal stresses.**
- **P-wave instrumentation in each direction.**

(After Papadopoulos, 2015)

Lab: stress ratio has small influence on the small-strain stiffness as long as the material is away from failure.



Characterization of unbound aggregate base stiffness:

- **Granular Bases: inherent & stress-induced anisotropy exist.**
- **M_{max} : function of normal stress**
- **Loading conditions: almost no effect on M_{max}**

(Adapted from Papadopoulos, 2015)

Field and Lab: Soil compaction is omnipresent in construction and has known impact on performance.

Inadequate compaction results

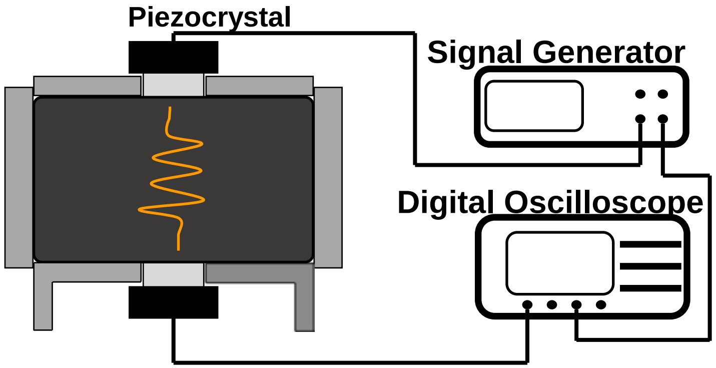
Post-placement changes in material

Lab-field discrepancies

≠

Lab: an extensive lab study was conducted to assess the compaction process in terms of stiffness.

- Specimens compacted using Modified Proctor (Adapted from Papadopoulos, 2015)
- Stress-dependent stiffness for different water contents

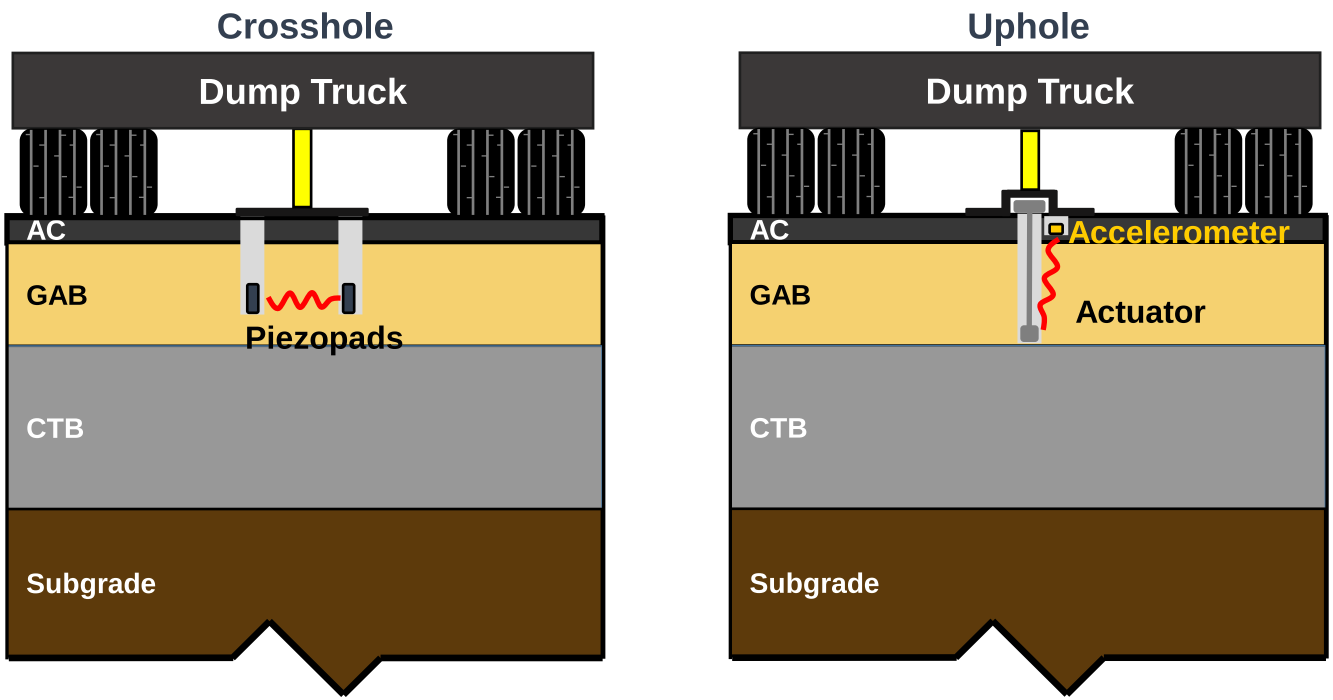


Effect of compaction on granular base stiffness:

- ρ_{dry}: not sufficient to assess compaction
- Granular base stiffness not affected by water content
- Water content affects permanent deformation
- Velocity changes reflect accumulation of deformation

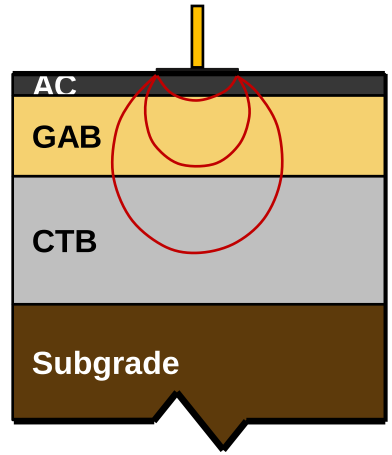
Field: Two new field tests were conceived to measure the stiffness of as-built aggregate bases.

Measure stiffness of as-built unbound aggregate bases



(After Papadopoulos, 2015)

Field: Successive forward simulations were conducted to determine the state of stress in the pavement.

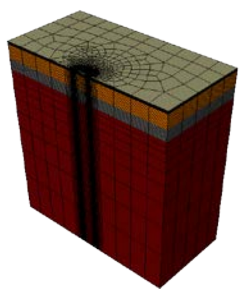


Two configurations to capture anisotropic stiffness – 2 case histories

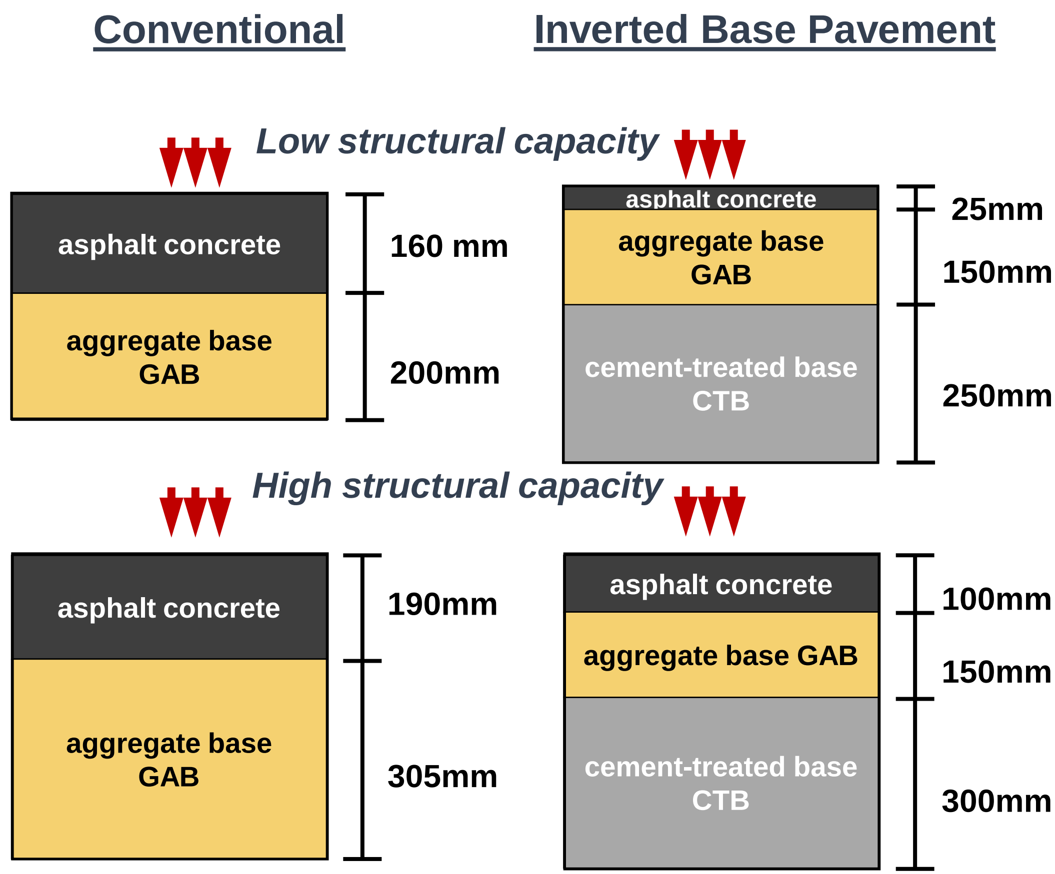
- **In situ GAB: anisotropic stress-dependent stiffness**
- **Field values ≠ lab values: Due to preconditioning and compaction method (field versus lab)**
- **Field-Compacted GAB: great stiffness**

(Adapted from Papadopoulos, 2015)

Modeling: Numerical simulations were conducted to compare IBP's to conventional pavements.



Mechanistic analysis



(Adapted from Papadopoulos, 2015)

Aggregate base stiffness in IBP is high due to the confinement provided by the CTB.

Constitutive model:

- **Anisotropy, stress-dependency, shear softening**

Inverted base pavements:

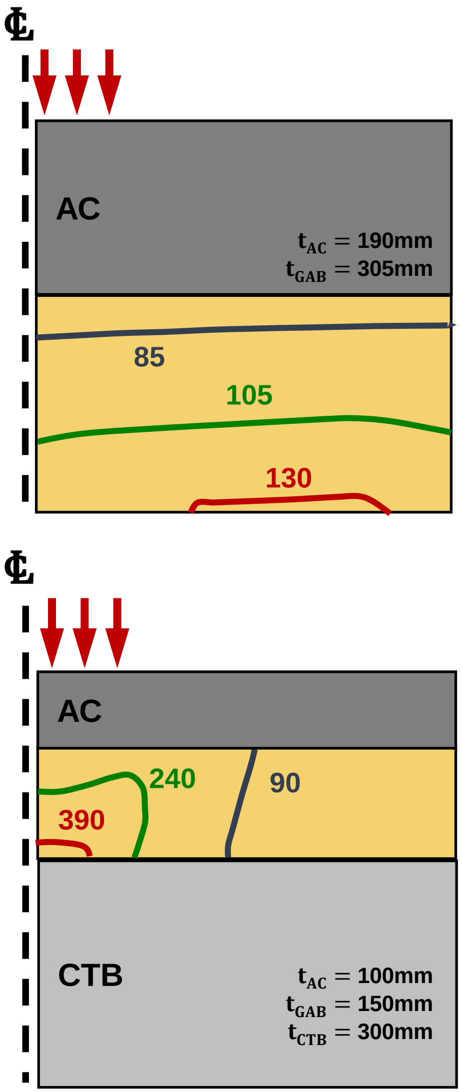
- **Unique load-bearing mechanism**

Granular base:

- **Underutilized in conventional pavements**
- **Great contribution in inverted base pavements**

Thin asphalt layers:

- **Potential for economic savings**
- **Caution when subjected to strong shear**



(Adapted from Papadopoulos, 2015)

Tangent Vertical Young's modulus E_v (MPa)

Construction ……….

Inverted Pavement Construction

- Standard construction methods may be used for most layers in an inverted pavement
- Subgrade, Cement Treated Base and Asphalt may be constructed in the normal way
- Unbound Aggregate Base course may take a little more effort to ensure the higher density required
  - South African methods vs. traditional

Subgrade Construction

- Generally use standard subgrade requirements
- Remove/correct saturated soils, organics, unsuitable, etc.
- Typical density requirements
- Variety of subgrades have been used in US inverted pavements

Subgrade Construction

- South Africa
  - 90% to 93% Modified Proctor
- Georgia
  - Mixed in graded aggregate base to improve CBR to 15
- New Mexico
  - Lime treated subgrade
- Luck Stone – Virginia
  - Standard VDOT subgrade requirements
- Vulcan – North Carolina
  - Standard NCDOT subgrade

Vulcan North Carolina Subgrade

New Mexico Subgrade Construction

Cement Treated Base

- Can generally use traditional CTB requirements
- Relatively low level of strength & cement
  - South Africa requires 100 to 200 psi
- Pugmill or mix in place
- Recommend spreader box to reduce segregation
- Typical density requirements

Cement Treated Base

- Pugmill system works well if available

Cement Treated Base

Cement Treated Base

- Asphalt paver used in NM for CTB
- Good control over depth and segregation

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

- Seal with emulsified asphalt tack coat

- Allow to cure for 7 days

Unbound Aggregate Base

- Typical laydown
  - Spreader box should be required for thickness and consistency
- Density requirements higher than normal
- How is this achieved
  - South Africa requires "slushing"
  - Will normal methods work?

Unbound Aggregate Base

Unbound Aggregate Base

Unbound Aggregate Base

Unbound Aggregate Base

Slushing Process

- What is slushing?
  - After initial compaction – UAB flooded with water

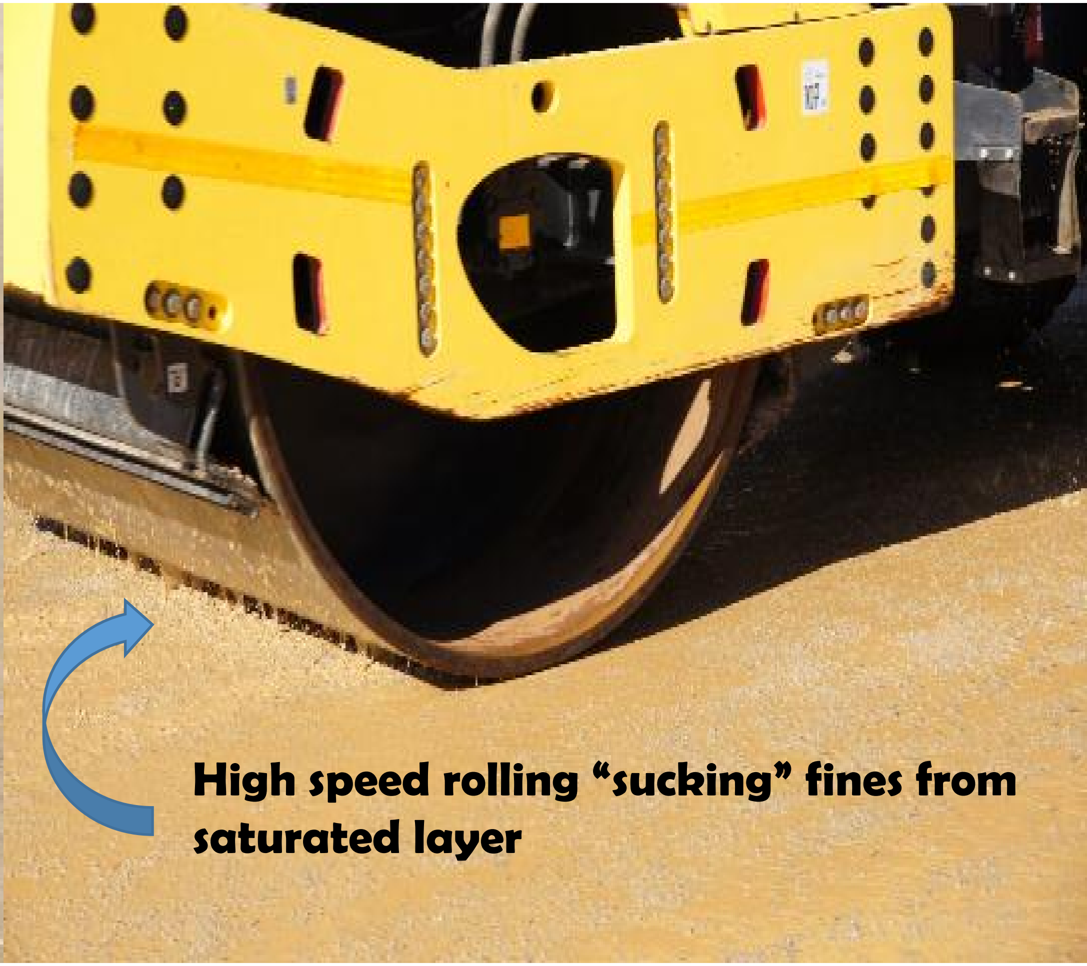
  - Rolled at high speed to “suck” the fines out of the UAB
    - Fines and water act as a lubricant
    - As they are removed, larger particles are consolidated for high density and stiffness

  - Excess fines collect on top of the UAB

  - Excess fines broomed off

Slushing Process

Slushing Process



Slushing Process

Slushing Process

Slushing Process

Slushing Process

Unbound Aggregate Base

- To Slush or not to Slush…that is the question
- First test section in Georgia saw no benefit to slushing
- New Mexico specified slushing
- All others used traditional compaction methods
    - Easily achieved 102 to 103% of modified Proctor

Unbound Aggregate Base

- On Vulcan section, the UAB on the conventional & inverted sections compacted same time
- Density on conventional: 99.8%
- Density on inverted: 103.4%
  - 86.4% of apparent

Unbound Aggregate Base

- Used the same compaction techniques on both
- Roller operated commented that the inverted section caused more “bouncing” when compacting with vibration

Hot Mix Asphalt

- Normal HMA construction in accordance with local DOT requirements

- Nothing new

Vulcan Final Density Comparison

Inverted
Layer Densities

	Required	Achieved
9.5mm A	90% of G_{mm}	90.8%
9.5mm B	92% of G_{mm}	94.3%
UAB	102% of Mod. Proc.	103.4%
CTB	97% of Mod. Proc.	99.2%

Conventional
Layer Densities

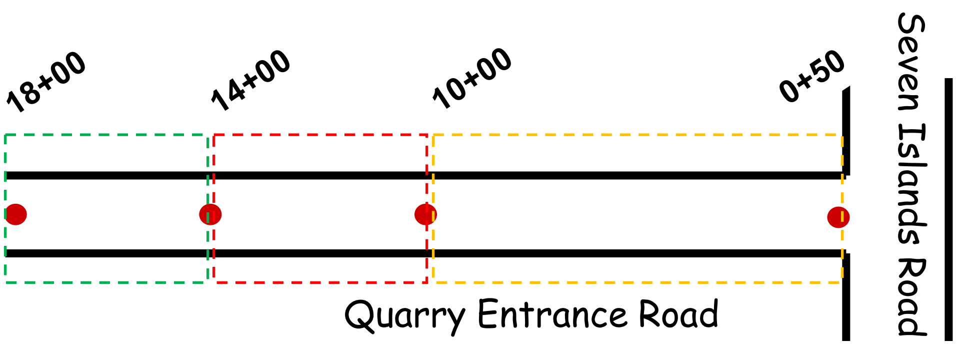
	Required	Achieved
9.5mm B	92% of G_{mm}	93.2%
19.0mm	92% of G_{mm}	93.1%
UAB	100% of Mod. Proc.	99.8%

Construction Summary

- Subgrade – standard methods
- Cement Treated Base – standard methods
- Unbound Aggregate Base – requires higher density
  - Standard methods have been shown to work
  - Slushing will work, but may not be required
- Asphalt Paving – standard methods
- QA/QC: Stiffness-based measurements vs density-based measurements
  - Intelligent Compaction (IC)
  - LWD, PLT, DCP .....

Performance Assessment

Test sections with well documented loading over 15 year period (Morgan County Quarry).



Station 0+50 through Station 10+00
Conventional Haul Road
Station 10+00 through Station 14+00
South African Base
Station 14+00 through Station 18+00
Georgia Base

Construction completed in 2001

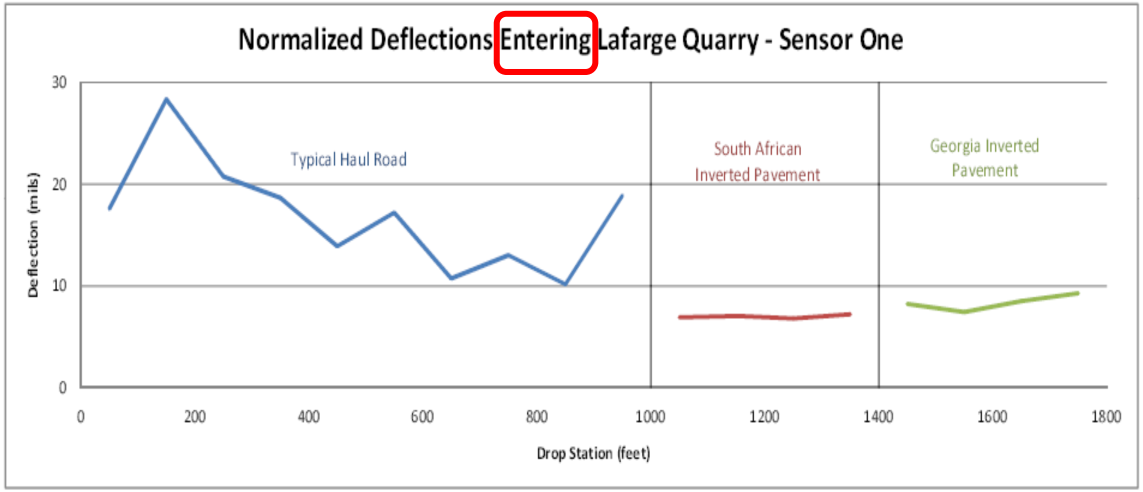
FWD evaluations of test sections (2009).

Inverted Pavement Structure GDOT Compaction Method (Typical)

Station 14+00 to 18+00

3.00 inches - Asphaltic Concrete Paving
6.00 inches - Graded Aggregate Base-Lafarge, Morgan Co.
86.4% of Apparent Density (145.2 PCF)
8.00 inches - Cement Treated Base
5% Type I Portland (145 psi to 435 psi)
2.00 inches - Graded Aggregate Base
(filler)

Prepared Subgrade
Minimum CBR Value of 15



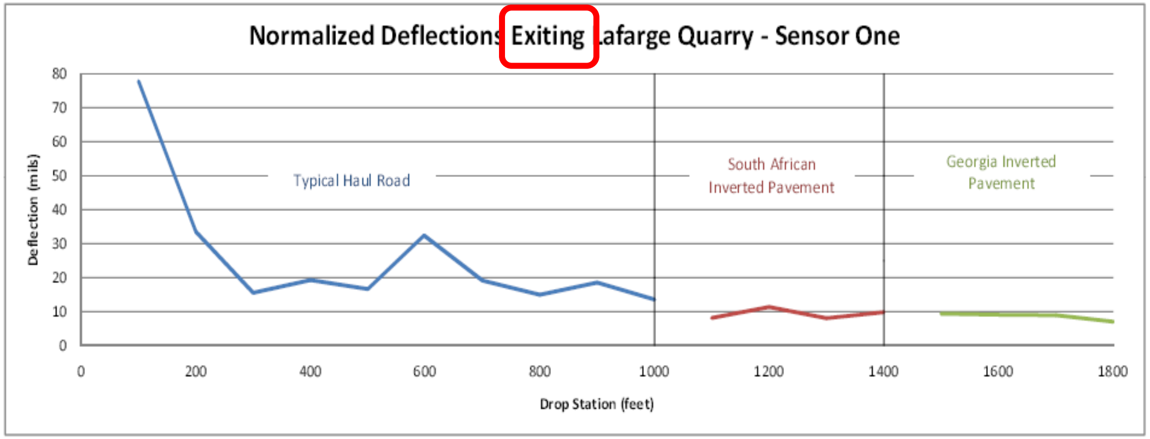
Performance Evaluation: **853,719 ESAL's** (63.5% design life cycle)

Inverted Pavement Structure SARB Compaction Method (Slushing)

Station 10+00 to 14+00

3.00 inches - Asphaltic Concrete Paving
6.00 inches - Graded Aggregate Base-Lafarge, Morgan Co.
86.4% of Apparent Density (145.2 PCF)
8.00 inches - Cement Treated Base
5% Type I Portland (145 psi to 435 psi)
2.00 inches - Graded Aggregate Base
(filler)

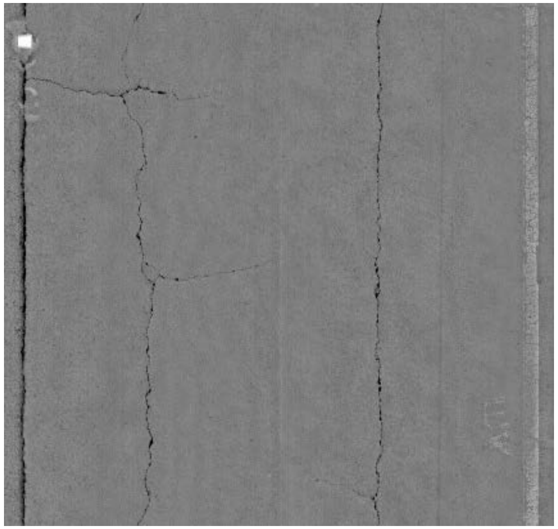
Prepared Subgrade
Minimum CBR Value of 15



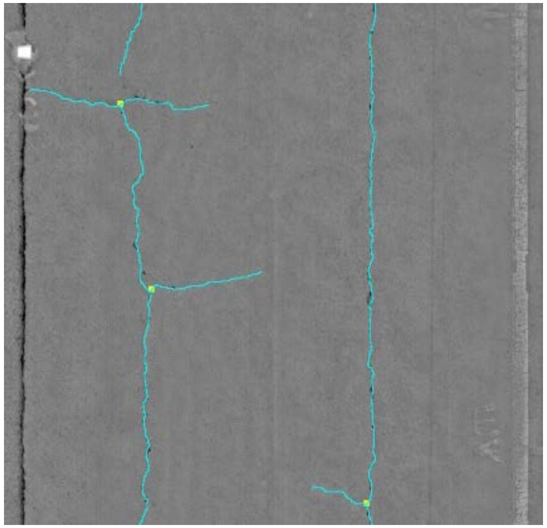
Lewis et al., 2012

Surface distress study using imaging and LiDAR (2016).

3D Laser Imaging System



Range Image



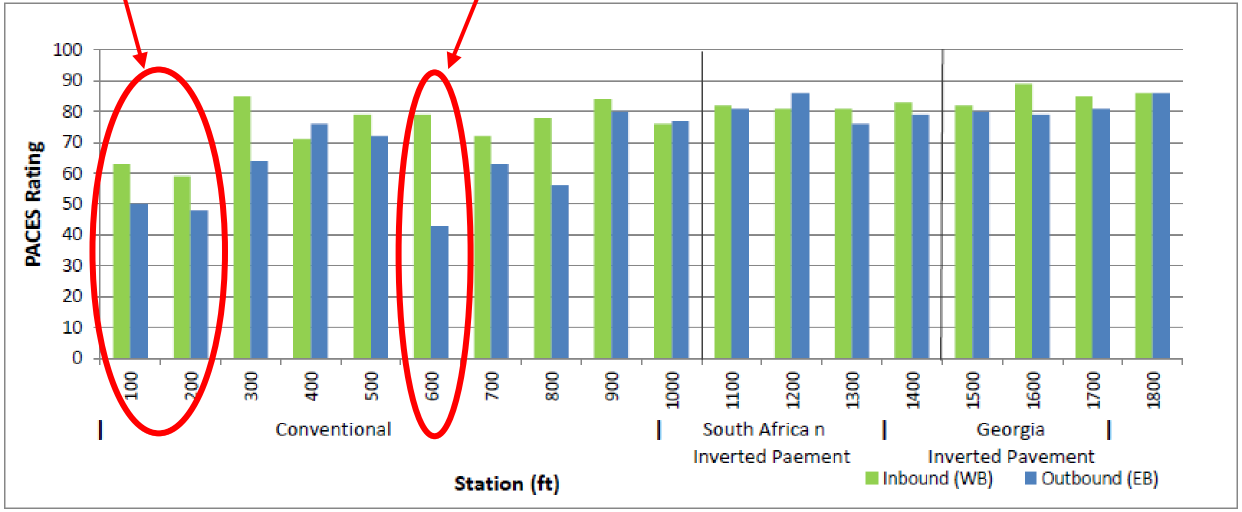
Detected Crack Map

The GDOT's Pavement Condition Evaluation System (PACES) is used for conducting the annual asphalt pavement condition surveys in Georgia.

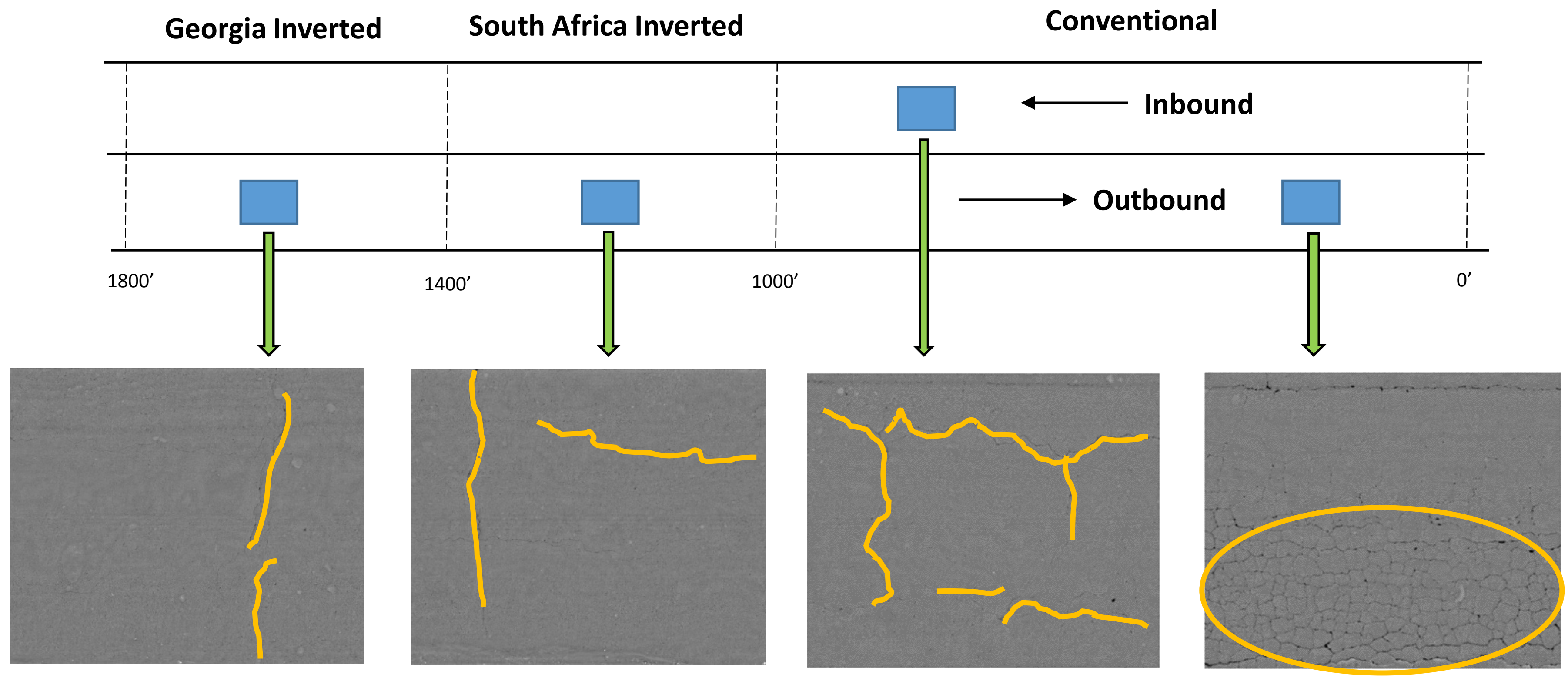
- Ten different distress types and their severity levels are defined.
- Four of them are crack related distresses: load cracking, B/T cracking, edge distress, and reflective cracking.

(Courtesy of James Tsai)

Surface distress study using Imaging (2016).



Surface distress study using Imaging (2016).



Fine transverse crack

Transverse and longitudinal crack

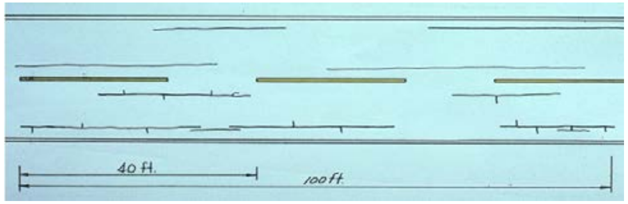
Block cracking

Alligator cracking

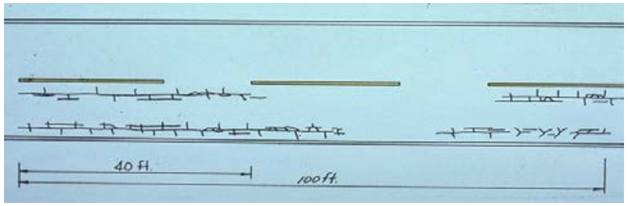
Pavement surface distress study using imaging.

- **Load cracking is caused by repeated heavy loads and always occurs in the wheel paths**:
    - **Severity Level 1** usually starts as single longitudinal cracks in the wheel path.
    - **Severity Level 2** has a single or double longitudinal crack with a number of 0-2 feet transverse cracks intersecting.
    - **Severity Level 3** shows an increasing number of longitudinal and transverse cracks in the wheel paths. This level of cracking is marked by a definite, extensive pattern of small polygons.
    - **Severity Level 4** has the definite “alligator hide” pattern but has deteriorated to the point that the small polygons are beginning to pop out.

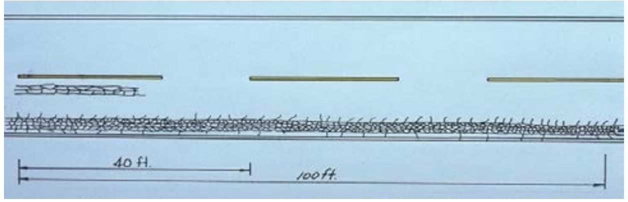
(Courtesy of James Tsai)



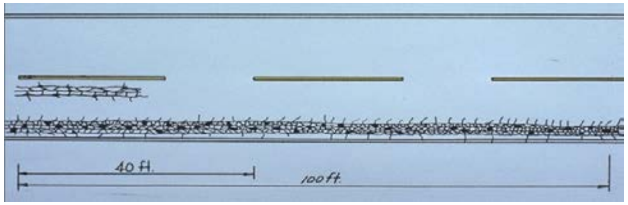
(a) Severity Level 1



(b) Severity Level 2



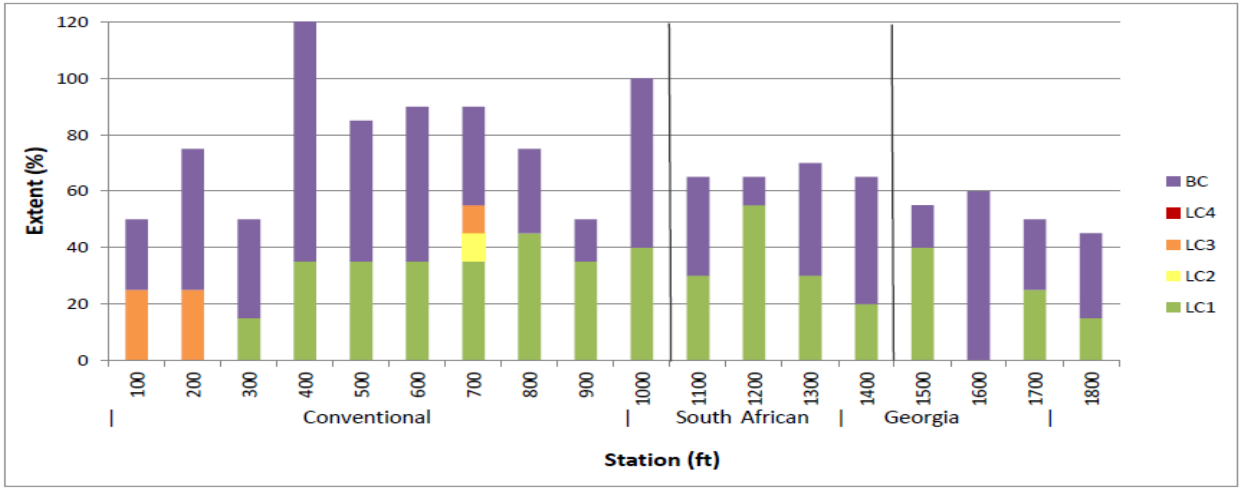
(c) Severity Level 3



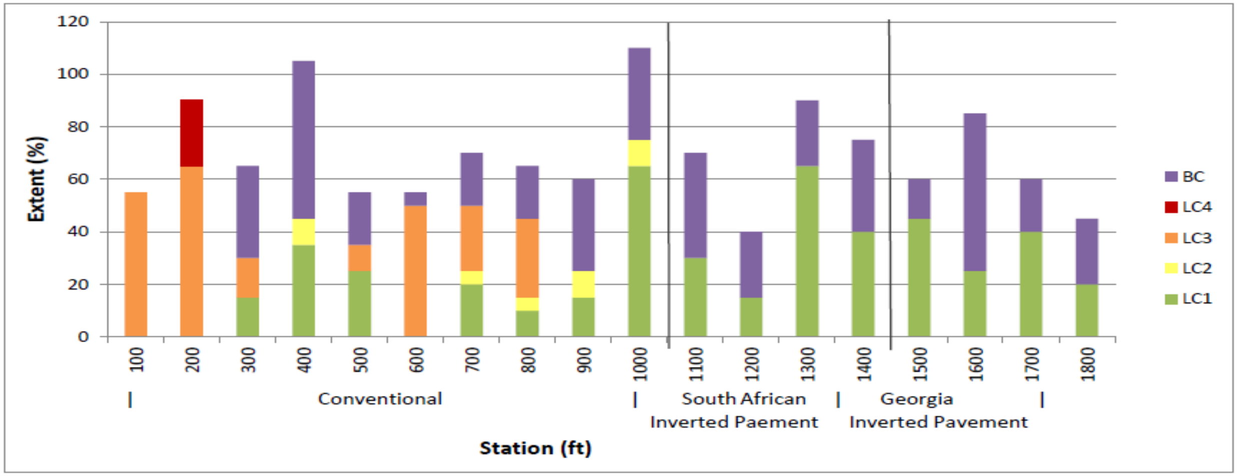
(d) Severity Level 4

Surface distress study using imaging (2016).

Inbound



Outbound

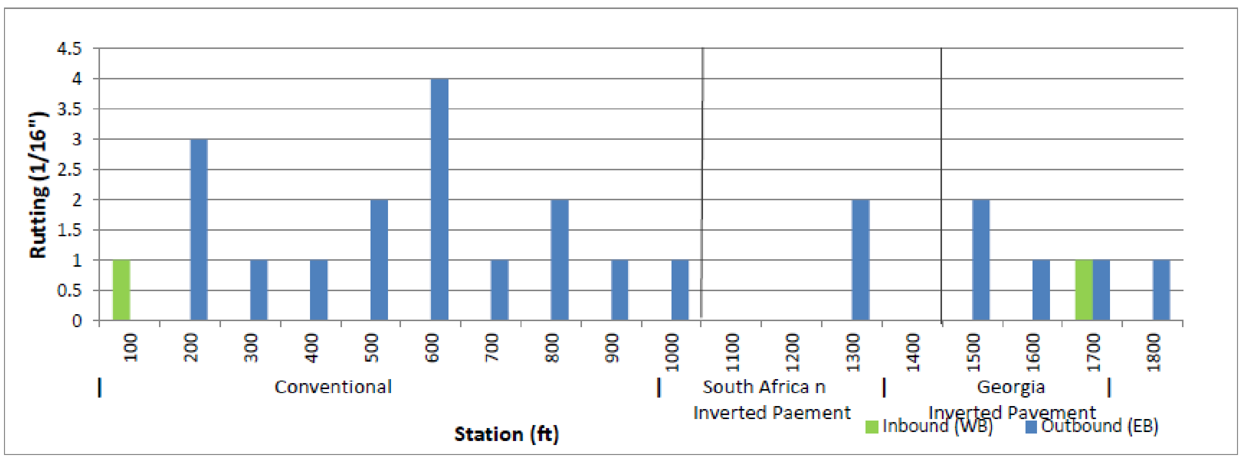


Surface distress study using imaging (2016).

		Conventional		South African IP		Georgia IP	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Load Cracking	1	32.5 %	25.8%	33.8%	37.5%	20 %	32.5%
	2	0%	5. %	0	0	0	0
	3	0%	12.5%	0	0	0	0
Block Cracking	1	52.5%	31.7%	32.5%	31.3%	32.5%	30%

Rutting study using LiDAR (2016).

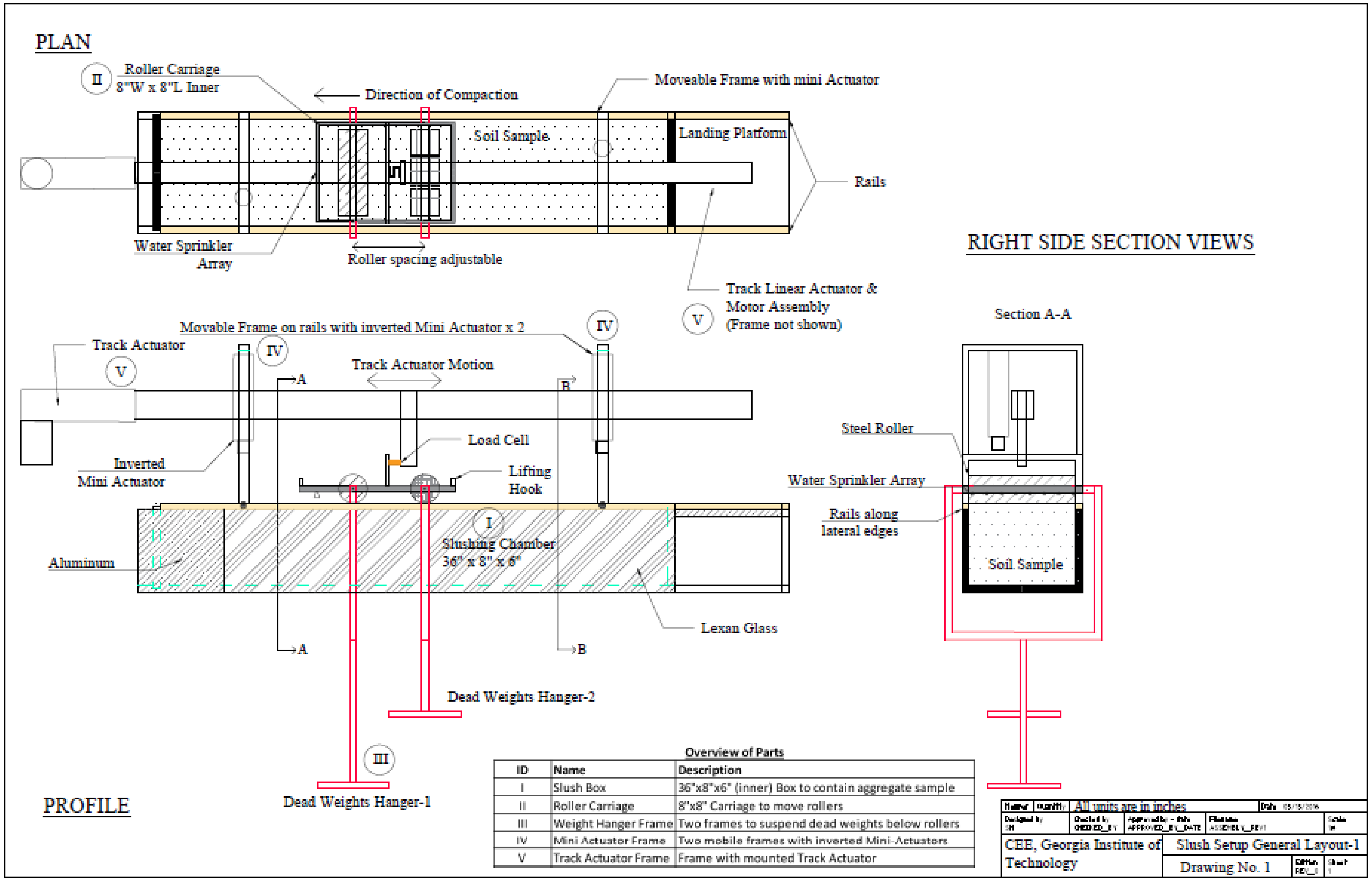
		Conventional		South African IP		Georgia IP	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Load Cracking	1	32.5 %	25.8%	33.8%	37.5%	20 %	32.5%
	2	0%	5. %	0	0	0	0
	3	0%	12.5%	0	0	0	0
Block Cracking	1	52.5%	31.7%	32.5%	31.3%	32.5%	30%
Max Rutting (1/8”)		0	4	0	0	1	2
Average Rating		79	68.7	81.8	80.5	85.5	81.5
Rating Range		71-85	43-80	81-83	76-86	82-89	79-86



Comparable rating for SA IBP and GA IBP – far superior to conventional design.

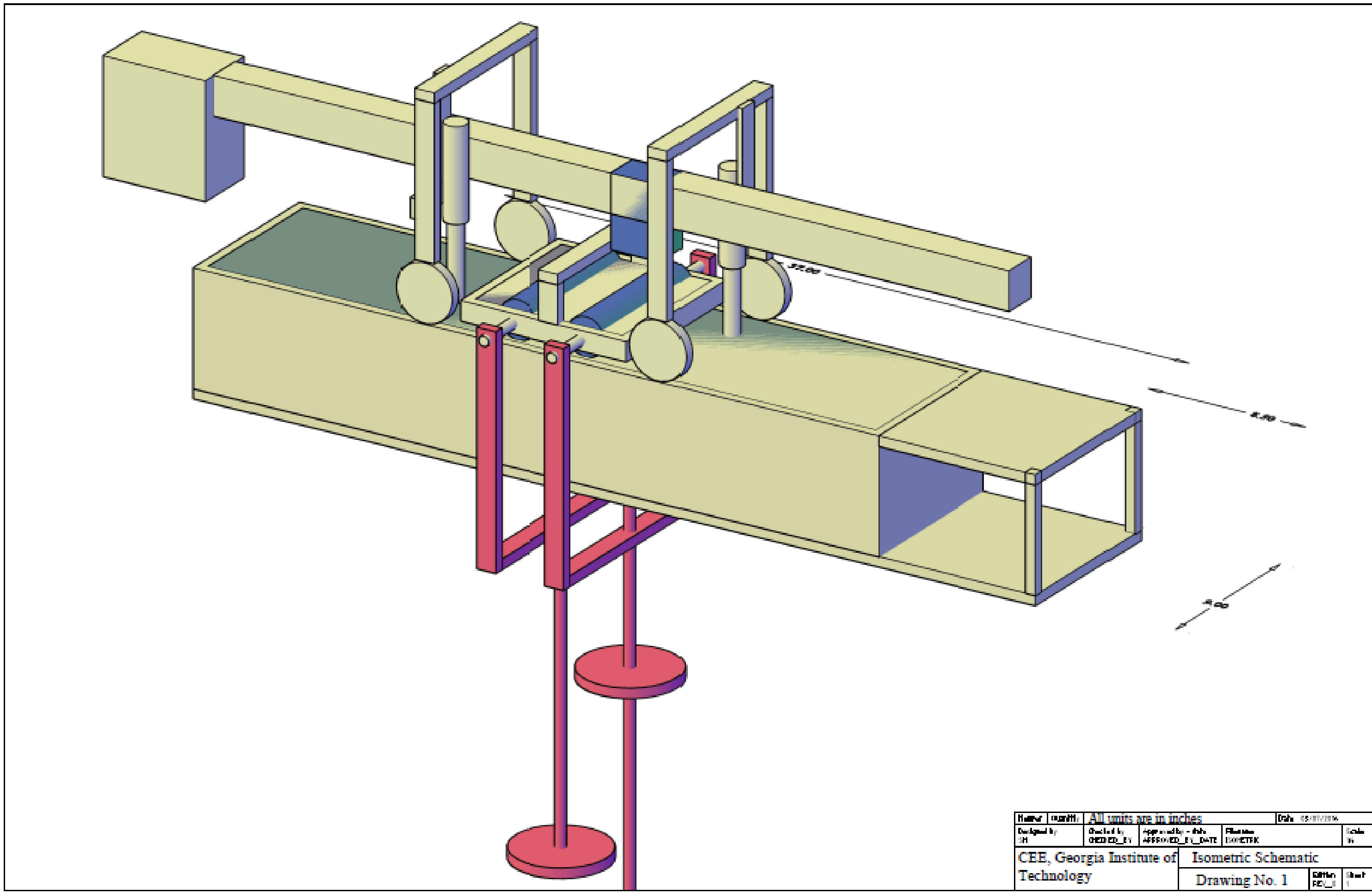
Less rutting with SA IBP than with GA IBP – possible link to benefits of slushing?

Laboratory simulation study of slushing process.



Ongoing laboratory simulation study to examine evolution of aggregate shape, pore structure and load path during slushing

Laboratory study of slushing on cracking and rutting.



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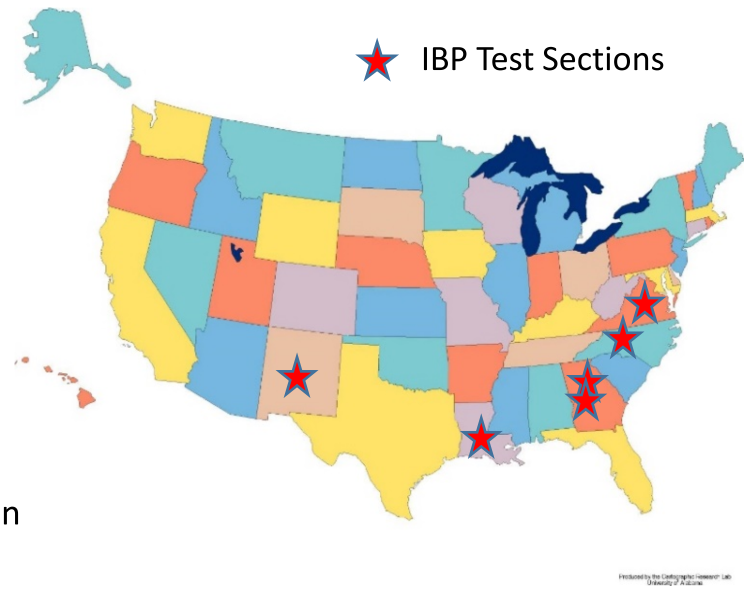
In Conclusion ....

Pooled fund study to leverage current knowledge to expedite implementation of IBP design specifications for US state DOT's.

GDOT Led Pooled-Fund Study:
Closing Sept 25, 2016
http://www.pooledfund.org/Details/Solicitation/1416



Objective:

- To expedite the implementation of inverted base pavement design specifications for state DoT's and to make IBP a practical and reliable alternative design approach for highway pavements.

Broad Tasks:

- Further study of existing field cases with detailed construction records and long-term performance monitoring data
- Advanced material characterization and modeling with emphasis on granular base
- Numerical simulation of IBP performance
- Relevant calibrations for design within framework of Mechanistic-Empirical Pavement design Guide (MEPDG)

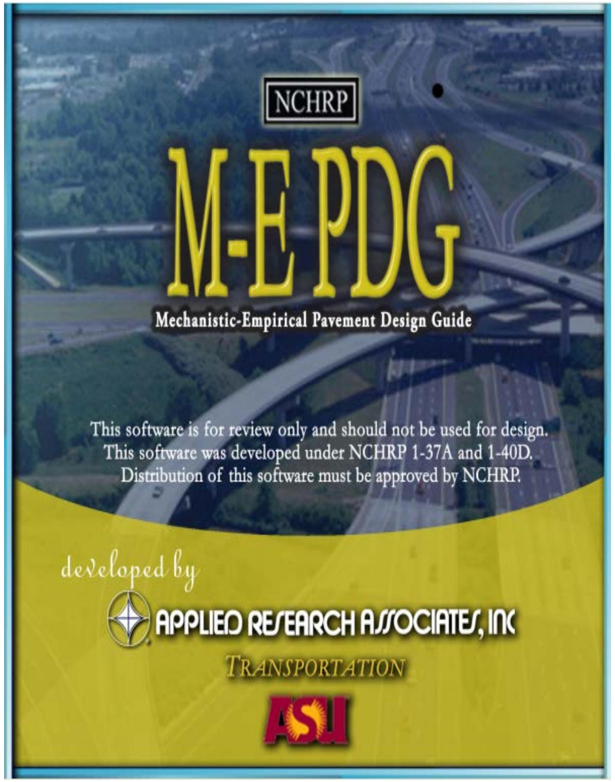
Pooled fund study to leverage current knowledge to expedite implementation of IBP design specifications for US state DOT's.

GAPS in knowledge:

- Improved understanding of IBP component performance, particularly of unbound granular base, through advanced material characterization and modeling
- Better understanding of relationship between construction and long-term performance of CTB, in particular, and IBP, in general, through continued assessment of test sections and associated numerical simulations

BARRIERS to implementation:

- Need for reliable framework for assessment of economics of IBP for both construction and performance stages
- Need for material model calibrations and damage functions suitable for IBP designs in MEPDG
- Guidelines for implementation through all phases of design, construction and maintenance



PROPOSED POOLED-FUND STUDY CAN RESOLVE GAPS AND ELIMINATE BARRIERS