Inverted Pavement

VULCAN MATERIALS COMPANY'S EXPERIENCE

What is an Inverted Pavement

2” to 3¼” HMA

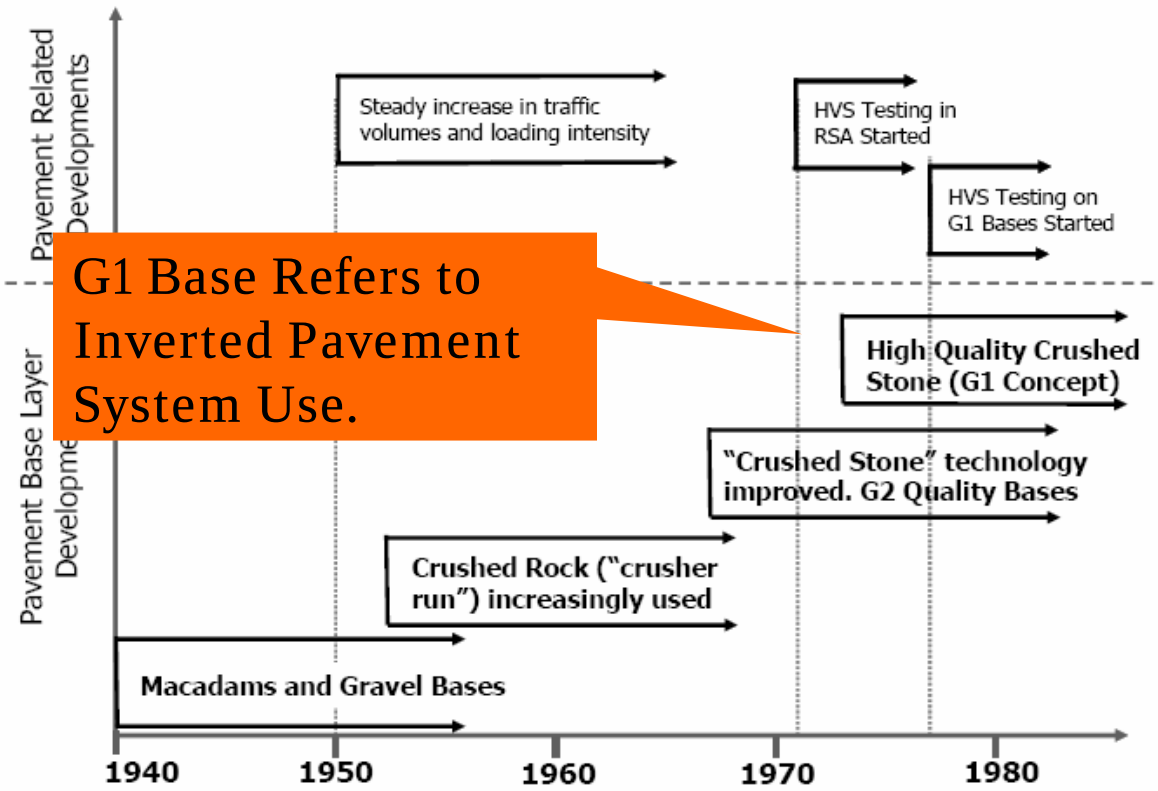
6” to 8” Unbound Aggregate Base Compacted to 100% + Modified Proctor

6” to 10” Cement-Treated Base (≈ 4% cement)

Prepared Subgrade

Inverted Pavement History

- Used successfully in South Africa since the 1970's



G1 Base Refers to Inverted Pavement System Use.

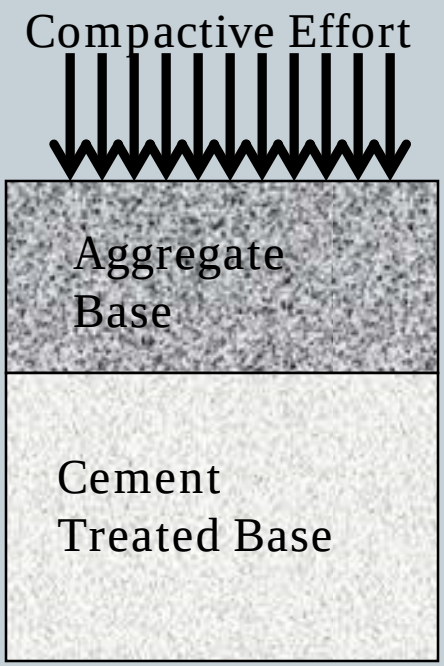
Figure 2: The evolution of unbound granular base pavements in South Africa

Inverted Pavement History

- Traffic levels increase
- US and Europe relied on thicker asphalt & increased concrete use
  - Not economically viable in South Africa
- Investigated ways to improve roads by improving the aggregate base
  - Instituted strict gradation limits
  - limited plasticity

Inverted Pavement History

- Wanted to improve/increase the density aggregate base
- Led to a cemented subbase being used as an “anvil” on which to compact the aggregate base
- Enables high level of compaction



Inverted Pavement History

- Soon discovered that this pavement
  - Could handle the highest traffic loads
  - Was impervious to water ingress
  - Performed well even when wet

- Decades of research have shown these pavements can be used on roads up to 50 to 100 million ESALs

Road (Pavement) Categories
South Africa

TABLE 1

Definition of the road categories

ROAD CATEGORY				
	A	B	C	D
Description	Major interurban freeways and major rural roads	Interurban collectors and rural roads	Lightly trafficked rural roads, strategic roads	Rural access roads
Importance	Very important	Important	Less important	Less important
Service level	Very high level of service	High level of service	Moderate level of service	Moderate to low level of service
TYPICAL PAVEMENT CHARACTERISTICS				
RISK	**Very low**	**Low**	**Medium**	**High**
Approximate Design Reliability (%) *	95	90	80	50
Total Equivalent Traffic Loading (E80/lane) **	$3 - 100 \times 10^6$ over 20 years	$0{,}3 - 10 \times 10^6$ Depending on design strategy	$< 3 \times 10^6$ Depending on design strategy	$< 1 \times 10^6$ Depending on design strategy

Structural Design of Flexible Pavements, Draft Technical Recommendation for Highways (TRH) 4, Pretoria, South Africa, 1996

Typical Pavement Structural Designs
South Africa

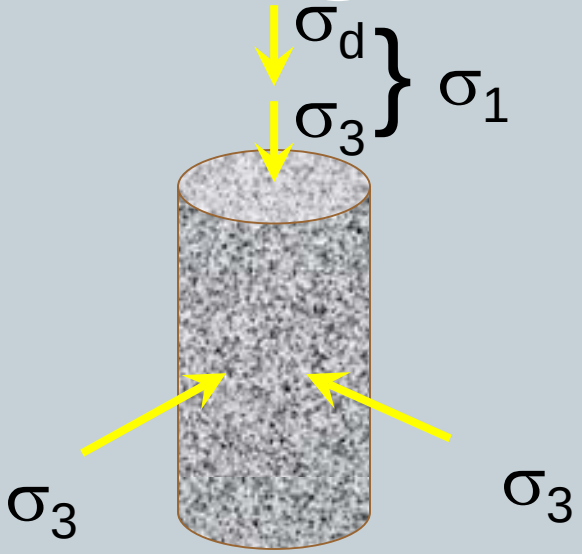
GRANULAR BASES (MODERATE OR DRY REGIONS) D

ROAD CAT.	PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)									
	ES0.003 < 3000	ES0.01 $0{,}3\text{-}1{,}0\times10^{4}$	ES0.03 $1{,}0\text{-}3{,}0\times10^{4}$	ES0.1 $3{,}0\text{-}10\times10^{4}$	ES0.3 $0{,}1\text{-}0{,}3\times10^{6}$	ES1 $0{,}3\text{-}1{,}0\times10^{6}$	ES3 $1{,}0\text{-}3{,}0\times10^{6}$	ES10 $3{,}0\text{-}10\times10^{6}$	ES30 $10\text{-}30\times10^{6}$	ES100 $30\text{-}100\times10^{6}$
A					1.5”		40A 125 G2 150 C3	40A 150 G2 250 C3	50A 150 G1 250 C3	50A 150 G1 300 C3
					6”		40A 150 G2 150 G5			
					10”					

ESALS	3M	10M	30M	100M

Structural Design of Flexible Pavements, Draft Technical Recommendation for Highways (TRH) 4, Pretoria, South Africa, 1996

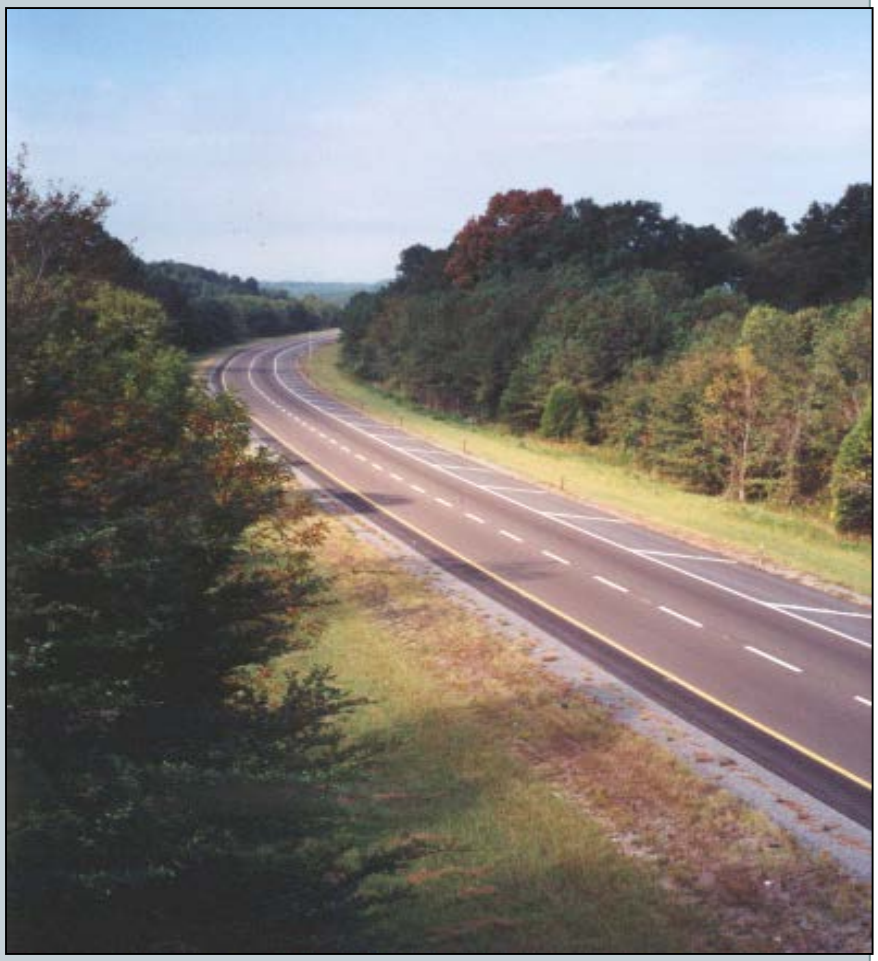
Mechanics of Inverted Pavement Systems



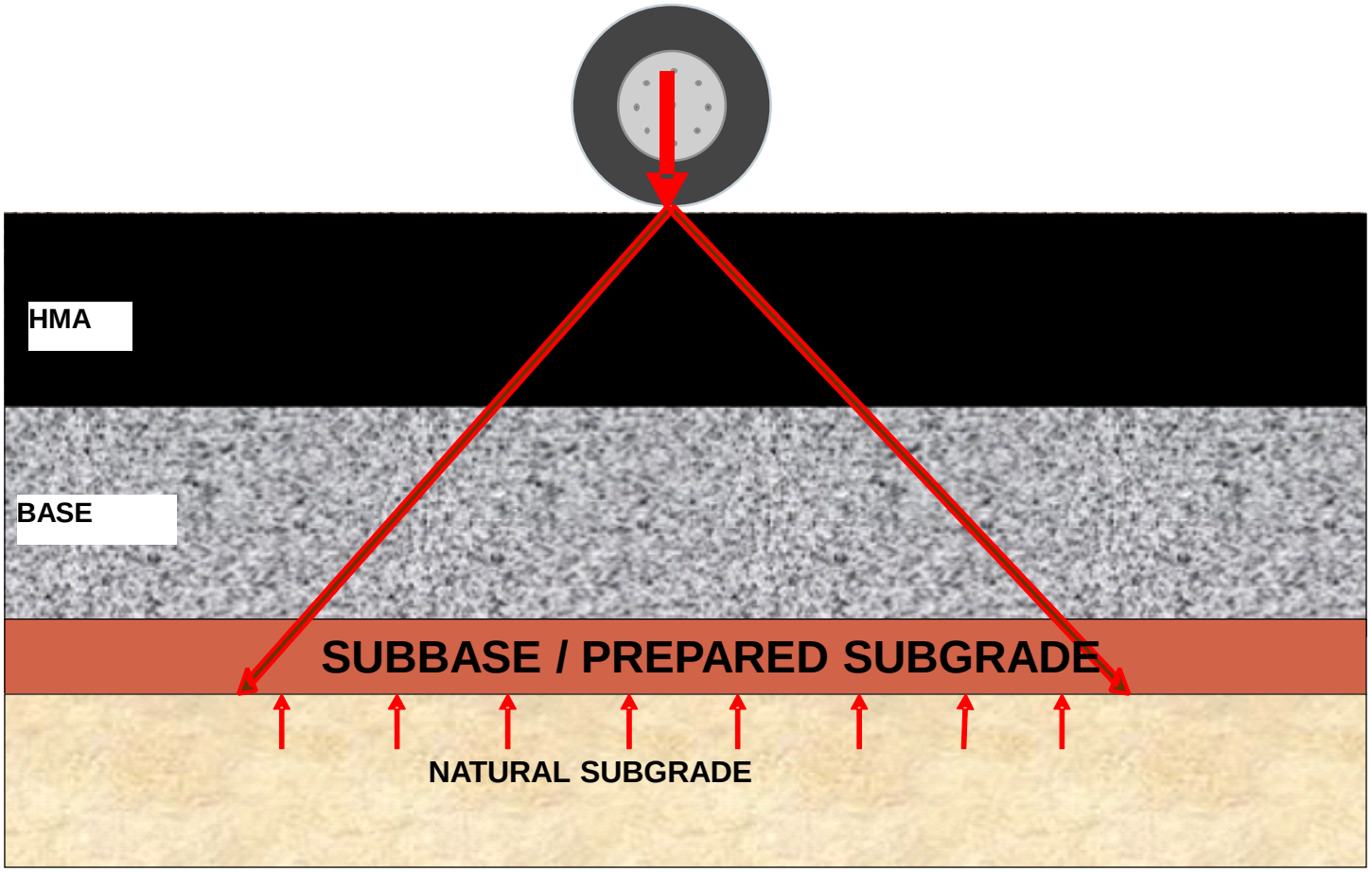
$$\theta = \sigma_1 + 2\sigma_3$$

Traditional Flexible Pavement System

- Successive stiffer layers from subgrade up
- Each layer “absorbs” the load as it’s distributed to subgrade
- Traditional designs put unbound aggregate base on top of subgrade
- Built on the idea of protecting the layer below



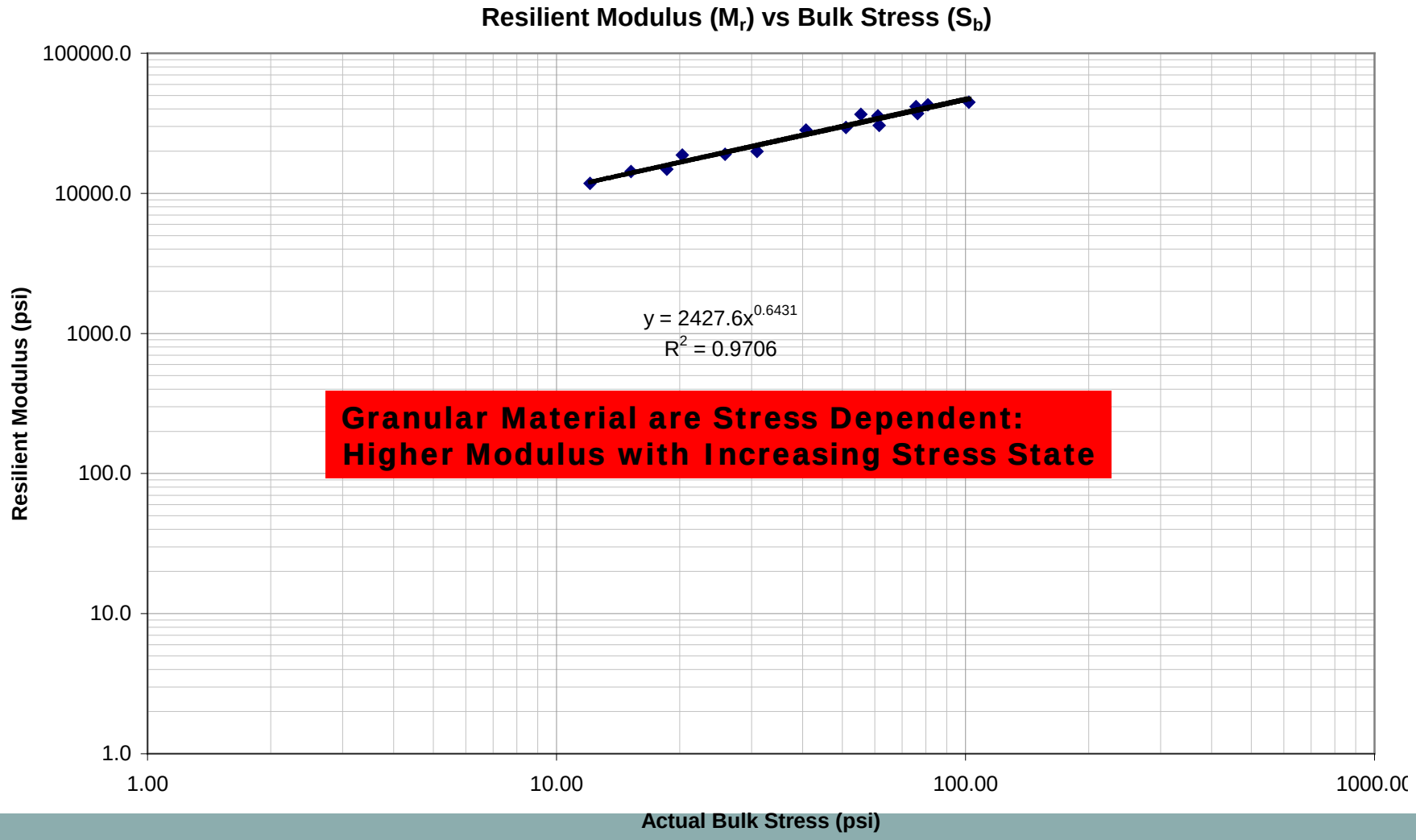
Flexible Pavement System



Inverted Pavement

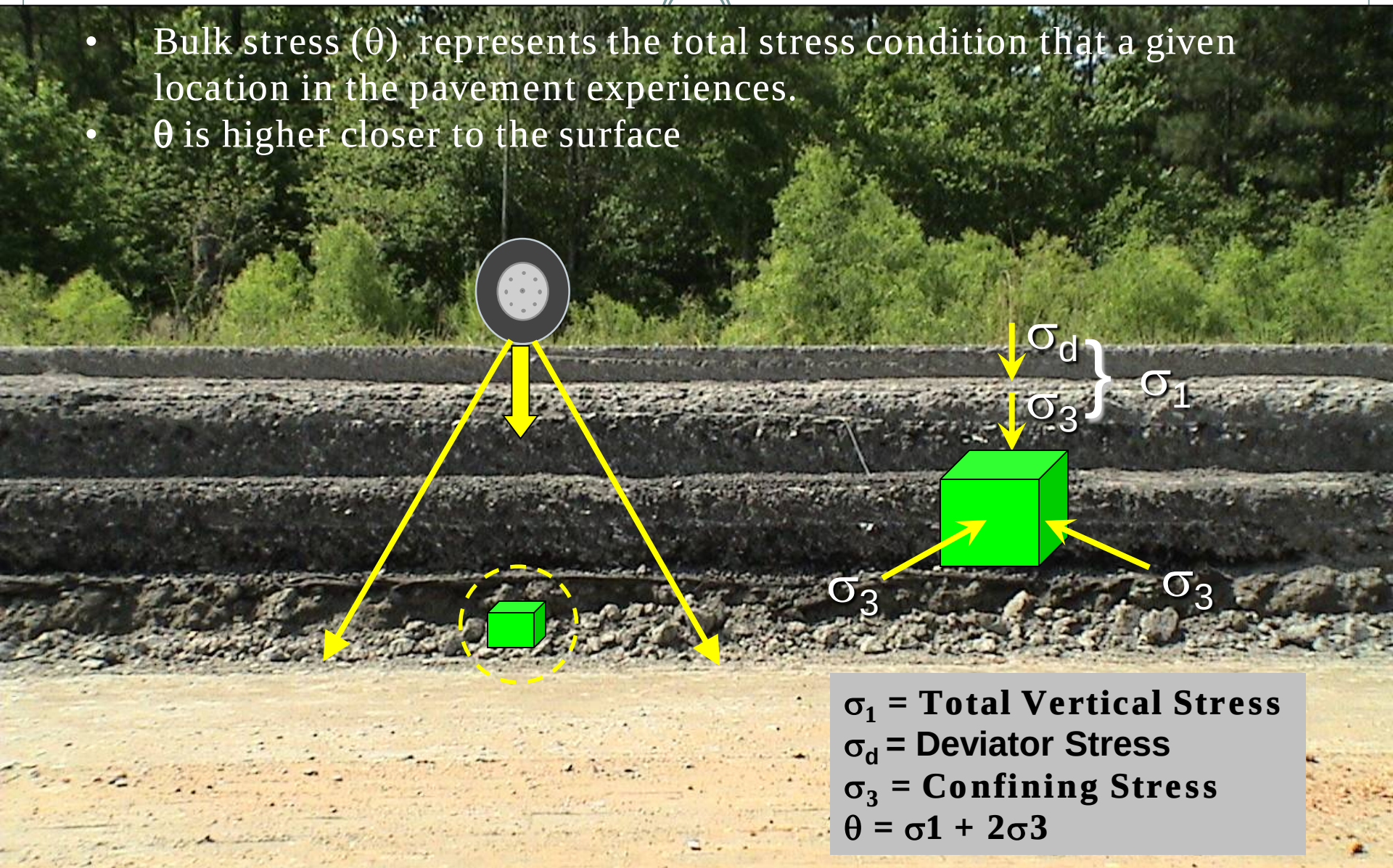
- Changes the way we think about pavement
- Utilizes the stress dependency of graded aggregate base

Resilient Modulus Stress Dependency



What is Bulk Stress?

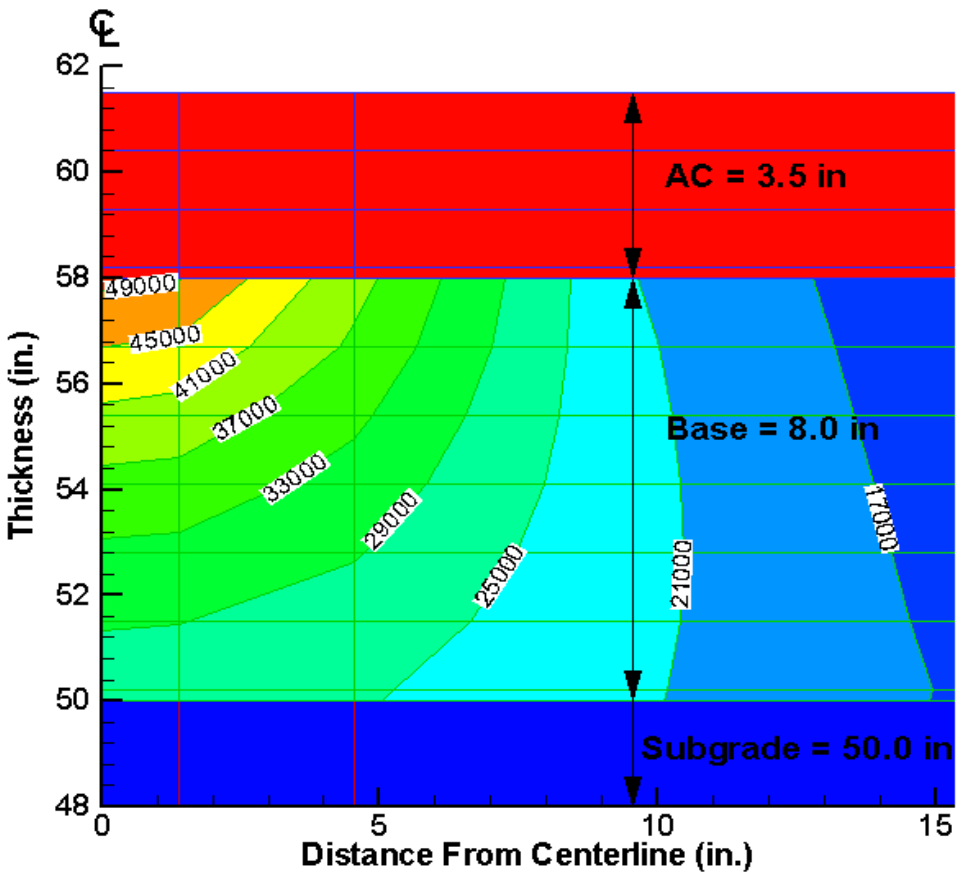
- Bulk stress (θ) represents the total stress condition that a given location in the pavement experiences.
- θ is higher closer to the surface



σ_1 = Total Vertical Stress
σ_d = Deviator Stress
σ_3 = Confining Stress
$\theta = \sigma 1 + 2\sigma 3$

Stress Dependency

- Higher stresses in unbound aggregate base result in increased stiffness and strength
- Value of the base is best captured when it is placed near the surface where stresses are the greatest
- Inverted pavement moves base to the top where it performs more efficiently



Credit: Erol Tutumluer

Inverted Flexible Pavement

2” to 3¼” HMA

6” to 8” Unbound Aggregate Base
Compacted to 100% + Modified Proctor

6” to 10” Cement-Treated Base
(≈ 4% cement)

Prepared Subgrade

Isn't This Asphalt Too Thin?

- The South African protocol uses very thin asphalt layers

ESALs (millions)

1-3 3-10 10-30 30-100

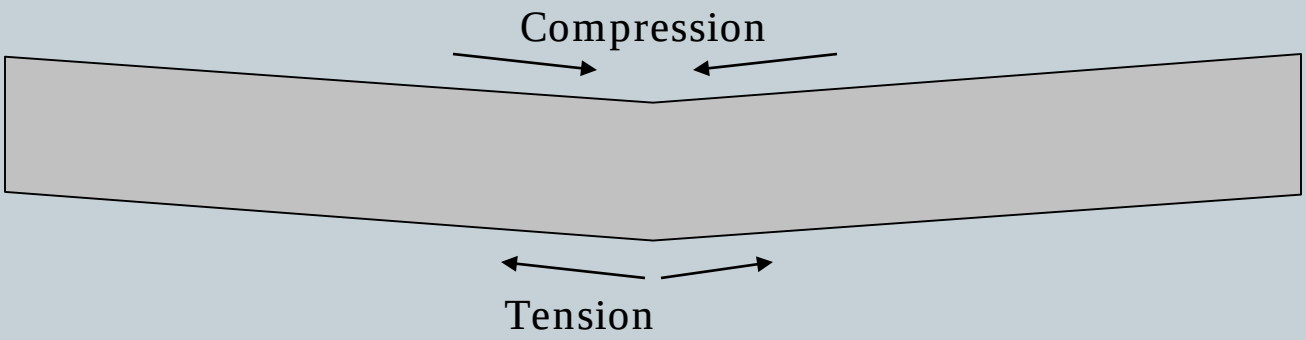
ROAD CAT.	ES0.003 < 3000	ES0.01 $0,3\text{-}1,0\times10^{4}$	ES0.03 $1,0\text{-}3,0\times10^{4}$	ES0.1 $3,0\text{-}10\times10^{4}$	ES0.3 $0,1\text{-}0,3\times10^{6}$	ES1 $0,3\text{-}1,0\times10^{6}$	ES3 $1,0\text{-}3,0\times10^{6}$	ES10 $3,0\text{-}10\times10^{6}$	ES30 $10\text{-}30\times10^{6}$	ES100 $30\text{-}100\times10^{6}$
A							40A 125 G2 150 C3 40A 150 G2 150 G5	40A 150 G2 250 C3	50A 150 G1 250 C3	50A 150 G1 300 C3

40mm = 1.6 in

50mm = 2 in

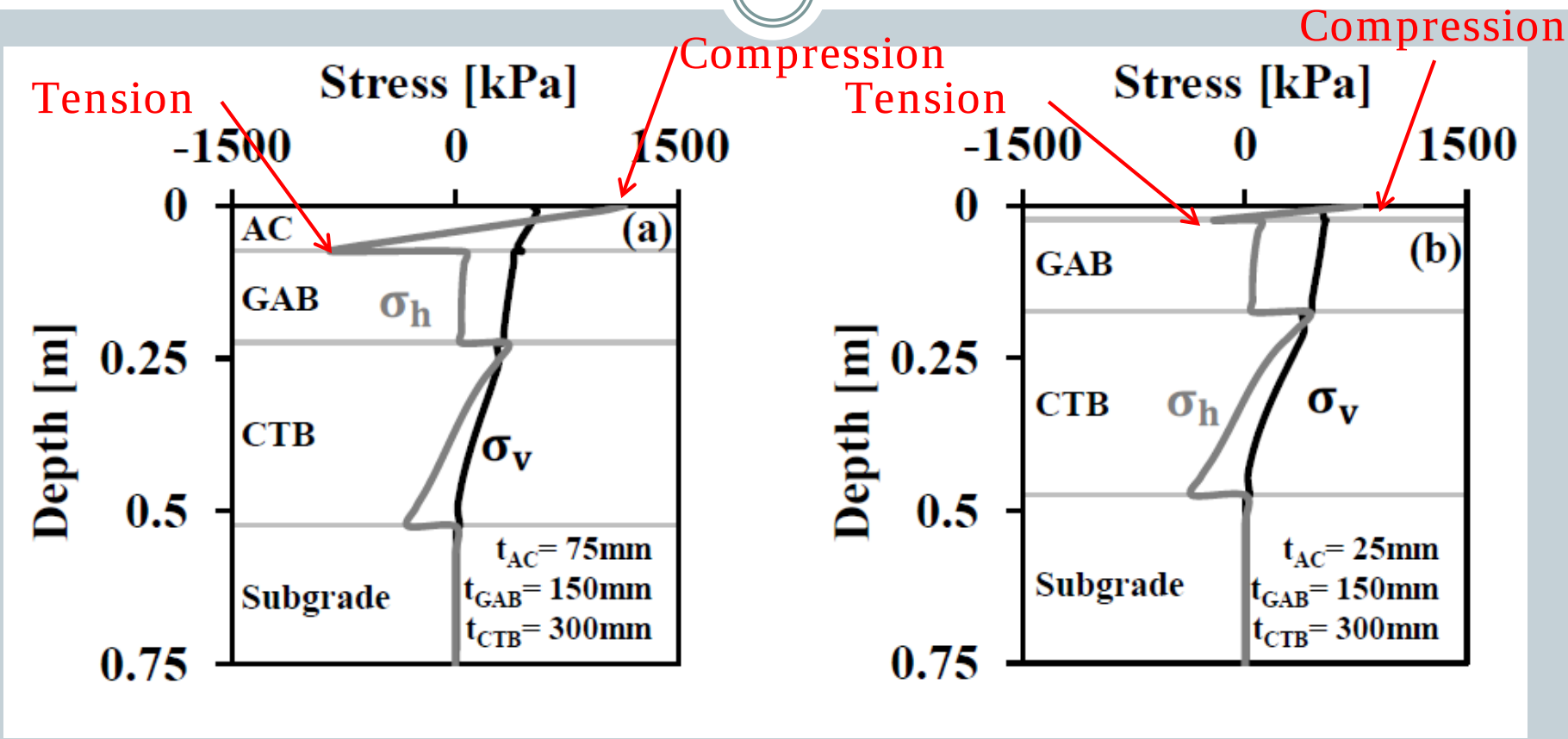
Recent Research

- Research at Georgia Tech on inverted systems
- Traditional pavement, asphalt acts like a beam



- Inverted pavement, thin asphalt performs like a membrane

Beam versus Membrane

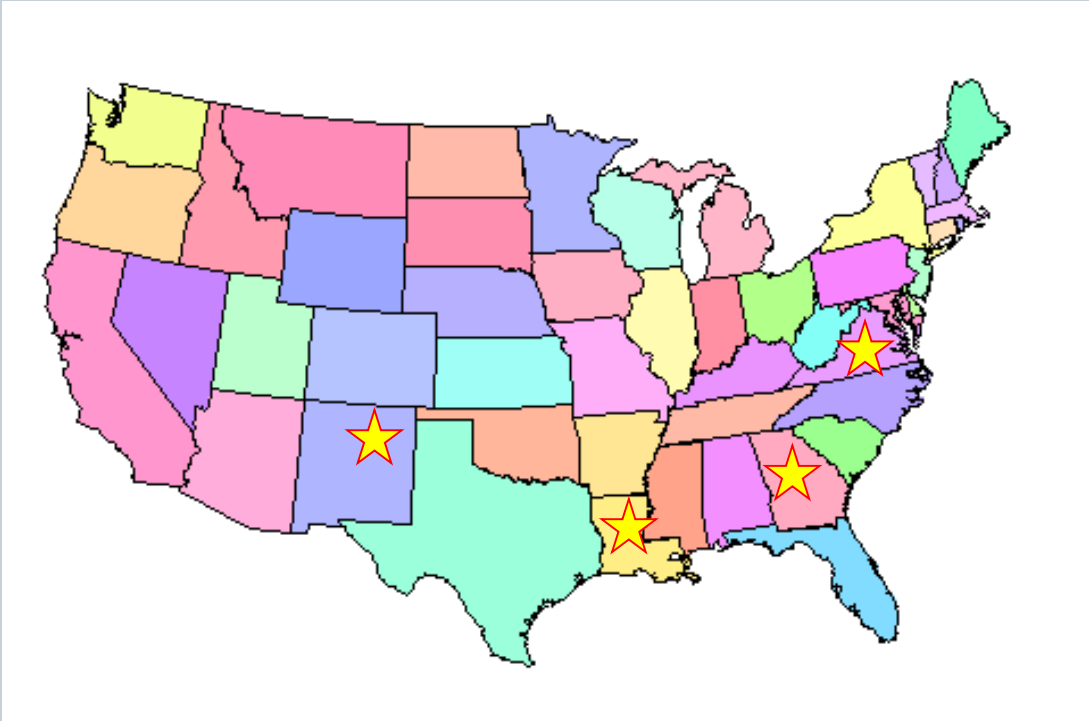


Source: Papadopoulos, "Performance of Unbound Aggregate Bases and Implications for Inverted Base Pavements", May 2014

Inverted Pavements

- CTB used as strong foundation
  - Anvil to compact aggregate base against
- Aggregate base placed in the optimal position
  - Near the surface
  - High stress increases stiffness
- Thin asphalt protects the aggregate base
  - Acts like a membrane
  - Reduced tension

Inverted Pavements in the U.S.



Morgan County Quarry Haul Road (GA)

Inverted Pavement Structure
GDOT Compaction Method (Typical)

Station 14+00 to 18+00

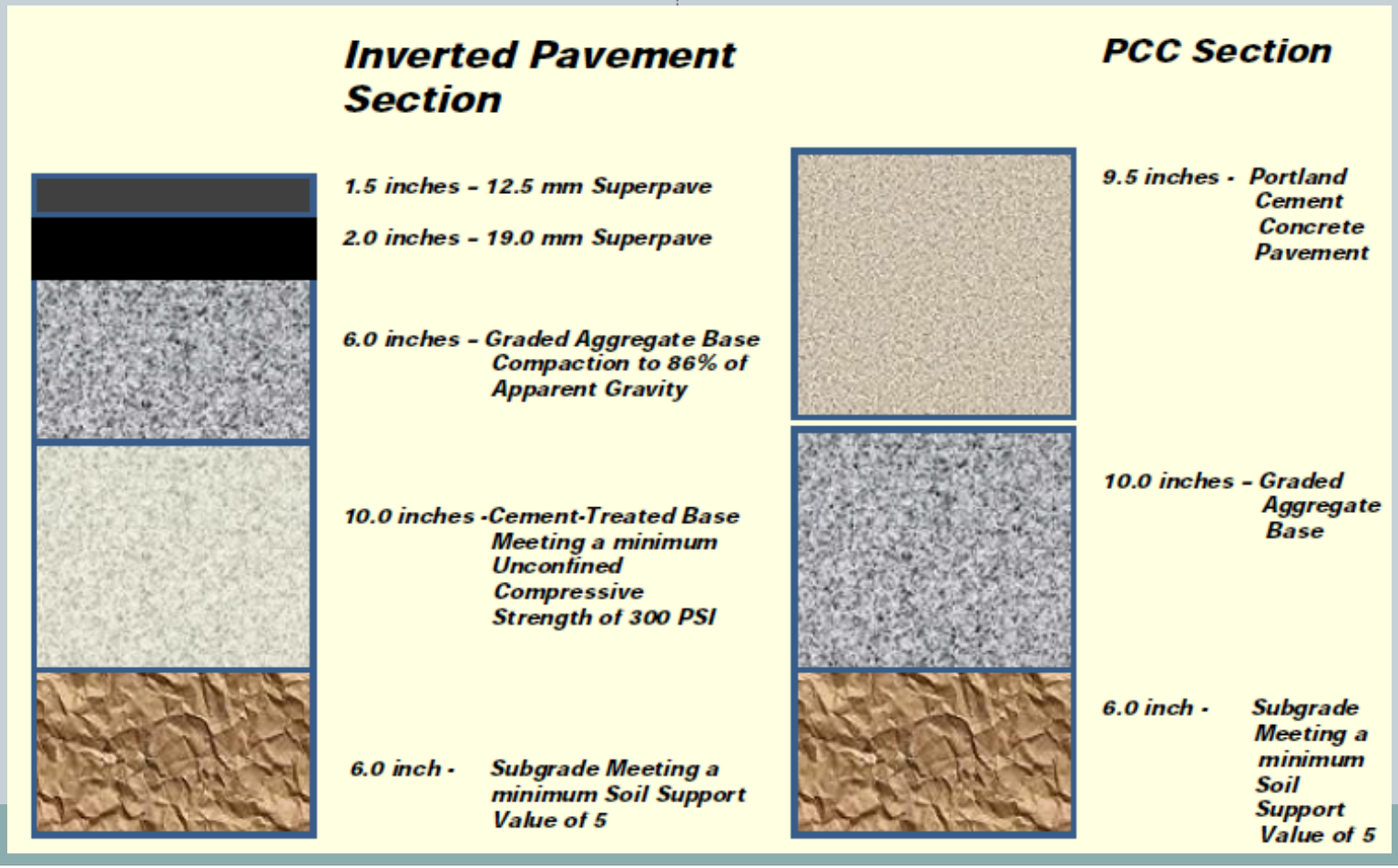
3.00 inches - Asphaltic Concrete Paving
6.00 inches - Graded Aggregate Base-Lafarge, Morgan Co.
86.4% of Apparent Density (145.2 PCF)
8.00 inches - Cement Treated Base
5% Type I Portland (145 psi to 435 psi)
2.00 inches - Graded Aggregate Base
(filler)

Prepared Subgrade
Minimum CBR Value of 15

- Constructed in 2003
- Still performing well

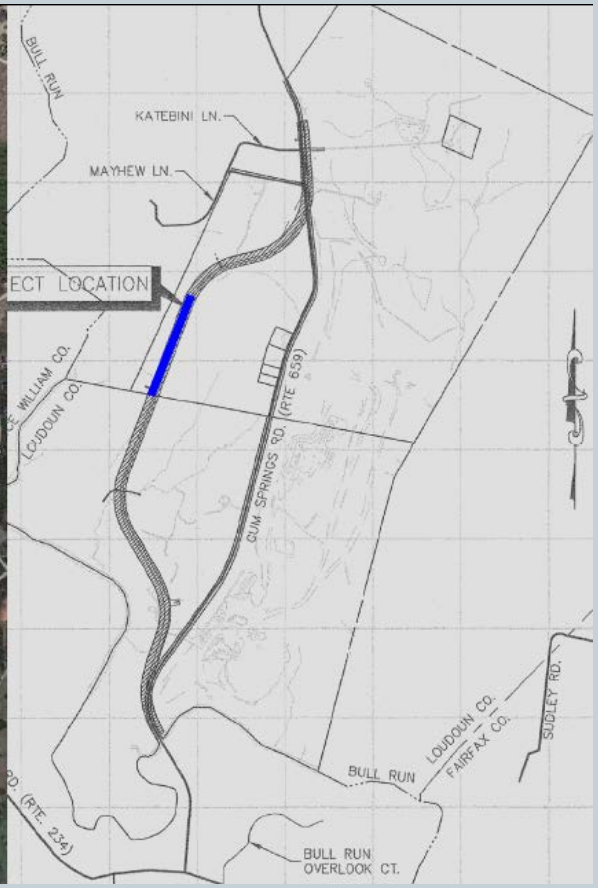
LaGrange Bypass, GA

- Constructed in 2009



Luck Stone, Bull Run Quarry, VA

- Constructed in 2011
- FHWA participating
  - Installed pressure and strain gauges
- Still gathering data



I-25 in Northern New Mexico

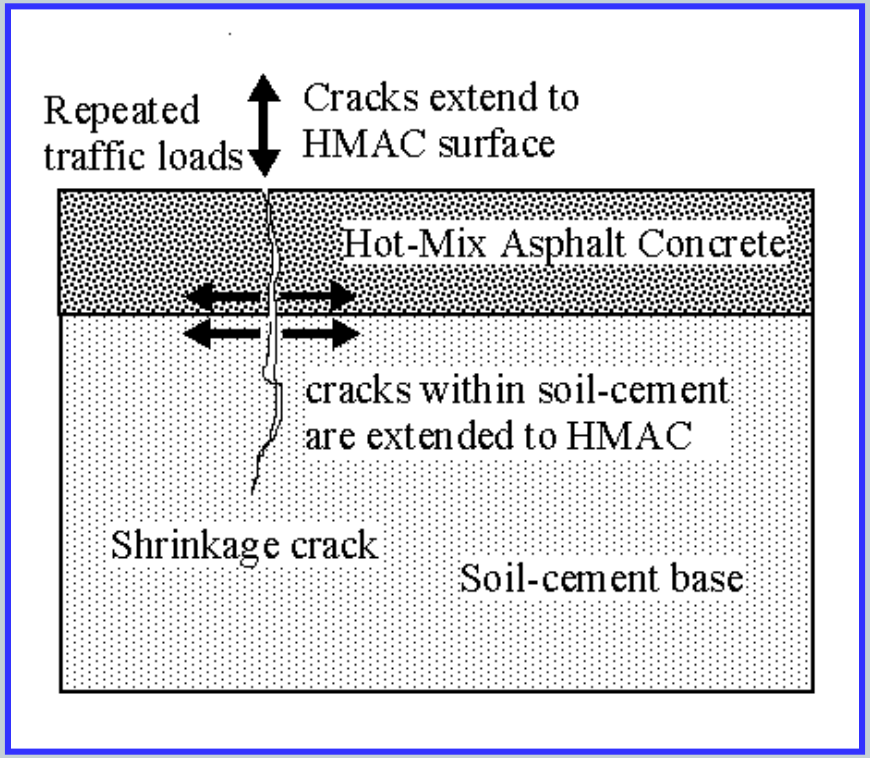
- Interstate 25, Raton, NM
- 54+ inches of snow per year
- Constructed in 2012

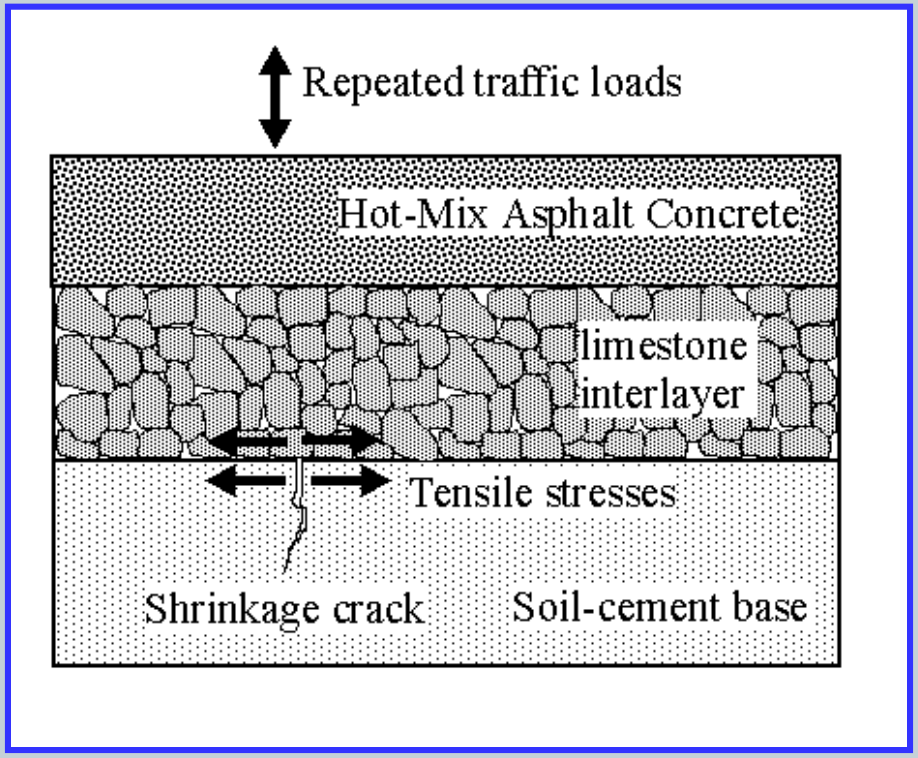
3” HMA

8” Aggregate Base

10” Cement-Treated Base

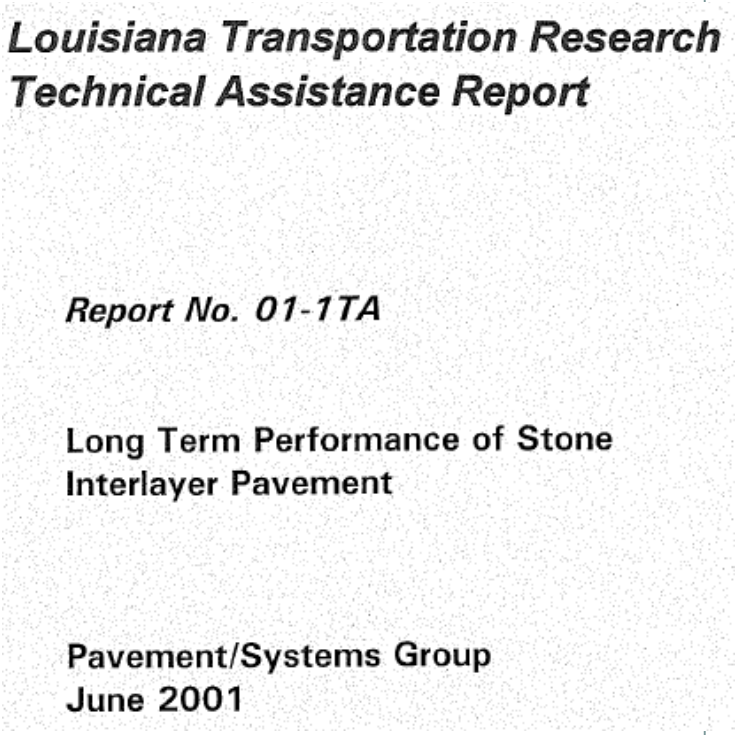
Louisiana DOT Stone Interlayer Pavements





Inverted Pavement Performance

- Louisiana DOTD Field Evaluation Project 97 constructed in 1991
  - Inverted: 3.5” HMA / 4” crushed limestone / 6” of soil cement base
  - Control: 3.5” HMA / 8.5” soil cement base
  - 10 year evaluation showed almost 50 percent reduction in cracking versus typical flexible section
- Accelerated pavement testing
  - Stone interlayer (inverted) pavement carried over four times the ESALs of the conventional pavement lane before failure.
- Louisiana DOTD adopted stone interlayer base course (inverted) design as a standard option.


Louisiana Transportation Research
Technical Assistance Report

Report No. 01-1TA

Long Term Performance of Stone Interlayer Pavement

Pavement/Systems Group
June 2001

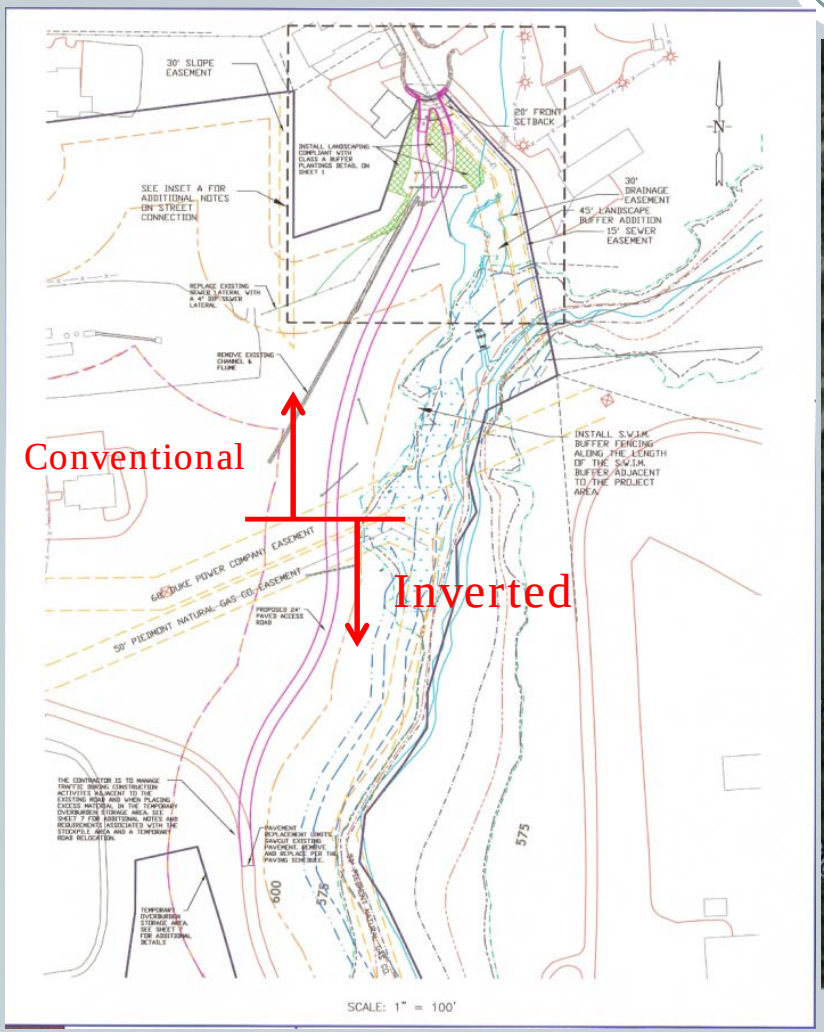
Vulcan's Inverted Pavement

- Need to relocate a road in our Pineville Quarry near Charlotte, NC
- Great opportunity for an inverted pavement
  - New road was long enough for a test section and control section
  - Cement silo and pugmill on site at the quarry

Road Relocation

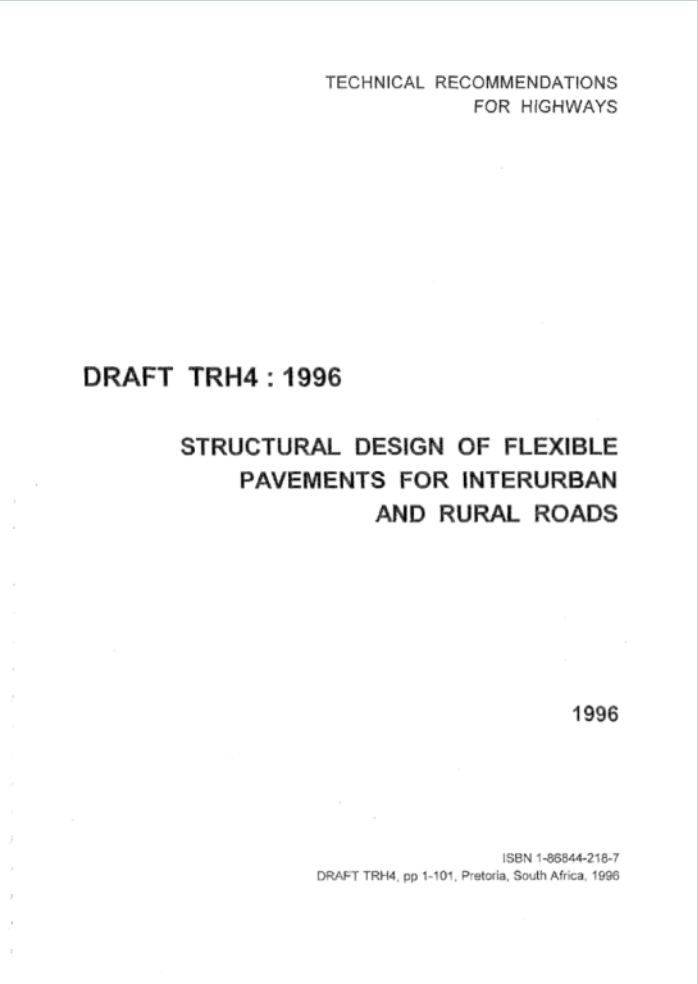
Road Relocation

Road Relocation



Pavement Design

- Estimate 1.5 to 2 million ESALs over 20 years based on sales forecast
- Used South Africa Department of Transport TRH 4 to develop a pavement design



TECHNICAL RECOMMENDATIONS
FOR HIGHWAYS

DRAFT TRH4 : 1996

STRUCTURAL DESIGN OF FLEXIBLE
PAVEMENTS FOR INTERURBAN
AND RURAL ROADS

1996

ISBN 1-86844-218-7
DRAFT TRH4, pp 1-101, Pretoria, South Africa, 1996

Pavement Design

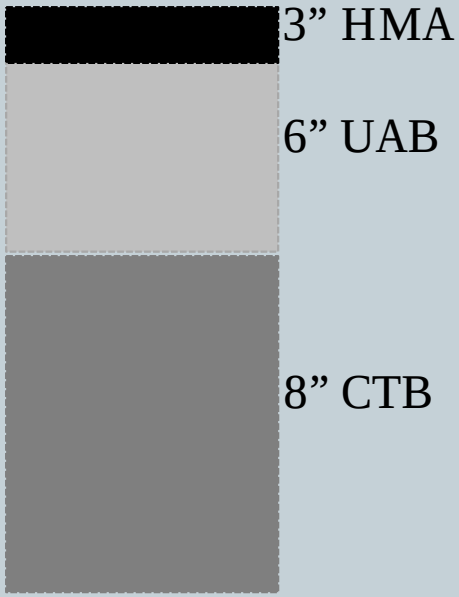
GRANULAR BASES (WET REGIONS) DATE 1996

ROAD CAT.	PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)										Foundation
	ES0.003 < 3000	ES0.01 $0,3\text{-}1,0\times10^4$	ES0.03 $1,0\text{-}3,0\times10^4$	ES0.1 $3,0\text{-}10\times10^4$	ES0.3 $0,1\text{-}0,3\times10^6$	ES1 $0,3\text{-}1,0\times10^6$	ES3 $1,0\text{-}3,0\times10^6$	ES10 $3,0\text{-}10\times10^6$	ES30 $10\text{-}30\times10^6$	ES100 $30\text{-}100\times10^6$	
A							30A 150 G1** 200 C3	40A 150 G1 300 C3 *(250 C3)	50A 150 G1 400 C3 *(300 C3)		

1.18 in Asphalt
6 in ABC
7.87 in CTB

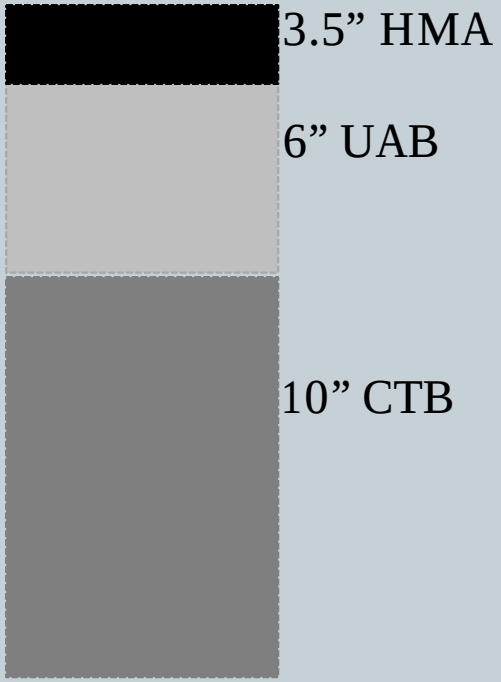
Other Inverted Designs in U.S.

Morgan, GA



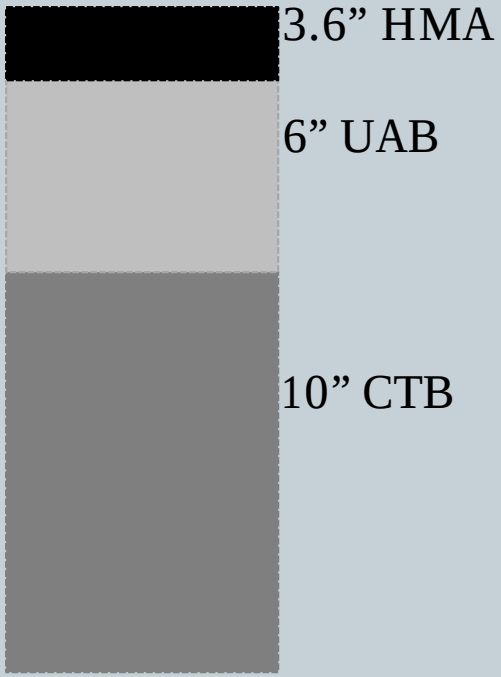
Subgrade mixed with UAB

LaGrange, GA



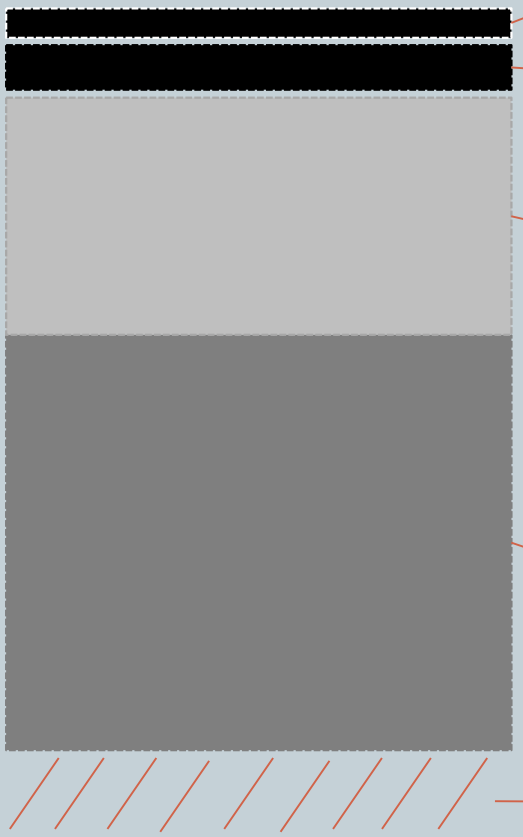
Subgrade mixed with UAB

Raton, NM



Cement Stabilized Subgrade

Pineville Inverted Pavement Design



1" NCDOT SF9.5A with PG 64-22

1.5" NCDOT S9.5B with PG 64-22

6" NCDOT Aggregate Base (102% modified proctor)

8" NCDOT Cement Treated Aggregate Base (97% modified proctor)

Subgrade (100% standard proctor)

Subgrade

Cement Treated Base -- Design

- Used a typical NCDOT Aggregate Base Course (ABC)
- 2% cement
- 7 day compressive strength: 550 psi

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT
1.5	100	100
1	94	75 - 97
0.75	82	
0.5	64	55 - 80
#4	42	35 - 55
#10	31	25 - 45
#40	20	14 - 30
#200	9	4 - 12

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

Cement Treated Base

- Density averaged 99.2% of modified proctor
- Sprayed with emulsified asphalt tack coat
- Allowed to cure for 7 days
- Final strength averaged 1,560 psi

Unbound Aggregate Base

- Used standard NCDOT Aggregate Base Course
- Required 102% modified proctor
  - Proctor: 153.8 pcf @ 5.3% moisture
  - Target: 156.9 pcf
  - Pineville Apparent SG: 2.95
  - Target: 85% of Apparent

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT
1.5	100	100
1	94	75 - 97
0.75	82	
0.5	64	55 - 80
#4	42	35 - 55
#10	31	25 - 45
#40	20	14 - 30
#200	9	4 - 12

Unbound Aggregate Base

Unbound Aggregate Base

Unbound Aggregate Base

Unbound Aggregate Base

Unbound Aggregate Base

- Compacted the UAB on the conventional section and the inverted section at the 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

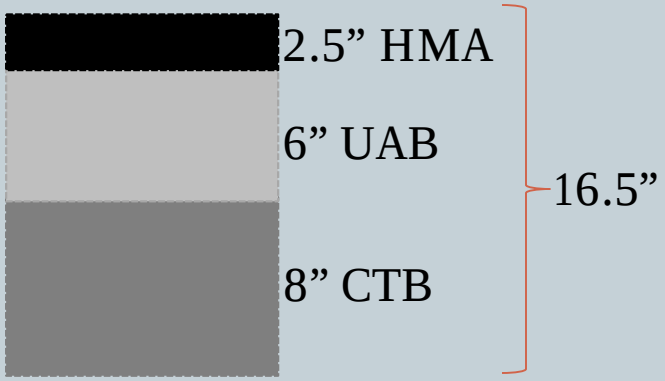
- Normal HMA construction in accordance with NCDOT
  - 1.5” 9.5mm B mix
  - 1” 9.5mm A mix as final lift

Final Density Comparison

- Achieved better density on all layers of inverted pavement
- Shows the importance of a good foundation in compaction

Final Pavement Sections

Inverted

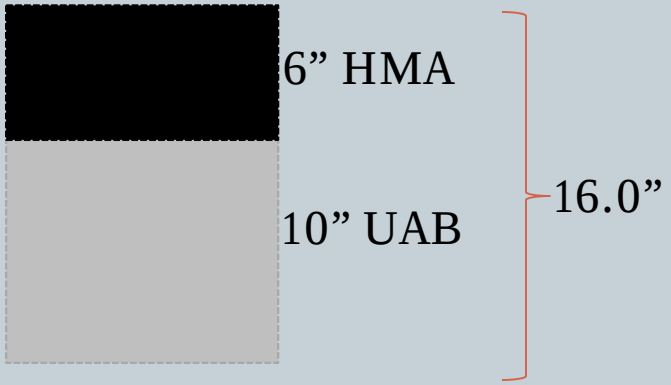


SN = 3.78

$35.92/SY

11.3% Less Expensive than Conventional

Conventional

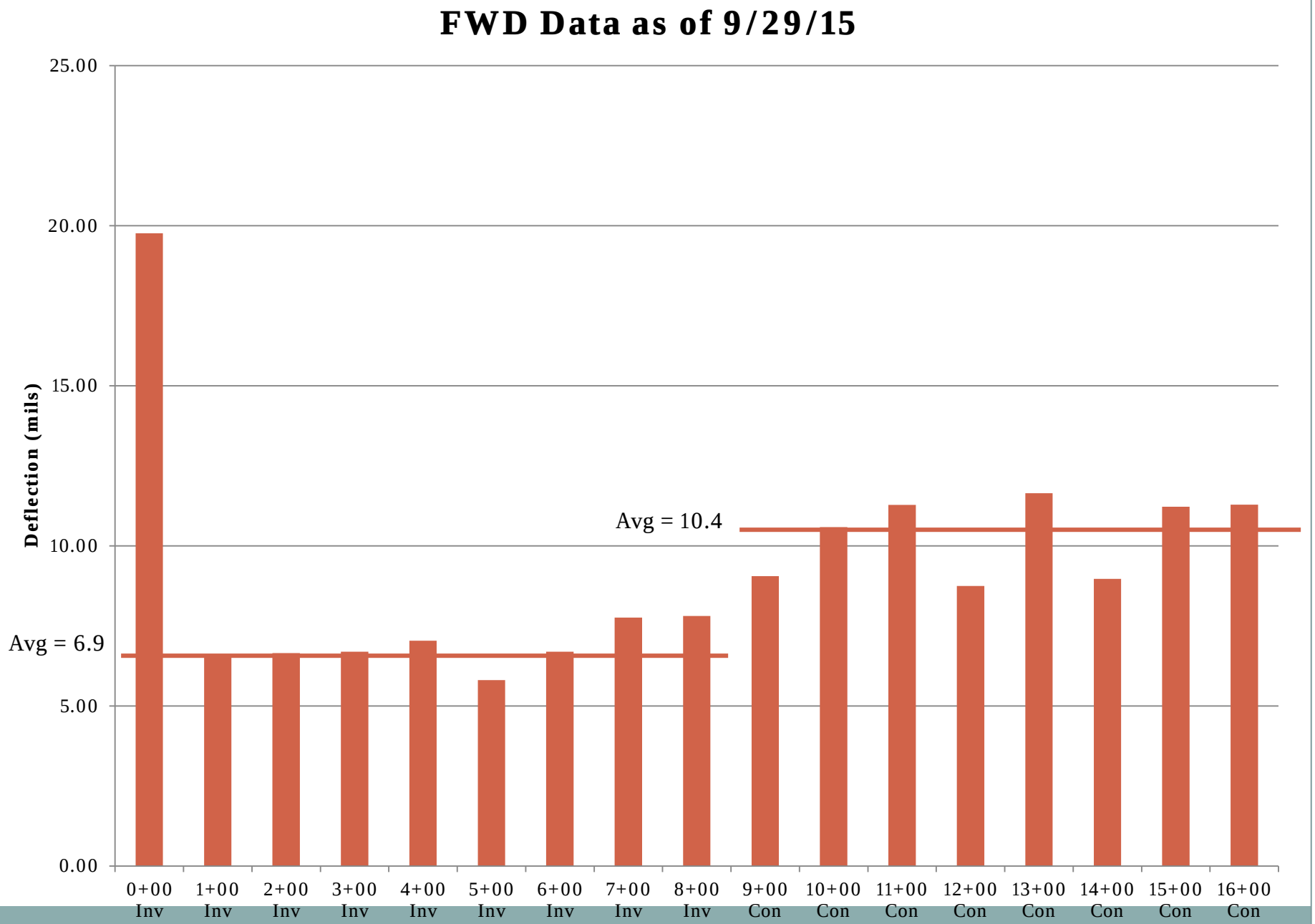


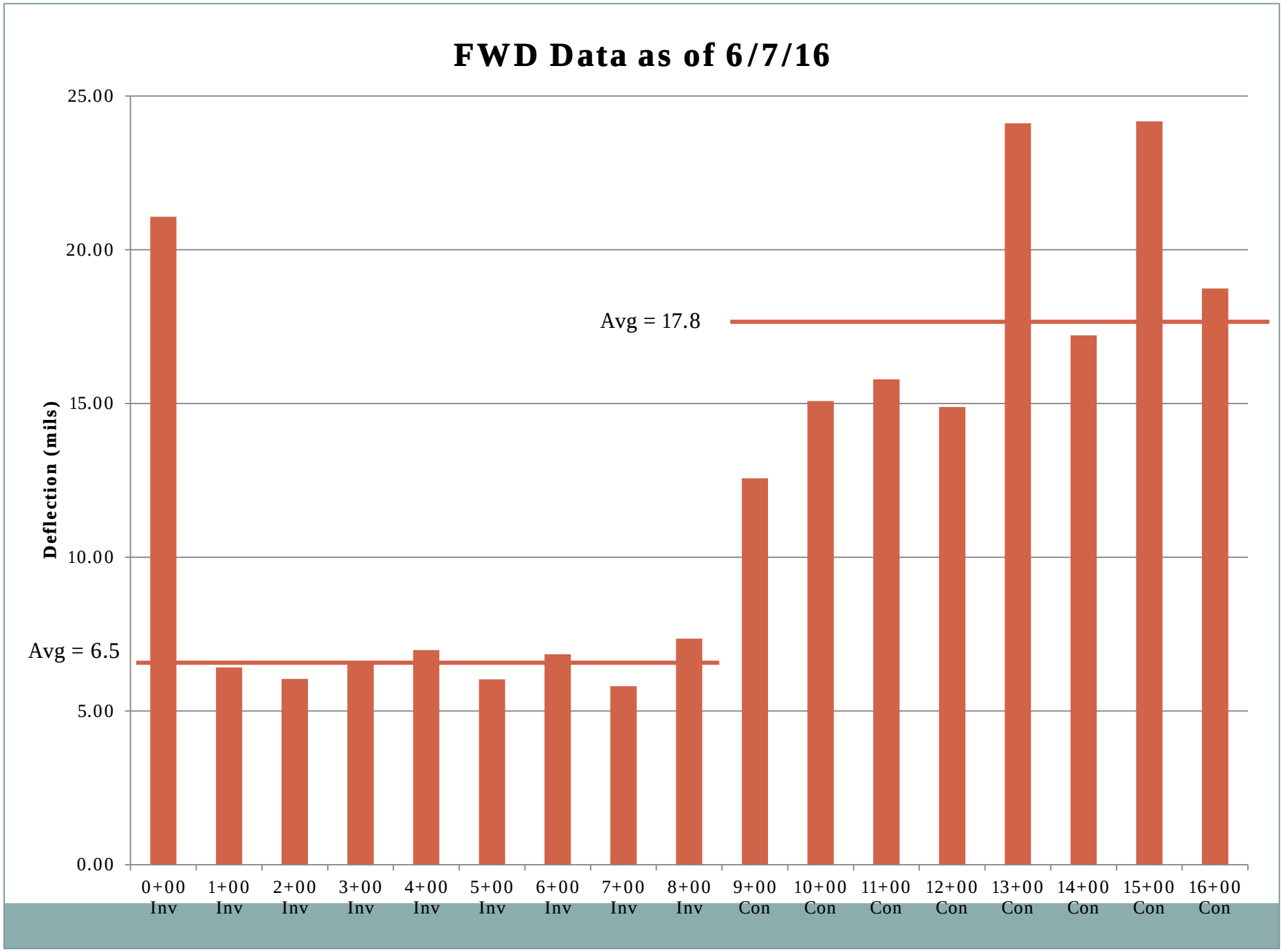
SN = 4.04

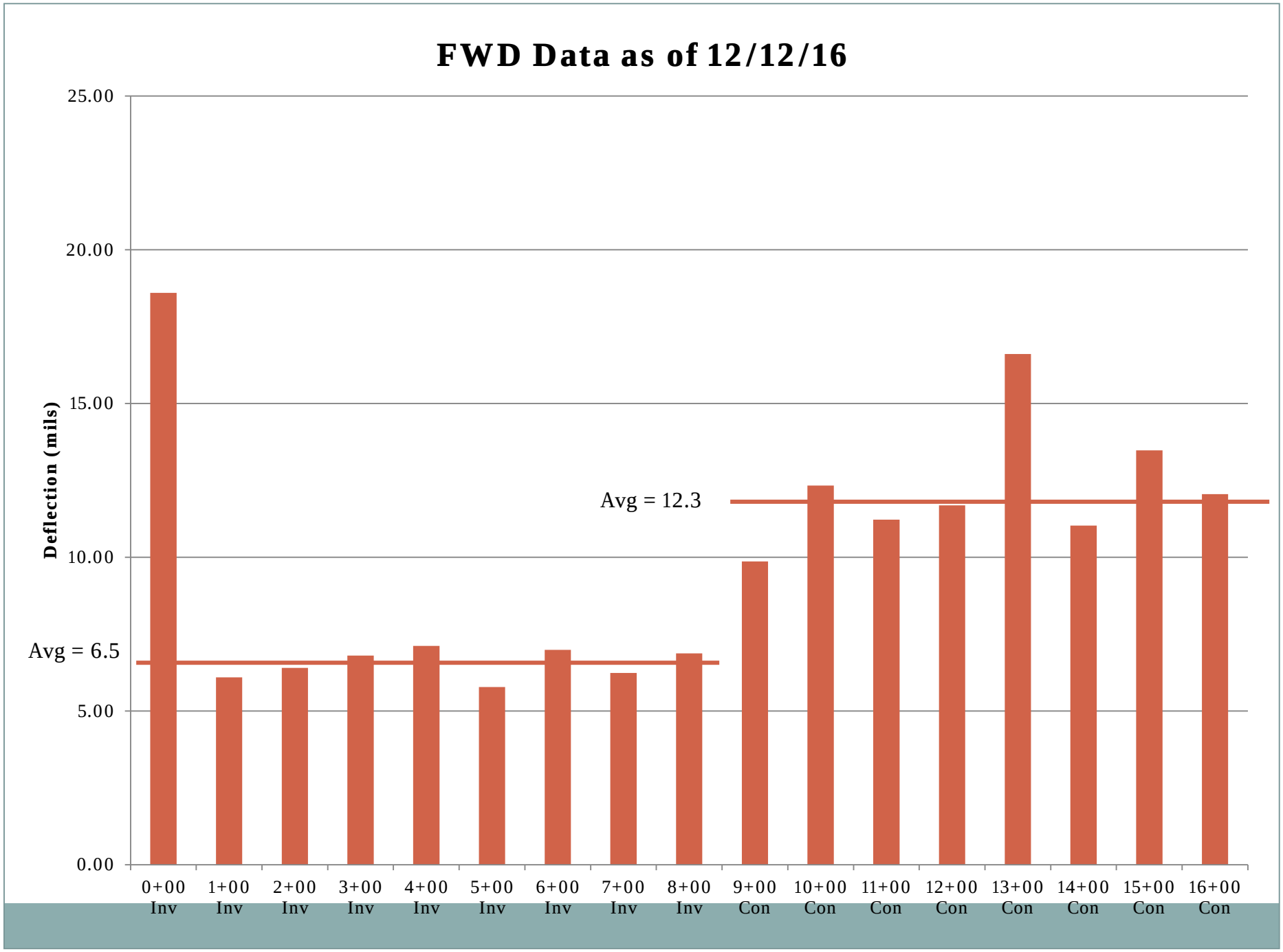
$40.51/SY

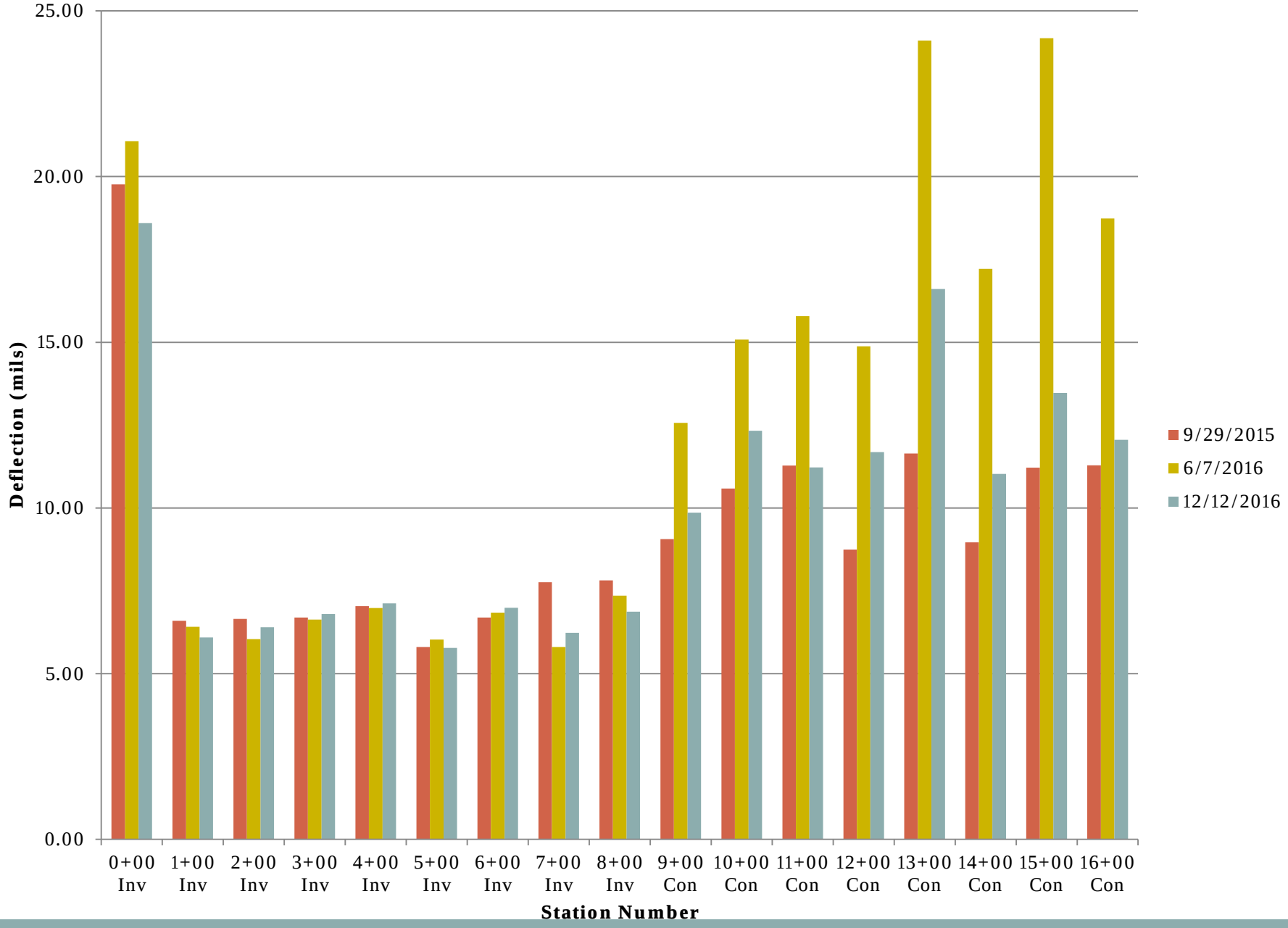
Falling Weight Deflectometer Testing

- NCDOT Performing FWD Testing periodically
  - September 2015
  - June 2016
  - December 2016


FWD Data as of 9/29/15
Deflection (mils)
25.00
20.00
15.00
10.00
5.00
0.00
Avg = 6.9
Avg = 10.4
0+00 Inv
1+00 Inv
2+00 Inv
3+00 Inv
4+00 Inv
5+00 Inv
6+00 Inv
7+00 Inv
8+00 Inv
9+00 Con
10+00 Con
11+00 Con
12+00 Con
13+00 Con
14+00 Con
15+00 Con
16+00 Con


FWD Data as of 6/7/16
Deflection (mils)
25.00
20.00
15.00
10.00
5.00
0.00
Avg = 6.5
Avg = 17.8
0+00 Inv
1+00 Inv
2+00 Inv
3+00 Inv
4+00 Inv
5+00 Inv
6+00 Inv
7+00 Inv
8+00 Inv
9+00 Con
10+00 Con
11+00 Con
12+00 Con
13+00 Con
14+00 Con
15+00 Con
16+00 Con


FWD Data as of 12/12/16
Deflection (mils)
25.00
20.00
15.00
10.00
5.00
0.00
Avg = 6.5
Avg = 12.3
0+00 Inv
1+00 Inv
2+00 Inv
3+00 Inv
4+00 Inv
5+00 Inv
6+00 Inv
7+00 Inv
8+00 Inv
9+00 Con
10+00 Con
11+00 Con
12+00 Con
13+00 Con
14+00 Con
15+00 Con
16+00 Con


25.00
20.00
15.00
10.00
5.00
0.00
Deflection (mils)
0+00 Inv
1+00 Inv
2+00 Inv
3+00 Inv
4+00 Inv
5+00 Inv
6+00 Inv
7+00 Inv
8+00 Inv
9+00 Con
10+00 Con
11+00 Con
12+00 Con
13+00 Con
14+00 Con
15+00 Con
16+00 Con
Station Number
9/29/2015
6/7/2016
12/12/2016

Conclusions to Date

- Inverted Pavement relatively easy to construct
  - No changes in techniques to achieve higher density levels
- Inverted Pavement results in stiffer pavement than similar conventional section
- Inverted Pavement approximately 11% less expensive than conventional pavement
- Stronger pavement at lower cost

Questions

KEVIN VAUGHAN
VULCAN MATERIALS COMPANY
VAUGHANK@VMCMAIL.COM