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

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

<table>
<thead>
<tr>
<th>ROAD CATEGORY</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Major interurban freeways and major rural roads</td>
<td>Interurban collectors and rural roads</td>
<td>Lightly trafficked rural roads, strategic roads</td>
<td>Rural access roads</td>
</tr>
<tr>
<td>Importance</td>
<td>Very important</td>
<td>Important</td>
<td>Less important</td>
<td>Less important</td>
</tr>
<tr>
<td>Service level</td>
<td>Very high level of service</td>
<td>High level of service</td>
<td>Moderate level of service</td>
<td>Moderate to low level of service</td>
</tr>
</tbody>
</table>

### Typical Pavement Characteristics

<table>
<thead>
<tr>
<th>RISK</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate Design Reliability (%) *</td>
<td>95</td>
<td>90</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Total Equivalent Traffic Loading (E80/lane) **</td>
<td>3 - $10^6$ over 20 years</td>
<td>0.3 - $10^6$ depending on design strategy</td>
<td>$&lt; 3 \times 10^5$ depending on design strategy</td>
<td>$&lt; 1 \times 10^6$ depending on design strategy</td>
</tr>
</tbody>
</table>

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### Typical Pavement Structural Designs

**South Africa**

#### Granular Bases (Moderate or Dry Regions)

<table>
<thead>
<tr>
<th>ROAD CAT</th>
<th>ES0.003</th>
<th>ES0.01</th>
<th>ES0.03</th>
<th>ES0.1</th>
<th>ES0.3</th>
<th>ES1</th>
<th>ES3</th>
<th>ES10</th>
<th>ES30</th>
<th>ES100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 3000</td>
<td>0,3-1,0x10^4</td>
<td>1,0-3,0x10^4</td>
<td>3,0-10x10^4</td>
<td>0,1-0,3x10^6</td>
<td>1,0-3,0x10^6</td>
<td>3,0-10x10^6</td>
<td>10-30x10^6</td>
<td>30-100x10^6</td>
<td>300-1000x10^6</td>
</tr>
<tr>
<td>A</td>
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</tbody>
</table>

- ESALS
- 3M
- 10M
- 30M
- 100M

<table>
<thead>
<tr>
<th></th>
<th>1.5”</th>
<th>6”</th>
<th>10”</th>
</tr>
</thead>
<tbody>
<tr>
<td>40A</td>
<td>125 G2</td>
<td>150 C2</td>
<td>250 C3</td>
</tr>
<tr>
<td>40A</td>
<td></td>
<td>150 G2</td>
<td>250 C3</td>
</tr>
<tr>
<td>50A</td>
<td></td>
<td></td>
<td>300 C3</td>
</tr>
</tbody>
</table>

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

- NATURAL SUBGRADE
- BASE
- HMA
- SUBBASE / PREPARED SUBGRADE
- NATURAL SUBGRADE
Inverted Pavement

- Changes the way we think about pavement
- Utilizes the stress dependency of graded aggregate base
Granular Material are Stress Dependent: Higher Modulus with Increasing Stress State

Resilient Modulus Stress Dependency

\[ y = 2427.6x^{0.6431} \]

\[ R^2 = 0.9706 \]
What is Bulk Stress?

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

\[
\begin{align*}
\sigma_1 &= \text{Total Vertical Stress} \\
\sigma_d &= \text{Deviator Stress} \\
\sigma_3 &= \text{Confining Stress} \\
\theta &= \sigma_1 + 2\sigma_3
\end{align*}
\]
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

<table>
<thead>
<tr>
<th>ROAD CAT.</th>
<th>ES0.003 &lt; 3000</th>
<th>ES0.01 0.3-1x10⁴</th>
<th>ES0.03 1.0-3x10⁴</th>
<th>ES0.1 3.0-10x10⁴</th>
<th>ES0.3 0.1-0.3x10⁶</th>
<th>ES1 0.3-1x10⁶</th>
<th>ES3 1.0-3x10⁶</th>
<th>ES10 3.0-10x10⁶</th>
<th>ES30 10-30x10⁶</th>
<th>ES100 30-100x10⁶</th>
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- ESALs (millions)
  - 1-3
  - 3-10
  - 10-30
  - 30-100

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
Morgan County Quarry Haul Road (GA)

Inverted Pavement Structure
GDOT Compaction Method (Typical)

Station 14+00 to 18+00

- 3.00 inches - Asphalitic 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

Inverted Pavement Section
- 1.5 inches - 12.5 mm Superpave
- 2.0 inches - 19.0 mm Superpave
- 6.0 inches - Graded Aggregate Base Compaction to 86% of Apparent Gravity
- 10.0 inches - Cement-Treated Base Meeting a minimum Unconfined Compressive Strength of 300 PSI
- 6.0 inch - Subgrade Meeting a minimum Soil Support Value of 5

PCC Section
- 9.5 inches - Portland Cement Concrete Pavement
- 10.0 inches - Graded Aggregate Base
- 6.0 inch - Subgrade Meeting a minimum Soil Support Value of 5
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
Repeated traffic loads

Cracks extend to HMAC surface

Hot-Mix Asphalt Concrete

Cracks within soil-cement are extended to HMAC

Shrinkage crack

Soil-cement base

Repeated traffic loads

Repetitive traffic loads

Hot-Mix Asphalt Concrete

Limestone Interlayer

Shrinkage crack

Soil-cement base
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.
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

Scalehouse

Truck Traffic
Road Relocation
Road Relocation

Conventional

Inverted
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
Pavement Design

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1.18 in Asphalt
6 in ABC
7.87 in CTB
Other Inverted Designs in U.S.

Morgan, GA
- 3” HMA
- 6” UAB
- 8” CTB

LaGrange, GA
- 3.5” HMA
- 6” UAB
- 10” CTB

Raton, NM
- 3.6” HMA
- 6” UAB
- 10” CTB

Subgrade mixed with UAB

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

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<th>PERCENT FINER</th>
<th>SPEC.* PERCENT</th>
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<tbody>
<tr>
<td>1.5</td>
<td>100</td>
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<tr>
<td>1</td>
<td>94</td>
<td>75 - 97</td>
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<td>0.75</td>
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<td>0.5</td>
<td>64</td>
<td>55 - 80</td>
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<td>#4</td>
<td>42</td>
<td>35 - 55</td>
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<td>#10</td>
<td>31</td>
<td>25 - 45</td>
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<td>#40</td>
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<td>14 - 30</td>
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<tr>
<td>#200</td>
<td>9</td>
<td>4 - 12</td>
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Cement Treated Base
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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

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Unbound Aggregate Base
Unbound Aggregate Base
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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

- 2.5” HMA
- 6” UAB
- 8” CTB

SN = 3.78
$35.92/SY
11.3% Less Expensive than Conventional

Conventional

- 6” HMA
- 10” UAB

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)

Avg = 10.4

Avg = 6.9
FWD Data as of 6/7/16

Avg = 6.5

Avg = 17.8
FWD Data as of 12/12/16

Deflection (mils)

Avg = 6.5

Avg = 12.3
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

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