DESIGNING BASES AND SUBGRADES FOR BETTER PAVEMENT PERFORMANCE

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Houston Foundation Performance Association

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Better Models for Base Course and Subgrade for Pavement Design and Performance Prediction

NCHRP 1-53 Project

AASHTO Pavement ME Design Product Task Force

Hilton Savannah Desoto Hotel
Savannah, Georgia
April 4-5, 2017
Introduction and Objectives

- Problem: performance of flexible and rigid pavements shows low sensitivity to subgrade/unbound layer properties

- Objective: propose enhancements needed to better reflect the influence of subgrade/unbound layers (properties and thickness)
What do we need to emphasize? (1/2)

- Unbound layers
  - Modulus: moisture-sensitive, stress-dependent, cross-anisotropic
  - Permanent deformation: moisture-sensitive, stress-dependent
  - Shear strength: moisture-sensitive
  - Erosion
  - Thickness
What do we need to emphasize? (2/2)

- **Subgrade**
  - Modulus: moisture-sensitive, stress-dependent
  - Permanent deformation: moisture-sensitive, stress-dependent
  - Shear strength: moisture-sensitive
  - Foundation
**Wet Season**

**Dry Season**

**Equilibrium**

**Suction of the Water**

**Ground Surface**

**Water Table**
Hierarchical Input Level

Level 1:
- Laboratory-measured $k_1$, $k_2$, $k_3$
- SWCC
- Equilibrium suction and its depth

SWCC in Pavement ME Design
A Family of Generated SWCCs

Volumetric Water Content ($\theta_w$)

Suction (pF)
THORNTWHAITE MOISTURE INDEX
(20 Year Average, 1955–1974)
Variation of mean Subgrade pF and TMI

CLAY pFmin=6.0

CLAY pFmin=4.5

SAND pFmin=6.0

SOIL MOISTURE SUCTION (pF)

Thornthwaite Moisture Index (TMI)

Calculated

Russam & Coleman

(1961) Field data
Some Characteristic Curves

- Soil water characteristic curve
- Soil dielectric characteristic curve
- Soil conductivity characteristic curve
- Soil osmotic suction – evaporable water content curve
- Soil osmotic suction – electrical conductivity curve
Soil Water Characteristics Curve (SWCC)
A Family of Generated SWCCs
Filter Paper Suction Test Setup

Two filter papers for total suction measurements

Ring support

Soil sample

Bring the samples together for an intimate contact in matric suction measurements

One filter paper in between two protective papers

Soil sample
Soil Water Characteristics Curve (SWCC)
Fredlund and Xing Equation (1994)

\[
\theta_w = C(h) \times \left[ \frac{\theta_s}{\ln \left( \exp(1) + \left( \frac{h}{a} \right)^b \right) \right]^c
\]

Volumetric water content

\[
C(h) = \left[ 1 - \frac{\ln \left( 1 + \frac{h}{h_r} \right)}{\ln \left( 1 + \frac{10^6}{h_r} \right)} \right]
\]

Saturated volumetric water content

Four soil parameters
Four Parameters

Correlations for parameters $a_f$ and $b_f$:

$$a_f = 3.4994MBV^{0.0002}$$

$$b_f = 2.0044MBV^{-0.003}$$
Four Parameters

Correlations for parameters $c_f$ and $h_r$:

$c_f = 0.4956MBV^{-0.415}$

$h_r = 20.00xMBV^{9.5E-06}$
Soil Dielectric Characteristics Curve (SDCC)
Soil Dielectric Characteristics Curve (SDCC)

\[
\varepsilon_r = \varepsilon_{sat} + \varepsilon_{min} \left[ \frac{h}{(1.45 \times 10^5 - h)} \right]^\gamma \\
1 + \alpha \left( \frac{h}{h_m - h} \right)^\gamma
\]

Saturated dielectric constant

Dielectric constant

Curve fitting parameters

Minimum dielectric constant

Suction

Maximum Suction

Saturation
A Standard Percometer Device with Surface Probe
Dielectric Constant Measurements
Process with a Percometer

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.0</td>
</tr>
<tr>
<td>Water</td>
<td>81.0</td>
</tr>
<tr>
<td>Asphalt</td>
<td>4.0-6.0</td>
</tr>
<tr>
<td>Concrete</td>
<td>8.0-12.0</td>
</tr>
<tr>
<td>Clay</td>
<td>4.0-40.0</td>
</tr>
</tbody>
</table>
A Family of Generated SDCCs

![Graph showing the relationship between Suction (pF) and Dielectric Constant (\(\varepsilon_r\)). The graph includes various curves labeled with different combinations of numbers, such as E-01 1-3-2-3, E-02 1-3-4, E-02 3-1-2, E-03 4-3-10, E-03 6-10-1, E-03 6-10-3, E-04 2-6, E-05 61-12, E-06 3-10, E-06 2-6, E-06 1-13, E-07 68-2-6, E-07 69-1-14, E-08 235-1-12, E-08 2-1-6, E-09 1-14 and E-09 1-14.]
Minimum Dielectric Value

Correlation for minimum dielectric vs MBV

\[ \varepsilon_{\text{min}} = 0.1243 \log(MBV) + 1.0668 \]

R\(^2\) = 0.7642
Saturated Dielectric Value

Correlation for saturated dielectric vs MBV

\[ \varepsilon_{\text{sat}} = 0.0334(MBV^2) - 0.1086(MBV) + 12.569 \]

\[ R^2 = 0.9311 \]
Base Course Aggregate

AASHTO T 330-07 Methylene Blue Scale
Methylene Blue Equipment

- Hach DR Colorimeter
- Timer
- Plastic Tube
- Micropipette
- Small tube
- Syringe
- Syringe filter
- Eyedropper
- Methylene Blue Solution
- Weight Balance
Grace Methylene Blue Test

Weigh 20g of sample and 30g MB. Mix them and shake for 5 min.

Take solution into syringe that has 2 micrometer filter.

Replace the plunger and push solution to filter into a 1 mL plastic tube.

Dilute the 130 mL aliquot with distilled water to accurately total 45 g.

Fill the glass tube with the diluted solution and place in the colorimeter.

Place cover over the glass tube and take a reading. MB Reading will display in couple seconds.

Determine the percent clay based on MB from the chart.
HORIBA Particle Size Distribution Analyzer

- Particle size distribution curve of passing No 200 sieve
- Total measurement time is less than 10 min

- Typical test result of a soil sample
- Determine size of 2 μm particle
What is pfc?

Percent passing
2 micrometer

Percent passing
No.200 sieve

\[ pfc = \frac{\text{-2} \mu m}{\text{-#200}} \times 100 \]

Percent Fines Content
The Relationship Between MBV and pfc

R² = 0.79

Methylene Blue Value (mg/g)
Percent Fines Content (%)

Zone I
Zone II

Measured Data Points  pfc Modeled Plot  MBV=7.0 Critical Point Line
"C" Shaped Curve Equation

Coefficient parameters depend on soil type

\[ pf_c = \frac{a}{(MBV)^n} + b(MBV) \]

Percent fines content

Methylene Blue Value

Typical Values

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>28.014</td>
</tr>
<tr>
<td>b</td>
<td>0.8131</td>
</tr>
<tr>
<td>n</td>
<td>0.6288</td>
</tr>
</tbody>
</table>
A Good Quality Base Course
A Poor Quality Base Course
Base Course Aggregate
Grace Methylene Blue Value Scale

Grace MBV (mg/g)
28
Failures
21
Problems / possible failures
14
Marginally acceptable
7
Excellent

Excellent
Matric Suction and Water Content Measurements

- Methylene blue value measurement
- Soil Dielectric Constant Curve
  - $\varepsilon_{sat}$, $\varepsilon_{min}$, $\alpha$, $\lambda$

Predict

- Percent fine content
- Soil Water Characteristic Curve
  - $a_f$, $b_f$, $c_f$, $h_f$
Resilient Modulus

\[ E_y = k_1 P_a \left( \frac{I_1 - 3\theta f h_m}{P_a} \right)^{k_2} \left( \frac{\tau_{oct}}{P_a} \right)^{k_3} \]

- **Saturation factor**: \( 1 \leq f \leq \frac{1}{\theta} \)
- **Octahedral shear stress**: \( \tau_{oct} \)
- **Atmospheric pressure**: \( P_a \)
- **Volumetric water content**
- **First invariant of the stress tensor**: \( I_1 \)
- **Matric Suction**
- **Coefficients of resilient modulus model**: \( k_1, k_2, k_3 \)
Aggregate Properties and k Values

![Graph showing predicted vs. measured resilient modulus with regression lines and R² values.]

- **Proposed Model (With Suction)**: $R^2 = 0.93$
- **Generalized Model (Without Suction)**: $R^2 = 0.23$
# Aggregate Properties and k Values

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>k Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>γ&lt;sub&gt;d&lt;/sub&gt; (Dry Density)</td>
<td>✓</td>
</tr>
<tr>
<td>ω (Water Content)</td>
<td></td>
</tr>
<tr>
<td>MBV</td>
<td>✓</td>
</tr>
<tr>
<td>pfc</td>
<td></td>
</tr>
<tr>
<td>Gradation</td>
<td>a&lt;sub&gt;G&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>λ&lt;sub&gt;G&lt;/sub&gt;</td>
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<tr>
<td>Angularity</td>
<td>a&lt;sub&gt;A&lt;/sub&gt;</td>
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<tr>
<td></td>
<td>λ&lt;sub&gt;A&lt;/sub&gt;</td>
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<tr>
<td>Shape</td>
<td>a&lt;sub&gt;S&lt;/sub&gt;</td>
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<tr>
<td></td>
<td>λ&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
<tr>
<td>Texture</td>
<td>a&lt;sub&gt;T&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>λ&lt;sub&gt;T&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
Compaction Curve Equation

Three fitting parameters change with soil type

\[
\frac{\gamma_d}{\gamma_w} = a_d \left[ \text{csch} \left( \frac{\theta_w \theta_{sat}}{G_s (\theta_{sat} - \theta_w)} \right) \right]^{n_d} - b_d \left[ \text{csch} \left( \frac{\theta_w \theta_{sat}}{G_s (\theta_{sat} - \theta_w)} \right) \right]
\]

- Dry unit weight
- Unit weight of water
- Specific gravity
- Volumetric water content
- Saturated volumetric water content
Saturated Volumetric Water Content

Predicted and calculated saturated volumetric water contents

\[ \theta_{sat} = 0.214926485H_{1\theta_{sat}} + 0.27640261H_{2\theta_{sat}} - 0.12511932H_{3\theta_{sat}} + 0.30045553 \]

\[ H_{1\theta_{sat}}, H_{2\theta_{sat}}, \text{and } H_{3\theta_{sat}} = f(MBV \text{ and } pfC) \]
Typical Compaction Curve as Tested in the Laboratory and as Modeled
Optimum Moisture Content

\[
\theta_{opt} = G_s \theta_{sat} \ln \left[ \frac{1}{2} \left( 1 + \sqrt{1 + 4 \left( \frac{2^{1-n_d} b_d}{a_d n_d} \right)^{\frac{2}{1+n_d}} \left( \frac{2^{1-n_d} b_d}{a_d n_d} \right)^{-\frac{1}{1+n_d}}} \right) \right] \\
\theta_{sat} + G_s \ln \left[ \frac{1}{2} \left( 1 + \sqrt{1 + 4 \left( \frac{2^{1-n_d} b_d}{a_d n_d} \right)^{\frac{2}{1+n_d}} \left( \frac{2^{1-n_d} b_d}{a_d n_d} \right)^{-\frac{1}{1+n_d}}} \right) \right]
\]
A Family of Compaction Curves

Generated compaction density curves
Stress-Dependent Mechanistic-Empirical Permanent Deformation Model

- Proposed model (Gu, Zhang, et al. 2015)

\[ \varepsilon_p = \varepsilon_0 e^{-\left(\frac{p}{N}\right)^\beta} \left(\sqrt{J_2}\right)^m (\alpha I_1 + K)^n \]

\[ \alpha = \frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)} \quad K = \frac{c \cdot 6\cos\phi}{\sqrt{3}(3-\sin\phi)} \]

- Model components
  - Laboratory test design
  - Laboratory verification
  - Numerical verification
  - Hierarchical input level
## Repeated Load Permanent Deformation Test

### Test Equipment

### Test Protocol

<table>
<thead>
<tr>
<th>Stress State</th>
<th>Confining Pressure, $\sigma_3$ (kPa)</th>
<th>Deviatoric Stress, $\sigma_d$ (kPa)</th>
<th>Bulk Stress, $I_1$ (kPa)</th>
<th>Second Invariant of Shear Stress Tensor, $J_2$ (kPa$^2$)</th>
<th>Test Purpose</th>
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<tr>
<td>1</td>
<td>27.6</td>
<td>192.9</td>
<td>275.6</td>
<td>12406.0</td>
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<td>2</td>
<td>48.2</td>
<td>130.9</td>
<td>275.6</td>
<td>5712.5</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>68.9</td>
<td>192.9</td>
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<tr>
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<td>192.9</td>
<td>503.0</td>
<td>12406.0</td>
<td></td>
</tr>
</tbody>
</table>
Proposed AASHTO Standard for Permanent Deformation Test

Standard Method of Test for

Determining the Permanent Deformation Properties of Geosynthetic-Reinforced and Unreinforced Granular Material

AASHTO Designation: T xx xx

1. SCOPE

1.1. The test method described is applicable to unbound granular materials and geosynthetic-reinforced granular materials prepared for testing by compaction in the laboratory.

1.2. The values of permanent deformation properties determined from this procedure recognize the stress dependent nonlinear characteristics of granular material.

1.3. Permanent deformation properties can be used with structural response analysis models to predict the permanent deformation of unbound base courses and geosynthetic-reinforced base courses under certain number of load repetitions.

1.4. This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1. AASHTO Standards:
   - T 207, Determining the Resilient Modulus of Soils and Aggregate Materials
   - T 295, Unconfined, Unrestrained Compressive Strength of Cohesive Soils in Triaxial Compression

3. SIGNIFICANCE AND USE

3.1. The permanent deformation test provides a basic relationship between stress and permanent deformation of pavement materials for the structural analysis and performance prediction of layered pavement systems.

3.2. The permanent deformation test provides a means of characterizing pavement construction materials, including unbound granular materials, and geosynthetic-reinforced (i.e., geogrid and geotextile) granular materials, under a variety of conditions (i.e., moisture, density, etc.) and stress states that simulates the conditions in a pavement subjected to moving wheel loads.

4. APPARATUS

4.1. Triaxial Pressure Chamber-The pressure chamber is used to contain the test specimen and the confining fluid during the test. A typical triaxial chamber, suitable for use in permanent deformation test of granular material shall be as described in T 207.
Repeated Load Permanent Deformation Test Results

Proposed model is sensitive to cohesion. Moisture change results in change of cohesion.

Korkiala-Tanttu (K-T) model (Korkiala-Tanttu 2009)  
UIUC model (Chow et al. 2014)
Role of Shear Strength Model

Erosion Enablers:
- Mechanical shear stress due to deflection
- Hydraulic shear stress due to pumping
- Permanent deformation (causing voids between slab & base)

Erosion Resistors:
- Interface shear strength
- Interfacial bonding
- Resistance to permanent deformation
- Permeability

Water infiltration through joints & cracks
Pumping water & fines out
Saturated material
Deflection due to traffic & temperature
Concrete Slab
Unbound Base
Subgrade
Hamburg Wheel-Tracking Device (HWTD) to Measure erodibility
HWTD Test Results

Dry Test

Wet Test

Unbound
Stabilized

Number of Passes

Deflection (mm)

Number of Load

Erosion Depth (mm)

Dry Test

Wet Test

Unbound
Stabilized

Number of Load

Erosion Depth (mm)
Critical Erosion Depth Model

Erosion depth curve:

\[ N = N_\infty e \left( \frac{\rho_c}{D_e} \right)^{\beta_e} \]

Critical erosion depth:

\[ D_{ce} = \rho_c \left( \frac{\beta_e}{\beta_e + 1} \right)^{\frac{1}{\beta_e}} \]

Number of load cycles at the point of inflection:

\[ N_{PI} = N_\infty e \left( \frac{\beta_e + 1}{\beta_e} \right) \]
Validation of Erosion Model

Model prediction vs. lab measurements from HWTD

Model prediction vs. observed performance from 17 LTPP sections
LTPP Pavement Sections with Faulting Data

- Unbound Base Course: 351
- Stabilized Base Course: 359

Total: 710
A Case Study: Verification GPR and FWD
Test Location

Delta county in Texas
Total length 4.5 miles (~24000 ft)

Martin Marietta Material in Oklahoma
Ground Penetrating Radar Van

Vehicle-Mounted Four-Antenna Configuration for Highway Speed Data Acquisition

12 foot lane coverage
Return Reflection at Interfaces
Radar Hyper Optics Animation
Information from GRP

Dielectric constant

Base course thickness
Information from GRP

**Matric Suction**

![Matric Suction Graph]

**Volumetric Water Content**

![Volumetric Water Content Graph]
Information from GRP

Dry Density

Resilient Modulus

FWD Back-calculated Resilient Modulus

Predicted Resilient Modulus
Location of Identified Pavement Sections

- : only done by lab characterization;
- : done by lab characterization and field FWD and GPR testing;
- : on-going lab characterization.
Relationship between MBV and pfc
Identified Pavement Sections from SH 21

- 3-inch HMA
- 6-inch Flexible Base
- Geogrid Layer
- 6-inch Cement-treated Road Mix
- Subgrade

Hunter or Knife River Base Material

Hunter Base Material

Knife River Base Material

Alligator cracking
Model-Predicted Mr Vs. FWD-Calculated Mr

Resilient Modulus of In-situ Base Course (ksi)

Station (ft)

Hunter Section Backcalculated

Knife River Section Backcalculated

Hunter Section Model-Predicted

Knife River Section Model-Predicted
Location of Identified Pavement Sections

- ✭: only done by lab characterization;
- ★: done by lab characterization and field FWD and GPR testing;
- ★★: on-going lab characterization.
Water Content Determination from Conductivity

- **Neat US 259**
- **US 259 + 2% cement**
- **US 259 + 4% cement**
- **US 259 + 6% cement**
Osmotic Suction vs Water Content

- **Osmotic Suction (pF)**
- **Evaporable Volumetric water content**

Graph showing the relationship between Osmotic Suction (pF) and Evaporable Volumetric water content for US 259 and US 259 + 2% cement.
Osmotic Suction vs Conductivity

- US 259
- US 259 + 2% cement
- US 259 + 4% cement
- US 259 + 6% cement

Osmotic Suction (pF) vs Electrical Conductivity (μs/cm)
Conductivity vs Water Content

Electrical Conductivity (μs/cm) vs Evaporable Volumetric water content

- **US 259**
- **US 259 + 2% cement**
- **US 259 + 4% cement**
- **US 259 + 6% cement**
Some Characteristic Curves

- Soil water characteristic curve
- Soil dielectric characteristic curve
- Soil conductivity characteristic curve
- Soil osmotic suction – evaporable water content curve
- Soil osmotic suction – electrical conductivity curve
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