Housekeeping

- Webinar will be recorded and available at a later time @ NRRA Website
- Due to large participation, please type any question or comment on chat box. Moderator will ask questions to Panelists during QA sessions
- Webinar organizers are not planning to provide a certificate of participation. However, to best of our knowledge, this course/activity meets continuing education requirements for PDHs as outlined in Minnesota Statute 326.107. (Please check your state statute)
Agenda

- Welcome – Introduction – T. Beaudry
- Fundamental Concepts in Unsaturated Soil – W. Likos
- Measurement of Unsaturated Properties – R. Velasquez
- Q&A – Fundamentals – All
- Break (10 min)
- Impact of Moisture on Pavement Foundation Materials – B. Cetin
- Importance of Unsaturated Soil Mechanics in ME Design – B. Cetin
- Correlations between Unsat Soil Parameters and ME Design Input – B. Cetin
- Use of Unsaturated Soil Mechanics by MnDOT – J. Siekmeier
- Q&A – Applications – All
- Closing Remarks – T. Beaudry
Introduction

Terry Beaudry P.E.
Why Should I Care?

- Recent developments in soil mechanics warrant a change in classic conservative approach.
- Saturated conditions is not appropriate design assumption in explaining heave of road foundations, through swelling of expansive subgrades soils.
- Technology has improved our ability to measure and characterize unsaturated soil.
- Designing based upon saturated conditions is too conservative and more costly.
Unsaturated Soil Mechanics and the Great Pyramids?
Wall painting from 1880 B.C. on the tomb of Djehutihotep in southeastern Egypt (Newberry, 1895).

Colossal statue of Djehutihotep (7 m high) transported by 172 workers using ropes and a slide.

Water being poured in the path of the sled.

Ritual or Unsaturated Soil Mechanics?
(from Fall et al., 2014, Phys. Rev. Letters, 112, 175502)
Topics for Discussion

- What is unsaturated soil?
  - Soil as a multiphase system
  - Properties depend on degree saturation

- What are differences between saturated and unsat. soils?
  - Concepts from interfacial physics

- What is soil suction?
  - Concept of pore water potential

- Why is unsaturated soil mechanics important?
  - Examples of engineering problems with unsat. soils.
Soil is a multiphase system

\[ S = \text{Solids} \]
\[ W = \text{Water} \]
\[ A = \text{Air} \]

Relative amount of each phase will affect behavior

“block diagram”
Aeolian Sand – Alamosa, CO
Average Grain Diameter = 150 µm.
2-Phase System

- Pore Fluid Pressure, $u_w$
  
  $u_w (+)$

- Volumetric Water Content, $\theta$
  
  $\theta = \frac{V_w}{V_t} = \frac{V_w}{V_t} = n$

- Degree of Saturation, $S$
  
  $S = \frac{V_w}{V_v} = 1.0 \ (100\%)$

- Conductivity (hydraulic, thermal) is constant at constant state (volume, temp.)
Unsaturated Soil

- **3-Phase System**
- **Pore Fluid Pressure,** $u_w$ and $u_a$
  
  $u_a = 0$ (atmospheric)
  
  $u_w < u_a$
  
  $\psi = u_a - u_w$ (matric suction)

- **Volumetric Water Content,** $\theta$
  
  $\theta = f(\psi), \ 0 < \theta < n$

- **Degree of Saturation,** $S$
  
  $S = f(\psi), \ 0 < S < 1.0$

- **Hydraulic Conductivity,** $k$
  
  $k = f(\theta)$
  
  or $k = f(\psi)$

**Soil-water characteristic curve (SWCC)**

**Hydraulic conductivity function (HCF)**
Hydraulic Conductivity

Thermal Conductivity

Strength and Compressibility?
Concepts from Interfacial Physics

- surface tension
- capillarity
- soil-water characteristic curve (SWCC)
- components and units of soil suction
Surface Tension, $T_s$

gas (air)
air pressure, $u_a$

liquid (water)
water pressure, $u_w$

imbalanced cohesive forces

balanced cohesive forces

$L$ and $L$ (Lu and Likos, 2004)
Height of Capillary Rise, $h_c$

\[ h_c \frac{\pi}{4} d^2 (\rho_w g) = T_s \pi d \cos \alpha \]

\[ h_c = \frac{4T_s \cos \alpha}{d \rho_w g} \]

\[ \Rightarrow h_c (cm) \approx \frac{0.3}{d (cm)} \]
Soil-Water Characteristic Curve (SWCC)

*a.k.a. Water Retention Curve (WRC)*

*Capillary Pressure – Saturation Curves ($P_c$-$S$)*

*etc...*

(Buckingham, 1907)

(Lu and Likos, 2004)
Components of Soil Suction

Pore Water Potential, $\mu$ (energy per unit mass of water)

Free Water, $\mu_i$

Soil Water, $\mu < \mu_i$

Total change in potential:

$$\Delta \mu_t = \Delta \mu_c + \Delta \mu_a + \Delta \mu_o$$

$\Delta \mu_c$ : Reduction from capillary effects

$\Delta \mu_a$ : Reduction from adsorptive effects

$\Delta \mu_o$ : Reduction from osmotic effects
Unsaturated soils in geotechnical engineering

- slopes
- compacted soils
- retaining walls
- excavations
- expansive soils
- shallow foundations
- pavement subgrades
- waste covers
- thermal backfills
Precipitation-induced landslides

Photograph showing abundant shallow landslides near Valencia, California. The un-vegetated scars are shallow failures caused by heavy rainfall in the winter of 2005. The internal stress-suction stress changes only a few kPa!
Landslide Case History: Edmonds WA (2006)
Soil Compaction

S ~ 80%
Expansive Clays

Source: Geology.com – “Swelling Clays Map of the Conterminous United States” (Olive et al.)
Buried high-voltage power cables

Shallow geothermal systems

Geosynthetic heat exchangers

“energy” piles
Measurement of Unsaturated Properties Pavement Applications

Raul Velasquez P.E. Ph.D.
MnDOT

NRRA Webinar
May 19, 2020
Measurement of Unsaturated Properties
Pavement Applications

1. Soil Water Characteristic Curve (\textit{SWCC})
   - Tensiometers
   - Axis Translation Techniques (Pressure Plates)
   - Humidity Measurement Techniques
   - Filter Paper Techniques

2. Unsaturated Hydraulic Conductivity (\textit{k-unsat or HCF})

3. Models for \textit{SWCC} and \textit{k-unsat}
   - \textit{SWCC}
     - Brooks and Corey (BC) Model
     - van Genuchten (VG) Model
     - Fredlund and Xing (FX) Model
   - \textit{k-unsat}
     - Empirical and Macroscopic Models
     - Statistical Models
Measurement of Unsaturated Properties
Pavement Applications

![Graph showing relationship between Matric Suction (kPa) and Saturation (%)]

![Graph showing relationship between Matric Suction (kPa) and k-unsat (m/sec)]
Soil Water Characteristic Curve (SWCC)

- Common to express as a pressure potential (suction)
- Energy per unit volume, $\psi$ (J/m$^3$ = N/m$^2$ = Pa)
- Lump total suction into matric and osmotic components

$$\Delta \mu_t = \Delta \mu_o + \Delta \mu_a + \Delta \mu_c$$

$$\psi_t = \psi_o + \psi_m$$

Typical Retention Curves

Wetting-Drying Hysteresis
Soil Water Characteristic Curve (SWCC)

- Axis Translation
- Conductivity Sensors
- Tensiometers
- Psychrometers
- RH Measurement Methods
- RH Control Methods

Suction (kPa)

Saturated → Dry
# Soil Water Characteristic Curve (SWCC)

<table>
<thead>
<tr>
<th>Component</th>
<th>Technique/Sensor</th>
<th>Range (kPa)</th>
<th>Principle</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matric Suction</strong> ((\psi_m))</td>
<td>Tensiometers</td>
<td>0 - 100</td>
<td>Measurement of negative pressure</td>
<td>Lab/Field</td>
</tr>
<tr>
<td></td>
<td>Axis Translation</td>
<td>0 - 1500</td>
<td>Elevated air pressure</td>
<td>Lab</td>
</tr>
<tr>
<td></td>
<td>Conductivity Sensors</td>
<td>0 - 400</td>
<td>Therm. cond. material in contact</td>
<td>Lab/Field</td>
</tr>
<tr>
<td></td>
<td>Contact Filter Papers</td>
<td>50 - 100,000</td>
<td>Sorption of filter paper in contact</td>
<td>Lab/Field</td>
</tr>
<tr>
<td><strong>Total Suction</strong> ((\psi_t))</td>
<td>Psychrometers</td>
<td>100 - 8,000</td>
<td>RH meas. by dew point method</td>
<td>Lab/Field</td>
</tr>
<tr>
<td></td>
<td>Chilled-Mirror Hygrometers</td>
<td>1,000 - 500,000</td>
<td>RH meas. by dew point method</td>
<td>Lab</td>
</tr>
<tr>
<td></td>
<td>Capacitance Sensors</td>
<td>1,000 - 500,000</td>
<td>RH meas. by polymer sensor</td>
<td>Lab/Field</td>
</tr>
<tr>
<td></td>
<td>Non-contact Filter Papers</td>
<td>1,000 - 500,000</td>
<td>RH meas. by filter paper not in contact</td>
<td>Lab/Field</td>
</tr>
<tr>
<td></td>
<td>Osmotic Humidity Control</td>
<td>10 - 50,000</td>
<td>RH control using salt solutions</td>
<td>Lab</td>
</tr>
<tr>
<td></td>
<td>Flow-Through RH Control</td>
<td>10,000 - 500,000</td>
<td>RH control using controlled gas flow</td>
<td>Lab</td>
</tr>
<tr>
<td></td>
<td>Dynamic Dew Point Method</td>
<td>10,000 - 500,000</td>
<td>Hybrid RH control/meas. method</td>
<td>Lab</td>
</tr>
</tbody>
</table>
Selecting Proper Technique

- Need to consider soil type & anticipated range
- Often need to combine multiple techniques
- Often need to consider wetting-drying path

![Graph showing soil types and suction ranges](image)

- **Tensiometers** (0 ~ 100 kPa)
- **Conductivity Sensors** (0 ~ 400 kPa)
- **Axis Translation** (0 ~ 1,500 kPa)
- **Psychrometers** (100 ~ 8,000 kPa)
- **Dew Point / RH Control Methods** (4,000 ~ 600,000 kPa)
High-Air-Entry (HAE) Materials

**HAE Ceramic**
- $2R_s \sim 2 \mu m$
- $AEV \sim 100 \text{ kPa}$

**HAE Nylon Filter Paper**
- $2R_s \sim 0.5 \mu m$
- $AEV \sim 250 \text{ kPa}$

**Equation**

\[
(u_a - u_a)_{b} = \frac{2T_s}{R_s}
\]

**Table**

<table>
<thead>
<tr>
<th>Type of HAE Ceramic</th>
<th>Approx. Pore Diameter ($\times 10^{-3} \text{ mm}$)</th>
<th>Saturated Hydraulic Cond. (m/s)</th>
<th>Air-Entry Value (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 bar high flow</td>
<td>6.00</td>
<td>$3.11 \times 10^{-7}$</td>
<td>48–62</td>
</tr>
<tr>
<td>1 bar</td>
<td>1.70</td>
<td>$7.56 \times 10^{-9}$</td>
<td>138–207</td>
</tr>
<tr>
<td>1 bar high flow</td>
<td>2.50</td>
<td>$8.60 \times 10^{-8}$</td>
<td>131–193</td>
</tr>
<tr>
<td>2 bar</td>
<td>1.10</td>
<td>$6.30 \times 10^{-9}$</td>
<td>262–310</td>
</tr>
<tr>
<td>3 bar</td>
<td>0.70</td>
<td>$2.50 \times 10^{-9}$</td>
<td>317–483</td>
</tr>
<tr>
<td>5 bar</td>
<td>0.50</td>
<td>$1.21 \times 10^{-9}$</td>
<td>550</td>
</tr>
<tr>
<td>15 bar</td>
<td>0.16</td>
<td>$2.59 \times 10^{-11}$</td>
<td>1520</td>
</tr>
</tbody>
</table>

*Source: Soilmoisture Equipment Corp. (2003).*
**SWCC - Tensiometers**

- Direct measurement of negative \( u_w \)
- Requires exchange of water
- Response time \( \sim 1-10 \) min
- Sensors require servicing
- Limited to \( \psi_m \sim 100 \) kPa

*UMS GmbH © 2012*
SWCC - Tensiometers

Raw Data

Tension (hPa)

Date

Bottom Tensiometer

Top Tensiometer

*UMS GmbH © 2012
SWCC – Tensiometers Issues

- Keeping ceramic clean
- Tips saturated
- Degassing shafts
SWCC – **Axis Translation Techniques**

**Concept:** Stay away from cavitation by using positive pressures

Original set up for the null type, axis-translation device for measuring negative pore-water pressure (from Hilf, 1956)
SWCC – **Axis Translation Techniques**

**Pressure Plate**

- Multiple “identical” specimens
- *Combine to construct SWCC*
- $\psi_{\text{max}} \sim 1500 \text{ kPa}$
- *Caution beyond residual suction!*

*Soilmoisture Equipment Corp*
SWCC – Axis Translation Techniques
Tempe Cell System

- Elevated air pressure and HAE material
- Matric suction, $\psi_m = (u_a - u_w)$
- Single specimen, primarily drainage path
- Typically back-calculate $S$ from effluent
- Range: ~ 100 kPa (sands)
**SWCC - Humidity Measurement Techniques**

**Kelvin’s Equation**

\[
\psi_t = -\frac{RT}{v_w} \ln \left( \frac{u_v}{u_{v,\text{sat}}} \right) = -\frac{RT}{v_w} \ln(RH)
\]

**Free Water**

\(\mu = \mu_i, \ RH = 100\%\)

**Soil Water**

\(\mu < \mu_i, \ RH < 100\%\)

**Practical lower limit of RH measurement/control approaches**

\(~1,000\ kPa\)
Water potential => measurement of energy status of water in a soil. It indicates how tightly water is bound structurally or chemically.

WP4c => uses the chilled mirror dew point technique (ASTM 6836 Method D)

Water potential can be computed from vapor pressure of air in equilibrium with soil sample in a sealed chamber.
WP4C Measure Osmotic and Matric Components of Water Potential

*Decagon (2013), How to Create a Full Moisture Release Curve Using the WP4C and HyProp, Inc, Pullman, WA.
SWCC- Filter Paper Techniques

\[ \Psi \text{ (log kPa)} = 5.327 - 0.0779W_{fp} \]
\[ \Psi \text{ (log kPa)} = 5.056 - 0.0688W_{fp} \]
\[ \Psi \text{ (log kPa)} = 2.412 - 0.0135W_{fp} \]
\[ \Psi \text{ (log kPa)} = 1.882 - 0.0102W_{fp} \]

(ASTM D5298)
SWCC- *Filter Paper Techniques*

- **Noncontact Method, \( \psi_t \)**
  - glass jar
  - filter paper
  - mesh
  - specimen

- **Contact Method, \( \psi_m \)**
  - measurement paper
  - sacrificial papers

*Lytton and Bulut, 2003*
Unsaturated Hydraulic Conductivity (*k*-unsat or HCF)

![Graph showing the relationship between matric suction and unsaturated hydraulic conductivity.](image)

Unsaturated Hydraulic Conductivity ($k_{unsat}$)

- *Mostly estimated/calculated* from $k_{sat}$ and SWCC

- Alternatively => evaporation method with two tensiometers:

\[
q^i = \frac{1}{\beta} \left( \frac{\Delta V^i}{\Delta t^i} \right) A
\]

$q^i$ = water flow at evaluation point $i$

$\Delta V^i$ = water loss determined by weight changes at evaluation point $i$

$\Delta t^i$ = time interval between two measurement points

$A$ = cross sectional area

$\beta$ = geometry coefficient (standard $\beta=2$)
Unsaturated Hydraulic Conductivity ($k_{unsat}$)

**Darcy’s law:**

$$K_{unsat}^i(\Psi) = -\frac{q^i}{\Delta h^i / \Delta z + 1}$$

- $K_{unsat}^i$ = unsaturated hydraulic conductivity at evaluation point $i$
- $\Psi$ = average suction between two measurement points in time
- $\Delta h^i$ = difference in water tension between tensiometers at evaluation point $i$
- $\Delta z$ = distance between tensiometers tips
Unsaturated Hydraulic Conductivity ($k_{unsat}$)

- Steady-state techniques:
  - *Constant-head method*
  - Constant-flow method

- Transient techniques (*hydraulic diffusivity*):
  - Horizontal infiltration method
  - Outflow methods
  - Instantaneous profile methods
    - Lab
    - Field
Common Models for **SWCC**

- Brooks and Corey (BC) Model
- *van Genuchten (VG)* Model
- Fredlund and Xing (FX) Model
Common Models for $\textbf{SWCC}$

van Genuchten (VG)

\[ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha \psi)^n]^{-m} \]

- $S_e$ = effective saturation
- $\psi$ = matric suction
- $\theta_s$ = sat vol. water content
- $\theta_r$ = residual vol. water content
- $\alpha, n, m$ = empirical fitting parameters
Common Models for $k$-unsat (HCF)

- Empirical and Macroscopic Models
- Statistical Models
  - van Genuchten (VG) Model
  - Fredlund Model

Basis of Statistical Modeling

Randomly sized and randomly distributed pores
Common Models for *k*-unsat (HCF) van Genuchten (VG)

\[ k_w = k_s \cdot \left[ 1 - \left( a\psi^{(n-1)} \right) \left( 1 + \left( a\psi^n \right)^{-m} \right) \right]^{2} \left[ \left( (1 + a\psi)^n \right)^{\frac{m}{2}} \right] \]

\( k_s = \) saturated hydraulic conductivity
\( \psi = \) matric suction
\( a, n, m = \) empirical fitting parameters

\[ n = \frac{1}{1 - m} \]

Closing Remarks

• Suction spans a range over 6 orders of magnitude
• No single measurement technique is ideal for every application
• Measurement approach must consider:
  • Soil type
  • Range of wetting
  • Wetting direction
  • Applicability in the lab or field
• Quality measurements require careful protocol and calibration
Acknowledgments

Material from W. Likos (UW-Madison) and M. Padilla (GCTS Testing Systems), ASCE 2011 Webinar
Break (10 min)

• Welcome – Introduction – T. Beaudry
• Fundamental Concepts in Unsaturated Soil – W. Likos
• Measurement of Unsaturated Properties – R. Velasquez
• Q&A – Fundamentals – All
• Break (10 min)
• Impact of Moisture on Pavement Foundation Materials – B. Cetin
• Importance of Unsaturated Soil Mechanics in ME Design – B. Cetin
• Correlations between Unsat Soil Parameters and ME Design Input – B. Cetin
• Use of Unsaturated Soil Mechanics by MnDOT– J. Siekmeier
• Q&A –Applications – All
• Closing Remarks – T. Beaudry
Compaction is the densification of a soil by the use of mechanical energy.

- The process of expelling \textit{air} from the soil
- Improves strength
  - Increases \textit{bearing capacity} of foundations
  - Increases \textit{stability} of embankment slopes
- Reduces compressibility
  - Decreases \textit{settlement} of foundations
- Reduces permeability
The basic principle of densification is the re-arrangement of particles into a denser state, which results in:

- **Modulus**: Increase
- **Strength**: Increase
- **Resistance to liquefaction**: Increase
- **Permeability**: Decrease
- **Collapsibility**: Decrease
Dry Unit Weight vs. Moisture Content Curve

- **Dry of optimum**
- **Wet of optimum**
- Zero-air-void curve ($G_s = 2.69$)
- Maximum $\gamma_d$
Particle rearrangement inhibited due to capillary tension
Types of compaction curves

30 < LL < 70

- Type A: Bell shaped
- Type B: One and one-half peaks

LL < 30

LL < 30 or > 70

- Type C: Double peak
- Type D: Odd shaped

LL > 70
STRUCTURE OF COMPACTED CLAY SUBGRADE WITH MOISTURE

Dry: flocculated

Wet: dispersed

High compactive effort
(more parallel orientation)

Low compactive effort
(less parallel orientation)
Effect of Moisture on Soil Properties

Stress-Strain and strength
Effect of Moisture on Soil Properties

Stress-Strain and strength

Dry Unit Weight (kN/m$^3$) vs. Moisture Content (%)

Shear Stress (kPa) vs. Moisture Content (%)

Moisture Increase
Effect of Compaction on Soil Properties

Permeability

- Shows change in moisture and unit weight from permeation.
EFFECT OF MOISTURE ON SOIL PROPERTIES

Compressibility / Settlement

If compacted **Wet of optimum**: more compressible at **low pressure**
(greater slope = greater change in void ratio for given increase in applied pressure)

If compacted **Dry of optimum**: more compressible at **high pressure**
(steeper slope)

---

(a) Low-pressure consolidation

(b) High-pressure consolidation
Strength of clayey soils

Figure 5.18 Effect of compaction on the strength of clayey soils
Effect of Moisture Content on Resilient Modulus of Granular Aggregate Base Materials

(Haider et al. 2014)
Effect of Moisture Content on Permanent Deformation of Granular Aggregate Base Materials

(Haider et al. 2014)
Effect of Freeze-Thaw Cycles on Moisture/Resilient Modulus

BS: Brandon Shores Power Plant Fly Ash
PS: Paul Smith Power Plant Fly Ash
DP: Dickerson Precipitator Plant Fly Ash
LKD: Lime Kiln Dust

(Cetin et al. 2010)
Importance and Integration of Unsaturated Soil Mechanics in Pavement M-E Design

Bora Cetin, PhD
Assistant Professor
Michigan State University
cetinbor@msu.edu

NRRA Webinar
May 19, 2020
Importance of Matric Suction for Pavement Structure

• Having unsaturated geomaterials in the pavement foundation leads many researches to focus on the behavior of the unsaturated geomaterials by investigating the relationship between:

  • *Saturation degree* versus *matric suction*
  
  • *Shear strength* versus *matric suction*
  
  • *Stiffness (Resilient Modulus)* versus *matric suction*

(Yang et al. 2008)
• Matric suction in a pavement structure changes as water content changes.
Importance of Matric Suction for Pavement Structure

• The increase in the matric suction has a significant effect on the shear strength and modulus of geomaterials in the pavement and it is directly related to:

  • **Total Rutting**: Shear strength directly affects total rutting; it decreases as shear strength increases

Rutting failure due to the weak shear strength of subgrade

Colorado Department of Transportation 2017 Pavement Design Manual
Importance of Matric Suction for Pavement Structure

- **Load-related Cracking (Alligator and Longitudinal):** A larger shear strength and modulus improve the integrity of supporting layers and also resistance to load-related cracking.

- **Smoothness (IRI):** High shear strength and modulus result in low IRI values.
• **Environmental conditions** such as precipitation, change in the water table level and drainage conditions, causing distress to the pavement by changing the moisture content → matric suction

http://www.macdrain.com.br/?page_id=56
Pavement ME Design Guide Features

- Hierarchical approach to inputs
- Axle load spectra data (not ESALs)
- Consideration of climatic effects
- Use of intrinsic material properties
- Consideration of key distress types
- Incremental damage approach
Incremental Damage

• Changes over time are addressed
  • Material strength and stiffness
  • Seasonal moisture and temperature
  • Variations in traffic seasonally and over time
Incremental Damage/Stiffness

Graph showing incremental damage/stiffness with different material layers and traffic conditions.

Inside (Main Traffic) - OWP
9,000 lb (40 kN)

Composite $E_{FWD}$ (ksi)

Cell Number

Composite $E_{FWD}$ (MPa)

Legend:
- Nov 2017
- Mar 2018
- Mar 2019
- Jul 2019
Incremental Damage/Moisture & Temperature

Cell 127
18 in LSSB

Temperature (°F)

Temperature (°C)

3 in  9 in  18 in  48 in
4 in  10 in  24 in  60 in
6.5 in  12 in  36 in  72 in

Volumetric Water Content

-0.1  0.0  0.1  0.2  0.3  0.4  0.5  0.6

Cell 127
18 in LSSB

6.5 in  29 in  36 in

• Step 1 – Input
  • Subgrade soil properties, AASHTO classification
  • Resilient modulus at reference condition, gradation, engineering and index properties, Atterberg limit tests

• Step 2 – Background
  • Estimation of adjusted resilient modulus for varying moisture and temperature condition for each month over the design life (i.e. 20 years)

• Step 3 – Distress
  • Determination of pavement distress (i.e. cracking, rutting, IRI) for due to seasonal variation in resilient modulus
Subgrade Inputs for Pavement-ME

Gradation

Atterberg Limit Tests

Index Properties

Soil Water Characteristics Curve Parameter

Resilient Modulus
Soil Water Characteristics Curve (SWCC)

- SWCC determines the relationship between water content and suction for a given soil.
- Pavement-ME generates the SWCC curve based on four parameters.
  - $a_f$ (psi)
  - $b_f$
  - $c_f$
  - $h_r$ (psi)
Pavement – ME SWCC Flow Chart

**Step 1 – Inputs**
- **Required**
  - $P_{200}$ & $D_{60}$ (AASHTO T27)
  - PI (AASHTO T90)
- **Optional**
  - $W_{opt}$
  - $\gamma_{d_{max}}$ (AASHTO T180, T99)
  - $G_s$ (AASHTO T100)

**Step 2 – EICM Background**
- **Mass – Volume parameters**
  - $S_{opt}$, $\theta_{opt}$, $\theta_{sat}$
  - $W_{opt}$, $\gamma_{d_{max}}$, $G_s$
- **SWCC parameters**
  - $a_f$, $b_f$, $c_f$, $h_r$

**Step 3 – SWCC Formation**

**Step 4 – Update Initial $M_r$**
- Equilibrium condition
- Field moisture condition
- Varying depths, nodes, time
Enhanced Integrated Climatic Model (EICM)

- 1 – dimensional coupled heat and moisture flow program
- Simulates the changes in pavement layers and subgrade due to climatic condition over the years
- Determines Mass – Volume parameters, Soil Water Characteristics Curve (SWCC) parameters based on
  - $P_{200}$ and $P_4$ (% passing #200 and #4)
  - $D_{60}$ (effective grain size for 60 % passing)
  - PI (plasticity index)
Mass-Volume Parameters

\[ S_{opt} = 6.752 \times (P_{200} \times PI)^{0.147} + 78 \]
\[ G_s = 0.041 \times (P_{200} \times PI)^{0.29} + 2.65 \]
\[ \gamma_d \text{ (max comp)} = \frac{G_s \times \gamma_{water}}{1 + \frac{W_{opt} \times G_s}{S_{opt}}} \]

where,

\[ G_s \] = Oven dry specific gravity of soil

\[ S_{opt} \] = Initial degree of saturation of soil

\[ P_{200} \] = % passing #200 sieve

\[ PI \] = Plasticity Index of soil

\[ \gamma_d \text{ (max comp)} \] = Maximum dry unit weight of soil

\[ W_{opt} \] = Optimum gravimetric water content of soil
Mass-Volume Parameters

\[ W_{opt} = 1.3 \times (P_{200} \times PI)^{0.73} + 11 \]
\[ W_{opt} = 8.6425 \times (D_{60})^{-0.1038} \]
\[ \theta_{opt} = W_{opt} \times \gamma_{d \text{ max}} \]
\[ \theta_{sat} = \frac{\theta_{opt}}{S_{opt}} \]

where,

- \( W_{opt} \) = Optimum gravimetric water content of soil
- \( P_{200} \) = % passing #200 sieve
- \( PI \) = Plasticity Index of soil
- \( D_{60} \) = Effective grain size for 60% passing
- \( \theta_{opt} \) = Optimum volumetric water content
- \( \theta_{sat} \) = Saturated volumetric water content
- \( \gamma_{d \text{ max}} \) = maximum dry unit weight of soil

If \( P_{200} \times PI > 0 \)

If \( P_{200} \times PI = 0 \)
Soil-Water Characteristic Curve Parameters

\[ a_f = \frac{0.00364 (P_{200} PI)^{3.35} + 4 (P_{200} PI) + 11}{6.895} \]

\[ b_f = -2.313 (P_{200} PI)^{0.14} + 5 \]

\[ c_f = 0.0514 (P_{200} PI)^{0.465} + 0.5 \]

\[ h_r = 32.44 e^{0.0186 (P_{200} PI)} \]

if \( P_{200} \times PI > 0 \)

where,

\( P_{200} = \) % passing #200 sieve

\( PI = \) Plasticity Index of soil
Soil-Water Characteristic Curve Parameters

\[
a_f = \frac{0.8627(D_{60})^{-0.751}}{6.895}
\]

\[
b_f = 7.5
\]

\[
c_f = 0.1772 \ln(D_{60}) + 0.7734
\]

\[
h_r = \frac{1}{D_{60} + 9.7e^{-4}}
\]

if \( P_{200} \times PI = 0 \)

where,

\( P_{200} = \% \) passing #200 sieve

\( PI = \) Plasticity Index of soil

\( D_{60} = \) Effective grain size for 60% passing
Soil-Water Characteristic Curve Parameters

\[ S_{equil} = C(h) \times \frac{1}{\left( \ln\left( EXP(1) + \left( \frac{h}{a_f} \right)^{b_f} \right) \right)^{c_f}} \]

\[ C(h) = 1 - \frac{\ln\left( 1 + \frac{h}{h_r} \right)}{\ln\left( 1 + \frac{1.45 \times 10^5}{h_r} \right)} \]

where,

\[ h = \gamma_{GW} \times \gamma_{water} \]

\[ S_{equil} = \text{Equilibrium degree of saturation} \]
Effect of Soil Moisture on Resilient Modulus

\[
\log \frac{M_r}{M_{R_{opt}}} = a + \frac{b-a}{1+\exp\left(\ln\frac{-b}{a} + k_m(S_{equil} - S_{opt})\right)}
\]

\[
\log \frac{M_{R_{equil}}}{M_{R_{opt}}} = a + \frac{b-a}{1+\exp\left(\ln\frac{-b}{a} + k_m(S_{equil} - S_{opt})\right)}
\]

where,

- \(M_r\) = Resilient modulus at a given time
- \(M_{R_{equil}}\) = Equilibrium resilient modulus
- \(M_{R_{opt}}\) = Resilient modulus at a reference condition
- \(a, b\) = Min & max of \(\log\frac{M_r}{M_{R_{opt}}}\)
- \(k_m\) = Regression parameter
- \(S - S_{opt}\) = Variation in degree of saturation
Importance of Matric Suction for Pavement Structure

- The Pavement ME Design incorporated the suction in the MR model through NCHRP Project 9-23A:

\[ M_R = k_1 P_a \left( \frac{\theta + w_c \times \text{matric suction}}{P_a} \right)^{k_2} \left( \frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \]

where \( \theta \) is bulk stress, \( w_c \) is water content.
Integration of Matric Suction in Pavement ME

- Sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Model Formulation (detailed definitions of parameters in Appendix B)</th>
<th>Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture-sensitive Model</td>
<td>$\log \frac{M_R}{M_{Ropt}} = a + \frac{b - a}{1 + \exp \left[ \ln \frac{-b}{a} + k_m (S - S_{opt}) \right]}$</td>
<td>Granular Base/Subgrade Soil</td>
</tr>
</tbody>
</table>
| Moisture-sensitive and Stress-dependent Model | $M_R = k_2 + k_3 (k_1 - \sigma_d) + k_s (u_a - u_w)$  
$M_R = k_2 + k_4 (\sigma_d - k_1) + k_s (u_a - u_w)$ | Subgrade Soil                       |
| Moisture-sensitive and Stress-dependent Model | $M_R = k_1 P a \left( \frac{I_1 - 3k_4}{Pa} \right)^{k_2} \left( \frac{\tau_{oct}}{Pa} \right)^{k_3}$ | Granular Base/Subgrade Soil         |
The Pavement ME suggests the Moisture-sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019) (cont.)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Model Formulation (detailed definitions of parameters in Appendix B)</th>
<th>Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 P a \left( \frac{I_1 - 3\theta f h_m}{P a} \right)^{k_2} \left( \frac{\tau_{oct}}{P a} \right)^{k_3}$</td>
<td>Granular Base/Subgrade Soil</td>
</tr>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 P a \left[ I_1 - 3\theta f \left( h_m + \beta \frac{I_1}{3} + \alpha \tau_{oct} \right) \right]^{k_2} \left( \frac{\tau_{oct}}{P a} \right)^{k_3}$</td>
<td>Granular Base/Subgrade Soil</td>
</tr>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 \left( \sigma_d + \chi_w \psi_m \right)^{k_2}$</td>
<td>Subgrade Soil</td>
</tr>
</tbody>
</table>
Integration of Matric Suction in Pavement ME

- The Pavement ME suggests the Moisture-sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019) (cont.)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Model Formulation</th>
<th>Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 P_a \left( \frac{\theta + \chi_w \psi_m}{P_a} \right)^{k_2} \left( \frac{\tau_{oet}}{P_a} + 1 \right)^{k_3}$</td>
<td>Subgrade Soil</td>
</tr>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 P_a \left( \frac{\theta_{net} - 3 \Delta u_{w-sat}}{P_a} \right)^{k_2} \left( \frac{\tau_{oet}}{P_a} + 1 \right)^{k_3} \left( \frac{\psi_m - \Delta \psi_m}{P_a} + 1 \right)^{k_4}$</td>
<td>Granular Base</td>
</tr>
<tr>
<td>Moisture-sensitive and Stress-dependent Model</td>
<td>$M_R = k_1 P_a \left( \frac{\sigma - 3k_6}{P_a} \right)^{k_2} \left( k_7 + \frac{\tau_{oet}}{P_a} \right)^{k_3} + k_{uz} P_a \Theta^\kappa \left( \mu_a - \mu_w \right)$</td>
<td>Subgrade Soil</td>
</tr>
</tbody>
</table>
Importance of Matric Suction for Pavement Structure During Freeze-Thaw Cycles

(Albadri et al., 2020)
Three factors are introduced to account for base/subgrade resilient modulus due to freeze–thaw action:

- Reduction Factor (RF)
- Recovery Ratio (RR)
- Environmental Adjustment Factor ($F_{env}$)
Environmental Adjustment Factor ($F_{env}$)

\[ F_F = \frac{M_{Rfzr}}{M_{Ro}pt} \]

\[ F_R = RF + R_{equil} \times RR - RR \times RF \quad \text{if } S_{equil} - S_{opt} < 0 \]

\[ F_R = R_{equil} \times (RF + RR - RR \times RF) \quad \text{if } S_{equil} - S_{opt} > 0 \]

\[ \log F_U = \log \frac{M_R}{M_{Ro}pt} = a + \frac{b - a}{1 + EXP(ln \frac{-b}{a} + k_m(S - S_{opt}))} \]

where,

\[ M_R = \text{Resilient modulus at unfrozen / normal condition} \]
\[ M_{Ro}pt = \text{Resilient modulus at a reference condition} \]
\[ M_{Rfzr} = \text{Resilient modulus at a frozen condition} \]
Environmental Adjustment Factor (F_{env})

\[ M_R = F_{env} \times k_1 \times p_a \times \left( \frac{\theta}{p_a} \right)^{k_2} \times \left( \frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \]

where,
\[ M_R = \text{stress dependent resilient modulus} \]
\[ F_{env} = \text{composite environmental adjustment factor} \]
\[ k_1, k_2, k_3 = \text{regression coefficients} \]
\[ p_a = \text{atmospheric pressure} \]
\[ \theta = \text{bulk stress} \]
\[ \tau_{oct} = \text{octahedral shear stress} \]
THANK YOU
Correlations between Unsaturated Soil Parameters and Pavement-ME Design Input

Bora Cetin, PhD
Assistant Professor
Michigan State University
cetinbor@msu.edu

NRRA Webinar
May 19, 2020
Relationship between Matric Suction and Stiffness

Properties of Materials

- Maximum Shear Modulus \(- G_{\text{max}} (G_o):\)

\[
G = \rho \times v_s^2
\]

where \(\rho\) is density and \(v_s\) is shear wave velocity.

- Measurement of Shear Wave Velocity \(\rightarrow\) Shear Modulus

Bender Element

Ultrasonic Velocity Test

Resonant Column
Relationship between Matric Suction and Stiffness
Properties of Materials

• Four key factors that directly influence the magnitude of $G_{\text{max}}$
  
• Void ratio

• Net stress

• Matric Suction

• Saturation degree

(Sawangsuriya et al. 2008)
Effect of wetting and drying cycles on Maximum shear modulus

\[ \sigma_{vn} = 20 \text{ kPa} \]
\[ e_o = 0.332 \]

*Fig. 11. \( G_{\text{max}} - \psi \) relationship during the three drying-wetting cycles.*

(Ngoc et al., 2019)
Relationship between Matric Suction and Stiffness Properties of Materials

- Correlations between Maximum Shear Modulus and Matric Suction

\[ G_{\text{max}} = p_r f(e) \left[ b_1 \left( \frac{\psi S_r}{p_r} \right)^{m_1} + c(1 - S_r)^k \right] \text{ for } S_r \geq S_{rs} \]

\[ G_{\text{max}} = p_r f(e) \left[ b_2 \left( \frac{\psi S_r}{p_r} \right)^{m_2} + c(1 - S_r)^k \right] \text{ for } S_r < S_{rs} \]

Ngoc et al., 2020

\[ \frac{G_o}{w \xi \omega} = \alpha \log \psi - \beta \]

\[ G_o = \left( \frac{w \frac{E}{E_{\text{std}} \frac{w_{\text{opt}}}}}{w_{\text{opt, std}}} \right) (\alpha \log \psi - \beta) \]

Sawangsuriya et al., 2008
• **Young’s Modulus - E**

Uniaxial test ➔ Stress(σ) – strain relationship(ε) ➔ **Young’s Modulus**

\[ E = \frac{\sigma}{\varepsilon} \]
Relationship between Matric Suction and Stiffness Properties of Materials

- Relationship between Young’s Modulus and Matric Suction

(Oh et al., 2009)

- Moduli of elasticity behavior is different in the three stages of desaturation: the boundary effect zone, transition zone, and residual zone (Vanapalli et al. 1999).
  - Boundary effect zone
  - Transition zone
  - Residual zone
• **Relationship between Young’s Modulus and Matric Suction**

![Graph showing the relationship between matric suction and Young's Modulus.](image)

*Initial Properties*
- M2: $w=37\%$, $\rho_d = 1.14$ g/cm$^3$
- M3: $w=29\%$, $\rho_d = 1.14$ g/cm$^3$
- M5: $w=23\%$, $\rho_d = 1.14$ g/cm$^3$

*(Mendoza and Colmenares 2006)*
Correlations between Modulus of Elasticity and Matric Suction

Properties of Materials

\[ E_{\text{unsat}} = E_{\text{sat}} + E_{\text{sat}} \alpha \left( \frac{u_a - u_w}{(P_a/100)} \right) (S^\beta) \]

(Oh et al. 2009)

\[ E_{\text{max(unsat)}} = 30000 \left( \frac{2.3 - e}{1 + e} \right)^2 \left[ \ln(u_a - u_w) \right]^{1.35} \]

(Mendoza et al. 2005)
Resilient Modulus - $M_R$

$M_R = \frac{\sigma_d}{\varepsilon_r}$

- $M_r$: resilient modulus
- $\varepsilon_r$: resilient strain
- $\varepsilon_p$: permanent strain
- $\varepsilon_a$: axial strain
- $\sigma_d$: repeated deviator stress
- $\sigma_a$: repeated axial stress
- $\sigma_c$: constant confining pressure

(Yingliu 2010)
• Relationship between Resilient Modulus and Matric Suction

(Ba et al. 2013)
Relationship between Matric Suction and Stiffness Properties of Materials

- Correlations between Resilient Modulus and Matric Suction

\[
\frac{M_R}{M_{R_{\text{OPT}}}} = 0.385 + 0.267 \log (\psi)
\]

\[
M_R = 142 + 16.9\psi
\]

\[
M_R = k_1 p_a \left( \frac{\theta_b}{p_a} \right)^{k_2} \left( k_4 + \frac{\tau_{\text{oct}}}{p_a} \right)^{k_3} + \alpha_1 \psi^{\beta_1}
\]

\[
M_R = k_1 p_a \left( \frac{\theta_b - 3f \theta \psi}{p_a} \right)^{k_2} \left( \frac{\tau_{\text{oct}}}{p_a} \right)^{k_3}
\]

- Lytton, 1995
- Ba et al., 2013
- Ceratti et al., 2004
- Khoury et al., 2009
Matric Suction - Modulus

(Chu 2020)
Matric Suction - Modulus

SRM/SRM_{opt} = 0.62 + 0.23 \log_{10} \psi
R^2 = 0.74

SRM/SRM_{opt} = 0.35 + 0.62 \log_{10} \psi
R^2 = 0.80 (Ba, 2012)

(Nokkaew et al. 2013)
Matric Suction - Modulus

\[ E_{(\text{unsat})} = E_{(\text{sat})} \left[ 1 + \alpha \left( \frac{u_a - u_w}{P_a / 101.3} \right)^{S^\beta} \right] \]

(Oh and Vanapalli 2018)
## NRRA Funded Project Results

<table>
<thead>
<tr>
<th>185</th>
<th>186</th>
<th>188</th>
<th>189</th>
<th>127</th>
<th>227</th>
<th>328</th>
<th>428</th>
<th>528</th>
<th>628</th>
<th>728</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
<td>3.5 in Superpave</td>
</tr>
<tr>
<td>12 in Coarse RCA</td>
<td>12 in Fine RCA</td>
<td>12 in Limestone</td>
<td>12 in RCA+RAP</td>
<td>6 in Class 6 Aggregate</td>
<td>6 in Class 6 Aggregate</td>
<td>6 in Class 5Q Aggregate</td>
<td>6 in Class 5Q Aggregate</td>
<td>6 in Class 5Q Aggregate</td>
<td>6 in Class 5Q Aggregate</td>
<td>6 in Class 5Q Aggregate</td>
</tr>
<tr>
<td>3.5 in S. Granular Borrow</td>
<td>3.5 in S. Granular Borrow</td>
<td>3.5 in S. Granular Borrow</td>
<td>3.5 in S. Granular Borrow</td>
<td>18 in LSSB (1 lift)</td>
<td>18 in LSSB (1 lift)</td>
<td>9 in LSSB</td>
<td>9 in LSSB</td>
<td>9 in LSSB</td>
<td>9 in LSSB</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>Sand</td>
<td>Clay Loam</td>
<td>Clay Loam</td>
<td>TX</td>
<td>TX+GT</td>
<td>BX+GT</td>
<td>BX</td>
<td>Clay Loam</td>
<td>Clay Loam</td>
<td>Clay Loam</td>
</tr>
</tbody>
</table>

### Notes:
- **S. Granular Borrow** = Select Granular Borrow
- **Clay Loam**
- **Sand**
- **TX** = Triaxial Geogrid
- **BX** = Biaxial Geogrid
- **GT** = Nonwoven Geotextile
Matric Suction - Modulus

**Coarse RCA**

\[ y = 107.88 + 0.3943x \]

\[ R^2 = 0.81 \]

**Fine RCA**

\[ y = 99.289 + 0.1897x \]

\[ R^2 = 0.89 \]
Matric Suction - Modulus

- **Limestone**
  - Equation: $y = 66.163 + 3.2136x$
  - $R^2 = 0.94$

- **RCA+RAP**
  - Equation: $y = 73.482 + 2.6044x$
  - $R^2 = 0.88$
SUMMARY

• Determination of the Resilient Modulus for various matric suctions / water contents / saturation degree has a significant effect on the design process of long-lasting pavement structures.

  • The effect of various climate and traffic conditions
  • The moisture-sensitive models

*Improved Prediction of the Pavement Response*
• In various engineering designs such as compacted subgrades and support fills for highways, railroads, airfields, parking lots, earthquake resistant structures and foundations the Soil Modulus is required.

• Soil Modulus \((G_{\text{max}}, E, M_R)\) which represents the stiffness of geomaterials for different cases is related to Matric Suction.

Knowing the Effect of Matric Suction will Increase the Accuracy of the Design of Engineering Structures!
Acknowledgements

- Counties, Cities and MnDOT Districts
- Federal Highway Administration and State DOTs
- Manufacturers, Contractors and Consultants
- Universities and the National Academies
Outline

• Pavement Foundations are Important
• Pavement Design Framework
• Performance Based Specifications
• Lessons Learned
Pavement Foundations are Important

Surface Condition

Remaining Service Life
What is Remaining Service Life?

Step 1: Annual condition of each road section is measured.

Step 2: Future performance is estimated based on previous design and construction. We can change this.

Step 3: If ride quality is estimated as 2.5 in 2022.

Then the remaining service life estimated in 2016 would be 6 years.
Need to Construct Better Foundations

More uniform “good” aggregate base and subbase during construction is an example. So that the remaining service life can be extended from 6 to 11 years.
Importance of Good Base and Subbase

“Good” Class 5 and Select Granular

“Poor” Class 5 and Select Granular

Pavement Lane Miles

Service Life (Years)

Courtesy of Erol Tutumluer, Best Value Granular Project, July 20, 2010
DATE: March 20, 2002

TO: District Engineers (DISTENG), District Materials Engineers, District State Aid Engineers (DSAIE) VIA Groupwise

FROM: Gerald J. Rohrbach, Director Office of Materials & Road Research

PHONE: 651-779-5590


Through cooperative efforts with the University of Minnesota and the Local Road Research Board, the Minnesota Department of Transportation has developed a software program entitled MnPAVE. MnPAVE is a mechanistic-empirical design procedure based on structural analysis of a layered pavement system and is intended for use by state and local agencies. It is now time to move into the training/implementation phase and begin using the design procedure on a trial basis.

MnPAVE has several key advantages over our current Mn/DOT design procedures. These include the capability to 1) adapt to different distress modes, 2) implement better materials tests, 3) adapt to changing load limits and configurations, and 4) achieve agreement between structural and material design. In short, MnPAVE will allow agencies to design and construct more cost-effective flexible pavements.
MnPAVE Design Inputs are Layer Thickness and Stiffness

- Provides the framework for using performance based material properties
- Free pavement design software available: www.dot.state.mn.us/app/mnpave/index.html
- Just Google “MnPAVE”
MnPAVE also Requires Moisture Inputs

### Structure

#### Design Mode
- Use values from Basic Design Level
- Use values from Intermediate Design Level
- Advanced mode (enter values now)

#### Parameter Shown Below
- Design Modulus, ksi
- Adjusted
- Poisson's Ratio
- Seasonal Modulus Multipliers
- Modulus Coefficient of Variation, %

#### Edit Structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HMA</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>AggBase</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Subbase</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>EngSoil</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>UndSoil</td>
<td></td>
</tr>
</tbody>
</table>

#### Moisture Included Here

<table>
<thead>
<tr>
<th></th>
<th>Fall</th>
<th>Winter</th>
<th>Early Spring</th>
<th>Late Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>10</td>
<td>0.36</td>
<td>0.84</td>
<td>1.02</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>10</td>
<td>0.7</td>
<td>0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>10</td>
<td>0.7</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>10</td>
<td>0.7</td>
<td>0.85</td>
<td></td>
</tr>
</tbody>
</table>
Gradation used to Estimate Suction

For typical moisture range. Suction range is 1 – 60 kPa
Moisture Condition Case Studies

Pavement Foundations are Important
Pavement Design Framework
Performance Based Specifications
Quantifying Moisture
Lessons Learned and Next Steps

unsaturated geomechanics

seasonal properties

unsaturated geomechanics
Lessons Learned from Case Studies

• Modulus and strength are greatly affected by the moisture between the particles, which causes a suction or tensile stress between the particles.

• Tensile stress between particles depends on:
  • Gradation (quantity of sand, silt, and clay)
  • Particle shape (roughness)
  • Porosity (void space “openness”)
  • Moisture content (how much water is in the voids)
Construction request.
Need to eliminate unsafe Testing
MnPAVE Outputs are Pavement Life and Moisture Corrected LWD Deflections

<table>
<thead>
<tr>
<th>Surface Material</th>
<th>Field Modulus (MPa)</th>
<th>Field Resistance Factor</th>
<th>LWD Deflection (mm) at top of Surface Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Opt. -20%</td>
</tr>
<tr>
<td>AggBase</td>
<td>180.5</td>
<td>1.15</td>
<td>0.52</td>
</tr>
<tr>
<td>EngSoil</td>
<td>29.98</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>UndSoil</td>
<td>19.23</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Estimated Target Values

Simulated using material properties from Intermediate design level.
Ralph Proctor reminds us.

- Density does not determine strength.
- Optimum moisture is for compaction.
- Need to avoid rutting during construction.

Photo courtesy of Dr. J. David Rogers
Missouri University Science & Technology
“No use is made of the actual peak dry weight.”

“Methods for hand compaction, such as dropping various weight tampers from different heights and mechanical tampers, were tried and discarded.”

“The measure of soil compaction used is the indicated saturation penetration resistance.”
What went wrong during WWII?
Density was used, not penetration test.

Photo courtesy of Dr. J. David Rogers
Missouri University Science & Technology
Strength Compared to Density, Proctor 1948

“Modified” Compaction

“Standard” Compaction

Clay Soil

Strength

Compaction Effort
Density Does Not Determine Strength
Need Correct Moisture for Compaction

### Moisture Content

<table>
<thead>
<tr>
<th>Dry Density (pcf)</th>
<th>5%</th>
<th>7%</th>
<th>9%</th>
<th>11%</th>
<th>13%</th>
<th>15%</th>
<th>17%</th>
<th>19%</th>
<th>21%</th>
<th>23%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>15%</td>
<td>22%</td>
<td>28%</td>
<td>34%</td>
<td>40%</td>
<td>46%</td>
<td>53%</td>
<td>59%</td>
<td>65%</td>
<td>71%</td>
<td>77%</td>
</tr>
<tr>
<td>95</td>
<td>17%</td>
<td>24%</td>
<td>31%</td>
<td>38%</td>
<td>45%</td>
<td>52%</td>
<td>59%</td>
<td>66%</td>
<td>72%</td>
<td>79%</td>
<td>86%</td>
</tr>
<tr>
<td>99</td>
<td>19%</td>
<td>27%</td>
<td>35%</td>
<td>43%</td>
<td>50%</td>
<td>58%</td>
<td>66%</td>
<td>74%</td>
<td>81%</td>
<td>89%</td>
<td>97%</td>
</tr>
<tr>
<td>104</td>
<td>22%</td>
<td>31%</td>
<td>39%</td>
<td>48%</td>
<td>57%</td>
<td>66%</td>
<td>74%</td>
<td>83%</td>
<td>92%</td>
<td>101%</td>
<td>109%</td>
</tr>
<tr>
<td>109</td>
<td>25%</td>
<td>35%</td>
<td>45%</td>
<td>55%</td>
<td>65%</td>
<td>75%</td>
<td>85%</td>
<td>95%</td>
<td>105%</td>
<td>115%</td>
<td>125%</td>
</tr>
<tr>
<td>115</td>
<td>29%</td>
<td>40%</td>
<td>52%</td>
<td>64%</td>
<td>75%</td>
<td>87%</td>
<td>98%</td>
<td>110%</td>
<td>121%</td>
<td>133%</td>
<td>145%</td>
</tr>
<tr>
<td>121</td>
<td>34%</td>
<td>48%</td>
<td>61%</td>
<td>75%</td>
<td>88%</td>
<td>102%</td>
<td>116%</td>
<td>129%</td>
<td>143%</td>
<td>156%</td>
<td>170%</td>
</tr>
<tr>
<td>127</td>
<td>41%</td>
<td>57%</td>
<td>74%</td>
<td>90%</td>
<td>106%</td>
<td>123%</td>
<td>139%</td>
<td>155%</td>
<td>172%</td>
<td>188%</td>
<td>204%</td>
</tr>
<tr>
<td>133</td>
<td>51%</td>
<td>71%</td>
<td>91%</td>
<td>111%</td>
<td>131%</td>
<td>152%</td>
<td>172%</td>
<td>192%</td>
<td>212%</td>
<td>233%</td>
<td>253%</td>
</tr>
<tr>
<td>140</td>
<td>65%</td>
<td>91%</td>
<td>118%</td>
<td>144%</td>
<td>170%</td>
<td>196%</td>
<td>222%</td>
<td>248%</td>
<td>274%</td>
<td>300%</td>
<td>327%</td>
</tr>
<tr>
<td>147</td>
<td>90%</td>
<td>127%</td>
<td>163%</td>
<td>199%</td>
<td>235%</td>
<td>271%</td>
<td>308%</td>
<td>344%</td>
<td>380%</td>
<td>416%</td>
<td>452%</td>
</tr>
<tr>
<td>154</td>
<td>143%</td>
<td>200%</td>
<td>257%</td>
<td>314%</td>
<td>371%</td>
<td>428%</td>
<td>486%</td>
<td>543%</td>
<td>600%</td>
<td>657%</td>
<td>714%</td>
</tr>
</tbody>
</table>

### Percent Saturation

- 95: 50%
- 90: 40%
- 85: 35%
- 80: 30%
- 75: 25%
- 70: 20%
- 65: 15%
- 60: 10%
- 55: 5%
- 50: 0%

Courtesy of Soheil Nazarian, 2018 NRRA Pavement Workshop, May 23-24, 2018
Construction Tests Verify Design Properties

DCP

LWD
Dynamic Cone Penetrometer

ASTM D 6951-03

Grading and Base Manual, MnDOT
Light Weight Deflectometer

ASTM E 2583 07
(includes load measurement)

ASTM E 2835 11
(no load measurement)

Grading and Base Manual, MnDOT
## DCP and LWD
### Aggregate Base Target Values

<table>
<thead>
<tr>
<th>Grading Number</th>
<th>Moisture Content</th>
<th>Dynamic Cone Penetrometer Target Value</th>
<th>Light Weight Deflectometer Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>mm / drop</td>
<td>mm</td>
</tr>
<tr>
<td>3.1-3.5</td>
<td>5 - 7</td>
<td>10</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>7 - 9</td>
<td>12</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>9 - 11</td>
<td>16</td>
<td>0.60</td>
</tr>
<tr>
<td>3.6-4.0</td>
<td>5 - 7</td>
<td>10</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>7 - 9</td>
<td>15</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>9 - 11</td>
<td>19</td>
<td>0.71</td>
</tr>
<tr>
<td>4.1-4.5</td>
<td>5 - 7</td>
<td>13</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>7 - 9</td>
<td>17</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>9 - 11</td>
<td>21</td>
<td>0.79</td>
</tr>
</tbody>
</table>
S-47.3 CONSTRUCTION REQUIREMENTS

Compact the entire lift to achieve the LWD-TV per Table 1. Either LWD-TV parameter (Maximum Allowable Deflection or Minimum Allowable Elastic Modulus) may be used, unless specifically designated in the contract. Ensure the same LWD-TV parameter is used throughout the entire project. Re-evaluate the selected LWD-TV, and contact the Grading and Base Engineer, when failing results consistently occur and adequate compaction is observed through quality compaction.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Material Type</th>
<th>Maximum Allowable Deflection (mm)</th>
<th>Minimum Allowable Elastic Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2105 or 2106</td>
<td>Granular</td>
<td>0.78</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Clay and Clay Loam</td>
<td>1.47</td>
<td>20</td>
</tr>
<tr>
<td>2211</td>
<td>Base</td>
<td>0.55</td>
<td>50</td>
</tr>
</tbody>
</table>

MnDOT Detroit Lakes
### Table 1. Chemically Modified Soils and Aggregate over Chemically Modified Soils

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Average</th>
<th>Maximum at a Single Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime Modified Soil</td>
<td>≤ 0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Cement Modified Soil</td>
<td>≤ 0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>Aggregate over Lime Modified Soil</td>
<td>≤ 0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Aggregate over Cement Modified Soil</td>
<td>≤ 0.27</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Table 2. Aggregate over Untreated Soils Where Proofrolling Can Be Performed

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Average</th>
<th>Maximum at a Single Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.51</td>
<td>0.57</td>
</tr>
<tr>
<td>12 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.34</td>
<td>0.40</td>
</tr>
<tr>
<td>18 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.31</td>
<td>0.35</td>
</tr>
</tbody>
</table>

### Table 3. Aggregate over Untreated Soils Where Proofrolling Cannot Be Performed

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Average</th>
<th>Maximum at a Single Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>12 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.47</td>
<td>0.52</td>
</tr>
<tr>
<td>18 in. Thick Coarse Aggregate No. 53</td>
<td>≤ 0.44</td>
<td>0.49</td>
</tr>
</tbody>
</table>
AASHTO Draft Specifications

• Just Google “NRRA Geotechnical Team”

• Standard Specification for Quality Management of Earthwork and Pavement Foundation Layers using Modulus

• Acknowledgements
  • Maryland DOT Transportation Pooled Fund 5-285
  • University Texas El Paso NCHRP 10-84
    • NCHRP 24-45 new April 2020
Lessons Learned and Next Steps

• DCPs and LWDs can be used during construction to verify design values.

• It is important to measure moisture because both our ability to compact soils and aggregates, and their long term performance requires knowledge of the moisture content.

• Implementation continues so that the people’s investments are well spent.
Thanks for Listening. Please ask questions.

It’s not rocket science. It is rock science.😊

john.Siekmeier@state.mn.us
Moisture Tension in Sand

https://www.youtube.com/watch?v=a-6YbkZJ5UY
Q&A – Applications

All

NRRA Webinar
May 19, 2020
Closing Remarks

Terry Beaudry P.E.

NRRA Webinar
May 19, 2020
THANK YOU!