In Situ Testing for Mechanistic Empirical Pavement Design

OMRR Research Seminar
Unsaturated Soil Engineering – Applications in Pavements
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Maplewood, MN

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Office of Materials and Road Research
Why Mechanistic Empirical Design?

- Our current procedures cannot adequately address issues facing us today
  - Traffic Volume
  - Axle Loads
  - New Materials
  - Seasonal Optimization
  - Field Staff Reductions
Outline of Presentation

- Current Design Procedure
- Empirical Design and Index Tests
- Mechanistic Design
- In Situ Testing Devices
- Mechanistic Properties Table
Current Design Procedure

- Predominantly Empirical
  - AASHO Road Test
  - Mn/DOT Investigation 183

- Depends on Conditions Remaining the Same
  - Traffic and Materials

- Limited Failure Modes

- Worst Case or Simplified Time Periods
Figure 5-3.6 Bituminous Pavement Design Chart (Aggregate Base)

BITUMINOUS PAVEMENT DESIGN CHART (AGGREGATE BASE)

See Table 5-3.4 for bituminous wearing and binder thickness requirements and Table 5-3.5 for base type and width.
“80% of the flexible test sections failed during the spring. The increased failure during the spring period did not allow ‘smooth’ development of axle load repetitions and damage to the subgrade.” (Peattie, 1965)

Therefore seasonal strains caused by temperature and moisture changes should be considered.
Index Tests and Method Specs

- Soil Classification and Gradation
- Compaction Testing and Test Rolling
- Moisture and Lift Thickness Limits
- R-Value and Compaction Testing
  - Not adequate for ME Design
R-Value compaction pressures vary considerably depending on the soil.

Relative moisture and density of R-Value specimens vary considerably within a soil group and between groups.

R-Value test does not conform to the usual concepts of controlling moisture and density in test specimens.
“Originally published objective of compaction in earth fills was a saturated penetration resistance of 300 lb per sq in."

“Soil would then have twice the penetration resistance required to permit loaded truck travel when fully saturated.”

“The 12 inch blow was required principally to assure accurate determination of this penetration resistance and was never intended as a ‘standard’ or ‘optimum’.”
PERCENTAGES APPEARING ABOVE CURVES SHOW THE COMPACTIVE EFFORTS REQUIRED TO SECURE FROM 90% TO 100% OF THE SOIL DRY WEIGHT SECURED BY 56,250 FT. LB. PER CU FT COMPACTIVE EFFORT AND THE CORRESPONDING SHEAR STRENGTHS.

PERCENTAGES APPEARING BELOW CURVES SHOW THE COMPACTIVE EFFORTS REQUIRED TO SECURE FROM 80% TO 100% OF THE SOIL DRY WEIGHT SECURED BY 12,375 FT. LB. PER CU FT. COMPACTIVE EFFORT AND THE CORRESPONDING SHEAR STRENGTHS.

INDICATED SATURATED PENETRATION RESISTANCE
Mechanistic Tests Are Needed

- Achieve agreement between construction quality assurance and seasonal pavement design.

- Quantify alternative materials and construction practices. Show economic benefit of improved materials. Reward good construction.

- This requires new specifications and new tools. Tools must be quantitative, portable, and accurate in the field.
In-Situ Testing of Mechanical Properties
Prima Portable FWD

- **Impulse Device**
  - Load measured
  - Velocity measured
  - Deflection calculated
  - Variable falling mass
Test Type and Equipment

- **Shear Strength**
  - Dynamic Cone Penetrometer (DCP)
  - Rapid Compaction Control Device (RCCD)

- **Elastic Modulus**
  - Dynatest Falling Weight Deflectometer (FWD)
  - Loadman Portable FWD (PFWD)
  - PRIMA PFWD
  - Humboldt GeoGauge

- **Density**
  - Sand Cone, Nuclear Gauge
Soil Properties Table

- Provide Standardized Input Values
- Left to Right
- Classification and Index Properties
- Strength Tests and Moisture Conditions
- MnPAVE Design Moduli
- Basic to Intermediate to Advanced
## Soil Classification

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>Field Identification</th>
<th>Ribbon Length (inches)</th>
<th>Rating</th>
<th>Possible Equivalent Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (Sa)</td>
<td>Will form a cast when wet. Crumbles easily. 100% passes 2</td>
<td>0</td>
<td>Good to Excellent</td>
<td>50-75 A-1, A-3 SP-SM</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>Grains clearly seen. Will form a cast. Will stand light jarring.</td>
<td>0</td>
<td>Good to Excellent</td>
<td>50-75 A-2 SM, SC</td>
</tr>
<tr>
<td>Sandy Loam (SaL) plastic (10 to 20 % clay)</td>
<td>Slightly plastic to plastic. Sand grains seen and felt. Gritty.</td>
<td>0.75 - 1.5</td>
<td>Fair</td>
<td>100-130 A-4 SM, SC</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>Smooth, shiny, moderate resistance to ribboning.</td>
<td>1.5 - 2.5</td>
<td>Fair to Good</td>
<td>100 A-6 CL</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>Dull appearance, slippery. Less resistance to ribboning than CL.</td>
<td>1.5 - 2.5</td>
<td>Poor</td>
<td>120-130 A-6 ML/CL, MH/CH</td>
</tr>
</tbody>
</table>

### Mn/DOT Standard Textural Classification

- **Sand (Sa)**
- **Loamy Sand (LSa)**
- **Sandy Loam (SaL)**
- **Clay Loam (CL)**
- **Silty Clay Loam (SiCL)**
## Soil Index Tests

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>Sieve Analysis</th>
<th>Atterberg Limits</th>
<th>Standard Proctor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passing #200</td>
<td>Plastic Limit</td>
<td>Density</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Optimum Moisture</td>
</tr>
<tr>
<td></td>
<td>Std Dev</td>
<td>Std Dev</td>
<td>Saturation</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>lb/ft³</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Sand (Sa)</td>
<td>7</td>
<td>NA</td>
<td>112 - 134</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>NA</td>
<td>7 - 12</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>NA</td>
<td>60 - 86</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>15</td>
<td>NA</td>
<td>116 - 133</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>NA</td>
<td>8 - 11</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>NA</td>
<td>62 - 92</td>
</tr>
<tr>
<td>Sandy Loam (SaL) plastic (10 to 20 % clay)</td>
<td>42</td>
<td>17</td>
<td>113 - 125</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>10 - 14</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>27</td>
<td>79 - 89</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>62</td>
<td>19</td>
<td>103 - 115</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3</td>
<td>14 - 20</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>37</td>
<td>81 - 91</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>85</td>
<td>23</td>
<td>99 - 112</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>9</td>
<td>15 - 21</td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>37</td>
<td>80 - 86</td>
</tr>
</tbody>
</table>
Soil Strength Tests in Minnesota

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>R-Value (240 psi Exudation Pressure) Estimated From</th>
<th>Measured</th>
<th>Plate Load Estimated From</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#200</td>
<td>Silt Content</td>
<td>Plastic Limit</td>
</tr>
<tr>
<td>Sand (Sa)</td>
<td>61%</td>
<td>51%</td>
<td>NA</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>39%</td>
<td>30%</td>
<td>NA</td>
</tr>
<tr>
<td>Sandy Loam (SaL) plastic (10 to 20 % clay)</td>
<td>18%</td>
<td>17%</td>
<td>16%</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>14%</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>11%</td>
<td>10%</td>
<td>8%</td>
</tr>
</tbody>
</table>
R-Value vs Silt Content
R-Value vs Silt Content

- Silt causes more problems than clay
- Simple one variable relationship
- Should do resilient modulus test
- Need to develop Minnesota database
## Soil Strength Tests in Illinois

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>ERIMN</th>
<th>CBR</th>
<th>DCP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated From</td>
<td>Estimated From</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silt Content</td>
<td>R-Value Silt Content</td>
<td>R-Value</td>
</tr>
<tr>
<td></td>
<td>MPa</td>
<td>ksi</td>
<td>MPa</td>
</tr>
<tr>
<td>Sand (Sa)</td>
<td>70</td>
<td>10.2</td>
<td>83</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>65</td>
<td>9.4</td>
<td>68</td>
</tr>
<tr>
<td>Sandy Loam (SaL) plastic (10 to 20 % clay)</td>
<td>52</td>
<td>7.5</td>
<td>54</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>44</td>
<td>6.4</td>
<td>46</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>27</td>
<td>3.9</td>
<td>34</td>
</tr>
</tbody>
</table>
Laboratory Eri vs Silt Content
Laboratory Modulus $E_{ri}$

- Laboratory conditions
- standard Proctor 95% maximum density
- standard Proctor optimum moisture
- 10 psi deviator stress
# In Situ Soil Moisture

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>Lab Optimum</th>
<th>In Situ Equilibrium (water depth greater than 5 feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saturation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated From</td>
<td>Pore Suction Resistance Factor</td>
</tr>
<tr>
<td></td>
<td>Clay Content</td>
<td>Plastic Limit</td>
</tr>
<tr>
<td>Sand (Sa)</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>81</td>
<td>75</td>
</tr>
<tr>
<td>Sandy Loam (SaL)</td>
<td>83</td>
<td>85</td>
</tr>
<tr>
<td>plastic (10 to 20 % clay)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>85</td>
<td>90</td>
</tr>
</tbody>
</table>
Resistance Factors

- **Saturation Resistance Factor**
  - Adjustment from lab to in situ conditions
  - Resistance to taking on water

- **Available Water Resistance Factor**
  - Resistance to moisture influence
  - Dependent on soil type
  - Normalized to clay loam

- **Seasonal Moisture Resistance Factor**
  - Based on Mn/ROAD clay loam
Unsaturated Moisture Conditions

- **Laboratory**
  - Proctor
  - Resilient Modulus
- **In Situ Construction**
  - Compaction Testing
  - DCP/PFWD/GeoGauge
- **In Situ Seasonal**
  - Manual and Automated Dielectric Measurement
Moisture vs Dielectric

\[ y = 0.68x \]
\[ R^2 = 0.72 \]

\[ y = 1.27x \]
\[ R^2 = 0.79 \]
Density vs Moisture

- Density Dry
- Density Wet
- Dielectric Moisture Only
Modulus vs Available Water

\[ y = -253.59x + 62.84 \]

\[ R^2 = 0.77 \]
Soil Moduli for Design

<table>
<thead>
<tr>
<th>Mn/DOT Standard Textural Classification</th>
<th>Early Spring</th>
<th>Late Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 weeks</td>
<td>Various Lengths Based on Location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seasonal Moisture Resistance Factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frozen</td>
<td>0.7</td>
<td>0.85</td>
<td>1.0</td>
<td>Frozen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MPa ksi</td>
<td>MPa ksi</td>
<td>MPa ksi</td>
<td>MPa ksi</td>
<td></td>
</tr>
<tr>
<td>Sand (Sa)</td>
<td>350 50</td>
<td>56 8.1</td>
<td>68 9.8</td>
<td>80 11.5</td>
<td>350 50</td>
</tr>
<tr>
<td>Loamy Sand (LSa)</td>
<td>350 50</td>
<td>48 7.0</td>
<td>58 8.5</td>
<td>69 10.0</td>
<td>350 50</td>
</tr>
<tr>
<td>Sandy Loam (SaL) plastic (10 to 20 % clay)</td>
<td>350 50</td>
<td>35 5.1</td>
<td>43 6.2</td>
<td>51 7.3</td>
<td>350 50</td>
</tr>
<tr>
<td>Clay Loam (CL)</td>
<td>350 50</td>
<td>31 4.5</td>
<td>38 5.4</td>
<td>44 6.4</td>
<td>350 50</td>
</tr>
<tr>
<td>Silty Clay Loam (SiCL)</td>
<td>350 50</td>
<td>18 2.6</td>
<td>21 3.1</td>
<td>25 3.7</td>
<td>350 50</td>
</tr>
</tbody>
</table>
Useful “Rule-of-Thumb”
Conclusions

- Sand cone testing has been useful, but is not time efficient, does not verify design properties, and should be replaced.
- Field tests are now available that can measure the mechanistic properties used to design pavements.
Conclusions (continued)

- Useful correlations exist between the strength, measured using the DCP, and the elastic deformation modulus, measured using the PFWDs and GeoGauge.

- Need to define which modulus: static or dynamic loading, stress level, boundary conditions, relative density, and moisture.
Recommendations

- Continue transition to mechanistic design. Conduct additional testing during the 2002 construction season.
- Implement quality control and quality assurance tests that measure the mechanical properties of constructed pavement system.
- Verify relationships between the properties measured during construction and the seasonal material properties.
Recommendations (cont)

- Standardize laboratory modulus testing to provide the designer with the best-case and worst-case material properties.
- Develop other quantitative in situ testing techniques that better define moisture sensitivity and drainage characteristics.
- Provide incentives for producing pavement structures that are stronger, stiffer, and more uniform than minimum specified.
University of Minnesota ME Projects

- Mechanistic Design 1999
- Seasonal Properties 2000
- Dynamic Analysis of FWD 2001
- PFWD Calibration 2002
- Modulus of Select Granular 2002
- MnROAD TDR Data Analysis 2002
- Moisture Retention Characteristics 2003
- Moisture Effects on DCP/PFWD 2003
Thank you.

- Questions?
- http://mnroad.dot.state.mn.us
Appendix

- The following slides may be of interest, but were not included in the seminar presentation.
New DCP Specification 2211

- Defines Minimum Shear Strength of Aggregate Base.

- "The full thickness of each layer of Classes 5 and 6 shall be compacted to achieve a penetration index value less than or equal to 10 mm per blow."
"...must be tested and approved within 24 hours of placement and final compaction. Beyond the 24 hour limit, the same aggregate can only be accepted by the Specified Density Method" (sandcone and standard Proctor).
State DOTs Using DCP

California  Michigan  Ohio
Colorado   Minnesota  Oklahoma
Florida    Mississippi Pennsylvania
Illinois    Missouri  South Carolina
Iowa       Montana   Texas
Kansas     New Jersey Utah
Kentucky   North Carolina Wisconsin
Maryland   North Dakota
Current/Future Standards

- Mn/DOT DCP Specification Aggregate Base
- ASTM DCP Test Method
- ASTM GeoGauge Test Method
- FHWA GeoGauge Pooled Funds Study
- FHWA Subgrade Performance Study
- AASHTO Test Procedures
- AASHTO 2002 Pavement Design
- United Kingdom Performance Specs.
In Situ Mechanistic Test Equipment

- **Stiffness Measurement**
  - GeoGauge Humboldt [http://www.hmc-hsi.com](http://www.hmc-hsi.com)
  - PFWD PRIMA [http://www.pavement-consultants.com](http://www.pavement-consultants.com)
  - PFWD LWDT [http://www.controls.it](http://www.controls.it)

- **Strength Measurement**
  - DCP Kessler [http://www.kesslerdcp.com](http://www.kesslerdcp.com)
  - DCP CSIR Nick Coetzee [nfcoetzee@dynatest.com](mailto:nfcoetzee@dynatest.com)
  - DCP TMC Tool Tom Clark (763) 559-2896
  - DCP Vertek ARA [http://www.vertek.ara.com](http://www.vertek.ara.com)