Minnesota Experience with GPR Based Rolling Density Meter

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Acknowledgements

- FHWA/AASHTO – Steve Cooper
- GSSI
- TTI
- MnDOT district materials and constructions
Why MnDOT is interested in?

➢ MnDOT Uses Cores Density for Acceptance
  ➢ Need a tool for continuous assessment: RDM

➢ Longitudinal Joint deterioration

➢ Paver Mounted Thermal Profiling

➢ Intelligent Compaction

➢ RDM in 2015 with Maine and Nebraska
MnDOT Equipment

- Push Cart Type RDM
- Vehicle Mounted RDM
Equipment Calibration

- High Density Polyethylene (HDPE)
- Reported dielectric: 2.3-2.35

\[ \varepsilon_{HM4} = \left( 1 + \frac{A_0}{A_P} \right)^2 \frac{1}{1 - \frac{A_0}{A_P}} \]
Footprint area of an antenna (Fresnel Zone)?

\[ Fr \approx 0.5 \sqrt{\frac{tr}{fc}} \]

D = 12”, Fr (Radius) ~ 3.6” (for 2.7Ghz-RDM)
Playback File: 052SW1UU_21_14___004

PaveScan RDM

Core ID: W6 Low
Core ID: W5 High

5% Air Voids
10% Air Voids
RDM Principal

➢ Mainline Survey: multiple passes

➢ Joint Survey: one antenna close to joint
Summary Field Use - Equipment Validation

Green-MnDOT with Vehicle Mounted RDM

Red – Consultant with Walking Cart RDM
Use histogram to assess uniformity and quality.

- All Data Collected
- Sampling Rate = 0.4 in/scan.
- > 26 million measurements
- Analysis based on 4 in. moving average
- Equivalent to >1 million cores
- Summary Stats
  - 93.2% median density
  - STD: 1.18
  - 97.5% locations density > 90.8%
Examples: TH 52 – Left and Right Mainline

- Median Density
  - Right: 93.4%
  - Left: 93.1%

- STD: 0.92(R) and 0.96(L)

- 97.5% locations:
  - > 91.6% (R)
  - > 91.2% (L)
TH 52 – Longitudinal Joint

Top lift Mainline Average Density:

- Mat 93.5%
- Confined Joint 92.6%
- Unconfined Jnt 91.4%
TH 14 – Mainline

➢ Comparison of Test Sections

➢ Mix B (3/4-) to A(1/2-): not much difference on compaction.

➢ Adding a roller: density slightly increased on this project.

<table>
<thead>
<tr>
<th>Highway 014W Project</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Median Density:</strong></td>
</tr>
<tr>
<td>Blue: 94.1%</td>
</tr>
<tr>
<td>Red: 94.2%</td>
</tr>
<tr>
<td>Yellow: 93.5%</td>
</tr>
<tr>
<td>Green: 93.3%</td>
</tr>
</tbody>
</table>

- Red – ¾” mix + 4 rollers
- Blue – ½” mix + 4 rollers
- Yellow – ½” mix + 3 rollers
- Green – ¾” mix + 3 rollers [control (4’-8’)]
### GPR Asphalt Compaction: Roller Technique Evaluation

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Stationing range, ft.</th>
<th>Offset range, ft.</th>
<th>Color</th>
<th>Samples</th>
<th>Core Taken at 10(^{th}) %, Air Void Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller Technique #1</td>
<td>920+00 to 925+00</td>
<td>Centered on Joint</td>
<td>Red</td>
<td>1000</td>
<td>9.6%</td>
</tr>
<tr>
<td>Roller Technique #2</td>
<td>935+00 to 940+00</td>
<td>Centered on Joint</td>
<td>Green</td>
<td>1000</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

- Example 500 ft section where 2 different echelon breakdown roller techniques were used on the joint:
  - On-site RDM dielectric indicated greater compaction using technique 2
  - Core taken at 10\(^{th}\) percentile indicated greater compaction in technique 2
- On-site dielectric can be used to give feedback as to what techniques are more effective for compaction
Summary Field Use: 2018 TH371 contractor experience – equipment validation

Good agreement between Contractor and MnDOT data:
Median dielectric difference in swerve tests less than 0.05
On-Site Feedback

- Contractor could identify low and high density locations
- R01 – dielectric 4.1
- R02 – dielectric 4.6
- Corresponded to 87.8% and 94.2% relative density respectively
Core Locator for Implementation

➢ Automatic to identify core locations at the end of each paving day
  ➢ At low and high dielectric locations
  ➢ Ex: 10% and 90%
## Core Locations Output

<table>
<thead>
<tr>
<th>Core Number</th>
<th>Distance (ft)</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Elevation (m)</th>
<th>Lateral Offset (ft)</th>
<th>Dielectric</th>
<th>Northing</th>
<th>Easting</th>
<th>Stability Difference</th>
<th>Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R84.1</td>
<td>9785</td>
<td>43.7403</td>
<td>-93.7140</td>
<td>357.9600</td>
<td>-0.5000</td>
<td>5.4851</td>
<td>1.8768e+05</td>
<td>5.6237e+05</td>
<td>0.0601</td>
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<tr>
<td>2</td>
<td>R85.1</td>
<td>11016</td>
<td>43.7384</td>
<td>-93.7101</td>
<td>357.6800</td>
<td>-2.5000</td>
<td>8.0004</td>
<td>1.8700e+05</td>
<td>5.6340e+05</td>
<td>0.0733</td>
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<tr>
<td>3</td>
<td>R86.1</td>
<td>1.2754e+04</td>
<td>43.7357</td>
<td>-93.7047</td>
<td>356.0600</td>
<td>-0.5000</td>
<td>5.4209</td>
<td>1.8603e+05</td>
<td>5.6484e+05</td>
<td>0.0538</td>
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<tr>
<td>4</td>
<td>R87.1</td>
<td>1.1433e+04</td>
<td>43.7378</td>
<td>-93.7085</td>
<td>357.3900</td>
<td>-2.5000</td>
<td>7.7417</td>
<td>1.8675e+05</td>
<td>5.6374e+05</td>
<td>0.0464</td>
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<tr>
<td>5</td>
<td>R88.1</td>
<td>1.4217e+04</td>
<td>43.7333</td>
<td>-93.6999</td>
<td>356.4300</td>
<td>-2.5000</td>
<td>5.4010</td>
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<td>5.6614e+05</td>
<td>0.0148</td>
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<tr>
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<td>7</td>
<td>R90.1</td>
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<td>357.8700</td>
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<td>5.3488</td>
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<td>0.0701</td>
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<tr>
<td>8</td>
<td>R91.1</td>
<td>9908</td>
<td>43.7401</td>
<td>-93.7136</td>
<td>357.9300</td>
<td>23.0000</td>
<td>5.8927</td>
<td>1.8760e+05</td>
<td>5.6248e+05</td>
<td>0.0675</td>
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<tr>
<td>9</td>
<td>R92.1</td>
<td>1.1628e+04</td>
<td>43.7373</td>
<td>-93.7079</td>
<td>357.1600</td>
<td>0.5000</td>
<td>5.1195</td>
<td>1.8659e+05</td>
<td>5.6399e+05</td>
<td>0.0155</td>
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<tr>
<td>10</td>
<td>R93.1</td>
<td>1.0657e+04</td>
<td>43.7388</td>
<td>-93.7109</td>
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<td>4.5000</td>
<td>5.7674</td>
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<tr>
<td>11</td>
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<td>1.3948e+04</td>
<td>43.7337</td>
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<td>355.8800</td>
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<td>1.3935e+04</td>
<td>43.7338</td>
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<td>4.5000</td>
<td>5.5770</td>
<td>1.8531e+05</td>
<td>5.6591e+05</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

- Also saved as a .xlsx file
Summary Field Use – Core Locator

- automatically guide field person to the core location for coring
Conversion from Dielectric to Air Voids

Current Method: Field Empirical

Limestone vs Granite

\[ y = 4588.7e^{-1.328x} \]
\[ R^2 = 0.7774 \]

\[ y = 4226.3e^{1.19x} \]
\[ R^2 = 0.6892 \]

Theoretical Method: Mix Modeling

\[ AV\% = Ae^{-B \cdot \text{dielectric}} \]
Conversion from Dielectric to Air Voids: Laboratory Empirical

\[ AV = \exp \left( -7.53 \left( 3.40 \left| \frac{1}{1.797} \frac{1}{1.997} - 1 \right| \right) \right) \]

\[ R^2 = 0.97 \]
Conversion from Dielectric to Air Voids: Laboratory Empirical TH371

- All predictions based on gyratory pucks 10-1-2018 through 10-6-2018 predicted similarly
- Predictions based on 9-29-2018 under predicted air void content relative to others
- Field cores R01 and R02 from 10-1 confirmed October predictions
Activities

- Calibration of Equipment
  - Field Testing:
    - 2016: TH52 and TH14: Surveyed about 18 miles.
    - 2017: I35; Th52; Th22; Th60; CR86; Th110; CSAH13 and MnROAD
      - Hired American Engineering Testing (AET) to collect data
      - Educating consultant and contractors on this new technology
      - Testing application feasibility of vehicle mounted RDM system on construction projects.
    - 2018: “Ghost” specification and core locator – 1 or 2 projects
      - TH47, TH14, TH109 and TH50 so far
      - Work with GSSI on software improvements

- Research on Laboratory Calibration
- Gyratory Specimen
Summary

➢ RDM is a good tool for mapping a continuous coverage of the relative compaction levels (higher dielectric = higher compaction)

➢ Histograms and general statistics can be used to give a complete assessments of the in-place compaction

➢ Immediate Feedback : Millions of Data Points

➢ Potential Uses:
  ➢ Assess compaction density and uniformity for QC/QA.
  ➢ Provide on-site feedback to contractor of high and low compaction locations that they can cross-check with differences in mix or paving strategies in those locations to determine optimal construction procedures
  ➢ Identification of trends in the air void content maps that can be cross-checked with IC and other data to determine the most critical factors in achieving higher density
Thanks for your time and attention
<table>
<thead>
<tr>
<th>Aggregate Source</th>
<th>% of mix</th>
<th>% of mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powers BA Sand</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Powers 1/2 Rock</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Powers Dust</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Powers 5/8 Rock</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Swenson 3/4 Rock</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rap</td>
<td>30</td>
<td>32</td>
</tr>
</tbody>
</table>
Underlying layer effect on surface measurement?

How thick does the HMA layer need to be so that the underlying layer (agg. base) has no effects?

\[ h_1 = v^* \Delta t_1 / 2 \]

\[ v = c / \sqrt{\varepsilon_1} \]

\[ dT \sim 0.439 \text{us} \]