Webinar: Part 3 – Procedures
Advanced Method for Compaction Quality Control
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Webinar 60 mins
Questions 5 mins
GoTo Webinar functions

Attendee microphones are muted

Please type your questions here
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P60: Best practice in compaction quality assurance for subgrade materials

ARRB Project Leader: Dr. Jeffrey Lee

TMR Project Manager: Siva Sivakumar

NACOE P60

Aim and Background of the Project

• **Aim**
  – To modernise testing procedure for compaction quality assurance

• **Background**
  – Quality is conventionally been verified using density measurements
  – Alternative methods have been developed over the past two decades
  – Many of these methods takes less time to do, results become available in a much shorter time frame, and is able to measure in situ stiffness.
Summary of Previous 2 Webinars + Basics

Density Ratio
- Moisture Ratio
  - Compaction

Material Quality
- CBR / Gradings / Atterbergs

Underlying Material
- Depth of influence
- Quality
- Compaction
Multiple Targets measured: DR + Quality + Underlying interaction

Alternate Tests are measuring more than 1 variable

Partly accounts for the low $R^2$

Alternate Tests measure – One Target
What industry wants and equipment position

Accuracy vs Other Equipment Characteristics

- Poor Accuracy
- Ideal Test
- PANDA, CLEGG, GEOGAUGE, DCP, LFWD (Prima + Zorn)
- PLT Best Accuracy
- Poor Test
- Density Best Precision
- Poor Overall Characteristics

Precision + Ease of Use + Ease to Process Data + Time to do test + Time to report Test + Amount of Data + Capital Cost

Accuracy
Correlation of ICMV to NG dry unit density

Figure 96 presents the correlation results between ICMVs and the NG dry unit density $r_d$. The main conclusions are summarized as follows:

- ICMV increases with increasing $r_d$ as expected, and overall a poorer correlation is achieved than that of $E_{LWD}$, $E_{FWD}$, and $E_{V1}$ and $E_{V2}$;

- Dependent on the specific test strip and materials, either the direct linear, or the logarithmic scaled linear function may achieve better correlation;

- For some cases, significant scatter in the relationships is shown (e.g. MS TBs1, 2, 4 CCV, and KS TB1 and TB2 MDP80). These values are likely influenced by different material type encountered and narrow range of MDP80 values on each material type.

- Different materials show different correlation results and variation trends (e.g. KS TB3 foundation shale and clay materials). These separate trends could be a result of differences in the underlying support, material, and moisture conditions.
The future of Modulus Based Measurements

Measuring Modulus for Better-Performing Pavements

WHAT WE LEARNED

The proposed Standard Specification for Modulus-Based Quality Management ofEarthwork and Unbound Aggregates provides a flexible method for measuring the modulus of compacted geomaterials that can be adapted to local requirements and materials. The proposed specification also includes a process for selecting a target modulus for specific compacted geomaterials. Several devices successfully measured modulus, although lightweight deflectometers are recommended due to their ease of use and widespread availability. Different kinds of deflectometers provided different measurements, however, so construction specifications should specify which model of deflectometer should be used.

WHY IT MATTERS

Modulus is one material property that directly relates to the long-term performance of pavement. As a result, it can be used in mechanistic-empirical design, which can help agencies maximize the value they get from their construction investments by designing roads to meet performance needs without using more construction materials than necessary. A specification for measuring modulus will also be valuable as agencies use more recycled geomaterials in construction.

NEXT STEPS

Put It into Practice

DEMONSTRATE

Introduce the new specification gradually in pilot projects with your staff and contractors who are open to the new approach.

COLLABORATE

Work closely with your staff and contractors to eliminate the culture shock that may result from the new approach.

EVALUATE

As projects are built using the new specification, collect feedback and adjust protocols as needed.

REAL-WORLD NEED

Proper compaction of roadway base and subbase is vital to ensuring good performance of a pavement throughout its life span. While density measurement has traditionally been used to indicate geomaterial compaction, this practice has limitations. Modulus, a measure of stiffness, is a better predictor of performance and provides inputs necessary for mechanistic-empirical design. Measuring modulus is particularly important for predicting the performance of recycled materials since there is little data relating the density of these materials to their strength.

ADAPT

Take advantage of the new specification.
Dendrogram Clusters (20 variables)

| 3rd Order Clustering | • OMC  
|                      | • MDD  
| 2nd order Clustering | • e before  
|                      | • Air voids after 
|                      | • DOS after 

### Density Cluster
- • DR at compaction
- • Dry Density

### Swell Cluster
- • Swell
- • [DOS Change / Air Voids Change] / Air Voids before
- • MR soaked / AP Avg MC / e after

### CBR Cluster
- • 2.5 / 5.0mm
- • MR at compaction / Compaction MC
- • DOS Before
- • DR Soaked

Measuring Density may not be indicative of strength / modulus

Not clustered

CBR related mainly to MC and MR at compaction
CBR (~Modulus) is less related to compaction density

In CH Clays Wet of OMC has higher soaked CBR
CBR (Modulus) is related to compaction MC
Unsaturated soil models based on VMC

Note Dry Density is only a minor part of these strength models


\[ \tau = c' + (\sigma - u_w)\tan \phi' + (u_a - u_w) \left[ \theta \kappa \tan \phi' \right] \]

Volumetric Moisture Content (\( \theta \))

\[ \theta = \frac{w \gamma_d}{\gamma_w} \]

\( \gamma_w \) = unit weight of water
\( \gamma_d \) = dry unit weight of soil

\[ \tau = c' + (\sigma - u_w)\tan \phi' + (u_a - u_w) \left[ \tan \phi' \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right] \]

\( \theta = \text{normalized volumetric moisture content} = \frac{\theta}{\theta_s} \) where \( \theta = \text{volumetric moisture content} \) and \( \theta_s = \text{volumetric water content at saturation} \)

\( \kappa = \text{fitting parameter dependent on the Plasticity Index} \)
\( \kappa = -0.0016 l_p^2 + 0.0975 l_p + 1 \)

Other relationships for \( \kappa \) (eg Tang et al. (2019), “Model Applicability for prediction of residual soil apparent cohesion”)

\( \gamma_w = \text{unit weight of water} \)
\( \gamma_d = \text{dry unit weight of soil} \)

Monte Carlo Simulation of all variables

$$\tau = c' + (\sigma - u_w) \tan \phi' + (u_a - u_w) \left[ \tan \phi' \left( \frac{\theta - \theta_f}{\theta_s - \theta_s} \right) \right]$$

Not practical to measure these parameters

$\hspace{1cm}$

$\begin{array}{c|c|c}
\text{Shear Strength (} \tau \text{)} (\text{Sim#1}) & 81 & 127 \\
\text{Cohesion (kPa)} & 159.9 & 189 \\
\text{Friction Angle (} ^\circ \text{)} & 30 & 35 \\
\text{Tan (Friction Angle)} & 0.577 & 0.700 \\
\text{Confining Stress (kPa)} & 24.17 & 100 \\
\text{Pore Water Pressure (kPa)} & 2.33 & 10 \\
\text{Soil Suction (kPa)} & 316.67 & 250 \\
\text{VMC (%)} & 45% & 35% \\
\text{Sat VMC (%)} & 50% & 35% \\
\text{Residual VMC (%)} & 10% & 5% \\
\end{array}$

$\begin{array}{c}
\text{Gravimetric Moisture content (%)} \\
\text{Dry Density (t / cu m)} \\
\text{Confining Stress (kPa)} \\
\text{Pore Water Pressure (kPa)} \\
\text{Soil Suction (kPa)} \\
\text{VMC (%)} \\
\end{array}$

$c' = 5 \text{ kPa}$

$\phi' = 35 ^\circ$
Spearman Rank of all variables

\[ \tau = c' + (\sigma - u_w) \tan \phi' + (u_a - u_w) \left[ \tan \phi' \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right] \]
Summary

We emphasise density in QC but it is not the primary parameter

- Unsaturated soil models
- 9 Variables
- MC effect is No. 3
- DD effect is No. 6

- Dendrogram Clustering analysis
- 20 Test variables
- CBR affected by MC more than DR

- Lab Correlations
- CBR affected by MC more than DR

- Field Testing
- Modulus has low correlation with DR
- Instruments well correlated to each other

Total unit weight = Total density \( (\rho_b) = \frac{W}{V} \)

Dry unit weight = Dry density = \( W_s / V = \rho_b / (1 + w) \)
2019 Test site Lessons Learnt
Compaction Levels
Test QA – Thresholds Related to RDD

Available data used to develop correlations during ‘Live’ Construction Project

Based on 72 Tests using Prima 100 LWD

<table>
<thead>
<tr>
<th>Threshold</th>
<th>RDD</th>
<th>LFWD</th>
<th>Fail / Fail</th>
<th>Pass / Pass</th>
<th>Density = Fail LFWD = Pass</th>
<th>Density = Pass LFWD = Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>96%</td>
<td>15 MPa</td>
<td>0</td>
<td>69</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>98%</td>
<td>30 MPa</td>
<td>5</td>
<td>50</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>60 MPa</td>
<td>16</td>
<td>30</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>103%</td>
<td>160 MPa</td>
<td>54</td>
<td>1</td>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Correct Assessment (RDD + LFWD Agree)  | RDD + LFWD Disagree (1 Test Passes / 1 Test Fails) |
96%                                  | 4%                    |
77%                                  | 22%                   |
64%                                  | 36%                   |
76%                                  | 24%                   |
A density pass → but fail LFWD → disagreement
Spot check with NDG testing may not be able to effectively identify the “soft” spots such as wet zones.
Lot 24 - LFWD Tests

- Lot 24 LFWD “failing” ≠ assumed density “passing” results
- Recheck of values: allow to dry back → increase of modulus values. Is this allowed? Density had already passed
- < 12 hr dry back: Median 125% of Dry Value: 163% of quartile
- 24 hr dry back: 3.5 – 5.1 increase in modulus

<table>
<thead>
<tr>
<th>Testing Period</th>
<th>No. of Tests</th>
<th>LFWD Modulus (MPa) @ 50kPa</th>
<th>100kPa</th>
<th>50kPa</th>
<th>100kPa</th>
<th>50kPa</th>
<th>100kPa</th>
<th>Ratio Change</th>
<th>Median / Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shortly after fill compaction</td>
<td>4</td>
<td>46.5</td>
<td>23.0</td>
<td>28.4</td>
<td>15.6</td>
<td></td>
<td></td>
<td>Reference Value</td>
<td></td>
</tr>
<tr>
<td>Next Day – Dry backed</td>
<td>4</td>
<td>58.0</td>
<td>37.4</td>
<td>18.2</td>
<td>16.3</td>
<td>1.25 / 0.6</td>
<td>1.6 / 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Further Dry Back</td>
<td>10</td>
<td>167.0</td>
<td>116.5</td>
<td>99.4</td>
<td>70.2</td>
<td>3.6 / 3.5</td>
<td>5.1 / 4.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Water content evaporation loss

Water content losses through the entire thickness from
- 2 X 200mm thick, loose,
- Uncompacted soil layers
- Arid conditions

5% loss in 5 hrs whether in shade or sun
Varies on wind and ambient temperature

Water content is not a constant

Blight and Leong, 2012
Sun, wind or rain after density test
Lot 21 - LFWD Tests

- Density testing was carried out shortly after final layer compaction occurred.
- A period of rain then occurred shortly after testing.
- Tests 2 days after compaction shows significant changes due to rainfall wetness.
- Density testing was business as usual i.e. proceeding without explicitly acknowledging or taking action for changing conditions.

<table>
<thead>
<tr>
<th>Testing Period</th>
<th>No. of Tests</th>
<th>LFWD Modulus (MPa) @ 50kPa</th>
<th>LFWD Modulus (MPa) @ 100kPa</th>
<th>LFWD Modulus (MPa) @ 50kPa</th>
<th>LFWD Modulus (MPa) @ 100kPa</th>
<th>Ratio Change</th>
<th>Median / Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry – shortly after fill compaction</td>
<td>4</td>
<td>116.9</td>
<td>113.0</td>
<td>64.1</td>
<td>72.8</td>
<td>Reference Value</td>
<td></td>
</tr>
<tr>
<td>Rain fell – adjacent to previous tests</td>
<td>4</td>
<td>91.1</td>
<td>98.3</td>
<td>59.6</td>
<td>67.4</td>
<td>0.78 / 0.93</td>
<td>0.87 / 0.93</td>
</tr>
</tbody>
</table>
Lot 21 – Field Volumetric Moisture Content

ProCheck TEROS-12

- A passing density should not mean that subsequent layers can be placed, especially following rainfall.
- VMC X 2 following rainfall
- 88% X Initial Modulus values
- PANDA – little change - deepens by 0.03m

Median = 9.9% → 20.9% / 21.9%
Effect of Temperature on Proctor compaction curves

Soil Temperature varied by up to 6.2 °C - ambient would be more ~ 10 °C warmer than lab. → Not usually considered

Fry (1977) - Figure is here from Caicedo (2019), "Geotechnics of Roads: Fundamentals"
Moisture measurements in active + (assumed) stable zone

Below existing (30yr) road at Cooroy (1700mm annual rainfall)
Monitoring of trial embankments

Constructed at various moisture contents (Cooroy – CH clays)

Moisture Content at construction is not the long term moisture content

Equilibrium Moisture Content (EMC) determines long term strength NOT the OMC at construction which is the short term construction condition
Test site with 100% passing 75mm

Mainly 100% Passing 75mm
Sampling – Test site in practice

Excavations not vertically sided

Shallow excavation samples crushed material at top

Discarding boulders ( > 200mm) from samples
Sampling – Ideal hole

✓ Sampling requires that all material from a vertical-sided hole (excavated to the depth that the NDG source rod was placed) must be recovered for laboratory testing.

✓ The hole permitted to be enlarged in plan, but no deeper than the depth of test, to obtain sufficient material for moisture content and laboratory compaction testing.

✓ It is extremely important to take the sample from the full depth of the test, this captures any moisture gradient in the layer being tested. Failure to take the sample properly can lead to very erroneous results.
Summary

Moisture Content + Construction

- Water content loss
- Varies significantly during placement

- Equilibrium Moisture Condition
  - EMC – Long term
  - OMC – short term

- Field density Sampling
  - Often non representative
  - Gradings + oversize + depth

- Field Testing
  - 1/3 to ¼ disagreement between high density and modulus controls
  - OK at lower density values

Density is not a fundamental indicator of strength or modulus + Moisture content (a better indicator of modulus) is highly variable and changes

<table>
<thead>
<tr>
<th>Assessment (RDD + LFWD Agree)</th>
<th>Disagree (1 Test Passes / 1 Test Fails)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96%</td>
<td>4%</td>
</tr>
<tr>
<td>77%</td>
<td>22%</td>
</tr>
<tr>
<td>64%</td>
<td>36%</td>
</tr>
<tr>
<td>76%</td>
<td>24%</td>
</tr>
<tr>
<td>Contractor Risk</td>
<td>Good</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Accept</td>
<td>Correct</td>
</tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Reject</td>
<td>Type I Error</td>
</tr>
<tr>
<td></td>
<td>Contractor’s</td>
</tr>
<tr>
<td></td>
<td>Risk</td>
</tr>
<tr>
<td></td>
<td>Rejecting a</td>
</tr>
<tr>
<td></td>
<td>Lot when it</td>
</tr>
<tr>
<td></td>
<td>is OK</td>
</tr>
</tbody>
</table>
Specifications options

Specify Values?

- Correlation Approach linked to Standard Density approach
- Project and material specific. Parallel Testing
- Likely to be most variable. Many “good” values fail and “bad” values pass
  Skews QA approach
- Method Of matching PDFs linked to Standard Density approach
- Project and material specific. Parallel Testing
- Uses 10% QA – acceptance decision
- Method of change reduction
- Not linked to Standard Density approach
- Parallel testing not mandatory
- Uses QA acceptance decision
- Intelligent Compaction verification
- NCHRP 676 Options
- Various approaches linked with parallel non density testing
### Typical Specifications – Values

**Issues with correlations to DDR**

<table>
<thead>
<tr>
<th>DDR</th>
<th>LFWD$_{100 \text{kPa}}$</th>
<th>Correct Assessment (RDD + LFWD Agree)</th>
<th>RDD + LFWD Disagree (1 Test Passes / 1 Test Fails)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96%</td>
<td>15 MPa</td>
<td>96%</td>
<td>4%</td>
</tr>
<tr>
<td>98%</td>
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<td>22%</td>
</tr>
<tr>
<td>100%</td>
<td>60 MPa</td>
<td>64%</td>
<td>36%</td>
</tr>
<tr>
<td>103%</td>
<td>160 MPa</td>
<td>76%</td>
<td>24%</td>
</tr>
</tbody>
</table>

When correlated with DDR
In situ $E$ correlated to 95% Density ratio - Values

<table>
<thead>
<tr>
<th>Fill Material Origin</th>
<th>Plate Load Test (PLT) $E_{V2}$ (MPa)</th>
<th>Light Falling Weight Deflectometer (LFWD) $E_{LFWD-100kPa}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone: 70% Gravel size; 10% fines</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Interbedded Siltstone / Sandstone</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>70% Gravel size; 11% fines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt: 65% Gravel size; 12% fines</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

Varies with each material
Various acceptance LFWD for Base Course materials & Layers

Laying and compaction specification for road construction in Germany

<table>
<thead>
<tr>
<th>Soil layers</th>
<th>Density (Standard Proctor)</th>
<th>Bearing capacity (load bearing test, EV2)</th>
<th>Eveness (4 m straight edge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subbase</td>
<td>100 - 103 % *</td>
<td>100 - 150 MN/m² *</td>
<td>20 mm</td>
</tr>
<tr>
<td>Capping layer</td>
<td>100 - 103 % *</td>
<td>100 - 120 MN/m² *</td>
<td>40 mm</td>
</tr>
<tr>
<td>Formation</td>
<td>97 - 100 % *</td>
<td>45 - 80 MN/m² *</td>
<td>60 mm</td>
</tr>
</tbody>
</table>

* depending on road classification and road design

From BOMAG
LFWD
PROCEDURE
QA
Key Elements in LWD specification

LWD Preliminary
- LWD Brand/Manufacturer
- Plate Size
- Drop Height/Drop weight/Buffer Configuration
- Design Pressure
- Other Requirements
- Moisture Condition
- Loose Layer Thickness
- Construction Plant
- Material Quality
- Trial Embankment Preliminary

LWD Testing
- 20 No. tests
- 6 Valid drops: First 3 Drops are seating, Second 3 Drops modulus measurements
- Tastes within 2hrs of compactive effort
- Moisture Condition
- 40m Length X 4.2m wide (2 roller widths - avoid overlaps)
- Acceleration Lane either end
- 3 > 100 m Embankment

Representative LWD Data Interpretation
- Permanent Deformation/Irregular force or pulse/Excessive Recoind
- Calculate quartile, mean/median, COV
- Or Minimum Value governs if < 5 No. representative test

LWD Modulus Project/Material/Equipment specific

Applicable Standards

Relevant Standards:
- ASTM E2563-07 (2011)
  - Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)
- ASTM E2635-11 (2011)
  - Standard Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device

AASHTO Designation:
- TP 123-01 (2017)
  - Standard Method of Test for Laboratory Determination of Target Modulus Using Light-Weight Deflectometer (LWD) Drops on Compacted Proctor Mold.
- TP 456-01 (2017)
  - Standard Method of Test for Compaction Quality Control Using Light Weight Deflectometer (LWD)
Proposed LWD Specification

1. Define Initial Inputs – LWD Configuration

   What **design pressure** is to be verified by onsite testing?

   What **LWD Brand** is proposed to be utilised for onsite testing?

   Is the **LWD Configuration** capable of achieving the \( \sigma_{\text{Design}} \) pressure?
   (and +/- 20% of \( \sigma_{\text{Design}} \))

   What equipment will be utilised to **assess the Insitu Moisture Condition** at time of LWD Testing?

\( \sigma_{\text{Design}} \)

LWD Type

**Defined LWD Variables** – Plate Diameter, Drop Weight, Buffer Arrangement & Drop Height

**Defined Insitu Moisture Content Assessment Technique**
Proposed LWD Specification

2. Define Initial Inputs – Earthworks Variables

- What **Material** is to be used as the source for Earthworks?
- What **Loose Layer Thickness** is to be utilised during Earthworks?
- What **Compaction Equipment & Methodology** is to be utilised to achieve effective compaction?
- What **Moisture Conditioning** will occur prior / during completion of compaction?

- **Material Type and Quality**
- **Lift Thickness**
- **Compaction Technique – Equipment & Method**
- **Insitu Moisture Condition (at time of LWD Testing)**
Proposed LWD Specification

3. Construct Trial Embankment

PLAN

Min. Area = 170 m²

ELEVATION

Layer 1

Layer 2

Min > 1.5 x LWD Plate Diameter

Layers Compacted from ‘Loose Layer Thickness’
Proposed LWD Specification

4. Test Completed Trial Embankment with LWD

- 20 No. Locations (min.)
- Min. 6 Valid Drops at $\sigma_{\text{Design}}$
- LWD Test in accordance with ASTM Test Method (relevant to LWD type)
Proposed LWD Specification

5. Inspect and Standardize LWD Dataset

- Identify and Remove all ‘Seating’ Test Records
- Identify and Remove any Test Records that demonstrate irregular load / deformation shape
- Identify and remove all Test Records that departed from $\sigma_{\text{Design}}$ pressure
- Review all Test Records for demonstration of permanent deformation under $\sigma_{\text{Design}}$ pressure

Valid LWD Test Data

REVIEW – Indicative of Bearing Capacity Issue!
Proposed LWD Specification

6. Assess In situ Modulus-Moisture Relationship (if Present)

- Determine In situ Modulus ($E_{LWD}$) parameter for each Test Site

- Pair individual $E_{LWD-SITE}$ with corresponding In situ Moisture Condition at time of LWD Testing

- Evaluate paired [$E_{LWD-SITE}$, Moisture Content] dataset for presence of modulus-moisture relationship

- $E_{LWD}$ Parameter is NOT Moisture Dependent

- $E_{LWD}$ Parameter IS Moisture Dependent

- Define Function of $E_{LWD}$ – Moisture Condition Relationship
Moisture dependent

**Material Type**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Typical Coefficient of Variation (CoV) of $E_{LWD-SITE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAVEL dominated materials</td>
<td>10 – 20 %</td>
</tr>
<tr>
<td>SAND dominated materials</td>
<td>15 – 35 %</td>
</tr>
<tr>
<td>FINES dominated materials</td>
<td>30 – 60 %</td>
</tr>
</tbody>
</table>

% Fines : Passing 0.075mm sieve

- Not sensitive to moisture < 15% fines
- Partially sensitive to moisture 15% to 35% fines
- Sensitive to Moisture > 35% Fines
Proposed LWD Specification

7. Define $E_{\text{LWD}}$ Acceptance Thresholds (for Production Earthworks QA Testing)

A. For Materials where $E_{\text{LWD}}$ IS NOT Moisture Dependent

Criteria #1 – All $E_{\text{LWD}}$ results for a single earthworks Lot must exceed the minimum $E_{\text{LWD-SITE}}$ value (i.e. Assessment that minimum insitu modulus parameter has been achieved at all locations)

Criteria #2 – Mean $E_{\text{LWD}}$ within a single earthworks Lot must exceed 80% of the mean of the $E_{\text{LWD-SITE}}$ dataset (i.e. Assessment that typical insitu modulus parameter has been achieved across a Lot)

Criteria #3 – Lower Characteristic $E_{\text{LWD}}$ within a single earthworks Lot must not fall below the Lower Characteristic of the $E_{\text{LWD-SITE}}$ dataset (i.e. Assessment that variability of insitu modulus parameter does not exceed expectations)
7. Define $E_{LWD}$ Acceptance Thresholds (for Production Earthworks QA Testing)

B. For Materials where $E_{LWD}$ IS Moisture Dependent

Criteria #4 – Measured $E_{LWD}$ must exceed $[E_{LWD-SITE} – \text{Average of Function Residuals}]$ when $E_{LWD}$ & $E_{LWD-SITE}$ are determined at corresponding Insitu Moisture Contents (i.e. Assessment that observed insitu modulus parameter achieves typical value)

Criteria #5 – Measured $E_{LWD}$ must remain above the Lower Bound 95th Confidence Interval Value for defined $E_{LWD-SITE}$ – Insitu Moisture Content relationship (i.e. Assessment that observed insitu modulus parameter exceeds minimum requirement)
Correlation which avoids curve fitting
Method of Matching PDFs
QA
Paired matching of DR and LFWD (Prima) tests

High Modulus values (> 100 MPa) can “fail” a 100% DR tests

And

values below 30 MPa can “pass” a DR criterion
Method of Matching PDFs
Relating PDFs to DDR

Scatterplot of DCP (Blows / 100mm) vs DDR (%) of SBP Embankment - Lots 1 - 29

$$y = 6E-06e^{0.1388x}$$
$$R^2 = 0.9495$$

Prediction / DDR / Actual
Matching the Dry Density Ratio and LFWD PDFs
Relating PDFs to DDR

<table>
<thead>
<tr>
<th>DDR</th>
<th>LFWD 100 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>96%</td>
<td>15 MPa</td>
</tr>
<tr>
<td>98%</td>
<td>30 MPa</td>
</tr>
<tr>
<td>100%</td>
<td>60 MPa</td>
</tr>
<tr>
<td>103%</td>
<td>160 MPa</td>
</tr>
</tbody>
</table>

Correct Assessment (RDD + LFWD Agree)

- 96%
- 77%
- 64%
- 76%

RDD + LFWD Disagree (1 Test Passes / 1 Test Fails)

- 4%
- 22%
- 36%
- 24%
% Maximum Target Value

H

Method of Change Reduction

QA
% Maximum Target values

Minimum Area = 40 m length X 4.2m wide: No. tests = 2 X 5 = 10 Min / Layer : 2 Layers

2 Layers X ~ 300mm loose

Method of change reduction
QA - Acceptance Criteria

10 Min Tests (Ideally 20 No.)

Minimum Values

- All values $\eta_{\text{min}}$ at 4 passes in trial

4 $\rightarrow$ 6 $\rightarrow$ 8 $\rightarrow$
10 $\rightarrow$ 12
Passes

- Measure $\eta$ every 2nd pass

Maximum Values

- All values $\eta_{\text{max}}$ at 12 passes in trial

Acceptable values (LCV) from trial

- $\eta_{95} < 5\%$ increase (subgrade) or $95\%$ $\eta_{\text{max}}$
- $\eta_{90} < 10\%$ increase (below subgrade) or $90\%$ $\eta_{\text{max}}$

Variation at acceptable value

- COV < 20\% (Gravels)
- COV < 35\% (Sands) -?
- COV < 60\% (Fines) -?

Acceptable values (LCV) from trial

- $\eta_{95} < 5\%$ increase (subgrade) or $95\%$ $\eta_{\text{max}}$
- $\eta_{90} < 10\%$ increase (below subgrade) or $90\%$ $\eta_{\text{max}}$

Variation at acceptable value

- COV < 20\% (Gravels)
- COV < 35\% (Sands)
- COV < 60\% (Fines)

Varies with test equipment
Intelligent compaction QA
IC + Modulus testing


FIGURE 2 (a) Relationship between CMV and deflections measured from LWD mass drops for all sites and (b) proposed protocol for project acceptance.
Is Density Ratio the end game?
Summary and conclusions

3 most common tests are PLTs, Density and DCPs → do not correlate well with each other.

✓ Density Ratio testing is the most precise test. However, poor indicator of strength or modulus, once the pass compaction has been achieved

✓ PLT is very accurate, but low precision

✓ DCPs has a low precision but has other characteristics (ease of use and depth profiling) which make this test attractive

No clear leader for the combined 8 criteria used

✓ Direct or meaningful correlations should be project + material specific

✓ Many Alternative tests are more related to Moisture content rather than density

✓ Moisture content changes likely to occur and affect modulus values

✓ Correlating back to density is unlikely to advance the use of alternative testing
Specifications options

Target Value cannot be universal

- Correlation Approach linked to Standard Density approach
- Project and material specific. Parallel Testing
- Likely to be most variable. Many “good” values fail and “bad” values pass
  - Skews QA approach

- Method Of matching PDFs linked to Standard Density approach
- Project and material specific. Parallel Testing
- Uses 10% QA – acceptance decision

- Method of change reduction
- Not linked to Standard Density approach
- Parallel testing not mandatory
- Uses QA acceptance decision

- Intelligent Compaction verification
- NCHRP 676 Options
- LFWD parallel testing
Thank you for your participation today.

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