In Situ Modulus Measurement Using APLT for State Wide ME Design Calibration

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**What is Mechanistic QC/QA/PC?**

Mechanistic QC/QA/PC refers to in situ verification of properties assumed in design – Typically $M_r$ or $k$ values

<table>
<thead>
<tr>
<th>Design Guide</th>
<th>Rigid Pavement</th>
<th>Flexible Pavement</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHTO 1972</td>
<td>Mod. of subgrade reaction, $k$</td>
<td>Soil support value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural layer coefficient.</td>
</tr>
<tr>
<td>AASHTO 1986</td>
<td>$k$ for subgrade, $k_{comp}$ if base layer is present</td>
<td>Resilient modulus ($M_r$) for subgrade and base</td>
</tr>
<tr>
<td>AASHTO 1993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AASHTO 2008</td>
<td>$M_r$ (stress-dependent constitutive model) for subgrade and base</td>
<td></td>
</tr>
<tr>
<td>PCA 1984</td>
<td>$k$ for subgrade, $k_{comp}$ if base layer is present</td>
<td>N/A</td>
</tr>
<tr>
<td>Asphalt Institute</td>
<td>N/A</td>
<td>Resilient modulus ($M_r$) for subgrade</td>
</tr>
</tbody>
</table>
Mechanistic parameters are: Stress-Dependent

Fine-grained materials exhibit stress-softening behavior

Coarse-grained materials exhibit stress-hardening behavior

\[ M_r = k_1^* P_a \left( \frac{\theta}{P_a} \right)^{k_2} \left( \frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \]

AASHTO (2015) Universal Model

CL, A7-6(2) Fairbault Clay

GW, A-1-a, Class 5 Base
How are the foundation input parameters measured?

*Direct* measurement methods
- Static (repetitive or non-repetitive) plate load testing
- Laboratory resilient modulus testing

*Indirect* measurement methods (*empirical relationships*)
- Falling weight deflectometer (FWD) testing
- Light weight deflectometer (LWD) testing
- CBR testing
- DCP testing
- R-Value testing
- Relative compaction
- Soil classification results
Indirect methods and **empiricism** are convenient and cost less up front but introduce substantial risks.

Terzaghi (1955) noted when describing coefficients of subgrade reaction, “widespread among engineers” is the “erroneous conception” that the “numerical value of coefficient of subgrade reaction depends exclusively on the nature of the subgrade”, and without proper consideration of the test methods, “such values can be very misleading”.

**Example of empirical relationships to estimate k-value from CBR**
APLT – Real Time Resilient Modulus

APLT imparts controlled load pulses (e.g., 0.15 sec pulse + 0.45 sec dwell)

Measure permanent and resilient deflections

\[ E = (1-v^2) \sigma_o \left( \frac{a}{d_o} \right) \]

\( d_o = \text{Elastic deformation} \)

\[ M_r = (1-v^2) \sigma_o \left( \frac{a}{d_r} \right) \]

\( d_r = \text{recoverable deformation} \)
APLT can perform static and cyclic plate load test in accordance with U.S. and European Standards

30 in. Static Plate Load Test according to AASHTO T222, ASTM D1196, and CRD-C 655-95

![Graph showing the relationship between applied stress and deformation for a static plate load test. The graph includes a corrected curve for the area of least curvature.](image)

I-25, Denver, CO
In situ APLT overcomes limitations of lab testing.

1. Limited to small sample sizes (100 mm to 200 mm diameter specimens).
2. Must remove larger particles (19 mm to 25 mm diameter particles).
3. Does not account for interaction between different material layers.
4. Boundary conditions are altered from field conditions.
5. Many inherent laboratory experimental limitations including sample preparation.
6. Does not determine modulus for multiple layers or account for in situ stress transfer.
Foundation layer resistance to permanent deformation is KEY to long-term pavement performance

Subgrade Composite
$M_r = 3,293 \text{ psi}$

Subbase/Subgrade Composite
$M_r = 25,162 \text{ psi}$
A power model describes the permanent deformation versus load cycles response to provide deformation forecasting comparisons.

\[ \delta_p = CN^d \]

Monismith et al. (1975) described the power model relationship for relating permanent strain to cycle loadings.

Post-compaction permanent strain is a function of the shear stress magnitude and can reach an equilibrium state following the “shakedown” concept (see Dawson and Feller 1999).
### APLT offers direct measurements and significant advantages over FWD & LWD testing

<table>
<thead>
<tr>
<th>Feature</th>
<th>FWD</th>
<th>Ingios APLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the test automated? [i.e., No operator bias]</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Can the test be used for testing on pavement layers to determine in situ modulus values?</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Can the test results be used to determine layered moduli values?</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Can controlled cyclic loading be applied?</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Can extended conditioning cycles be applied prior to testing?</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Are peak deformations measured during testing?</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Are rebound deformations measured to calculate in situ resilient modulus ($M_r$)?</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Are permanent deformations (rutting) measured during testing?</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Can load pulse durations/loading frequencies and confinement be controlled to simulate traffic loading?</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Can the results be used to determine frequency-dependent moduli values for testing on visco-elastic HMA layers</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>What is the duration of each test?</td>
<td>5 min (3-6 drops)</td>
<td>5 to 30 min. (100 to 1,400 load cycles)</td>
</tr>
<tr>
<td>Is the test safe to perform on roadways with some traffic control?</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

1Only uses peak deformations, so true resilient modulus cannot be determined. Further, no conditioning cycles are applied to achieve a "near-linear-elastic" state, per assumptions in backcalculation analysis. See feature # 4, 5, and 6.

2Multiple loads can be dropped, but the load pulses are not controlled with a defined load and dwell times.
Field testing was performed at 10 project sites selected by Iowa DOT
Different typical foundation layer support conditions were evaluated at the 10 project sites.
Project 2: Hwy 20 EB near Moville, IA - 10/19/2017
[Recycled Granular Subbase over Select Subgrade]
[Select Subgrade & Modified Subbase]
Project 4: Hwy 330 near Hwy 65 – 11/2/2017
[2 ft of Special Backfill (RAP) Subgrade Improvement]
Project 5: Hwy 100 N., Linn County – 11/3/2017
[Select Subgrade]
Project 9: US20, Woodbury County – 05/16/2018
[Recycled Granular Subbase over Select Subgrade]
Example test results: Composite $M_r - 11$ in. Modified Subbase over Select Subgrade

Model: AASHTO (2015)

$$M_{r - \text{comp}} = k_1^* P_a \left( \frac{\theta}{P_a} \right)^{k_2^*} \left( 1 + \frac{\tau_{oct}}{P_a} \right)^{k_3^*}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1^*$</td>
<td>1.7597</td>
<td>2.29E-07</td>
</tr>
<tr>
<td>$k_2^*$</td>
<td>-0.008</td>
<td>9.21E-01</td>
</tr>
<tr>
<td>$k_3^*$</td>
<td>-0.551</td>
<td>3.66E-01</td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>0.835</td>
<td></td>
</tr>
<tr>
<td>Std. Error [psi]</td>
<td>626</td>
<td></td>
</tr>
</tbody>
</table>

| $M_{\text{comp (pred.)}} [\text{psi}]$ | 25,812 |
| $\sigma_{\text{cyclic-BP}} [\text{psi}]$ | 2.0    |
Example test results: Layered $M_r$ (Base and SG) values – 11 in. Modified Subbase over Select Subgrade

Model: AASHTO (2015)

$$M_r = k_1^* p_a \left( \frac{\theta}{p_a} \right)^{k_2^*} \left( 1 + \frac{\tau_{oct}}{p_a} \right)^{k_3^*}$$

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<tr>
<th>Parameter</th>
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<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1^*$ (Base)</td>
<td>2053.0</td>
<td>1.02E-06</td>
</tr>
<tr>
<td>$k_2^*$ (Base)</td>
<td>0.037</td>
<td>7.91E-01</td>
</tr>
<tr>
<td>$k_3^*$ (Base)</td>
<td>0.151</td>
<td>8.74E-01</td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>0.405</td>
<td></td>
</tr>
<tr>
<td>Std. Error [psi]</td>
<td>1095</td>
<td></td>
</tr>
<tr>
<td>$k_1^*$ (SG)</td>
<td>1298.3</td>
<td>3.89E-06</td>
</tr>
<tr>
<td>$k_2^*$ (SG)</td>
<td>-0.094</td>
<td>2.23E-01</td>
</tr>
<tr>
<td>$k_3^*$ (SG)</td>
<td>-3.858</td>
<td>1.86E-02</td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>0.997</td>
<td></td>
</tr>
<tr>
<td>Std. Error [psi]</td>
<td>155</td>
<td></td>
</tr>
</tbody>
</table>
Project 2: Static PLTs conducted on subbase layer and the underlying subgrade showed similar $k$ values.

[11 in. Recycled Granular Subbase over Select Subgrade]
Site with granular subbase over 2 ft of special backfill provided the highest support values.

Results show that there are variations in $M_r$ values at each site and across the state, that are not adequately accounted for in design.

COV = 5% to 82% at each site.
How reliable is it to assume “typical” $M_r$ values proposed in the ME Design for a given material type?

![Box plot graph showing $M_r$ values for different materials and projects.](image)
How reliable is it to assume “typical” $k$ values proposed in the ME Design for a given material type?

$k = 150$ pci is typically assumed for rigid pavement design in IA.

The diagram shows box plots for two different types of subgrades:

1. **Granular / Modified Subbase over Select Subgrade; $n = 10$**
   - Projects 1, 2, 7, 8
   - $k_u(1)$-Comp at $\delta = 0.05$ in.
   - $k_u(1)$-Comp at $\delta = 10$ psi

2. **Select Subgrade and Embankment Cut/Fill; $n = 7$**
   - Projects 2, 3, 5, and 6
   - $k_u(1)$ at $\delta = 0.05$ in.
   - $k_u(1)$ at $\delta = 10$ psi

$k = 150$ pci
Static PLT results show that there is a strong relationship between $k$-value and $\delta_p$

$$y = 27.309x^{-1.227}$$  
$$R^2 = 0.9726$$

$\delta_p = 0.05$ in. critical for void beneath pavement

$k = 170$ pci
FE analysis was conducted on a Jointed PCC pavement to analyze pavement stresses and impact of $\delta_p$.
Bending stresses in the pavement layer are more significantly influenced by the $\delta_p$ than $k$-value.
Analysis of SR values for different \( k \)-value and LOS cases for different \( H \) revealed that…

\( \delta_p \) and \( H \) are the MOST significant parameters in controlling the bending stresses. \( k \)-value alone is not the most significant factor.
KEY Outcomes of this project are:

✓ $M_r$ values are variable across the state and within each project site. $C_v$ between 5% and 80% at each site.

✓ k-values across the site varied between 35 and 300 pci. 11 out of 14 tests showed < 150 pci.

✓ Sites with 2 ft of special backfill material provided higher $M_r$ values than other sites.

✓ Typical values provided in the ME Design guide based on soil classification are not reliable.

✓ $\delta_p$ from static PLT varied between 0.05 and 0.4 in., with 11 out of the 14 tests > 0.05 in. critical limit.
KEY Outcomes of this project are:

✓ FE analysis showed that the two most important factors to reduce bending stresses in the pavement layer are Pavement Thickness and $\delta_p$.

✓ Bending stresses calculated can be misleading just by simply changing the $k$ or $M_r$ without accounting for LOS due to $\delta_p$. 
MEPDG Field Local Calibration

**GOAL:** Reduce bias and increase precision of the empirical models used to predict performance indicators

AASHTO (2010) guide provides a 11 step procedure to perform local calibration. It covers:

- Developing an experimental plan,
- Estimating the sample size
- Selecting the roadway segments
- Collecting the required field data, and
- assessing bias/standard error in the global calibration factors for local conditions
MEPDG Field Local Calibration

**GOAL:** Reduce bias and increase precision of the empirical models used to predict performance indicators

**STEP 6:** Field and forensic investigations to confirm or obtain any missing key input parameter values for the roadway segment selected

APLTs can be used to provide an accurate measure of stress-dependent $M_r$ values and $k_1$, $k_2$, and $k_3$ regression parameters, and permanent deformation.
MEPDG Field Local Calibration

**GOAL:** Reduce bias and increase precision of the empirical models used to predict performance indicators

Calibration sites typically involve existing pavement sites with some level of distress.

Test sites with georeferenced *mechanistic* measurements during construction can also be utilized for future calibration as distresses develop.
Thank you.

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We started in 2015.
82 projects to-date.