Implementation of Unsaturated Soil Mechanics During Pavement Construction QA

By John Siekmeier, P.E., M.ASCE

Pavement foundations are constructed using compacted materials that have unique soil structures and are initially in an unsaturated condition. Because the strength and stiffness of unsaturated materials are greatly influenced by suction, several design and construction measures are implemented with the intent of maintaining unsaturated conditions throughout the lifetime of the pavement foundation. Saturated conditions are a potential worst-case situation which must be considered during pavement design in order to prevent failure, but long term estimates of pavement performance are driven by unsaturated conditions.

Therefore, the in situ unsaturated mechanistic properties of compacted pavement foundation materials must be quantified. While historically elusive, this quantification is now practical using newly developed performance-related test equipment and procedures. This puts geoprofessionals in a position to actually implement what leaders like Hveem, Proctor, and Seed suggested during the 1950s – perform tests which will truthfully measure the quantity that determines performance, and consider the cohesion, or tensile strength, furnished by films of moisture.

Minnesota DOT's Approach

Many state DOTs have begun implementing new, mechanistic-empirical pavement design programs (e.g., see May/June 2009 *Geo-Strata*), which rely on accurately quantifying the stiffness and thickness of the foundation layers. Minnesota DOT's new flexible pavement design method (MnPAVE) is a mechanistic-empirical method that uses powerful mechanistic calculations to optimize flexible pavement design. Material properties have previously been largely based on empirical tests and experience because Minnesota's traditional pavement design method preceded the development of modern soil mechanics and unsaturated soil science. Recent studies on a range of unsaturated soil specimens have shown that the soil water characteristic curve (SWCC), shear strength, and stiffness vary greatly between soil types. Therefore, pavement design and construction quality assurance (QA) testing are changing in Minnesota, and unsaturated soil mechanics is being implemented using new performance-related construction testing and specifications.

Both contractors, as part of their quality control (QC) process, and MnDOT and other transportation agencies, during their QA process, are modifying testing techniques and coverage to better assess construction uniformity. Because staffing resources have been reduced, the traditional testing methods must be replaced with performance-related tests which are also more time efficient than those traditionally used. This challenge has been aided somewhat by the concurrent implementation of intelligent compaction and continuous compaction control as part of the contractor's QC on some projects. The full-coverage

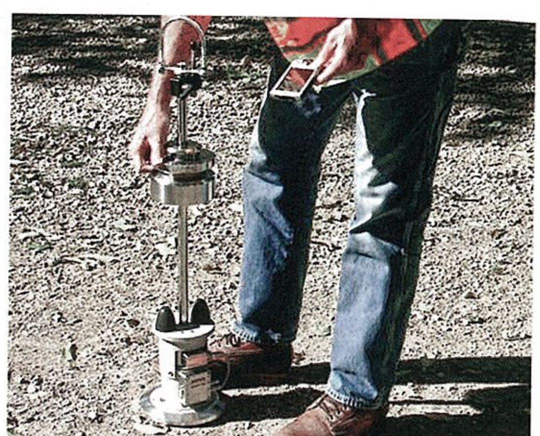

Figure 1. (a) Lightweight deflectometer (LWD) hardwired to a portable printer. (b) LWD transmitting results wirelessly to a PDA.

mapping of compaction roller data by the contractor, which is provided to the agency, allows agency personnel to optimize their QA point testing while simultaneously assuring greater construction uniformity.

Moduli and deflection target values (TVs) for the unbound pavement foundation materials have been proposed for use during pavement design. These TVs are estimated using the plastic limit (PL) for cohesive soils because the PL has been found to be a reasonably accurate predictor of the SWCC. Therefore, a family of SWCCs has been defined based on the PL. TVs are then verified during construction of the unbound pavement foundation using the lightweight deflectometer (LWD) (Figure 1). Although the deflection values from LWD testing can be suitable to assess the performance of compacted soils, MnDOT has coupled the LWD response with laboratory resilient modulus testing and soil suction measurement to improve interpretation of the results.

The Methodology

There are many recent ASCE and Transportation Research Board publications by various authors that have contributed to advancing unsaturated soil mechanics to the verge of more widespread implementation. The most relevant equations related to the methodology used by MnDOT are:

The peak deflection at the pavement surface measured by a LWD test is:

$$\Delta_{lwd} = \frac{2 \times (1-\upsilon^2) \times F \times f_r \times f_{lwd}}{E_{hs} \times \pi \times r} \qquad \text{Equation 1}$$

where:

lwd = peak deflection at the surface measured by an LWD (mm)

υ = Poisson's ratio

F = peak force at the surface of elastic half space (kN)

f_r = plate rigidity factor ($\pi/4$ for rigid and 1 for flexible)

f_{lwd} = LWD factor (depends on LWD type defined by ASTM E2583)

E_{hs} = modulus of elastic half space (MPa)

r = plate radius (m)

Equation 2 is used to estimate the value of M_r, which is equal to $E_{HS,}$ for the stress condition beneath the LWD where the average vertical stress is assumed to be 100 kPa and the horizontal stress is assumed to be 40 kPa.

$$M_r = k_1 \times p_a \times \left(\frac{\sigma_{eb} + f_s\,\theta_w\,\psi}{p_a}\right)^{k_2} \times \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

Equation 2

where:

p_a = atmospheric pressure = 100 kPa

σ_{eb} = external bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$ (kPa)

t_{oct} = octahedral shear stress $\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$ (kPa)

q_w = volumetric moisture content (vol/vol)

q_{sat} = volumetric moisture content at saturation (vol/vol)

y = matric suction estimated using Eq. 3 (kPa > 0)

$k_1 = 800 \times \left(\frac{1}{5\theta_{sat}}\right)^{1.5} \times \left(\frac{1}{\log_{10}(\psi)}\right)$

$k_2 = \log_{10}\psi - 1$

$k_3 = -8\theta_{sat}$

f_s = soil suction resistance factor = $\theta_w^{10\theta_{sat}^3}$

The volumetric moisture content (θ_w) may be estimated using the relationship:

$$\theta_w = \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right] \times \frac{\theta_{sat}}{\left[\ln\left[e+(\alpha\psi)^n\right]\right]^m} \qquad \text{Equation 3}$$

where:

$\psi_r = 500\sqrt{q_r}$ (kPa)

$\theta_r = 1.6\theta_{sat}^{\ 2}$ (vol/vol)

$\theta_{sat} = -0.000431PL^2 + 0.0336PL - 0.162$ (vol/vol)

PL = plastic limit (%)

Note: Three significant figures are used so that saturation equals 100% at zero suction for the very limited data contained in the MnDOT reports.

$\alpha = \frac{1}{(100\theta_r)^2}$ (kPa^{-1})

$n = \frac{1}{(1-m)}$

$m = 0.8\theta_{sat}$

Equations 1-3 were implemented within a variety of spreadsheets to produce the design charts shown in Figures 2 and 3. These figures are intended to demonstrate the results of this approach, rather than justify the derivation of the underlying empirical factors.

Figure 2 shows the deflection target values estimated for the more than 30 LWDs currently being used on Minnesota highway projects. Because the stress condition has such an important influence but is not well known, it is necessary to be consistent and apply a common assumption. In

Minnesota, it is currently assumed that the Zorn LWD equipped with a 20-cm-diameter rigid plate delivers a 6.3 kN force to the surface. It is also assumed that this surface force results in a stress condition in the soil volume beneath the plate that can be approximated by an average vertical stress of 100 kPa and horizontal stress of 40 kPa.

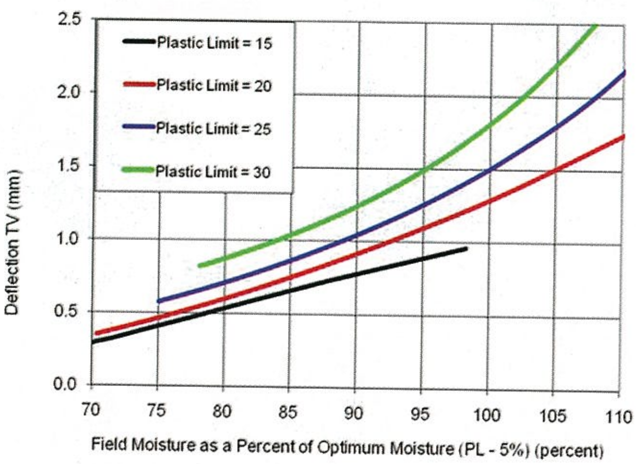

Figure 2. LWD deflection target value curves for soils with plastic limits between 15 and 30 percent.

The empirical factors in Equations 1-3 map the mechanistic equations to the measured field deflection using this stress condition assumption. Other reasonable assumptions can be used and the empirical factors modified accordingly. For example, these stress boundary conditions are affected by the stress dependency of the material being tested and therefore a future enhancement of this procedure could be to better estimate the in situ vertical and horizontal stresses as functions of the soil type. Also, because the horizontal stress is dependent on confinement, an important detail during field testing is the depth of the LWD plate relative to the surface. Recommended standard practice is that the plate be set 10 cm below the surface.

Unsaturated soil mechanics is being implemented using new performance-related construction testing and specifications.

Figure 3 shows the family of SWCCs estimated for a range of typical Minnesota soils. These SWCCs are estimated with Equation 3, using the plastic limit and a density that would be consistent with the compaction energy delivered during the standard Proctor test. The suction measurements used to create these estimated SWCCs are found in published MnDOT reports. From these curves, the in situ suction is estimated from the measured

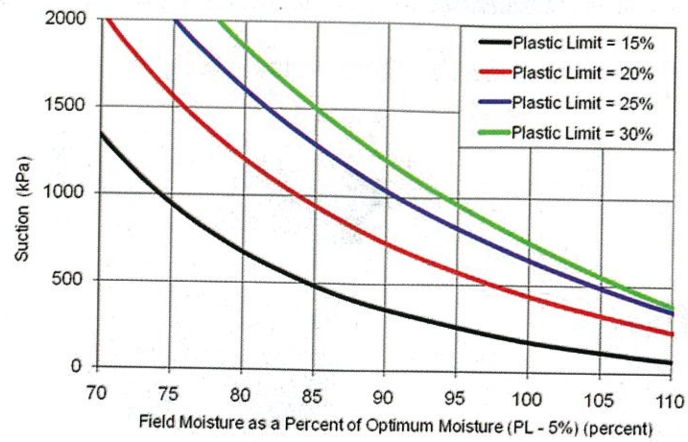

Figure 3. Soil water characteristic curves estimated for soils with plastic limits between 15 and 30 percent.

in situ moisture at the time of LWD testing. Certainly there are other index tests that could be used to estimate an alternative family of curves, such as those proposed by Dr. Zapata at Arizona State University. The empirical factors in Equations 1-3 map the mechanistic equations to the measured field deflection using the SWCCs shown. An alternative family of SWCCs can be used if desired and the empirical factors can be modified accordingly.

Figure 4 provides one example of how measured LWD deflections compare with the proposed LWD target value curve. The use of the PL to estimate the volumetric moisture content at saturation is demonstrated in Equation 3, but this is only one possible option. An alternative test could be used to estimate the optimum moisture content for compaction and that test could then be used to define the index parameter used to classify the soil. Alternative methods are relatively easy to implement into the proposed methodology if testing can be used to develop a reasonable estimate of the volumetric moisture content at saturation for the specimens tested. This testing would need to be for the range of soil types of interest compacted at the moisture condition recommended for construction compaction. For example, the equation that describes $\theta_{sat} = f(PL)$ could be replaced by an alternative relationship. Currently, there are research efforts underway at many organizations which are producing different approaches that will provide alternative ways to implement performance-based construction QA.

The products from this research implementation project include a method to estimate moduli and LWD deflection target values for the soils used to construct pavement foundations. In particular, for compacted fine grained soil, the PL and field moisture content are used to estimate LWD target values. The PL is used to classify the soil and also used to estimate the optimum moisture content for compaction.

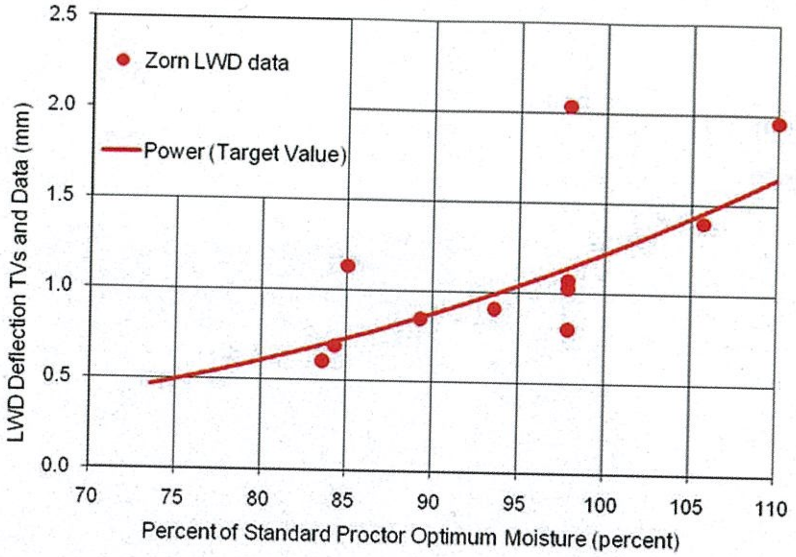

Figure 4. Measured LWD quality assurance data compared to target value curve for a soil with an optimum moisture of 14 percent (PL=19%).

What's Next?

The LWD is a practical tool that should be considered for the evaluation of compacted soils in pavement applications. This should be done using standardized testing procedures and estimated target values as reasonable starting points from which project-specific verification would occur. Performance-based construction QA testing not only results in a better product, it also provides the quantitative measures critical to better understanding the connection between pavement design and long term pavement performance. As the benefits of performance-based QA testing become increasingly apparent, more public agencies and private consultants are expected to acquire these tools and implement standardized procedures during their use.

To help move performance-based QA forward, the National Cooperative Highway Research Program has initiated research project D10-84 "Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate." This project is expected to produce draft construction specifications that are practical for implementation by state DOTs, local highway departments, and the private sector. The tools and methods that will be recommended by D10-84 are not known at this time. Use of the LWD as outlined here is only one of several possibilities that will be evaluated during the completion of D10-84. In addition, ASTM has published E 2583-07 "Standard Test Method for Measuring Deflections with a Light Weight Deflectometer" for LWDs that measure load. A second ASTM test standard is currently being finalized for other types of LWDs.

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