Laboratory and Field Measured Moduli of Unsurfaced Pavements on Weak Subgrade

Debakanta Mishra, Erol Tutumluer, M. ASCE, Maziar Moaveni, and Yuanjie Xiao

University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N Mathews Avenue, Urbana, Illinois, 61801

ABSTRACT

This paper presents findings on the effectiveness of field modulus determinations and modulus based assessment of constructed pavement foundation geomaterials, i.e. subgrade soil and base/subbase unbound aggregate material. Full-scale unsurfaced pavement test sections were constructed on controlled strength weak subgrades and tested to failure for studying effects of aggregate quality on pavement performance. Differences in aggregate quality were assessed by changes in aggregate properties such as particle angularity, fines content and plasticity of fines. In-situ moduli of the constructed layers were measured using both light weight deflectometer (LWD) and GeoGauge™ type field devices. Tests were conducted on the engineered subgrade as well as on the finished aggregate layer surface with data collected consistently from the same locations using the two devices. Both the GeoGauge™ and the LWD were successful in identifying anomalies in construction conditions, i.e., increasing or decreasing trends in moduli. However, field achieved dry densities and aggregate qualities could not be linked to the field modulus values, which also differed from the laboratory-measured resilient modulus properties.

INTRODUCTION

Quality control and quality assurance (QC/QA) of unbound aggregate layer construction in pavements has traditionally been based on target density values, expressed with respect to the maximum achievable densities in the laboratory through commonly used compaction tests. Although past research has successfully correlated higher densities to unbound aggregate layer stiffness or resilient modulus improvements (Rowshanzamir, 1995; Tutumluer and Seyhan, 1998), mechanistic-empirical (M-E) pavement design methods do not consider aggregate layer density as an input into pavement thickness design. The resilient modulus on the other hand, governs the nature of stress dissipation in an aggregate layer due to wheel load, and is therefore an essential input for mechanistic analysis of the layered pavement structure. This fact alone has made the alternative of measuring in-situ layer modulus very attractive for pavement designers although a challenging task now deals with how to develop related construction specifications for field modulus control.

Growing interest in modulus-based compaction control procedures has led to the development of several different alternatives for non-destructive field modulus measurement of pavement layers. The Light Weight Deflectometer (LWD) and the Humboldt® Soil Stiffness Gauge (GeoGauge™) are two such devices that facilitate
in-place measurement of pavement layer modulus without causing excessive delay to construction activities. In spite of significant differences in the operating principles, both devices apply a certain load on the pavement surface, and use resulting deflections to estimate the in-place layer modulus.

This paper presents findings on the effectiveness of field modulus-measurement techniques for distinguishing between different quality aggregate materials constructed as unsurfaced pavements on controlled strength weak subgrades and tested in accelerated loading. Both crushed and uncrushed aggregates conforming to a dense-graded gradation specification were used with varying aggregate properties. This paper discusses the effectiveness of these two devices for characterizing material quality aspects, compares field moduli trends with achieved moisture and density conditions, and contrasts differences between field and laboratory determined moduli.

PROJECT BACKGROUND

Four different aggregate types were used to construct unsurfaced pavement test “cells” over weak subgrade layers of controlled strength. Variation in aggregate material quality was primarily designed through changes in particle shape, texture and angularity, fines content, and plasticity of fines. Each test cell comprised three different “sections” constructed by placement of aggregate layers of different thicknesses over the engineered subgrade. The three test sections numbered from West to East as 1, 2 and 3 had constructed aggregate layers of thicknesses 356 mm, 305 mm, and 203 mm, respectively.

In-situ modulus measurements were carried out using two field modulus measurement devices, Dynatest® LWD (model 3031) and Humboldt® GeoGauge™. Tests were conducted on the engineered subgrade as well as on the finished aggregate layer surface with data collected for the primary objective of analyzing the differences in reported moduli values by the two devices. The primary focus of this paper is to compare the relative trends in the measured moduli from the two devices.

The Light Weight Deflectometer

The Dynatest® 3031 portable Light Weight Deflectometer (LWD) used in the current study is a portable, lightweight device that uses impact loads to estimate the stiffness of pavement layers. A load pulse, generated by dropping a fixed mass through a certain height onto a set of rubber buffers (for damping of the load, and controlling load pulse period), is used for estimating the stiffness of underlying layers. The force is transmitted to the ground through a circular plate (typically 300 mm in diameter, but interchangeable to 150 mm). Applied load levels are measured using a load cell, whereas induced surface deflections are measured by a geophone (velocity transducer) extending through a hole in the base plate. Relative velocity between the pavement surface and the base plate is measured by the geophone, and is subsequently integrated to calculate the induced displacement. Besides the geophone at the center of the base plate, the device has the capability to measure deflections
using two other geophones located at different offsets from the base plate, in a user-defined pattern. An LWD assembly equipped with one geophone for measuring center deflection only uses Boussinesq elastic half-space theory to estimate the composite stiffness (E) of the underlying layers.

\[ E = \frac{K \cdot p \cdot r}{d} \left(1 - \nu^2 \right) \]  

where E is the composite stiffness (also known as surface modulus), K is a stress distribution factor (depends on layer and base plate rigidity), p is the applied contact pressure, r is the plate radius, d is the deflection, and \( \nu \) is Poisson’s ratio. Deflection and load time history data are transferred to a Personal Digital Assistant (PDA) device using Bluetooth connection for real time data processing. In the current study, typical peak stress levels recommended by the manufacturer (Dynatest® International, 2009) for testing geomaterials were followed to ensure operation of the geophones within the calibrated range. Using at least three seating drops in each test location ensured proper contact between the base plate and the ground surface.

**The Humboldt® Soil Stiffness Gauge (GeoGauge™)**

The Soil Stiffness Gauge (GeoGauge™), manufactured by Humboldt® Mfg. Co., is a portable instrument for measuring in-place modulus and load carrying abilities of compacted soil and aggregate layers in a simple, rapid, and precise way (Humboldt Mfg. Co., 2007). The GeoGauge™ is 28 cm in diameter and 25.4 cm in height and weighs approximately 10 kg. Contrary to commonly used deflection based modulus measurement methods, i.e. Falling Weight Deflectometer (FWD) and LWD, that apply large impact forces to produce measurable deflections in a pavement layer, the GeoGauge™ imparts a very small dynamic force of approximately 9-N magnitude (Sawangsuriya, 2001) at 25 steady state frequencies ranging from 100 to 196 Hz. The force is transmitted to the ground by an annular ring attached to foot of the device, and induces surface deflections, often smaller than 1.27×10^\(-6\) m in magnitude. The surface deflections are used to calculate the layer stiffness value (ratio of applied force to resulting deflection) corresponding to each frequency. Ultimately an average stiffness value is calculated by considering the 25 steady state frequencies. With an assumed Poisson’s ratio, the Young’s modulus (E) and shear modulus (G) of the material can be determined using Equations 2 and 3 given below:

\[ E \approx \frac{P}{1.77R\delta} \left(1 - \nu^2 \right) \]  

\[ G \approx \frac{P}{3.54R\delta} \left(1 - \nu \right) \]  

where P is the applied load, R is outer radius of annular ring, \( \delta \) is the induced surface deflection, and \( \nu \) is Poisson’s ratio of the elastic medium. The GeoGauge™ modulus was reported to be influenced by density, moisture content, boundary conditions, and stiffness of underlying layers (Saawangsuriya, 2001; Seyman, 2003).
FIELD MODULUS MEASUREMENTS

Figure 1 shows the LWD and GeoGauge™ testing conducted consistently at the same locations on the compacted subgrade and aggregate layers. In-place moisture-density conditions were also measured using a Troxler® 3450 nuclear density gauge. For analysis of the LWD and GeoGauge™ test results, Poisson’s ratio values of 0.35 and 0.45 were assumed for the aggregate and subgrade layers respectively. Moreover, a uniform stress distribution was assumed underneath the LWD base plate (K = 2). Relative trends in the modulus values reported by LWD and GeoGauge™ are compared in the following sections.

Figure 1: (a) LWD Testing on Compacted Subgrade, (b) LWD Testing on Aggregate using the 3-Sensor Assembly, (c) GeoGauge™ Testing on Aggregate, and (d) Bedding Sand Layer Prepared on Aggregate for GeoGauge™ Testing

Modulus Measurements on Engineered Subgrade

Results from in-place modulus measurements on top of the subgrade layer are presented in this section. Test section subgrades were prepared in the field by adjusting moisture contents to achieve target California Bearing Ratio (CBR) values of 3% and 6%. Details on the subgrade preparation and moisture adjustment procedure to achieve the target subgrade CBR values have been presented elsewhere (Mishra and Tutumluer 2012). Figure 2 presents the subgrade modulus properties measured on a typical test cell (Cell 1), which was constructed at a target CBR of 3%. As shown in Figure 2, the modulus values reported by the GeoGauge™ were consistently higher than those measured by the LWD for all three test sections. This is expected, as the strain amplitudes imposed by the GeoGauge™ are significantly smaller than those imposed by the LWD. Ryden and Mooney (2009) extracted low-strain modulus values from seismic waves during LWD tests, and highlighted the
effect of strain levels on field-measured modulus values. Regardless, both devices reported consistent trends in the relative modulus values for the three sections (significantly higher modulus for Section 3 compared to Sections 1 and 2). The higher moduli for Section 3 were primarily due to a non-uniform moisture distribution during subgrade preparation in this section. In-place CBR measurements using an empirical correlation (Kleyn et al., 1982) with the penetration rate of a Dynamic Cone Penetrometer (DCP) confirmed the non-uniform moisture distribution across the three sections (Section 3 had an average CBR value of 3.9%, compared to 3.0% and 2.7% for Sections 1 and 2, respectively).

Figure 2: Field Modulus Values by LWD and GeoGauge™ Showing Similar Trends but Different Magnitudes on a Compacted Subgrade of CBR = 3%

Figure 3 shows subgrade modulus values measured on a significantly stronger subgrade (Cell 5) with a target CBR value of 6%. Note that both the LWD and the GeoGauge™ reported significantly higher modulus values for the stronger subgrade in Figure 3 when compared to the values shown in Figure 2. The GeoGauge™ measured moduli are slightly higher than those measured with the LWD. The consistent subgrade conditions across the three sections in Figure 3 are properly captured by both devices, and were confirmed through DCP testing.

Although the actual magnitudes reported by the two devices are different from each other, both the LWD and the GeoGauge™ successfully identified the anomaly in construction quality, which was the non-uniform moisture distribution in Cell 1 leading to higher strength for Section 3. This reinforces the findings from the recent NCHRP 10-65 study (Von Quintus et al., 2009) which reported that these field modulus measurement devices consistently identified differences in construction conditions, irrespective of the magnitudes of measured moduli. Further, Von Quintus et al. (2009) gave a higher success rate (79%) for the GeoGauge™ compared to the LWD (64%) for effectiveness in identifying differences in construction conditions.
Modulus Measurements on Compacted Aggregate Layers

Field modulus measurements on compacted aggregate layers were also carried out using the LWD and the GeoGauge™ to get a comparative idea about the moduli values associated with different aggregate qualities. Testing always at the same location facilitated such comparison of modulus trends measured with each device. Moisture-density conditions of the aggregate layers were also measured using a nuclear gauge to analyze the trends in field modulus values with traditional compaction QC/QA results. Figure 4 shows modulus measurements on the compacted aggregate layer constructed over Cell 1 (over the subgrade tested in Figure 2). The aggregate layers in Cell 1 were constructed using uncrushed “river-run” gravel with compaction targeting 95% of standard Proctor maximum dry density.

For Sections 1 and 2 (356-mm and 305-mm thick aggregate layers, respectively) presented in Figure 4, the field moduli reported by the two devices are reasonably close to each other. However, for Section 3 (203-mm thick aggregate layer), the modulus values from LWD were significantly lower than those measured with the GeoGauge™. Note that the Section 3 subgrade for Cell 1 had significantly higher modulus/stiffness properties compared to Sections 1 and 2 (see Figure 2). Moreover, from Figure 4, the achieved degree of compaction for the aggregate layer in Section 3 was higher than those for the other two sections. As higher degree of compaction usually corresponds to higher modulus values (Rowshanzamir, 1995; Tutumluer and Seyhan, 1998), the aggregate layer in Section 3 would then be expected to have higher moduli compared to Sections 1 and 2. Although the GeoGauge™ results followed this same trend, the LWD measured significantly lower modulus values for the aggregate layer in Section 3, which may be explained based on the depth of influence of the two devices. The depth of influence for LWD reported in literature is
between 270 to 280 mm (Nazal, 2003; Nazzal et al., 2007), deeper than the 203-mm thick aggregate layer in Section 3. According to Von Quintus et al. (2009), LWD tests on thin pavement layers were significantly influenced by the underlying layer, and therefore, the results were consistently higher or lower than laboratory measured modulus values for those particular materials. Moreover, Mooney and Miller (2009) reported a depth of influence for LWD between 0.9-1.1 times the plate diameter. Therefore for the given study, the depth of influence for the LWD would be between 270-330 mm. Accordingly, the lower LWD-measured modulus values corresponding to the 203-mm thick aggregate layer in Section 3 were probably due to the influence of the weak underlying subgrade layer.

Effect of Moisture-Density Conditions

Figure 5 shows together the nuclear gauge determined moisture content and dry density values with the field measured modulus values for all compacted aggregate layers tested in this field study. Note that both the LWD and the GeoGauge™ show decreasing moduli values with increasing moisture contents for the different test sections highlighted. However, the effect of dry density on layer modulus is not as clear from Figure 5 although Von Quintus et al. (2009) reported a strong correlation between GeoGauge™ moduli and achieved dry densities.

Aggregate Quality Linked to Laboratory and Field-Measured Moduli

Laboratory repeated load triaxial tests were conducted next on the four different aggregate materials used in this field study following the AASHTO T 307 test procedure. Figure 6 shows the stress dependent resilient modulus values graphed against the bulk stress (first stress invariant). Note that the uncrushed gravel with
12% fines, corresponding to Cell 1 aggregate in Figure 4, had significantly lower laboratory-measured modulus values when compared to the other three crushed aggregates. The crushed limestone with 10% fines had the highest modulus values. Note that Figure 6 indicates clear trends about how increasing fines content in an aggregate matrix can negatively impact its modulus properties.

Figure 7 summarizes the field modulus values measured on all unsurfaced pavement sections constructed using the four aggregate materials. Although the goal was to establish such possible linkages between aggregate type and/or fines percentage and the field measured modulus trends, from Figure 7, no clear trend of material quality on field modulus is apparent. Furthermore, in contrast with the laboratory-measured results, the crushed limestone with 10% fines is not indicated to have higher modulus properties than the others, and similarly, the much lower laboratory-measured moduli associated with the uncrushed gravel material are not seen in Figure 7.

![Figure 5: Achieved (a) Moisture Contents and (b) Dry Densities vs Field Moduli](image)

**CONCLUSIONS**

This paper presented findings from a recent research study at the University of Illinois aimed at evaluating the effects of aggregate physical properties or “quality” on unsurfaced pavement performance. As a secondary objective, field modulus measurements were carried out on the engineered subgrade, as well as compacted aggregate layers. Field modulus measurements were taken using light weight deflectometer (LWD) and GeoGauge™ devices always at the same locations to eliminate effects of spatial variability in construction conditions. From testing on the engineered weak subgrades as well as constructed aggregate layers, it was observed that GeoGauge™ reported modulus values were consistently higher than those measured by the LWD due to the fact the moduli from the two devices were defined in different ways. Both the GeoGauge™ and the LWD were successful in identifying anomalies in construction conditions, i.e., increasing or decreasing trends in moduli. The GeoGauge™ measured modulus values showed in general a decreasing trend
with increasing moisture contents. However, the effects of dry density and material quality, associated with aggregate type and properties, were not reflected from the field modulus values. In that sense, the field modulus values could not be associated with the laboratory-measured modulus properties, which properly captured not only stress dependencies but also the effects of aggregate angularity and fines content.

Figure 6: Effects of Aggregate Type and Fines Content on Laboratory-Measured Resilient Modulus Properties (specimen compaction information shown)

Figure 7: Effect of Aggregate Quality on Field Modulus

ACKNOWLEDGEMENTS

The authors would like to acknowledge Mr. Ed Hall of Humboldt® Mfg. Co., and Mr. Erwin Kohler, and Mr. Gary Mitchell of Dynatest® USA, for providing the field
modulus measurement devices reported in this paper. Special thanks are also due, to all the researchers and support staff at the Illinois Center for Transportation.

REFERENCES