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ABSTRACT

The application of modulus-based in-situ testing methods has been widely increasing for control of the compaction quality of earthwork construction in recent years. Since their introduction to the QA/QC process, it has been observed that there are several factors that influence the measured modulus of the soil, such as moisture content, influence depth, and temperature. To achieve more reliable test results, these factors should be accounted for in interpretation of the data. As noted by previous researchers, water content is one of the most important properties that affects the modulus measurements of compacted soil. To explore the sensitivity of measured modulus-based in-situ test results to the effect of compaction water content, a field study was performed in the State of Delaware in the summer of 2008. Two Light Weight Deflectometers (LWDs) were used in the study to measure compacted soil modulus values, one with a 300 mm contact plate diameter and one with a 200 mm plate diameter. The fill material tested during this study was a poorly graded sand with silt (SP-SM). The purpose of the current paper is to demonstrate the sensitivity of the measured soil modulus values to fluctuation in soil moisture content in the field, and to discuss possible approaches for interpreting this type of variable LWD data.

INTRODUCTION

Quality control and quality assurance are major parts of any earthwork construction project. In recent years, alternative quality control methods have sometimes been used to replace or supplement traditional density-based compaction control methods (e.g. ASTM D 1196, and ASTM D 4694). As mechanistic-empirical pavement design methods become more and more utilized by state DOTs and practicing engineers, it is likely that there will be a further push towards adoption of modulus-based in-situ compaction control tests (Kim et al. 2007). The Light Weight Deflectometer (LWD) is a relatively new modulus-based measurement tool that has significant potential for use as part of the compaction control process (Fleming et al. 2007), either used by itself or in conjunction with new emerging intelligent compaction or continuous compaction control systems (e.g. Tehrani 2009, White et al. 2007). The LWD test is currently being used for compaction control by the Minnesota DOT (Mn_DOT 2009), and it is quite possible that other DOT's may also consider the use of this device in the future.

Field modulus-based measurements have been shown to be significantly affected by the amount of moisture that is present in the soil that is being tested (e.g. Adam 1997, Davich et al. 2006). This paper outlines the results from a study that was performed to investigate the influence of water content on the modulus values that are measured by a typical LWD. Results from two different types of LWDs are presented.

LIGHT WEIGHT DEFLECTOMETER

The LWD (Figure 1) is a device that induces a soil deflection by dropping a weight onto a plate resting on the test layer (ASTM E 2583 – 07). A load cell within the instrument measures the time history of the load pulse and a geophone in contact with the test layer measures the time history of the soil's velocity (Hoffmann et al. 2003). The velocity is then integrated to determine the displacement. The time history files are automatically exported to a data acquisition system, where the peak load and displacement values are used to calculate modulus values. Time history files can also be analyzed using a fast Fourier transform for a more accurate modulus calculation (Hoffmann et al. 2003, Davich et al.).

Figure 1 Zorn LWD's with a plate diameter of 200 mm and 300 mm

The elastic modulus of the subgrade soil is calculated from the soil's surface deflection using the following Boussinesq's equation (Rahman et al. 2007):

$$E_{LWD} = \frac{k \cdot (1-\nu^2) \cdot \sigma_0 \cdot r}{z_{ave}} \quad (1)$$

where, E_{LWD} = LWD modulus (MPa); $k = \pi/2$ and 2 for rigid and flexible plate, respectively; z_{ave} = Average of three measured deflections at the center of the load plate (μm); σ_0 = Peak applied stress (kPa); ν = Poisson's Ratio ($\nu = 0.3$ used throughout); and r = Plate radius (mm). According to ASTM D 1196, a "rigid plate" is defined as a plate with deflection of less than 0.0025 mm from the center to the edge of plate, when the maximum load is applied.

FIELD STUDY

An experimental study was performed at Burrice Borrow Pit in Odessa, Delaware in July of 2008. A 61 m long by 6 m wide embankment was built out of poorly-graded sand with silt (SP-SM) and silty sand (SM) (the former was predominant) (ASTM D 2487), a commonly used borrow material for the Delaware Department of Transportation, which conforms to DelDOT class G borrow specifications, Grades V and VI (Figure 2). The soil used in this study was non-plastic in nature (fines were non-plastic), and its optimum water content ranged between 10.4% and 15.3%, as determined using a series of 1-pt standard Proctor tests with an associated family of curves (ASSHTO T 272).

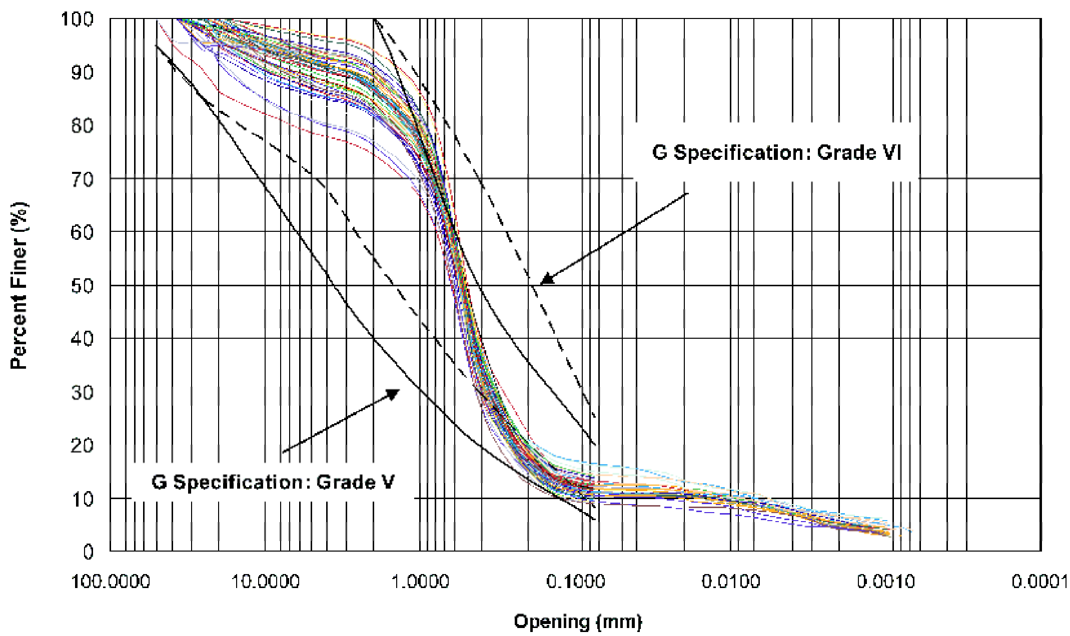

Figure 2 Gradation results for field samples taken from in-situ test locations

The embankment used in this study was constructed to an approximate total final height of 0.9 m, by compacting five 20.3 cm loose lift layers, in accordance with Delaware general specifications for road sub-base construction (DelDOT 2001). After compaction of each lift, a series of in-situ testing measurements were taken to control the quality of compaction. Additional information about the nature of the embankment that was constructed, the construction techniques that were utilized, and the results of other in-situ tests can be found in Tehrani (2009).

Two Zorn LWDs were employed in this field study to measure the in-situ modulus of the compacted soil: a LWD with plate diameter of 200 mm (LWD 200), which has a falling mass of 10 kg and a drop height of 540 mm; and a LWD with a plate diameter of 300 mm (LWD 300), which has a falling mass of 10 kg and a drop height of 730 mm. Each test was accompanied by disturbed soil sampling, for later determination of the moisture content in the laboratory (ASTM D 2216) and grain size analysis (ASTM D 422). After construction of the embankment (after completion of compaction for Lift 5), additional LWD measurements were recorded over time, to examine the sensitivity of the LWD results to changes in the in-situ moisture content.

IN-SITU TEST RESULTS AND ANALYSIS

Values of LWD modulus were recorded at nineteen test locations on 7/24/08, immediately after completion of the final compaction lift of the test embankment. LWD tests were performed using both the LWD 200 and the LWD 300. Five of the LWD test locations were clearly marked, and repeated LWD measurements were taken over time at these locations on 7/25/08, 7/30/08, 8/1/08, and 8/5/08. Representative moisture content samples were also taken at locations immediately in the vicinity of the LWD test area, but not so close as to affect the recorded modulus values.

This paper presents and discusses the changes in the LWD moduli and the corresponding water content values that were observed over time. Any changes in recorded value are due only to changes in the condition of the soil, as no additional compactive effort was applied to the soil from one day to the next. Figures 3-5 show the variations in recorded LWD 300, LWD 200, and water content values at each station over time.

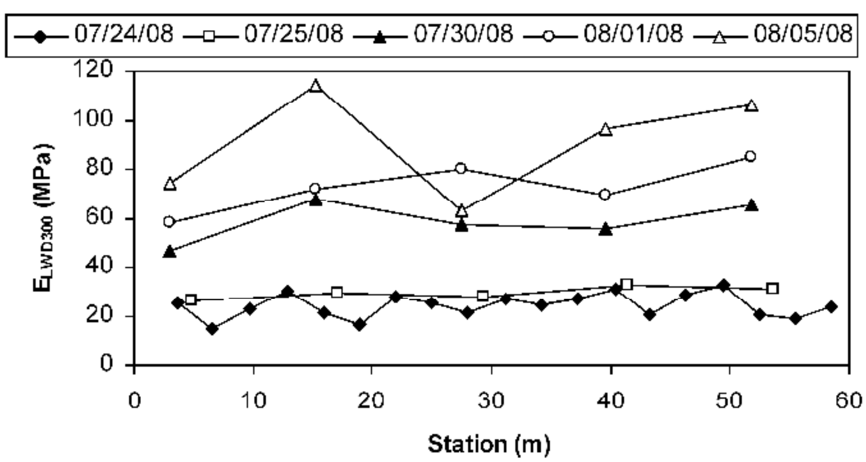

Figure 3 Variation of LWD 300 values at each station over time

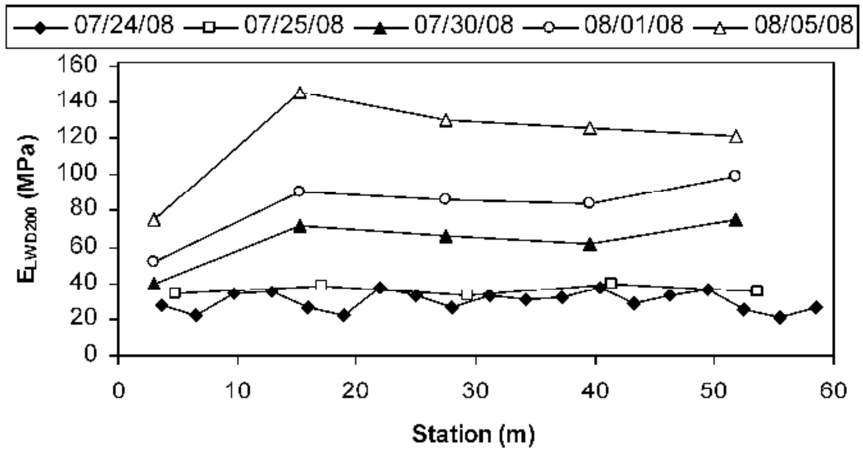

Figure 4 Variation of LWD 200 values at each station over time

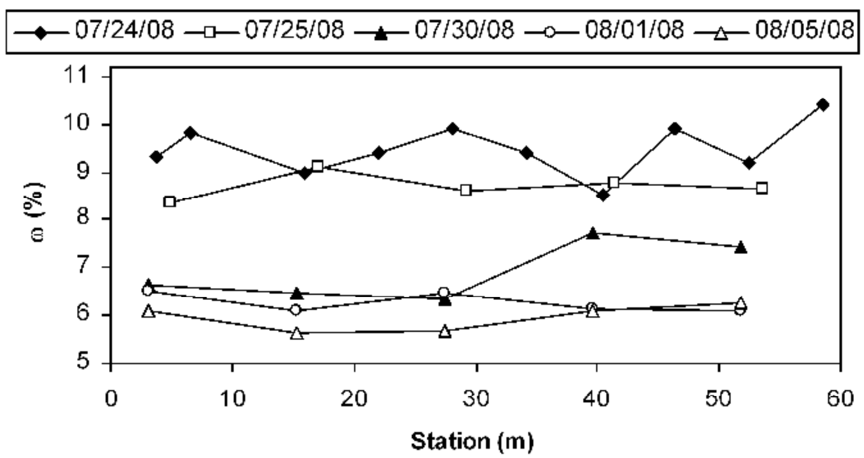

Figure 5 Variation of water content values at each station over time

To more clearly show the variation of the measured data and to demonstrate the relative magnitude of the LWD 300 and LWD 200 values, the mean of the recorded values for the five test locations that were examined on each day are provided in Figure 6.

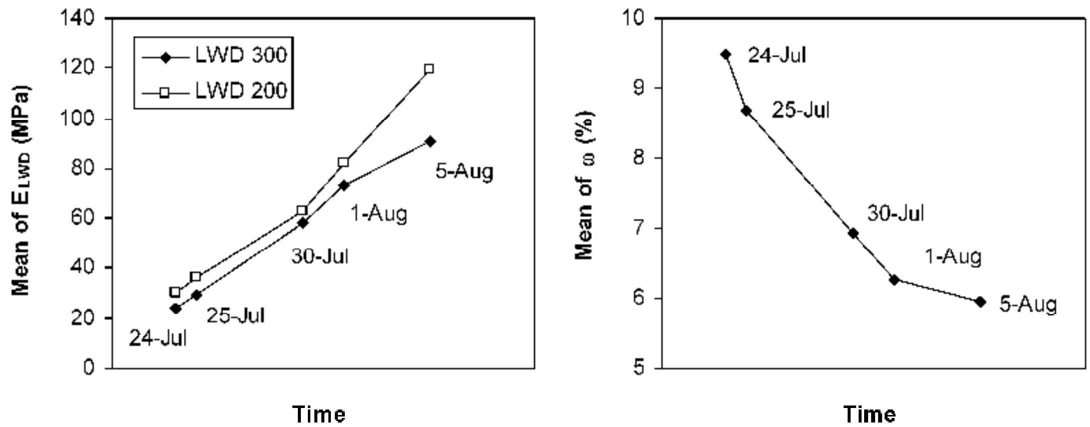

Figure 6 Variation of mean LWD and ω% values for the compacted area over time

As shown in Figures 3, 4, and 6, the LWD 200 generally provided higher recorded modulus values than the LWD 300 at each of the in-situ test locations. As shown in Figures 3-6, the soil modulus significantly increased over time while the water content decreased. This observed trend in behavior emphasizes the sensitivity of recorded soil modulus values to variations in the soil's water content. This sensitivity is believed to be caused by changes in soil suction that occur as the soil moisture content changes, which changes the effective stresses between the soil particles and affects the associated deflection response of the soil under load. To look for possible relationships between the measured data, correlation coefficients between each pair of data were calculated using Equation 2, and are presented in Table 1.

$$\rho = \frac{\frac{1}{N}\sum_{i,j=1}^{i,j=n}[V_i - \mu(i)][V_j - \mu(j)]}{\sigma(i)\sigma(j)} \tag{2}$$

where, N is the number of pairs of data, i and j denote each set of data (e.g. modulus and water content), $\mu(i)$ and $\mu(j)$ are the corresponding mean or average of each set of data, and $\sigma(i)$ and $\sigma(j)$ are the standard deviations of their respective data sets. The correlation coefficient ρ ranges between -1 and +1. A correlation coefficient $\rho = +1$ means that two variables vary together exactly. A correlation coefficient $\rho = -1$ means that two variables vary exactly inversely. A correlation coefficient $\rho = 0$ means that the two variables are unrelated to one another (Baecher and Christian 2003).

Table 1 Correlation coefficient of the measured values

Measurements	E_{LWD300} (MPa)	E_{LWD200} (MPa)	ω (%)
E_{LWD300} (MPa)	1.00	0.94	-0.89
E_{LWD200} (MPa)	0.94	1.00	-0.87
ω (%)	-0.89	-0.87	1.00

The data shown in Table 1 indicates that the different test results are relatively well correlated to each other, either in a direct or an inverse fashion. In order to examine the relationship between the LWD 300 and LWD 200 modulus values and the water content of the soil, univariate regression analysis was performed on the data. Figure 7 shows the recorded data points, and presents the results from linear regression analysis of the recorded values.

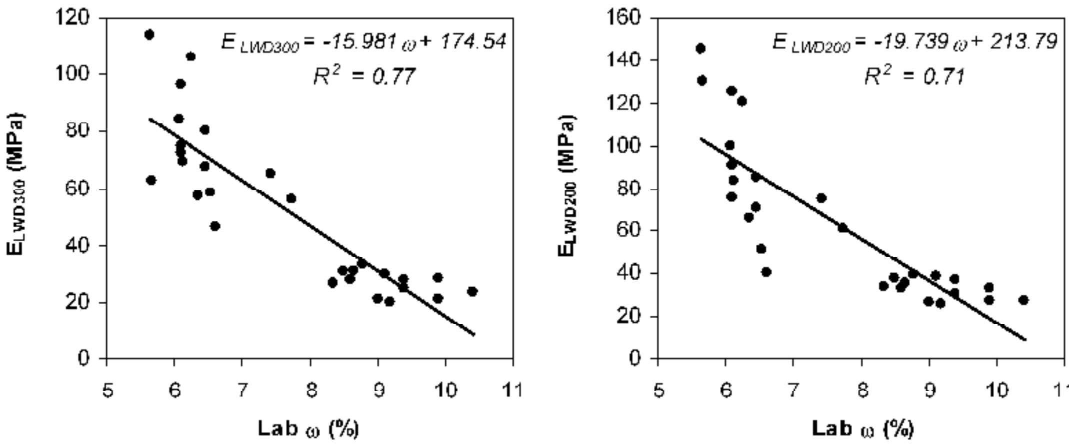

Figure 7 Regression analysis of LWD modulus vs. laboratory measured water content using a linear regression model

The results show only a moderate-quality linear relationship between the recorded data. However, the shape of the scatter plot indicates that a non-linear regression analysis may result in a better fit with the recorded data. The results from regression analyses on this data set using a power model are shown in Figure 8.

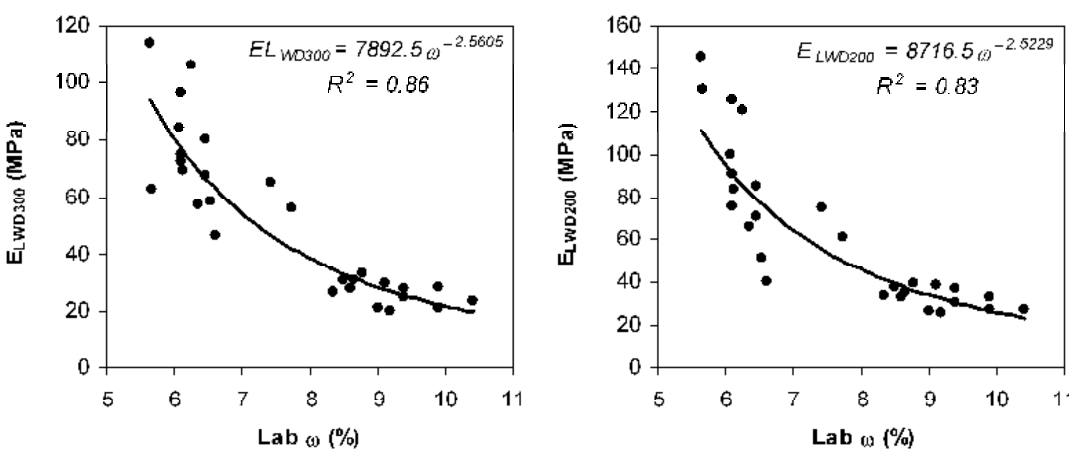

Figure 8 Regression analysis of LWD modulus vs. laboratory measured water content using a power model

As shown in Figure 8, the power regression model yields a relatively high coefficient of determination (R^2) for both the LWD 300 and LWD 200 test results.

However, fits that are nearly as good can be obtained using second order polynomial regression (R^2 = 0.80 R^2 = 0.79 for LWD 300 and LWD 200, respectively) or exponential regression (R^2 = 0.85 R^2 = 0.81 for LWD 300 and LWD 200, respectively) analyses as well. These regression analyses indicate that there is a promising relationship between LWD modulus values and the water content of the soil. In general, it can be observed that as the water content decreases, the soil moduli increased. This data points to the importance of including the effect of water content when interpreting LWD test results.

In order to effectively compare LWD test results to the results from other types of in-situ tests, it is necessary to include the effect of water content in the data interpretation. This means that multivariate regression is necessary for these types of comparisons. For those DOTs that wish to use LWDs for compaction control, a restriction on the time of LWD testing after compaction has occurred or an allowable change in water content should be included in the compaction control specifications, to prevent drying-induced higher modulus values from "passing" a lift that might not have otherwise met the specified performance criteria.

CONCLUSIONS

A series of modulus-based in-situ tests using two different-sized Zorn LWD's were conducted on a poorly graded sand with silt after completion of compaction of a five-lift embankment. The moisture content of the soil was determined at the same locations that the in-situ moduli were measured. Additional LWD measurements were recorded over time, to examine the sensitivity of the LWD results to changes in the in-situ moisture content. Univariate regression analysis performed on the measured properties indicated that there was a promising relationship between the LWD modulus and soil water content. The compacted soil was initially on the dry side of optimum, according to 1-pt standard Proctor tests conducted using an associated family of curves (ASSHTO T 272), and the measured results confirmed that as the water content decreased over time the soil modulus increased. Among the various regression models that were examined, the Power model had the highest quality fit through the measured data.

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