A Comparison of Density-Based and Modulus-Based In Situ Test Measurements for Compaction Control

Christopher L. Meehan[1]; **Faraz S. Tehrani**[2]; **Farshid Vahedifard**[3]

Abstract: This paper presents and compares the results from a series of in situ density-based and modulus-based compaction control tests that were conducted during construction of a coarse-grained soil embankment. To simulate current construction practices as closely as possible, these in situ tests were performed on an embankment that was constructed and compacted by a vibratory smooth drum roller in a series of lifts. During construction of the test embankment, the compaction process was monitored using the nuclear density gauge device and a number of alternative modulus-based devices, including the lightweight deflectometer, the dynamic cone penetrometer, and the soil stiffness gauge. Comparison of the in situ test results illustrates that point-to-point variability in measured values is quite common for each of these test devices, to varying degrees for the different devices that were examined. Consistent increases in measured soil properties from pass-to-pass of the compactor are considered critical for proper control of the compaction process, with some devices faring better than others in this area of performance. The measured modulus values correlated poorly to the nuclear density gauge dry unit weights, and also correlated poorly with other measured moduli when the results from different devices were compared. This lack of agreement was likely caused by a variety of factors including: variations in the magnitude of strain and rate of strain application between the different modulus-based devices, variations in the tested volume between the different devices, and variations in the local moisture content and matrix suction conditions. Finally, the effect of soil moisture content was shown to be critically important when interpreting the results from modulus-based tests, and the utility of multiple regression analyses was explored for including this effect.

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1 Introduction

End-product-based specifications are commonly utilized to monitor and control the process of soil compaction in the field. Typically, this process involves the use of periodic in situ measurements of soil moisture and density (or unit weight), which are made by a field technician using the sand cone method (ASTM D1556-00), the rubber balloon method (ASTM D2167-94), or nuclear-based test devices (ASTM D2922-05; ASTM D3017-05). With the relatively recent adoption of mechanistic-empirical pavement design methodologies (e.g., NCHRP 2004), there is increased justification for developing and using alternative compaction quality control and quality assurance (QC/QA) procedures that utilize a stiffness- or strength-based criterion in place of a density-based criterion. A large variety of non-destructive strength-based or modulus-based in situ tests can potentially be used for this purpose, includ-

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ing the plate load test (ASTM D1195-93; ASTM D1196-93), falling weight deflectometer test (ASTM D4694-96), lightweight deflectometer test (ASTM E2583-07), dynamic cone penetrometer test (ASTM D6951-03), Clegg impact hammer test (ASTM D5874-02), and soil stiffness gauge test (ASTM D6758-02), which is sometimes referred to as the geogauge test.

The study described herein focused in particular on the use of three devices for compaction monitoring during embankment construction: the lightweight deflectometer test (LWD), the dynamic cone penetrometer test (DCP), and the soil stiffness gauge test (SSG). A number of existing publications have provided detailed descriptions of the operating principles of each of these devices, in some cases, providing discussion on their respective strengths and limitations for monitoring soil compaction in the field (e.g., LWD: Lin et al. 2006; Fleming et al. 2007; Mooney and Miller 2009; Vennapusa and White 2009; DCP: Gabr et al. 2000; Chen et al. 2001; Rathje et al. 2006; Roy 2007; SSG: Alshibli et al. 2005; Rathje et al. 2006; Jersey and Edwards 2009). Studies have also been performed to compare or correlate the results from individual modulus-based tests to the results from other single-location spot tests that were performed to monitor the process of soil compaction (e.g., Siekmeier et al. 2000; Alshibli et al. 2005; Chen et al. 2005; Lin et al. 2006; Mohammadi et al. 2008; Jersey and Edwards 2009).

To develop an understanding of the behavior of these three alternative modulus-based in situ tests for compaction control in a local coarse-grained soil, an experimental research study was conducted in the State of Delaware in the summer of 2008. Under carefully controlled conditions at a state borrow area site, a road sub-base test pad was constructed and compacted using a vibratory smooth drum roller. The soils utilized during this study were coarse-grained in nature, are considered to be "select fill" materials by the Delaware Dept. of Transportation (DelDOT 2001), and have a USCS classification of either poorly graded sand with silt (SP-SM) or silty sand (SM) (ASTM D2487-06). During construction of the test embankment, the compaction process was monitored using the traditional density-based methods that are currently employed by the Delaware DOT, as well as a number of alternative modulus-based methods, including the LWD, the DCP, and the SSG. This paper presents the in situ test measurements from the field study that was performed. The behavior of the recorded values for different lifts and with increasing compactive effort for a single lift is presented and discussed. Regression analyses are used to compare the various in situ test results that were recorded.

2 Embankment Construction Procedure

The field study described in this paper was performed at Burrice Borrow Pit in Odessa, DE in July of 2008. A 61 -m-long x 6 -m-wide (200 ft x 20 ft) embankment was constructed using "select fill" granular material (DelDOT 2001, Sec. 301). The embankment was constructed to an approximate total final height of 0.9 m (3.0 ft), by compacting five 20.3 cm (8 in.) loose lift layers, in accordance with Delaware general specifications for road sub-base construction (DelDOT 2001).

To construct each lift, a Caterpillar 980H bucket loader was used to place fill for spreading by an on-site bulldozer. A Caterpillar D6K dozer was then utilized for spreading the material to an approximate loose-lift thickness of 20.3 cm (8 in.). The D6K dozer was equipped with a GPS system, which proved beneficial for establishing a relatively uniform and consistent loose-lift thickness. Two methods were used to verify the expected loose-lift thickness of each lift; during fill placement the dozer operator checked it via the GPS control system mounted on the dozer blade, and after lift completion, the thickness was confirmed by spot-checking elevations throughout the test pad area using a GPS rover unit. After spreading each lift, a water truck was driven through the test area as needed (and when it was available) to adjust the moisture content of the fill material to achieve optimum compaction.

Upon completion of loose lift soil placement and moisture conditioning, each soil lift was compacted using a Caterpillar CS56 vibratory smooth drum roller. The roller drum was 2.1 m (7 ft) wide, and had an operating weight of 11,414 kg (25,164 lbs). During compaction, the roller speed was kept relatively constant, at around 3.25 km/h. Each lift was compacted in a series of passes using three side-by-side lanes (the roller width was 2.1 m (7 ft), the test pad width was 6 m (20 ft), which left approximately 15 cm (6 in.) of overlap at the edges of each compacted soil "lane"). For each lift, between six and nine compactor passes were performed to achieve the desired level of compaction. The number of compactor passes that were performed to achieve compaction in this study are consistent with the level of compactive effort that is typically required to meet the current DelDOT relative compaction specifications, based on technician experience with this borrow soil at other field construction projects (DelDOT representative, personal communication); this observation was later verified by examining the results from a series of nuclear density gauge tests and 1-pt. standard proctor tests.

3 Soil Properties

As noted previously, the embankment was constructed using a granular "select fill" borrow material (DelDOT 2001, Sec. 301). Representative samples of this material were taken at a large number of the in situ test locations by field personnel, and the associated grain size analysis curves were determined using sieve and hydrometer tests performed in accordance with the recommendations put forth in ASTM D6913-04 and ASTM D422-63 (Fig. 1). A few Atterberg limit tests (ASTM D4318-05) conducted on the fine portion of the soils indicated that the finer portion of the soils examined in this study were nonplastic (NP) in nature (Tehrani 2009).

Analysis of the data shown in Fig. 1 indicates that the soils that were used for embankment construction can be classified as either poorly graded sand with silt (SP-SM) or silty sand (SM) (ASTM D2487-06). The former classifica-

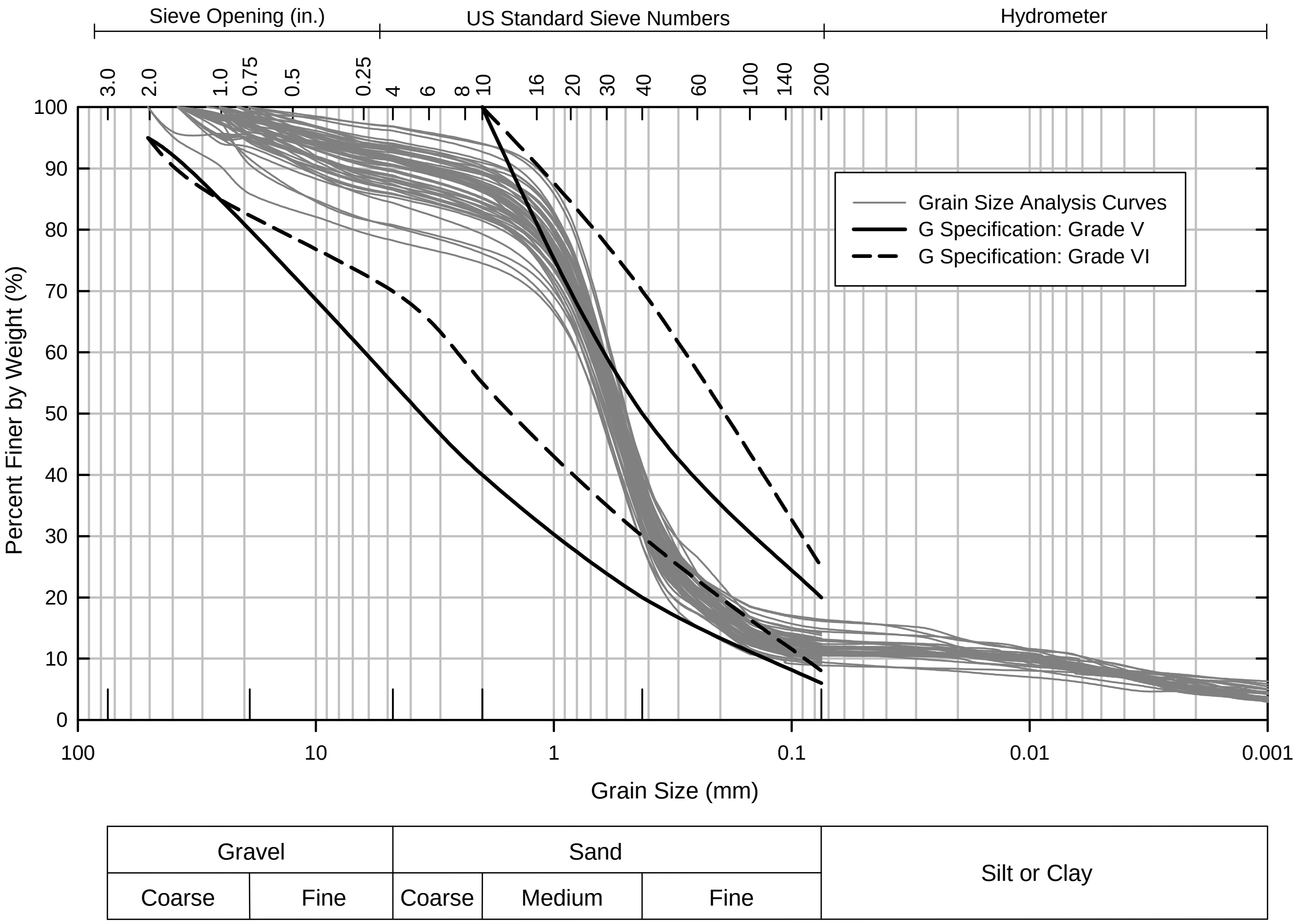

Fig. 1: Gradation results for field samples taken from in situ test locations.

tion was predominant, as indicated by 36 out of the 53 soil classification tests that were performed; however, in general, the material was relatively uniform for field construction of this type ($\mu_4 = 90.0\%$, $c_{v,4} = 0.04$, $\mu_{40} = 35.4\%$, $c_{v,40} = 0.08$, $\mu_{200} = 11.7\%$, $c_{v,200} = 0.14$), and only had two classifications because it tended to fall at the boundary between two soil types in the USCS. This soil is a commonly used borrow material for the Delaware Dept. of Transportation, and it conforms to DelDOT "select fill" borrow specifications: Class G, Grades V and VI (DelDOT 2001, Sec. 301), the criteria for which are shown in Fig. 1.

4 In Situ Testing of the Embankment Using Traditional Density-Based Methods

Currently, the conventional method that is used to control the quality of soil compaction in the State of Delaware is to perform a number of random spot tests over a given compacted area using a nuclear density gauge (NDG), and to compare the resulting in situ density (or unit weight) and moisture content values with those determined from standardized laboratory compaction tests (DelDOT 2001, which references the following AASHTO standards: AASHTO T238; AASHTO T239; AASHTO T99). The results from conventional compaction control tests for the embankment that was constructed are shown in Fig. 2.

Figure 2(a) presents the values of dry unit weight that were measured for the soil at various test locations after the final compactor passes on each lift, using the NDG (AASHTO T238). For example, for Lift 5, data are presented for the seventh compactor pass, out of a total of seven passes that were conducted for this lift. The in situ test locations that are indicated in this figure correspond to tests that were conducted along the middle lane of compaction, in general, along the centerline of the test pad area that was constructed, with only minor location offsets that were made to avoid conducting tests directly on top of previous test locations.

As shown in this figure, the dry unit weight values measured using the NDG varied in the range of 16.8 kN/m^3 to 18.9 kN/m^3. Many of the compacted lifts exhibited unit weight values that were in the same general range, which is expected as this soil is relatively uniform (Fig. 1) and tends to compact relatively well. Among the compacted lifts, the base layer had the lowest final dry unit weight. This is not surprising, as the base layer was not an engineered lift and instead was only proof-rolled using two compactor passes

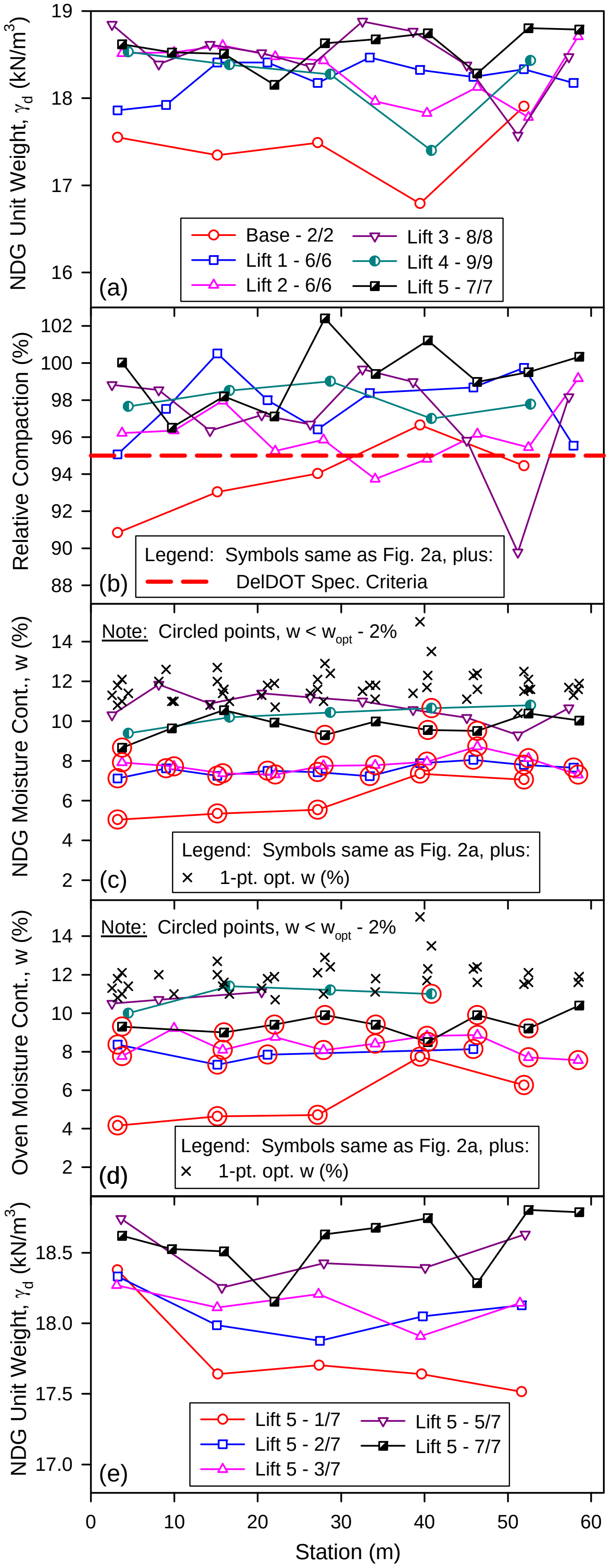

Fig. 2: Traditional compaction control test measurements: (a) NDG dry unit weights for the final passes for each lift, (b) relative compaction values for the final passes for each lift, (c) NDG-measured compaction moisture contents, (d) oven-measured compaction moisture contents, and (e) NDG dry unit weights for successive passes for Lift 5.

prior to embankment construction. Additionally, for the base layer, no moisture content adjustment was made prior to proof rolling.

The Delaware Specifications for Road and Bridge Construction indicate that compaction "shall continue until each layer is thoroughly and uniformly compacted to the full width of the embankment and to 95% or more of the maximum density of the same soils as determined by AASHTO T99 Method C, Modified" (DelDOT 2001). In practice, for larger projects of this type where a historical database of proctor compaction test results exists, compaction control is typically performed using a "family of curves" approach along with data from 1-pt. standard proctor tests (AASHTO T272). Figure 2(b) shows the relative compaction values that were calculated for each lift from the unit weight values shown in Fig. 2(a), from a series of 1-pt. standard proctor compaction tests conducted on samples taken at each in situ test location, and from an associated family of compaction curves that had been developed by the DOT for this borrow soil. For comparison purposes, the DelDOT relative compaction criterion of 95% is also shown in Fig. 2(b). As shown, with the exception of the base layer (which was only proof-rolled), the degree of compaction for the final passes of each lift generally met the DelDOT relative compaction criterion (only 3 to 4 of the points would have failed).

Figure 2(c) presents the values of moisture content that were measured for the soil at various test locations after the final compactor passes on each lift, using the NDG (AASHTO T239). The Delaware Specifications for Road and Bridge Construction indicate that "the moisture content of the soil at the time of compaction shall be within 2% of the optimum moisture content, as determined by the AASHTO T99 Method C, Modified" (DelDOT 2001). For larger projects in the State of Delaware, in a similar fashion as the maximum density determination discussed previously, optimum moisture content values are generally determined using 1-pt. proctor tests and a family of curves approach (AASHTO T272). For comparison purposes, the corresponding optimum moisture content values for each of the NDG in situ test locations are also shown in Fig. 2(c). By comparing the location of these points to the measured field values, it can be clearly seen that the soil compaction for this project was almost always conducted dry-of-optimum.

The NDG-measured moisture content points that fall outside of the ±2% criteria are circled in Fig. 2(c). From this figure, it can be observed that the base layer, Lift 1, and Lift 2 were all too dry at the time of compaction. This is not surprising, as this embankment was constructed during very hot weather during the peak of summer, and because of a number of logistical constraints, it was not possible to access a water truck for proper moisture conditioning of the soil during the first few days of this project (when the base layer, Lift 1, and Lift 2 were compacted). A light overnight rainfall event during the middle of the project, coupled with increased access to a water truck during the last few days of the project allowed for much better moisture conditioning of the soil for Lifts 3, 4, and

5.

As the base layer was not an engineered lift, and was simply proof rolled prior to construction of the embankment, moisture content values at the time of proof-rolling are a non-issue according to DelDOT specifications. However, for Lifts 1 and 2, the moisture content values at the time of compaction are outside the range of acceptability, and would typically be grounds for rejection by the field engineer if this embankment was part of an actual construction project. It could perhaps be argued that these lifts are acceptable, given that the relative compaction criteria was still met, even though the moisture content was outside of the acceptable range; this argument could be supported by the extensive compactive effort that was applied to the soil, and the ideal gradation characteristics of the material that allow for relatively easy compaction even though the moisture content was not ideal. In any case, given that this embankment construction was for a research project, exact conformance to state construction specifications was considered secondary to the primary objectives of the research. The data that were gathered for these lifts will consequently still be included in the comparisons and analyses that are described in the following sections, as they provide useful insight into the behavior of the different in situ tests that were examined.

For each lift, the moisture content of the compacted soil was also measured by performing oven-dried laboratory moisture content tests (ASTM D2216-05) on specimens taken from some of the in situ test locations, as shown in Fig. 2(d). For comparison purposes, the associated optimum moisture contents for these sampling locations are also presented in Fig. 2(d), and the failing points are circled. Although the specific moisture content values measured in the oven-dried tests are clearly different from those measured in the field using the NDG, the general conclusions that can be drawn from this data are the same as those from Fig. 2(c) (with perhaps Lift 5 also being viewed less favorably as well).

Figure 2(e) presents the values of dry unit weight that were measured for the soil at various test locations for sequential compactor passes on Lift 5, using the nuclear density gauge (NDG) test (AASHTO T238). This is the only lift for which sequential pass data was taken. This type of data is very interesting, as it shows the gradual improvement of soil density that occurs with successive compaction passes (Fig. 2(e)). Unfortunately, values of relative compaction could not be determined for the successive passes of Lift 5, as 1-pt. proctor tests could not be run at the same location for each pass without extensive soil sampling in the zone of interest, which would have affected the overall test results from the field study. Consequently, corresponding “per pass” relative compaction values are not presented in Fig. 2.

5 In Situ Testing of the Embankment Using Alternative Modulus-Based Methods

In addition to the traditional density-based tests described in the previous section, a number of alternative strength- or modulus-based tests were also used to monitor the compaction process during embankment construction: the LWD test, the DCP test, and the SSG test. Each of these tests were conducted in general accordance with standard practice (e.g., ASTM E2583-07; ASTM D6951-03; ASTM D6758-02); for brevity, the step-by-step details of each test procedure are omitted here. Two LWDs were used in this study (both manufactured by Zorn-Instruments), the first with a plate diameter of 300 mm (LWD 300), a falling mass of 10 kg, and a drop height of 730 mm, and the second with a plate diameter of 200 mm (LWD 200), a falling mass of 10 kg, and a drop height of 540 mm. The DCP that was used in this study (manufactured by Kessler Soils Engineering Products, Inc.) had a falling mass of 8 kg, a drop height of 575 mm, an overall penetration depth of 152 mm, and a conical point sloped at 60°. The SSG that was used in this study was manufactured by Humboldt Mfg. Co., with the dimensions and operating principles that are described in Humboldt Mfg. Co. (2000). The basic operating principles behind each of these tests are described in more detail in Tehrani (2009).

As with the NDG testing, modulus-based in situ tests were performed for the base layer, after the final passes for each lift for Lifts 1-4, and for nearly all of the successive passes on Lift 5. Each test series was accompanied by disturbed soil sampling, for later determination of the moisture content, particle size characteristics, and 1 pt.-proctor compaction characteristics. The order of the in situ tests and sampling that were performed was selected to minimize the effect of soil disturbance on the in situ test results. At each test location, the aforementioned in situ tests/sampling were performed in the following order: LWD 300, LWD 200, SSG, NDG, DCP, and finally bulk soil sampling. From lift to lift (or pass to pass on Lift 5), a slight test location offset was made with respect to previous test locations, to minimize the influence of prior soil sampling on the in situ test results for the soil layer that was being tested.

For both the LWD 300 and LWD 200 tests, modulus values were calculated from the soil’s surface deflection using Boussinesq’s equation (e.g., Rahman et al. 2007). For the SSG tests, modulus values were calculated using the method described by Humboldt Mfg. Co. (2000). For the DCP tests, both “average” (DCP-A) and “weighted mean” (DCP-M) cone penetration indices were calculated using the methods described by White et al. (2007). For comparison purposes, representative modulus values for the cone penetration tests were determined from the appropriate cone penetration indices using the correlation proposed by De Beer (1991). The resulting modulus values for each lift and pass are shown in Fig. 3. The number of tests conducted, mean values, and coefficients of variation for the dry unit weight and modulus data sets shown in Figs. 2

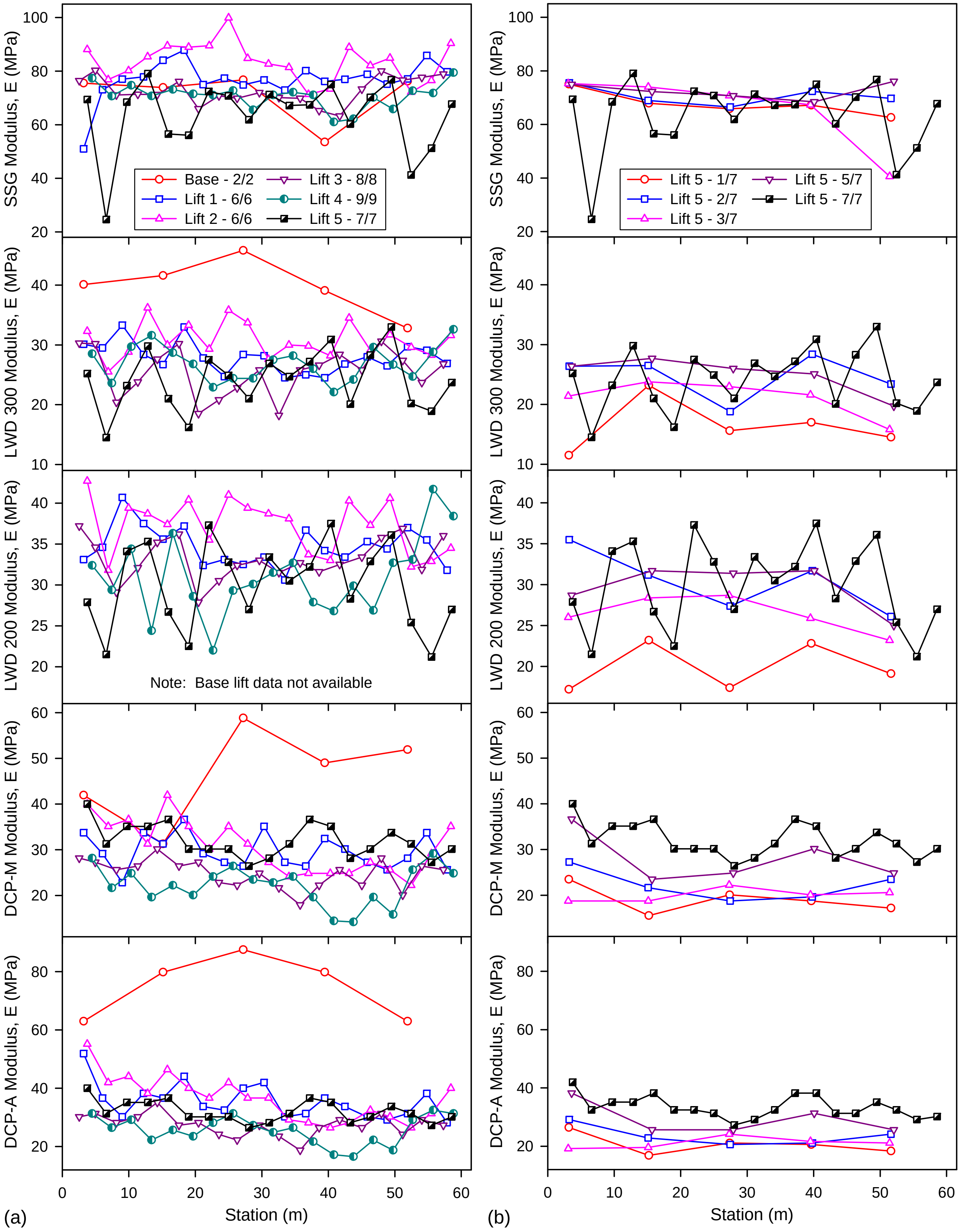

Fig. 3: Modulus values measured in alternative compaction control tests: (a) final passes for each lift, and (b) successive passes for Lift 5.

and 3 are provided in Table 1.

From a practical standpoint, for a uniform soil at a relatively consistent moisture content, an ideal in situ test for compaction control would tend to exhibit small variability from point to point for a given lift and pass, and would show a significant difference in measured values with successive compactor passes. This behavior would be reflective of the improvement in the soil's mechanical properties that occurs during the compaction process, and provided that the moisture content of the soil during compaction is relatively close to the optimum, the contractor would eventually meet the specified control criteria by applying sufficient compaction effort. It is expected that diminishing returns in performance improvement would be observed with each successive compactor pass; for example, a greater improvement in the soil's mechanical properties would likely occur during the first pass of compaction than during the seventh.

Unfortunately, as shown in Fig. 2, Fig. 3, and Table 1, reality is often much more variable than the ideal case described above. As shown, significant point-to-point variation was observed for the measured in situ test values, for both the traditional density-based tests and the modulus-based tests that were conducted. For this particular project, this variation is likely not caused by any significant changes in the material that is being placed, as indicated by the relatively uniform grain size distributions that were determined for samples taken from each in situ test location (Fig. 1); in many projects, variability in the borrow material will further increase the point-to-point variation in test results that is observed for a given lift and pass.

By observing the data shown in Fig. 2, Fig. 3, and Table 1, the following observations can be made:

1. The NDG test showed the most consistent increase in average measured values with successive compactor passes (the Lift 5 data). The DCP also appeared to work relatively well in this regard, with the average measured values tending to increase with successive compactor passes (although Lift 5, Pass 3 did exhibit a downward blip). These behavioral trends were also generally observed on a point-to-point basis, for many of the points shown in Figs. 2 and 3. For Lift 5, the SSG and LWD tests seemed to show no general increase in modulus values with additional compaction (much more random behavior was observed), with the seventh pass of compaction yielding modulus values that were less than or equal to the second pass of compaction. This type of behavior can make enforcement of compaction criteria in the field extremely difficult, as the contractor cannot see improvement in the soil properties with additional compactive effort.
2. For each lift/pass that was tested, the NDG-measured dry unit weights had a significantly smaller coefficient of variation than any of the measured modulus values. The coefficients of variation for the SSG, LWD, and DCP tests were generally in the same range, indicating that each of these tests exhibited about the same amount of relative variability around the mean for a given lift and pass.
3. For half of the measured lift/pass data sets, the SSG test results exhibited smaller coefficients of variation than the LWD and DCP tests. However, the SSG also had the greatest tendency to measure "significant outliers," which were typically lower than the rest of the measured data, and which occasionally yielded rather large coefficients of variation for some of the data sets.
4. The overall magnitude of the modulus values for the SSG, LWD, and DCP tests were significantly different from each other at a given test location. These nonconformities were caused by inherent differences in the operating principles for each test device. Consequently, some form of correction to the true soil moduli is necessary if these different test moduli are to be used in the pavement design process in a meaningful way.

6 Modulus-Based Test Results versus Nuclear Density Gauge Test Results

When exploring the possibility of using modulus-based techniques for compaction control, it is instructive to compare modulus-based test results to those from traditional density-based compaction control tests. Figure 4 compares the modulus values that were measured at each in situ test location with the corresponding NDG dry unit weights. As the base layer was only proof-rolled and was not an engineered lift, data from this layer is not included in Fig. 4. As shown, significant scatter in modulus values is typical, even at a relatively constant value of dry unit weight. The results from linear regression analyses (Fig. 4) support this observation, with low coefficients of determination being observed for the DCP data sets (e.g., $R^2 = 0.22 - 0.40$), and with extremely low coefficients of determination being observed for the SSG and LWD data sets (e.g., $R^2 = 0.03 - 0.07$).

Figure 5 compares the modulus values that were measured at each in situ test location against the results from other modulus-based tests that were conducted at the same point. From this figure, it can be observed that: (1) a moderately strong relationship exists between the LWD 300 and LWD 200 modulus values, with the LWD 200 moduli consistently being higher; (2) a strong relationship exists between the DCP-M and DCP-A data, with the DCP-A values consistently being higher – not surprising, given that these values were determined from the same set of penetration readings; and (3) there is essentially no relationship of significance between the LWD and DCP values. A similar lack of correlation was also observed between the SSG and LWD test results, and the SSG and DCP test results.

7 The Effect of Moisture Content on Lightweight Deflectometer Measurements

As shown in Fig. 3, modulus values from the LWD 300 and LWD 200 tests were recorded at 19 test locations on 7/24/08, immediately after completion of compaction for the final lift of the test embankment (the Lift 5, Pass 7

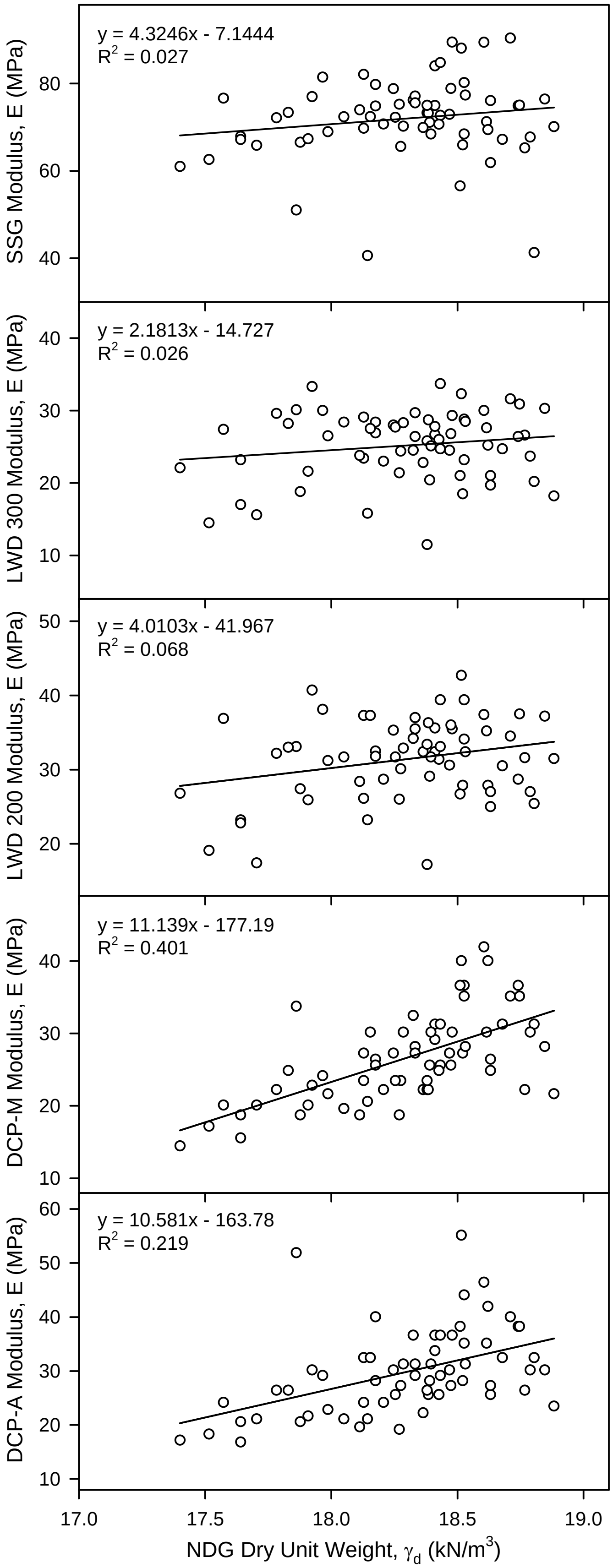

Fig. 4: Comparisons between modulus-based in situ test results and nuclear density gauge dry unit weights.

data shown in Fig. 3). Five of the LWD test locations along the centerline of the embankment 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. During this study period (7/24/08 to 8/5/08), representative soil samples were also taken at locations in the immediate vicinity of the LWD test areas, but not so close as to affect the recorded modulus values. The moisture content of each of these samples was then measured by performing oven-dried laboratory moisture content tests (ASTM D2216-05).

Figure 6 shows the variations in recorded LWD 300 modulus, LWD 200 modulus, and moisture content values at each test location over time. The purpose of this figure is to illustrate the effect that changes in moisture content can have on the measured modulus values, for soil that is at a consistent density (as it has not been subjected to any additional compactive effort of significance). As these measured modulus values are taken over time and are consequently not reflective of the values recorded immediately after compaction, none of the long-term data points shown in Fig. 6 (the 7/25/08, 7/30/08, 8/1/08, and 8/5/08 data) are included in Figs. 3-5.

As shown in Fig. 6, the LWD 200 generally provided higher recorded modulus values than the LWD 300 at each of the in situ test locations over time; this observation is consistent with the findings that are presented in Fig. 5. Also as shown in Fig. 6, the soil modulus values significantly increased over time while the moisture content decreased. This observed trend in behavior emphasizes the sensitivity of recorded soil modulus values to variations in the soil's moisture 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 examine the relationship between changes in the LWD 300 and LWD 200 modulus values and changes in the moisture content of the soil over time, regression analyses were performed on the data shown in Fig. 6, for those locations where the LWD tests and moisture content samples were in close proximity (Fig. 7).

As shown in Fig. 7, 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 ($R^2 = 0.80$ and $R^2 = 0.79$ for the LWD 300 and LWD 200 data, respectively) or exponential regression ($R^2 = 0.85$ and $R^2 = 0.81$ for the LWD 300 and LWD 200 data, respectively) as well.

These regression analyses indicate that there is a promising relationship between LWD modulus values and the moisture content of the soil. In general, it can be observed that as the moisture content decreases, the soil moduli increases. These data point to the importance of including the effect of moisture content when interpreting LWD test results. More broadly, it also provides an indicator that other types of tests that directly measure or infer the modulus of the soil (e.g., plate load tests,

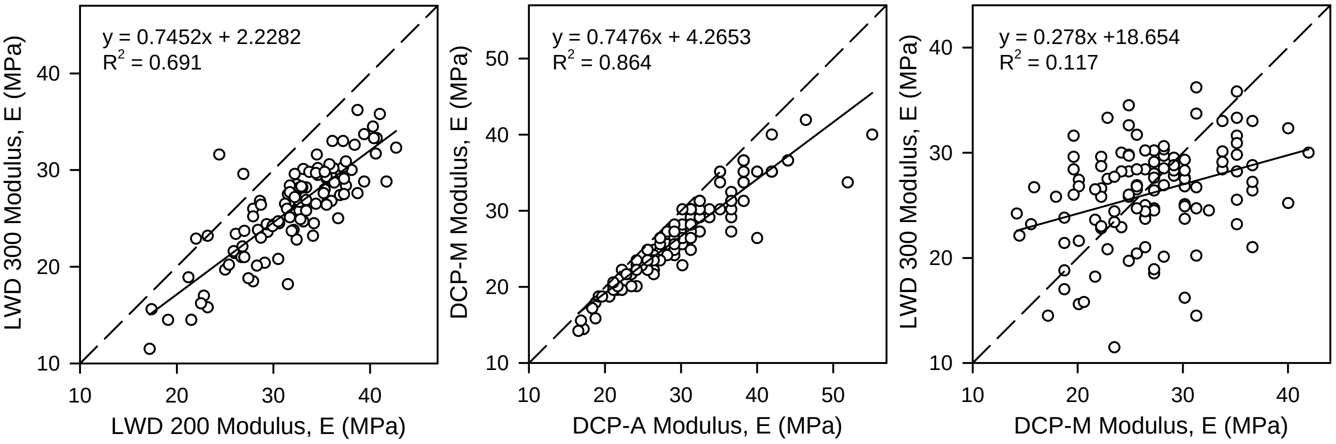

Fig. 5: Comparisons between modulus-based in situ test results.

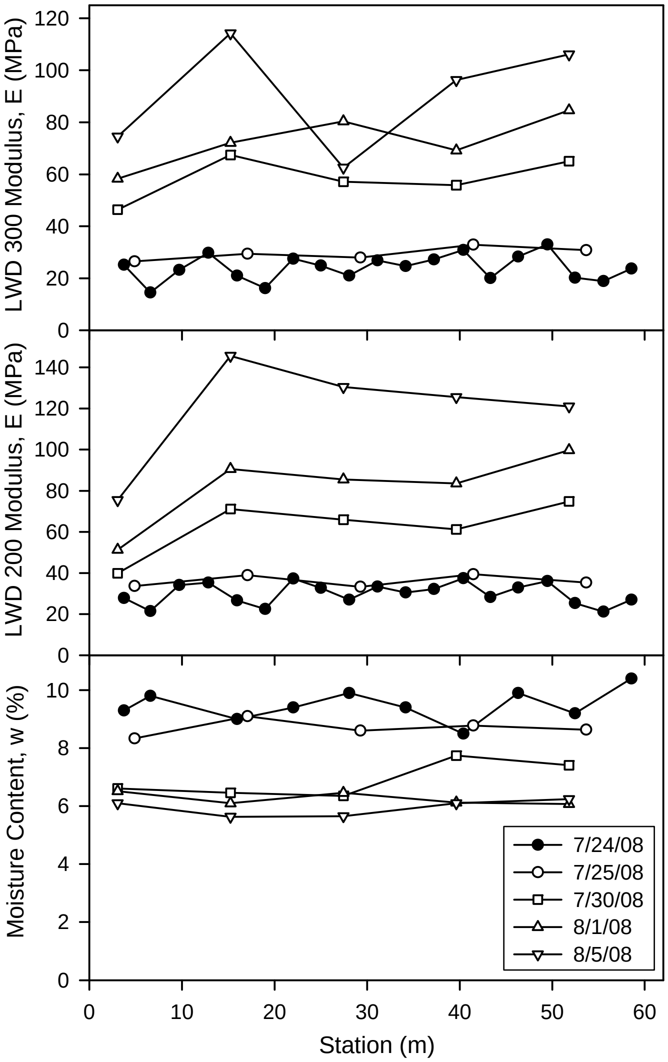

Fig. 6: Variation of LWD 300 modulus, LWD 200 modulus, and moisture content values over time for Lift 5, Pass 7 (the final pass for this lift), after completion of compaction.

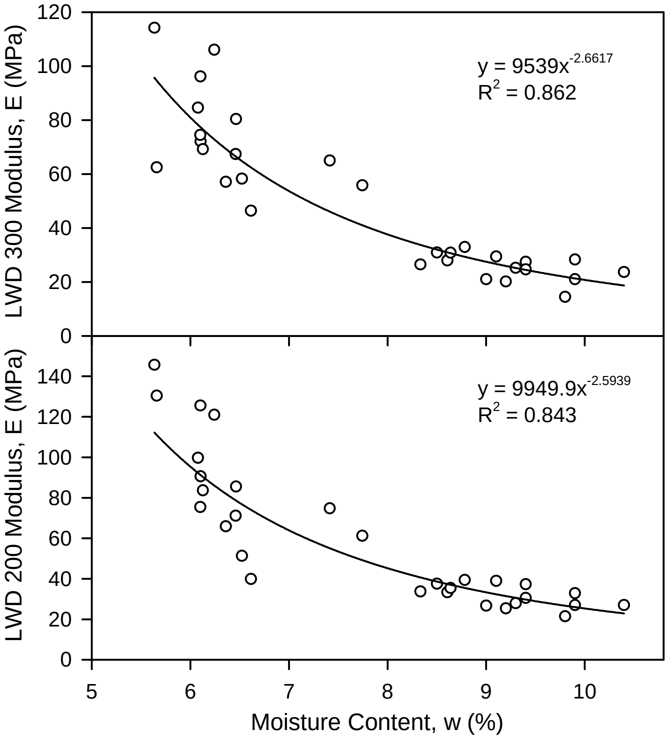

Fig. 7: LWD modulus versus laboratory-measured moisture content values.

falling weight deflectometer tests, SSG tests, DCP tests, etc.) may be sensitive to changes in soil moisture content and soil matrix suction in the long term. Consequently, for those DOTs that wish to use LWDs or other types of modulus-based tests for compaction control, a restriction on the time of testing after compaction has occurred or an allowable change in moisture 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. Additionally, as the effect of moisture content is shown to be critically important when interpreting modulus-based test results, end-result specifications need to somehow account for this behavior if these tests are to be used effectively for compaction control.

8 Including the Effect of Moisture Content in Modulus-Density Correlations

As shown in the previous section, LWD test results can be significantly affected by changes in the moisture content of a compacted soil. This is logical for partially saturated soils, as soil suction is directly related to the effective stress between soil particles, which in turn affects the deformation behavior of the soil under load. Consequently, when interpreting the results from any of the strength- or modulus-based in situ tests that were used in this study, it is critical to have some understanding of the moisture content of the soil, the degree of saturation of the soil, and/or the soil's matrix suction. In essence, all of these factors are related for soil at a constant density, as the soil's matrix suction is significantly affected by the amount of water that is present in the soil void space.

Physically, there is a dependence of the measured modulus values on both the density of the soil and its matrix suction. Mathematically, this dependence can be addressed using multivariate regression techniques in the data analysis process. Figure 8 shows the results from linear multiple regression analysis of the data shown in Fig. 4, which was performed to examine the relationship between the modulus values that were measured for the soil (dependent variable), the NDG dry unit weights (independent variable), and the NDG moisture contents (independent variable). Figure 8 is a 2-dimensional projection of a 3-dimensional plot, and, consequently, the resulting model fit for each point appears variable; the data is presented in this fashion so as to be consistent with Fig. 4 and with the data presentation approach that has been used by others (e.g., Thompson and White, 2007). It should be noted that oven-dried moisture contents can also be used in these types of analyses. For the sake of brevity, multiple regression results using oven-dried moisture contents are not presented here; however, the findings from these analyses were not substantively different than those where the NDG moisture contents were utilized (e.g., the R^2 values were similar). A relatively simple linear functional form was selected for use in the multivariate regression process, as shown in Fig. 8. By comparing the results shown in Figs. 4 and 8, the significance of including moisture content values in the data interpretation is evident, as indicated by the increases in the associated coefficients of determination that were observed.

The use of more sophisticated functional forms in the multivariate regression analyses was also explored (i.e., by using exponential functional forms, independent variable interaction terms, etc.), for the purpose of yielding higher coefficients of determination. A number of these functional forms were tested, with many of them yielding higher R^2 values, although typically not by a significant amount. Given that the number of data points in each data set was not large, it was felt that presentation of the more complicated functional forms that yielded slightly higher

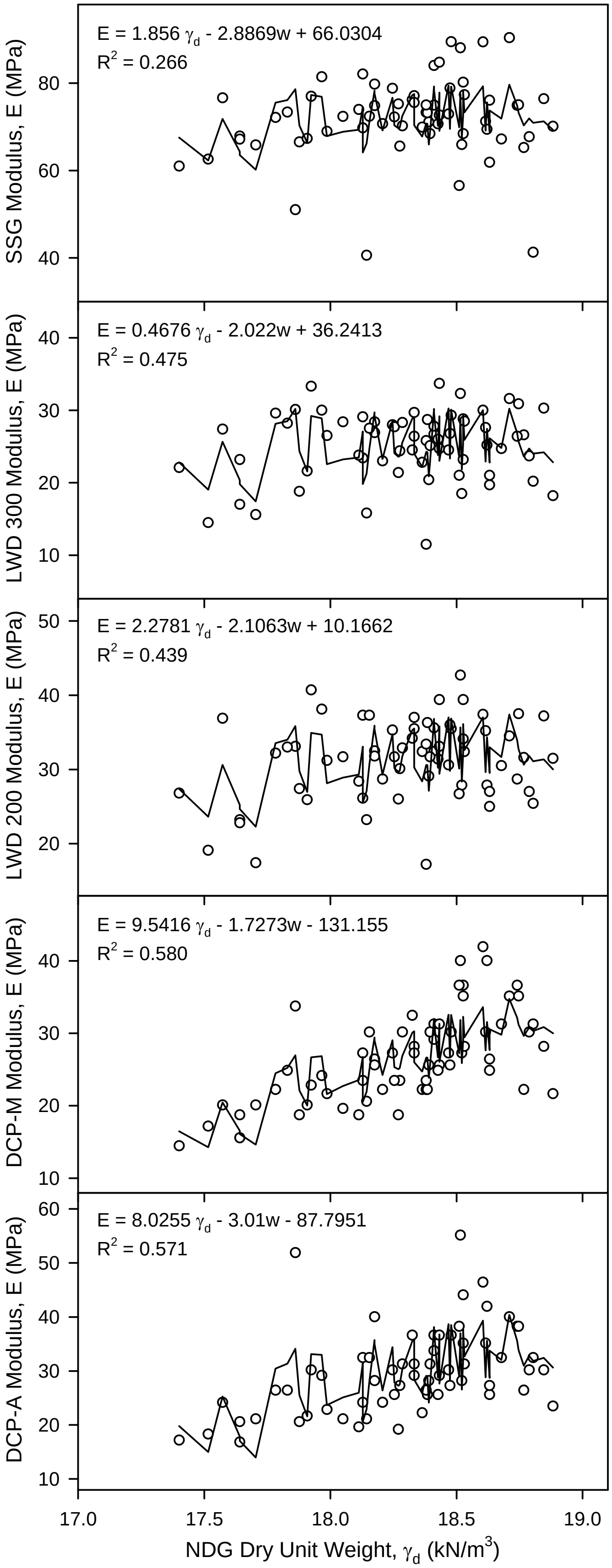

Fig. 8: Comparisons between modulus-based in situ test results and nuclear density gauge dry unit weights, including the effect of compaction moisture content.

R^2 values was not warranted here. In any case, from the results that are shown, it is clear that including the effect of water content in the data analysis approach can yield significant improvements in the relationships between the measured modulus values and the NDG dry unit weights.

9 Discussion of Results

For the LWD 300, LWD 200, SSG, and DCP test results described herein, it should be noted that the modulus values that were measured (e.g., LWD, SSG) or otherwise inferred (e.g., DCP) were determined using extremely different test principles. In particular, each of these devices determines a value of soil modulus by applying a certain amount of strain to the soil at a particular rate of strain. The magnitude of strain and rate of strain application are significantly different in the different devices, which makes it not surprising that the resulting values of modulus that are predicted by each device are significantly different.

Furthermore, as the surficial footprint and the amount of energy that is input at the ground's surface are different in each of these devices, the actual volume of soil that is tested varies. As soil grain size characteristics, moisture content, and soil matrix suction often change significantly throughout a soil mass, variations in the volume of soil that is tested are another potentially significant cause of the variability that was observed in the measured modulus results.

To develop a true understanding of the actual compressibility of a pavement sub-base, it is essential to understand the role that is played by matrix suction in the compacted soil. Based on what was observed in this study, modulus-based tests do not directly take this effect into account, and consequently tend to yield results (e.g., modulus values) that are more variable than those from density-based tests (e.g., unit weight values); this variability can be observed by comparing the coefficients of variation that are shown for each device in Table 1. Although the variability measured in modulus-based tests may be a more realistic measure of actual field behavior, it unfortunately makes the process of QC/QA much more difficult for a field engineer, as less reliance can be placed on the results from an individual spot test to be representative of a larger area.

As observed herein, the results from modulus-based tests must be interpreted in conjunction with the local moisture content and matrix suction conditions. As an example, some of the modulus-based tests tended to show no general increase in modulus values with additional compaction (e.g., the SSG and LWD showed modulus values from the seventh pass of compaction that were less than or equal to the second pass of compaction). This difference was likely a result of the effect of moisture content and matrix suction, which must be interpreted and understood in real-time by the field engineer to make a decision about whether to "pass" or "fail" a given lift. To use modulus-based test devices to control the compaction process effectively, the complex interplay of modulus and soil moisture (and matrix suction) must be understood by field personnel. As this relationship varies over different types of soil, experienced and sophisticated field personnel will likely be needed to ensure effective adoption of modulus-based QC/QA test procedures; the authors view this necessity for a higher-level understanding to be a potential hindrance to widespread adoption of modulus-based QC/QA test devices in the near term.

In any case, none of the results presented herein single-handedly promote the use of one device over another for the purpose of compaction control. Each device that was utilized has its own respective strengths and weaknesses, and potential users should be aware of these as they use the devices in the field. Each of these devices also has different sources of potential "operator error", which cannot be easily quantified.

In general, it should be noted that the more variable the results from a given QC/QA device, the more in situ testing is needed to develop an accurate picture of an entire compacted area. For compacted areas that exhibit highly variable modulus measurements, a lot of measured values are ideal; the relatively high measurement density of "intelligent compaction" (IC) or "continuous compaction control" (CCC) systems (e.g., Adam 1997, White et al. 2005, Meehan and Tehrani 2011) is one advantage of these emerging technologies over spot testing for QC/QA of the compaction process. The authors believe that future compaction control approaches will likely utilize both CCC/IC machine measurements as well as independent spot measurements for confirmation purposes.

It should be noted that the findings of this study are based on the results from tests conducted on only one type of soil. The results from similar tests on other soil types (e.g., gravels, clays, different soil blends, etc.) are needed before the general conclusions from this study can be more broadly extrapolated.

10 Conclusions

This paper presents and compares the results from a series of in situ density-based and modulus-based compaction control tests. To simulate current construction practices as closely as possible, these in situ tests were performed on a road sub-base test pad that was constructed and compacted by a vibratory smooth drum roller in a series of lifts. The soils utilized for construction were coarse-grained in nature, and are considered to be "select fill" materials by the Delaware Dept. of Transportation. During construction of the test embankment, the compaction process was monitored using the traditional density-based methods that are currently employed by the DOT (the nuclear density gauge device), as well as a number of alternative modulus-based devices, including the light weight deflectometer (LWD), the dynamic cone penetrometer (DCP), and the soil stiffness gauge (SSG). The following conclusions were drawn from the in situ test data that are presented and analyzed:

1. Significant point-to-point variation for a given lift and pass is typical for each type of in situ test that was conducted, for both the density-based and modulus-based tests. This variation occurs even when there

is no significant change in the material that is being placed. For many projects, variability in the borrow material can lead to greater point-to-point variability for a given lift and pass than what is shown herein.

2. The NDG test showed the most consistent increase in average measured values with successive compactor passes. The DCP also appeared to work relatively well in this regard, with the average measured values tending to increase with successive compactor passes. The SSG and LWD tests seemed to show no general increase in modulus values with additional compaction effort (subsequent compactor passes) for a given lift.
3. For each lift/pass that was tested, the NDG-measured dry unit weights had a significantly smaller coefficient of variation than any of the measured moduli values. The coefficients of variation for the SSG, LWD, and DCP tests were generally in the same range, indicating that each of these tests exhibited about the same amount of relative variability around the mean for a given lift and pass.
4. The overall magnitude of the modulus values for the SSG, LWD, and DCP tests were significantly different from each other at a given test location. These nonconformities were caused by inherent differences in the operating principles for each test device. Consequently, some form of correction to the "true" soil moduli is necessary if these different test moduli are to be used in the pavement design process in a meaningful way.
5. The modulus-based in situ test results correlate poorly to the nuclear density gauge dry unit weights. Moreover, the modulus-based in situ test results do not agree that well with each other if the modulus values from different test devices are compared directly. This lack of agreement was likely caused by a variety of factors, including: variations in the magnitude of strain and rate of strain application between the different modulus-based devices, variations in the tested volume between the different devices, and variations in the local moisture content and matrix suction conditions.
6. In particular, the effect of moisture content on the measured modulus values can be quite significant, as illustrated by examining the effect of changes in soil moisture content on the LWD-measured moduli over a long-term period after completion of compaction. This is logical for compacted soils, as these soils are partially saturated, and the associated magnitude of soil matrix suction is directly related to the effective stress between soil particles, and in turn the deformation behavior of the soil under load. Multiple regression analysis is a useful technique for including the effect of moisture content when comparing the results from density-based and modulus-based tests.

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Table 1: Number of Tests Conducted (#), Means (μ), and Coefficients of Variation (c_v) for the Measured Dry Unit Weight and Modulus Values for Each Lift and Pass

		NDG			SSG		LWD 300		LWD 200		DCP-M		DCP-A	
Lift/pass	#	$\mu_{\gamma d}$	$c_{v,\gamma d}$	#	μ_E	$c_{v,E}$	μ_E	$c_{v,E}$	μ_E	$c_{v,E}$	μ_E	$c_{v,E}$	μ_E	$c_{v,E}$
B/2	5	17.4	0.02	5	71	0.14	40	0.12	–	–	47	0.22	75	0.15
1/6	10	18.2	0.01	19	77	0.10	28	0.09	35	0.07	30	0.13	36	0.17
2/6	10	18.3	0.02	19	84	0.09	31	0.09	37	0.09	31	0.19	36	0.21
3/8	10	18.5	0.02	19	73	0.07	25	0.15	33	0.08	25	0.13	27	0.14
4/9	5	18.2	0.03	19	71	0.06	27	0.11	31	0.15	22	0.19	26	0.19
5/1	5	17.8	0.02	5	68	0.07	16	0.26	20	0.15	19	0.16	21	0.18
5/2	5	18.1	0.01	5	71	0.05	25	0.15	30	0.12	22	0.15	24	0.15
5/3	5	18.1	0.01	5	66	0.22	21	0.15	26	0.08	20	0.07	21	0.09
5/5	5	18.5	0.01	5	72	0.04	25	0.12	30	0.10	28	0.19	29	0.19
5/7	10	18.6	0.01	19	64	0.21	24	0.21	30	0.17	32	0.11	33	0.11

Note: Mean value units are the same as those shown in Figs. 2 and 3, and the coefficient of variation values are unitless. The same number of SSG, LWD, and DCP tests were conducted for each lift and pass.