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Evaluation of the Lightweight Deflectometer for In-Situ Determination of Pavement Layer Moduli

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16. Abstract:

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The primary objective of this study was to investigate the suitability of the lightweight deflectometer (LWD) to measure in-situ pavement layer moduli. The LWD, along with two other devices, the GeoGauge and dynamic cone penetrometer (DCP), were used to measure and monitor subgrade and base layer moduli during construction. Three existing gravel roads were also tested.

A high spatial variability was found for the stiffness modulus values measured by all three devices. There were no significant correlations among the results with the devices. Although no unique relationship between mean LWD moduli and either GeoGauge or DCP moduli was found, a good correlation was found when the 85th percentile stiffness values were compared. The effect of dry density was not evident, but moisture content showed a significant influence on the measured stiffness with all three devices, especially the LWD. A limited laboratory investigation indicated that the high modulus value for the LWD may be attributable to soil suction or a pore pressure development from transient loading of the LWD on a fine-grained soil.

The LWD is not recommended for use for construction quality control until further research has been conducted to determine the causes of the high spatial variability and the effect of moisture on the LWD-measured modulus. The study further recommends that additional well-controlled laboratory testing be performed to evaluate the effect of moisture on LWD-modulus measurements and that field studies be conducted to verify the findings.

The advantage of the LWD is the lower operating cost and lower health risk compared to the conventional nuclear density and moisture content devices. In addition, the LWD can directly measure the modulus properties that are the basis for the new MEPDG pavement design.

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ABSTRACT

The quality of base and subgrade construction has conventionally been evaluated using specifications based on density and moisture content. Such specifications for highway base and subgrade require the use of a nuclear density and/or moisture gauge that poses potential health hazards to the operator and requires expensive certification and monitoring. Moreover, density and moisture do not relate to pavement design input parameters or performance. The fundamental material properties such as elastic and resilient moduli that are key inputs in the new mechanistic empirical-based design cannot be obtained from density and moisture content measurements.

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INTRODUCTION

Soil compaction is one of the most critical factors in the construction of highway pavements (American Association of State Highway and Transportation Officials [AASHTO], 1993; Huang, 1993; Nazzal, 2003). The load-carrying capacity of a pavement is highly dependent on the proper compaction of the subgrade. The current empirical pavement design method (AASHTO, 1993) and the new mechanistic-empirical design method (ARA, Inc., 2004) both use soil modulus (resilient modulus) as the primary input parameter for pavement design. Therefore, the field measurement of subgrade resilient modulus should logically be the quality control parameter for subgrade construction. However, the current methods for evaluating the quality of subgrade construction are based on the field measurement of the dry unit weight using the nuclear density gauge (NDG) or the sand cone test (ASTM D1556). The main reasons for this are the lack of a reliable field measurement device/technique and the long history/experience with the density/moisture measurement method.

Conventional density and moisture content measurements used to control compaction are time-consuming and cumbersome. Because of its portability and potential for estimating fundamental material properties, the lightweight deflectometer (LWD) is gaining increasing international attention for quality control and construction acceptance during pavement construction. For example, the LWD has been used during construction of pavement foundation in Germany where the device was first developed (Nazzal et al., 2007). It has also been extensively evaluated in the U.K., where a standard specification for its use was developed (Fleming et al., 2007).

In the United States, there is a growing interest in the use of the LWD for compaction quality control and quality assurance (QC/QA) as evidenced by numerous research publications in the past decade. The device has been evaluated in several U.S. states, including Kansas (Petersen et al., 2007a,b), Louisiana (Nazzal, 2003), Minnesota (Hoffmann, 2003), Montana (Vischer, 2006), and New England (Steinert et al., 2005). The LWD has also been used to evaluate and control pavements in Montana (Vischer, 2006). The Minnesota Department of Transportation (MnDOT) is among the few states at the forefront of adopting the use of the LWD and has developed a pilot specification for LWD testing (Davich et al., 2006). In line with the growing interest in the application of the LWD as a QC/QA tool, this study was undertaken to evaluate the suitability of the LWD and two other devices, the GeoGauge and the dynamic cone penetrometer (DCP), for in-situ determination of pavement layer moduli in Virginia.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the LWD for in-situ determination of soil modulus. The objectives were as follows:

1. Determine the resilient modulus using the LWD, GeoGauge, and DCP for Virginia's subgrade soils and base aggregate on a number of construction projects.

2. Compare the subgrade resilient modulus obtained by the LWD with that obtained by the GeoGauge and DCP.

3. Investigate the possible effects of other soil properties such as density and moisture content on measured modulus values.

The scope of this study was limited to seven pavement sections in Virginia: three compacted subgrades, one compacted base, and three existing gravel roads. Additional laboratory testing on two soils was conducted to investigate the effect of density and moisture content on measured soil moduli.

METHODOLOGY

Overview

Five tasks were performed to achieve the objectives of this study:

1. The literature was reviewed to determine the state of the practice regarding the use of the LWD for compaction control of unbound pavement layers.

2. Pavement sections in five Virginia counties were selected for field testing using the LWD, GeoGauge, and DCP during the 2007 paving season. Test data were captured and stored for further analysis.

3. Nuclear density and sand cone tests were performed on some of the sites to determine densities. Limited laboratory testing was conducted on some of the soil samples to determine moisture contents for verification purposes.

4. Data were analyzed to determine any possible correlation among the various devices and the effect of soil properties such as density and moisture on them.

5. A small scale laboratory investigation was conducted to study the effect of moisture on soil modulus measurements using the GeoGauge, LWD, and DCP.

Literature Review

Literature on the use of the LWD for characterizing pavement layers during construction was identified using the resources of the VDOT Research Library and the University of Virginia Library. Additional resources used included online databases such as the Transportation Research Information System (TRIS), the Engineering Index (EI Compendix), Transport, WorldCat, and that of the American Society of Civil Engineers, among others.

Selection of Pavement Test Sections

Seven pavement sections in five Virginia counties (see Figure 1) were tested for the study. Three were existing gravel roads, and the others were flexible pavements. Modulus testing on existing gravel roads, prepared subgrade, and base was conducted on these pavement sections using three portable devices in the following order: (1) GeoGauge, (2) LWD, and (3) DCP. In most cases, these tests followed the determination of density and moisture content with a nuclear gauge. In some places, density was also verified using the sand cone method.

The resiliency factor (RF), design California bearing ratio (CBR), and soil support value (SSV) for the selected counties were predicted from the Virginia Department of Transportation's (VDOT) *Pavement Design Guide for Subdivision and Secondary Roads in Virginia* (VDOT, 2000). The existing gravel roads in Augusta County, i.e., Routes 782, 785, and 797, have an SSV of 12; the average SSV for all other projects is about 5 or 6. Prepared subgrades were tested on Routes 3, 644, and 743, and prepared base was tested on Route 15. Information regarding these sections is summarized in Table 1.

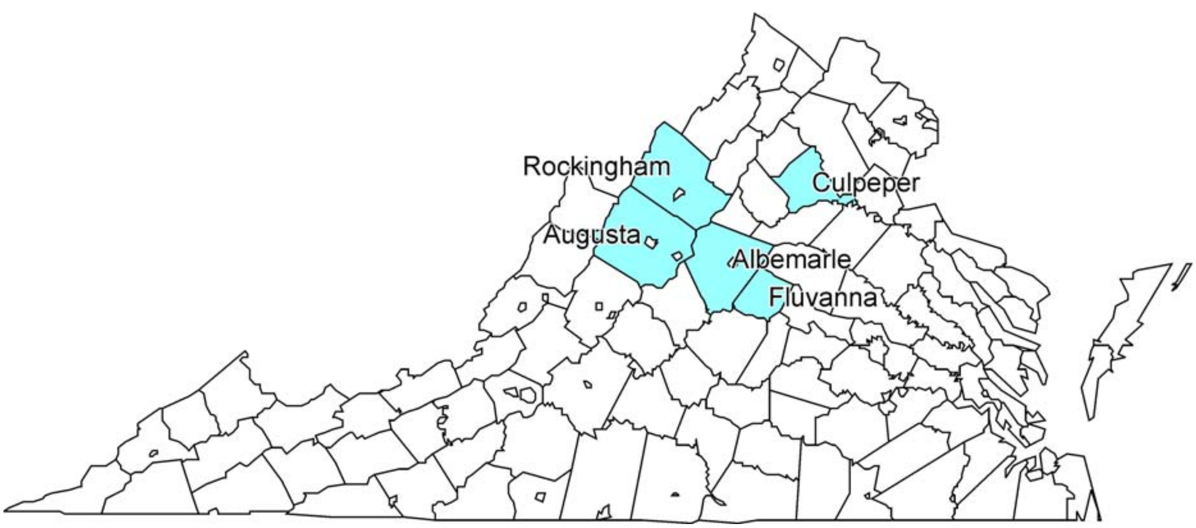

Figure 1. Pavement Test Sections in Albemarle, Augusta, Culpeper, Fluvanna, and Rockingham Counties, Virginia

Table 1. Test Sections with Estimated Soil Support Values

Project	County	Section Length (ft)	Tested Surface	Resiliency Factor (RF)	California Bearing Ratio (CBR)	Soil Support Value (SSV)
Route 3	Culpeper	250	Subgrade	1	5	5
Route 644	Rockingham	500		1	6	6
Route 743	Albemarle	300		1	5	5
Route 15	Fluvanna	500	Base	1.5	4	6
Route 782	Augusta	500	Existing gravel road	2	6	12
Route 785	Augusta	500		2	6	12
Route 797	Augusta	500		2	6	12

Route 3/Culpeper County

A 250-ft test section was located on a secondary road: Route 3 in Culpeper, Virginia. The subgrade was constructed of select fill material (Type 1) with a minimum required CBR of 30. Laboratory testing indicated the subgrade material had a maximum dry density (MDD) of 135.8 lb/ft^3 and an optimum moisture content (OMC) of 10.7%. Modulus testing was performed on the prepared subgrade for this section.

Route 644/Rockingham County

A 500-ft subgrade section on Route 644 in Massanutten, Virginia, was tested as outlined in Table 2. The soil was classified as lean clay (CL) with an MDD of 99 lb/ft^3 and an OMC of 18.8%.

Table 2. Testing Details for Route 644 in Rockingham County

Station (ft)	Tests	Sample Collection
22+00	GeoGauge, LWD, DCP, NDG	Sand cone
22+25	GeoGauge, LWD	
22+50	GeoGauge, LWD	
22+75	GeoGauge, LWD	
23+00	GeoGauge, LWD, DCP, NDG	Sand cone
23+25	GeoGauge, LWD	5-gal bucket
23+50	GeoGauge, LWD	
23+75	GeoGauge, LWD	
24+00	GeoGauge, LWD, DCP, NDG	Sand cone
24+25	GeoGauge, LWD	
24+50	GeoGauge, LWD	
24+75	GeoGauge, LWD	
25+00	GeoGauge, LWD, DCP, NDG	Sand cone
25+25	GeoGauge, LWD	
25+50	GeoGauge, LWD	
25+75	GeoGauge, LWD	5-gal bucket
26+00	GeoGauge, LWD, DCP, NDG	Sand cone
26+25	GeoGauge, LWD	
26+50	GeoGauge, LWD	
26+75	GeoGauge, LWD	
27+00	GeoGauge, LWD, DCP, NDG	Sand cone

LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

Route 743/Albemarle County

This 300-ft test section was located near Charlottesville-Albemarle Airport in Albemarle County, Virginia, on Route 743. Details of the testing plan are shown in Table 3. Tests were performed every 30 ft in each lane starting from station 22+50 and ending at station 25+50. Testing was done on finished subgrade, which consisted of sandy lean clay and sandy elastic silt with a USCS classification of CL and MH, respectively. The MMD of the soil was 80.5 lb/ft^3 at an OMC of 37%. A 1-ft by 1-ft area was marked out at each testing location to indicate where tests were to be performed. The non-destructive tests using the GeoGauge and LWD were performed within the 1-ft by 1-ft test square; the destructive DCP tests were performed around the outer edge of the test area. Three drops of the LWD and three runs of the GeoGauge were performed at each test location. Up to three DCP measurements and one NDG reading were taken at each location.

Table 3. Testing Details for Route 743 in Albemarle County

Station (ft)	Lane	Location	Tests
22+50	North (N)	Center of lane	GeoGauge, LWD, DCP, NDG
22+80	N, South (S)	Outer wheel path	GeoGauge, LWD, DCP, NDG
23+10	N	Center of lane	GeoGauge, LWD, DCP , NDG
23+40	N, S	Outer wheel path	GeoGauge, LWD, DCP, NDG
23+70	N, S	Outer wheel path	GeoGauge, LWD, DCP, NDG
24+00	N	Center of lane	GeoGauge, LWD, DCP, NDG
24+30	N, S	Outer wheel path	GeoGauge, LWD, DCP, NDG
24+60	N	Center of lane	GeoGauge, LWD, DCP, NDG
24+90	N, S	Outer wheel path	GeoGauge, LWD, DCP, NDG
25+20	N	Center of lane	GeoGauge, LWD, DCP, NDG
25+50	N, S	Outer wheel path	GeoGauge, LWD, DCP, NDG

LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

Route 15/Fluvanna County

This section was a bridge approach section on a secondary road: Route 15 in Fluvanna County, Virginia. Compacted aggregate base layer was monitored and tested. The base material was VDOT 21B aggregate. Details of the testing including test equipment and locations are summarized in Table 4. This 500-ft-long test section started at station 103+25 in the northbound direction.

Route 782/Augusta County

Route 782 in Augusta County, Virginia, is a gravel secondary road, and testing was done on the existing gravel surface. The road surface appears to be crusher run material placed on a, presumably, compacted clay base. A total of 500 ft of road section was tested as detailed in Table 5. Materials located at stations 400+00 ft and 500+00 ft showed very high moduli with the LWD testing and refusals at approximately 3-in depths for the DCP. NDG testing was not possible as the stiff ground made inserting the NDG probe impossible.

Table 4. Testing Details for Route 15 in Fluvanna County

Station	Tests	Sample Collection
103+40 m	GeoGauge, LWD, DCP, NDG	Sand cone
+25 ft	GeoGauge, LWD	
+50 ft	GeoGauge, LWD	
+75 ft	GeoGauge, LWD	
+100 ft	GeoGauge, LWD, DCP, NDG	Sand cone
+125 ft	GeoGauge, LWD	
+150 ft	GeoGauge, LWD	
+175 ft	GeoGauge, LWD	
+200 ft	GeoGauge, LWD, DCP, NDG	
+225 ft	GeoGauge, LWD	
+250 ft	GeoGauge, LWD	
+275 ft	GeoGauge, LWD	
+300 ft	GeoGauge, LWD, DCP, NDG	
+325 ft	GeoGauge, LWD	
+350 ft	GeoGauge, LWD	Sand cone
+375 ft	GeoGauge, LWD	
+400 ft	GeoGauge, LWD, DCP, NDG	
+425 ft	GeoGauge, LWD	
+450 ft	GeoGauge, LWD	
+475 ft	GeoGauge, LWD	
+500 ft	GeoGauge, LWD, DCP, NDG	

LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

Table 5. Testing Details for Route 782 in Augusta County

Station (ft)	Tests	Sample Collection
0+00	GeoGauge, LWD, DCP, NDG	Sand cone
0+25	GeoGauge, LWD	
0+50	GeoGauge, LWD	
0+75	GeoGauge, LWD	
100+00	GeoGauge, LWD, DCP, NDG	Sand cone
100+25	GeoGauge, LWD	5-gal bucket
100+50	GeoGauge, LWD	
100+75	GeoGauge, LWD	
200+00	GeoGauge, LWD, DCP, NDG	Sand cone
200+25	GeoGauge, LWD	
200+50	GeoGauge, LWD	
200+75	GeoGauge, LWD	
300+00	GeoGauge, LWD, DCP, NDG	Sand cone
300+25	GeoGauge, LWD	
300+50	GeoGauge, LWD	
300+75	GeoGauge, LWD	5-gal bucket
400+00	GeoGauge, LWD, DCP	Sand cone
400+25	GeoGauge, LWD	
400+50	GeoGauge, LWD	
400+75	GeoGauge, LWD	
500+00	GeoGauge, LWD, DCP	Sand cone

LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

Route 785/Augusta County

Route 785 in Augusta County is a gravel secondary road, and testing was conducted on the existing gravel surface. A 500-ft section of the road was tested as detailed in Table 6.

Table 6. Testing Details for Route 785 in Augusta County

Station (ft)	Tests	Sample Collection
000+00	GeoGauge, LWD, DCP	Sand cone
000+25	GeoGauge, LWD	
000+50	GeoGauge, LWD	
000+75	GeoGauge, LWD	
100+00	GeoGauge, LWD, DCP	Sand cone
100+25	GeoGauge, LWD	
100+50	GeoGauge, LWD	
100+75	GeoGauge, LWD	
200+00	GeoGauge, LWD, DCP	Sand cone
200+25	GeoGauge, LWD	
200+50	GeoGauge, LWD	
200+75	GeoGauge, LWD	
300+00	GeoGauge, LWD, DCP	Sand cone
300+25	GeoGauge, LWD	
300+50	GeoGauge, LWD	
300+75	GeoGauge, LWD	
400+00	GeoGauge, LWD, DCP	Sand cone
400+25	GeoGauge, LWD	
400+50	GeoGauge, LWD	
400+75	GeoGauge, LWD	
500+00	GeoGauge, LWD, DCP	Sand cone
600+00	GeoGauge, LWD, DCP	Sand cone

LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

Route 797/Augusta County

Route 797 in Augusta County is a gravel secondary road. Tests were conducted on the existing gravel surface. A 500-ft section was tested as detailed in Table 7.

In-situ Testing Devices

All three devices considered in this study are portable because of their low weight compared to other in-situ soil testing devices. The GeoGauge and LWD estimate stiffness from measured surface deflection by applying a dynamic load; the DCP uses resistance of a soil layer to penetration of a cone to estimate soil material stiffness.

GeoGauge

The GeoGauge is a non-destructive testing device about the size of a large hatbox that directly and quickly measures the stiffness of the soil or aggregate substrate directly beneath it. The GeoGauge used in this study was marketed by Humboldt Manufacturing, Chicago, Illinois, and is shown in Figure 2.

Table 7. Testing Details for Route 797 in Augusta County

Station (ft)	Test	Sample Collection
0+00	GeoGauge, LWD, DCP	Sand cone
0+25	GeoGauge, LWD	
0+50	GeoGauge, LWD	
0+75	GeoGauge, LWD	
100+00	GeoGauge, LWD, DCP	
100+25	GeoGauge, LWD	
100+50	GeoGauge, LWD	
100+75	GeoGauge, LWD	
200+00	GeoGauge, LWD, DCP	Sand cone
200+25	GeoGauge, LWD	
200+50	GeoGauge, LWD	
200+75	GeoGauge, LWD	
300+00	GeoGauge, LWD, DCP	Sand cone
300+25	GeoGauge, LWD	
300+50	GeoGauge, LWD	
300+75	GeoGauge, LWD	
400+00	GeoGauge, LWD, DCP	Sand cone
400+25	GeoGauge, LWD	
400+50	GeoGauge, LWD	
400+75	GeoGauge, LWD	
500+00	GeoGauge, LWD, DCP	Sand cone

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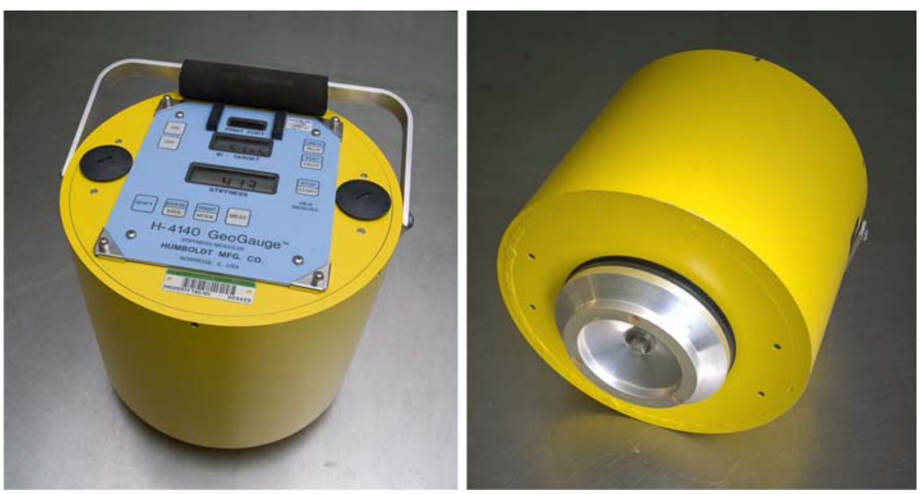

Figure 2. Humboldt GeoGauge (Model H-4140)

The device consists of an electromechanical vibrator that applies a small dynamic load as low frequency sound waves. The soil surface is oscillated at 25 different frequencies from 100 Hz to 196 Hz with 4-Hz intervals in between. The magnitude of the applied force and deflections are on the order of 9N and about 0.00005 in, respectively. It uses the force and dynamic deflections induced by the vibrator to compute surface stiffness. The layer stiffness is computed as an average of the 25 stiffness values found from the oscillation of the 25 different frequencies. Stiffness values can be converted to elastic moduli using Equation 1 (Alshibli et al., 2005):

$$E_G = H_{SG} \frac{(1-\upsilon^2)}{1.77R}$$ [Eq. 1]

where

E_G = soil elastic modulus in MPa
H_{SG} = GeoGauge stiffness reading in MN/m
υ = Poisson's ratio (assumed to be 0.35)
R = radius of GeoGauge foot (57.51 mm).

LWD

The LWD used in this study was manufactured by CarlBro, Inc., of Denmark and is marketed as PRIMA 100. The mode of operation of the LWD is similar to that of the heavier truck-mounted conventional falling weight deflectometer (FWD). The LWD applies an impulse load on a circular plate and calculates the stiffness of the subgrade under the plate. The LWD allows collection of up to three deflection values at a specified radial distance from the center of the load plate. The deflection collected establishes a deflection basin profile and allows for the back-calculation of the resilient modulus of the pavement layer or layers.

The LWD consists of three main sections: a base with a loading plate, load cell, and velocity transducer; a sliding drop weight; and an upper frame assembly consisting of a weight guide rod, a locking release mechanism, and rubber dampers. Figure 3 is a schematic representation of the LWD. As the sliding mass falls and strikes the rubber buffer, a load pulse of 15 to 20 ms duration is transferred through the load plate into the ground. A 12-in-diameter loading plate was used in this study. Up to two additional velocity transducers (geophones) may

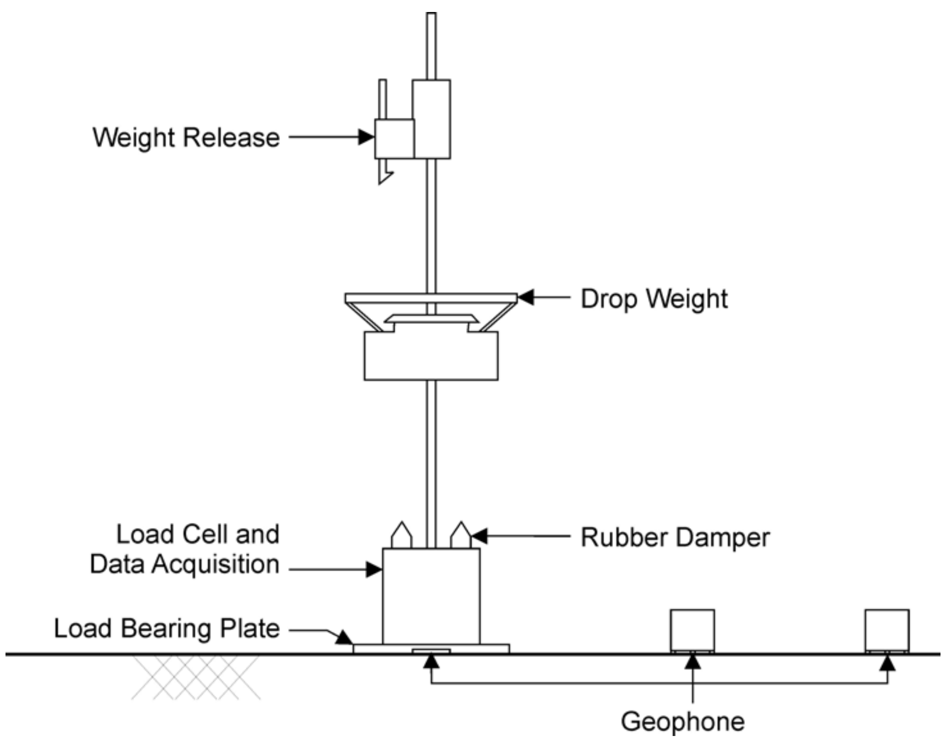

Figure 3. Lightweight Deflectometer

be attached to the device, allowing for the measurement of a deflection basin to determine layer properties at increasing depths. By varying the mass of the drop weight, diameter of the load plate, height of the drop, and number of rubber buffers, a user can control both the magnitude and duration of the induced stress pulse. Computation of surface stiffness modulus is based on Boussinesq elastic theory as shown in Equation 2 (Fleming et al., 2007).

$$E_0 = \frac{A\Pr(1-\upsilon^2)}{d_0} \quad \text{[Eq. 2]}$$

where

E_0 = composite layer stiffness modulus (MPa)
A = plate rigidity factor, default = 2 for a flexible plate, $\pi/2$ for a rigid plate
P = maximum contact pressure (kPa)
r = plate radius (m)
υ = Poisson's ratio (the range 0.3–0.45, depending on test material type)
d_0 = peak deflection (mm).

DCP

The DCP is a lightweight portable device for measuring in-situ soil strength. A schematic of the device is shown in Figure 4. A Model 4218A DCP with an 8-kg hammer from Kessler Soils Engineering Products Inc., Springfield, Virginia, was used. The mode of operation

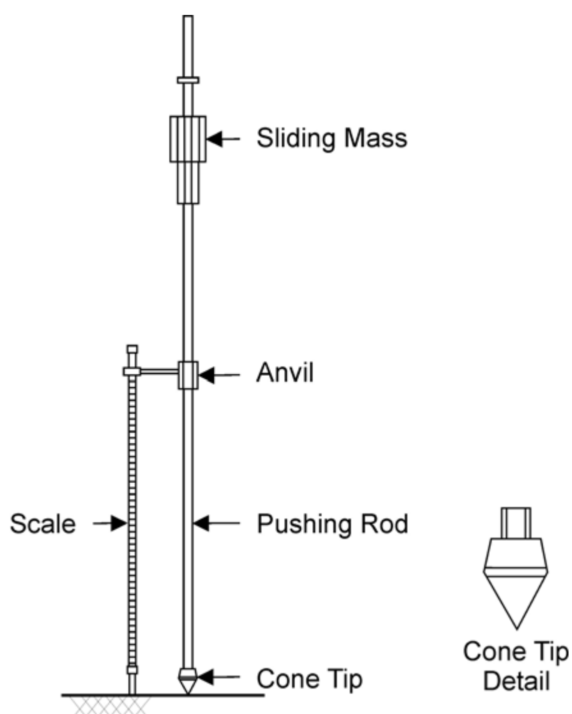

Figure 4. Schematic of Dynamic Cone Penetrometer (after Schmidt, 2008)

of the portable DCP is similar to that of the larger truck-mounted cone penetration test or the standard penetration test. During a test, the 8-kg (17.6 lb) mass drops onto an anvil from a height of about 575 mm (22.7 in). The anvil is attached to a 16-mm-diameter (0.6 in) steel pushing rod, the end of which holds a replaceable conical tip. The tip is 20 mm (0.79 in) in diameter with a cone angle of 60 degrees. Since the cone diameter is larger than the steel pushing rod, side friction along the length of the rod is reduced or eliminated. The penetration depth from each drop is recorded. After measuring the penetration depths for each blow, the DCP penetration index (DCPI) or DCP penetration rate (PR) in millimeters per blow may be computed. PR for a given layer is usually constant, and because of this, the DCP can also be used to determine layer boundaries and thicknesses. The derived DCPI correlates to the CBR and subsequently to the soil resilient modulus. There are also other regression equations available directly relating PR to soil modulus; one such relationship is shown in Equation 3 relating the PI and soil modulus (De Beer, 1991).

$$Es = 3.05 - 1.07 \log PR \qquad \text{[Eq. 3]}$$

where

E_s = soil elastic modulus in MPa
PR = penetration rate in mm/blow.

Laboratory Investigation

The effect of moisture on the soil stiffness modulus was investigated in a controlled laboratory study with two sources of soil:

1. Soil from Northern Virginia (NOVA): AASHTO A-7-5, OMC 28.2% and MDD 91.3 lb/ft^3
2. Soil from the grounds of the University of Virginia (UVA) near Scott Stadium: AASHTO A-4, OMC 21.6% and MDD 102.7 lb/ft^3

The soils were compacted in a 6-in mold to various densities and moisture contents to simulate various degrees of saturation and suction. In the case of the NOVA soil, both density and moisture content were varied. However, attempts were made to compact the UVA soil at approximately the same dry density while varying the moisture content. The compacted soil was tested using the GeoGauge, LWD, and DCP in that order on the compaction mold.

RESULTS AND DISCUSSION

Literature Review

The literature review is organized into the following topics: (1) issues with LWD use, (2) target LWD modulus values, (3) LWD specifications, (4) comparison of LWD stiffness with laboratory resilient modulus, and (5) problems associated with the analysis of LWD data.

Issues with LWD Use

Despite the growing interest in the use of the LWD for controlling compaction in the field, several key issues remain unanswered. First, poor correlation between compaction levels and LWD moduli has been reported. Steinert et al. (2005) evaluated the potential of the LWD for compaction quality control for aggregate base courses and subgrade soil. Two types of LWDs were used: (1) the LOADMAN LWD, and (2) the PRIMA 100 LWD. The correlation between LWD moduli and compaction levels was reported to be generally poor (R^2 ranges from 0.1 to 0.5).

Another problem preventing widespread use of the LWD is the high variability in measured modulus reported for the same material tested with different LWD devices. Steinert et al. (2005) compared subbase moduli measured with a LOADMAN LWD and a PRIMA 100 LWD and reported that moduli measured with the LOADMAN LWD were lower. White et al. (2007) compared subgrade moduli measured using two LWD devices: (1) the ZORN LWD, Model ZFG 2000, and (2) the KEROS LWD. The moduli measured with the KEROS LWD were 1.75 to 2.2 times higher. It was suggested that the differences in the measured subgrade moduli could be attributed to the different methods used to determine deflections in both devices: a geophone is used in the KEROS LWD, and an accelerometer is used in the ZORN LWD.

The LWD has been reported to yield unreliable measurements for cement-treated clay when the device was used to monitor strength gain with time and the benefit of adding cement (Alshibli et al., 2005). The authors reported a wide scatter and poor repeatability in the LWD measurements. They suggested further research was needed before the LWD could be recommended as a QC/QA device. The study was performed on carefully prepared full-scale laboratory-prepared subgrades.

There is no unique relationship between LWD moduli and FWD moduli (Livneh and Goldberg, 2001). Fleming and co-workers (2007) reported that LWD stiffness moduli differ to a varying extent depending on factors such as location, pavement thickness, soil type, gradation, and moisture content. Fleming et al. (2007) found no unique relationship between FWD- and LWD-determined stiffness moduli as the ratio between the LWD and FWD varied between 0.8 and 1.21 with an R^2 between 0.5 and 0.9. Conventional FWD moduli were found to be 2.5 to 3.3 times higher than LWD moduli (Livneh and Goldberg, 2001). The reasons given by the authors included the different loading level/rate used in the FWDs and LWDs. McKane (as cited in Li [2004]) reported no significant correlation among modulus values determined using the FWD, LWD, GeoGauge, and DCP on sandy clay Minnesota subgrades.

In addition to the poor correlation between LWD moduli and compaction, and the poor correlation among different modulus measuring devices, mixed results concerning the effectiveness of the LWD as a moduli measuring device have been reported. Steinert et al. (2005) used the LWD to determine weight restriction timing on low-volume roads during the spring thaw in New England. The LWD moduli were found to be sensitive to seasonal variations in pavement stiffness and compared well with FWD-derived moduli on both asphalt and gravel surfaces. Nazzal et al. (2007) reported an excellent correlation between LWD moduli and the

DCP, FWD, and plate load test; however, Petersen et al. (2007a) reported no universal correlation among the different stiffness measuring equipment.

Another issue affecting routine use of the LWD is spatial variability in moduli obtained along a pavement section. Fleming et al. (2007) found no unique correlation between the LWD and FWD for a site with a granular foundation containing 9 in of well-graded crushed rock over a granular subgrade, as the ratio varied between 0.8 and 1.3. The reasons given by the authors for the poor correlation included the different loading level/rate used in the FWD and LWD. It was not clear to the authors if the variability was due to the LWD equipment or material properties (water content, density, thickness, seating problems especially on granular soils, gradient of layer). The authors noted that the higher variability of LWD moduli of the same pavement section was related to wetter samples. This result was corroborated by studies (Davich et al., 2006) in Minnesota where the use of the LWD is limited to soils with a moisture content less than 10%.

Rahman et al. (2008) tested highway embankments in Kansas using several types of testing equipment including the soil stiffness gage (GeoGauge), CBR, FWD, LWD, and DCP and found no universal correlation among stiffness values. The authors attributed the discrepancy to the fact that different pieces of equipment were capturing responses from different volumes of soil on the same test section. The depth of influence, a measure of influence volume for the LWD, has been reported to be in the range of 240 to 280 mm (9.5 to 11 in) (Fleming et al., 2007; Nazzal et al., 2007; Petersen et al., 2006).

Stress dependency (represented by drop height) has also been reported to affect the LWD modulus (Petersen et al., 2006). No such stress dependency has been reported in FWD test results (Fleming et al., 2007; McQueen et al., 2001). The implication could be that if the thickness of a pavement layer is less than 280 mm (11 in), then the modulus determined using the LWD will represent a composite modulus. Nazzal et al. (2007) attributed the poor repeatability of LWD test data on material stiffness. Their results showed that poor repeatability was associated with weaker subgrade layers and good repeatability was associated with relatively stiff and well-compacted layers.

Despite the aforementioned issues associated with LWD use, the consensus is that the LWD could be a useful device for monitoring compaction in the field if certain procedures are followed. The recommended procedures include setting targets for the LWD modulus and deflection values.

Target LWD Modulus Values

Deflection and modulus target values have been adopted by various researchers internationally. FWD deflection targets have been used during subgrade construction in Israel. FWD deflection limits of 0.5 mm (0.0197 in) (coefficient of variation [COV] of 40%) are specified for subgrades in cuts and a deflection of 0.4 mm (0.0157 in) (COV of 30%) is recommended for fills and capping layers (Livneh and Goldberg, 2001). FWD stiffness target values of 50 to 60 MPa (7,250 to 8,700 psi) and 100 MPa (14,500 psi) have been suggested for completed formations (subgrade) and completed foundations (base layer), respectively, in the

U.K. (Fleming et al., 1998). Nunn et al. (1997) also suggested an FWD stiffness of 40 MPa (5,800 psi), measured on the top of the completed formation (subgrade), and 65 MPa (9,425 psi), measured on the top of the completed foundation (base layer) for U.K. conditions. A maximum stiffness value of 80 MPa (11,600 psi) was suggested by Chaddock and Brown (1995) for formations (subgrade) in the U.K. tested with the FWD using a 450-mm (17.7 in) plate and a 200-kPa (29 psi) contact stress.

Very limited data on target values using the LWD are available. Nunn et al. (1997) suggested an LWD stiffness value of 30 MPa (4,350 psi) measured on the top of the completed formation (subgrade) and 50 MPa (7,250 psi) measured on the top of the completed foundation (base layer). Livneh and Goldberg (2001) suggested an 80-MPa (11,600 psi) FWD deformation modulus or a 35-MPa (5,075 psi) LWD deformation modulus for pavement formation (subgrade).

Steinert et al. (2005) studied compaction of granular bases and concluded that both percent compaction and water content relative to OMC influence the composite modulus of granular bases in a significant way. They proposed a procedure for using the LWD to monitor construction of granular layers based on the relationship between percent compaction and composite modulus for granular bases at OMC. Both laboratory (soil compacted in 6 ft by 6 ft by 3 ft test pit/container) and field (12 test locations) measurements were conducted using the LWD to estimate modulus and nuclear gauges to measure moisture contents. Based on the results of the study, the authors also provided correction factors for materials at moisture contents other than optimum. Target modulus values and moisture correction factors for granular bases/subbase recommended for New England are shown in Tables 8 and 9, respectively (Steinert et al., 2005). In order to get the LWD modulus at optimum moisture, correction factors in Table 9 should be added to the measured modulus from the field. The

Table 8. Target LWD Modulus at Optimum Moisture Content (OMC) for Base and Subbase in New England

% Compaction Based on AASHTO T-180	LWD Composite Modulus at OMC (MPa)
90	92
95	115
98	130
100	139

1 MPa = 145 psi.

Table 9. Correction Factors to Account for Moisture Content Other Than Optimum Moisture Content (OMC)

Difference in Moisture Content From OMC		Correction Factor to Be Added to Composite Modulus Measured at Field Moisture Content (MPa)
Dry of Optimum	-4%	-31
	-3%	-23
	-2%	-15
	-1%	-8
OMC	0	0
Wet of Optimum	+1%	8
	+2%	15
	+3%	23
	+4%	31

1 MPa = 145 psi.

correlation coefficients in this study ranged from very poor (R^2 = 0.001) to very good (R^2 = 0.86); therefore, the authors indicated the suggested target values should be used with caution. In addition to setting target LWD modulus values, some transportation agencies have considered LWD specifications for controlling compaction in the field.

LWD Specifications

Draft specifications developed by MnDOT and the U.K. Highway Agency were reviewed. The MnDOT 2005 Special Provision for LWD is similar to its DCP specifications, which calculate the target LWD modulus value based on moisture content and grading number (GN) (Davich et al., 2006).

The GN (Eq. 4) is a measure of the soil gradation characteristics and is based on the following sieve sizes: 1 in, 3/4 in, 3/8 in, No. 4, No.10, No. 40, and No. 200. The GN is defined as the sum of the percent passing values for the seven specified sieves divided by 100. A lower GN corresponds to more granular soil, and a high GN usually corresponds to a fine-grained soil. It has been suggested that an inverse relationship exists between the GN and LWD modulus (Davich et al., 2006). Table 10 shows sample LWD target values used by MnDOT. It is important to note that the approximate GN for VDOT 21A aggregate would be about 3.9.

$$GN = \frac{1in + \frac{3}{4}in + \frac{3}{8}in + No.4 + No.10 + No.40 + No.200}{100} \qquad \text{[Eq. 4]}$$

In contrast to the MnDOT LWD specifications, which set target moduli based on gradation and moisture content, the U.K. specifications (Highway Agency, 2006) define four foundation classes (base layers) based on surface modulus measured using various devices, including the LWD. The four foundation classes and their corresponding surface moduli are:

Table 10. Typical Target LWD Modulus Values for Minnesota Soils

Grading Number (GN)	Moisture Content (%)	Target Modulus (MPa)
3.1-3.5	5-7	80
	7-9	67
	9-11	50
3.6-4.0	5-7	80
	7-9	53
	9-11	42
4.1-4.5	5-7	62
	7-9	47
	9-11	38
4.6-5.0	5-7	53
	7-9	42
	9-11	35
5.1-5.5	5-7	47
	7-9	38
	9-11	32
5.6-6.0	5-7	42
	7-9	33
	9-11	29

1 MPa = 145 psi.

1. Class 1, 50 MPa
2. Class 2, 100 MPa
3. Class 3, 200 MPa
4. Class 4, 400 MPa.

The stiffness modulus values are used for design purposes. A minimum subgrade modulus of 30 MPa (2.5 CBR) is specified. Subgrades with a modulus lower than 30 MPa require some form of stabilization or treatment or the use of a geosynthethic before they can be included in the permanent pavement works. For specifications during construction, the target and minimum values are specified for the four foundation classes as shown in Table 11 (Highway Agency, 2006).

Table 11. Top of Foundation (Base Layer) Surface Modulus Requirements for U.K. Soils

Foundation Class	Target Modulus (MPa)				Minimum Modulus (MPa)
	Unbound	Bound	Fast Curing (FS)	Slow Curing (SC)	
Class 1	40	50	-	-	25
Class 2	80	100	-	-	50
Class 3	-	-	300	150	150 FC / 75 SC
Class 4	-	-	600	300	300 FC / 150 SC

Source: Highway Agency (2006). 1MPa = 145 psi.

Comparison of LWD Stiffness and Laboratory Resilient Modulus

Results from nondestructive tests performed using the FWD (which is based on principles similar to those for the LWD) at the Federal Aviation Administration's National Airport Pavement Test Facility on full-scale pavement test sections indicated that subgrade moduli determined from the FWD are consistent with laboratory resilient modulus obtained at 6 psi confining stress and 2 psi deviator stress (McQueen et al., 2001). Petersen et al. (2007a) developed models to predict the in-situ modulus from laboratory resilient modulus values, moisture content, and dry density for bridge embankments in Kansas as previously mentioned. The authors reported that moduli predicted from results of laboratory resilient modulus tests did not correlate with the in-situ soil stiffness measured with the LWD. This is not surprising since a critical look at their data suggests that the predicted stiffness using the aforementioned models appears to be significantly higher than typical moduli for the soil tested. For example, the predicted modulus of 943 MPa (136,735 psi) for a Class A-6 soil (tested at a moisture content of 11.5% below the OMC) appears to be quite high. A typical modulus for such soils is in the 10 to 100 MPa (1,450 to 14,500 psi) range. The authors suggested that the dry nature of the soil tested could account for the rather high stiffness modulus predicted.

It must also be noted that for plastic soils under variable moisture conditions, it has been recommended by the manufacturer that the moduli determined by the Prima 100 LWD should not be compared to moduli obtained under static testing conditions or different moisture contents. Livneh and Goldberg (2001) suggested that density and moisture content tests should always be conducted alongside mechanical testing of soils. The reasons given by them was that soils compacted dry of the OMC could exhibit a high stiffness modulus because of high negative pore pressures from capillary suction. When the pore pressure dissipates upon subsequent changes in moisture content, the modulus values may also decrease.

Problems Associated with Analysis of LWD Data

Careful collection and analysis of LWD data are essential for accurate determination of pavement layer moduli. It has been suggested that some of the variability reported in the literature (Fleming et al., 2007) for pavement moduli measured with the LWD could have been caused in part by factors such as (1) number of seating loads applied, (2) level of contact between loading plate and pavement layer surface, and (3) the peak deflection recorded. Specifications for seating of the device must be established. Suggested remedies include using sand to provide a uniform surface, removing up to 4 in of compacted material before testing, and limiting testing to pavements with a gradient less than about 5%. The recorded peak deflection, which is also used to compute LWD moduli, has been found to contain both recoverable and permanent deformation and may occur out of phase with peak load/stress applied (Fleming et al., 2007). The authors recommended careful review of the load and deformation time history for accurate determination of layer moduli using the LWD. Some of their recommendations included:

- modifying the spring constant or increasing the contact area of the geophone so as to reduce punching failure
- providing good contact between loading plate and material being tested by using moist sand
- applying adequate seating loads
- performing careful analysis and use of measured peak deflection.

Hoffmann et al. (2003) indicated that prediction of the soil modulus based on LWD load and peak deflections results in inaccurate modulus values and proposed a spectral-based procedure to analyze LWD data with the aim of improving the prediction.

Summary

- The LWD could be a useful and handy field quality control and pavement investigation tool with a good understanding of how the device works, especially in the area of test variables and data quality. Careful analysis of peak deflection/load is critical.
- Specifications for seating of the device must be established. Suggested remedies include using sand to provide a uniform surface, removing up to 4 in of compacted material before testing, and limiting testing to pavements with a gradient less than about 5%.
- There is no universal agreement on the best prediction model for predicting LWD moduli from devices such as the FWD, DCP, and GeoGauge and the CBR. Prediction models for estimating FWD moduli from LWD testing appear to be accurate only if field density and moisture data are included. Thus, LWD testing alone may not completely replace routine moisture-density testing performed during subgrade compaction. The implication could be that if the subgrade modulus is required for design, both LWD and moisture-density testing

may need to be done to estimate the FWD modulus (which is universally recognized to give the "true" soil modulus parameter). On the other hand, if QC/QA is the objective, LWD testing could replace the slower more cumbersome nuclear density and moisture content determination with no attempt at predicting soil modulus.

- It appears that LWD testing would complement density and moisture content measurements and not replace them. For example, soils compacted dry of the OMC (high negative pore pressure) may exhibit high moduli, which may subsequently decrease upon saturation when the negative pore pressure decreases.

- Target LWD values may need to be established for different soil types, thickness, and moisture contents if routine usage of the LWD for controlling field compaction is anticipated. Average target moduli values are in the range of 50 to 80 MPa for pavement foundations when the FWD is used and about 35 MPa in the case of the LWD.

- Pavement thickness has a significant influence on LWD moduli. For pavement layers less than 280 mm (11 in) (depth of influence for the LWD), care needs to be taken when interpreting the results, as the determined modulus may be influenced by the underlying layer and represent a composite one. Studies also suggest the LWD may not be suitable for thicker, stiffer foundations.

- LWD application may be limited to unbound layers and lightly bound layers. Another limitation reported is that the LWD may not be suitable for plastic soils and under variable moisture conditions. In addition, different plate sizes are recommended for use with different materials or different soil types.

- Data for computing the LWD modulus may need further review, especially in relation to peak deflection. The commonly used three-drop seating load may need to be modified in certain soils. It has been suggested that the variation between three consecutive modulus values measured at the same location should not exceed 10%; otherwise, additional seating drops may be needed. However, for a single location, the number of drops should be limited to a maximum of 10.

GeoGauge, LWD, and DCP Field Measurement Results

GeoGauge Results

GeoGauge testing was conducted at designated locations described previously. The layer stiffness was computed internally into the device as an average of the 25 stiffness values measured at each test location. Stiffness values were converted to elastic (stiffness) modulus using Equation 1. As will be discussed, although repeat measurements did not show much variability, the average GeoGauge stiffness modulus for each project showed large spatial variability.

LWD Results

LWD testing followed GeoGauge testing, and several repeat measurements were taken at the same locations as the GeoGauge tests. The results are presented and discussed in subsequent sections. A soil stiffness modulus was estimated using Equation 2, which is based on Boussinesq's elastic solutions for homogeneous half-space. In using Equation 2, a flexible plate (plate rigidity factor, A = 2) and a Poisson's ratio of 0.40 was assumed.

As discussed in the literature review, several issues could affect the accuracy of the LWD modulus, especially LWD data analysis. The use of maximum deflection obtained during the LWD testing could lead to significant errors as the time lag between peak stress and peak deflection could be significant (Fleming et al., 2007). Results of the LWD deflection and load-time histories obtained on Route 743 showed a similar time lag, as illustrated in Figure 5. The time lag between the applied load and measured deflection decreases with subsequent load drops from 2.83 milliseconds to 1.70 milliseconds and stabilizes by the third drop. Therefore, in this study, the first three load drops were considered as seating loads and were not used for estimating soil modulus. Computed moduli were based on the average of at least three load drops following the applied seating loads for each location. It has also been observed that large errors in estimated modulus could occur if the LWD is used to obtain readings beyond prescribed load and deflection limits. Stress levels in the range of 50 to 200 kPa (7.25 to 29 psi) and deflection levels in the range of 100 to 1000 microns (0.0039 to 0.039 in) have been suggested by some investigators for meaningful results (Fleming et al., 2007). When these limits are violated, a very high variability in LWD results was observed. Therefore, all LWD data were filtered to satisfy the criteria. Using the aforementioned filtering approach, the variability (repeatability of the LWD modulus at the same location for multiple load drops) was comparatively lower (COV ranged from 3% to 12% on Route 3, for example) than previously reported.

DCP Results

Since the penetration of the DCP cone might create a minor disturbance of the prepared subgrade, testing with the DCP was conducted after testing with the GeoGauge and LWD at the same locations or within few inches of them. At a given location, the penetration depth for each blow was measured, recorded, and used to estimate the DCPI or DCP PR. Previous studies (Nazzal et al. 2007; Petersen et al., 2006) suggested the depth of influence of the GeoGauge and LWD are 8 and 12 in, respectively. Therefore to ensure consistent comparison between the various devices, the average DCP PRs computed for the top 8 to 12 in of each tested layer were used to estimate the DCP modulus values. The average DCPI for each pavement layer at a test location was used to estimate the soil stiffness modulus using Equation 3. Typical DCPIs computed for two test points on Route 644 are shown in Figure 6.

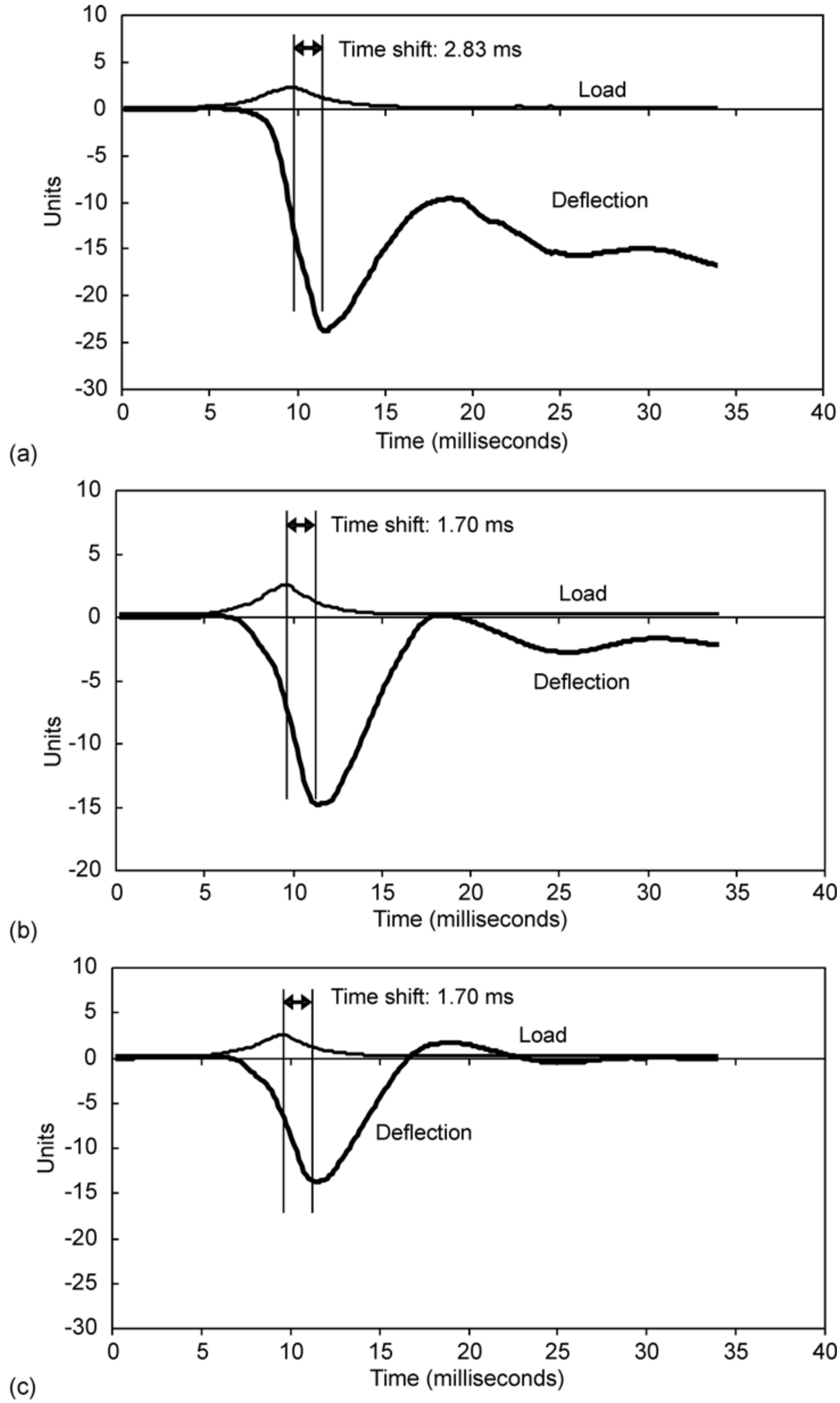

Figure 5. LWD Output Showing Time Lag Between Load and Deflection Pulses During Consecutive Load Drops: (a) first drop, (b) second drop, (c) third drop

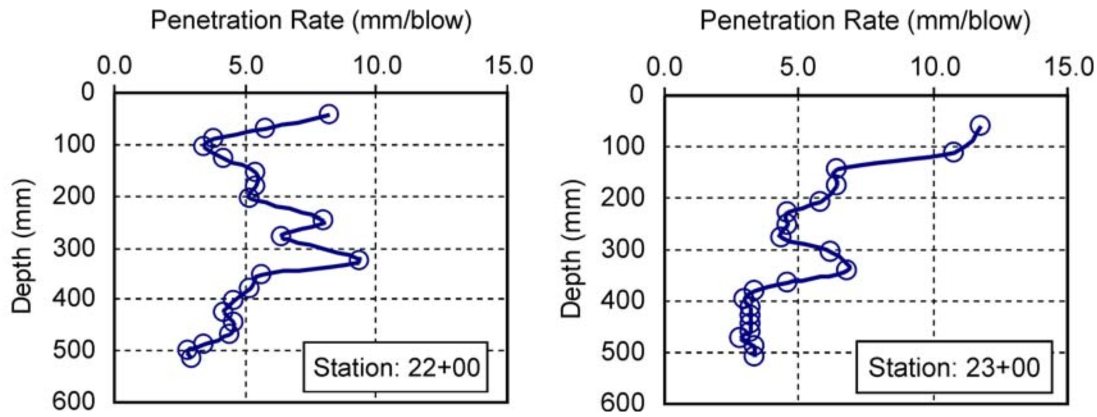

Figure 6. Typical DCP Penetration Rate Versus Depth (Example: Gravel Road on Route 644)

Average Field Density and Moisture Content

The average field density and moisture content from several field measurements are summarized in Table 11 for each project.

Table 11. Average Field Density and Moisture Content Results

Project	In-situ Density (lb/ft^3)	Moisture Content (%)	Dry Density (lb/ft^3)
Route 3	154.33	2.77	150.17
Route 15	126.68	4.15	121.63
Route 644	88.51	15.26	76.79
Route 743	89.67	26.33	70.98
Route 782	141.84	1.94	139.14
Route 785	138.00	4.27	132.35
Route 797	134.65	1.66	132.45

Results of Field Data Analysis

Effect of Density on Stiffness Modulus

Density is one of the most important parameters currently used to control compaction during pavement construction. It is generally believed that a suitable test method to replace density tests should show reasonable correlation with standard density tests. Any device that shows strong correlation with density may be considered suitable for compaction control.

To evaluate the effect of density on measured stiffness, the density at selected locations on seven projects was measured at the same locations the gauges were used. The measurements on the prepared subgrade and existing gravel roads are shown in Figures 7 and 8, respectively. The only project with a base layer is shown in Figure 9. A general trend of increasing stiffness modulus with increasing density was observed for the LWD and GeoGauge measurements. In the case of the DCP, there was no clear trend. The highest correlation ($R^2 = 0.44$) between density and modulus was obtained for the LWD on Route 3 compared with $R^2 = 0.15$ for the GeoGauge.

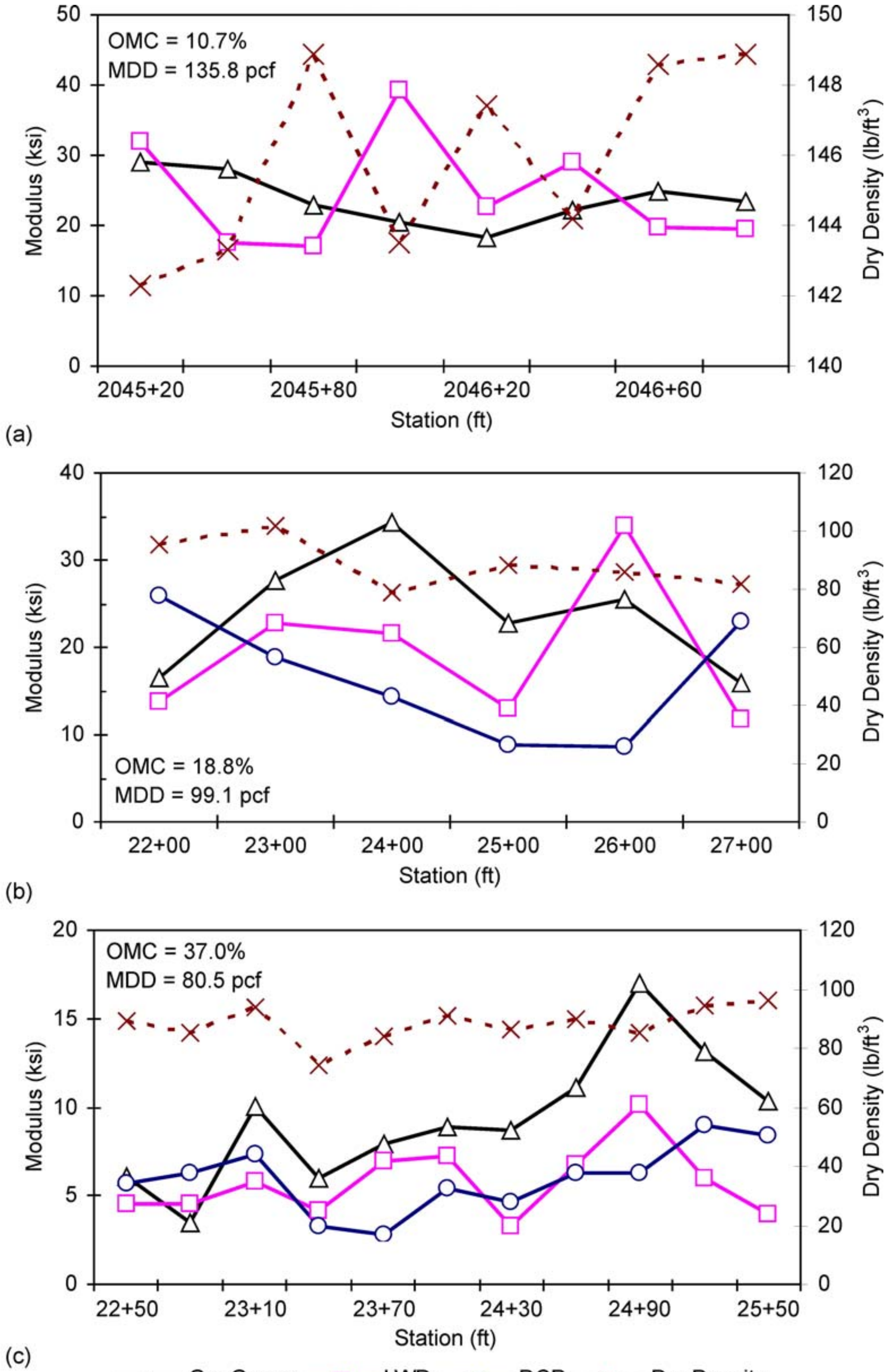

Figure 7. Comparison of Stiffness Modulus with Dry Density for Subgrade Soil: (a) Route 3, (b) Route 644 (c) Route 743

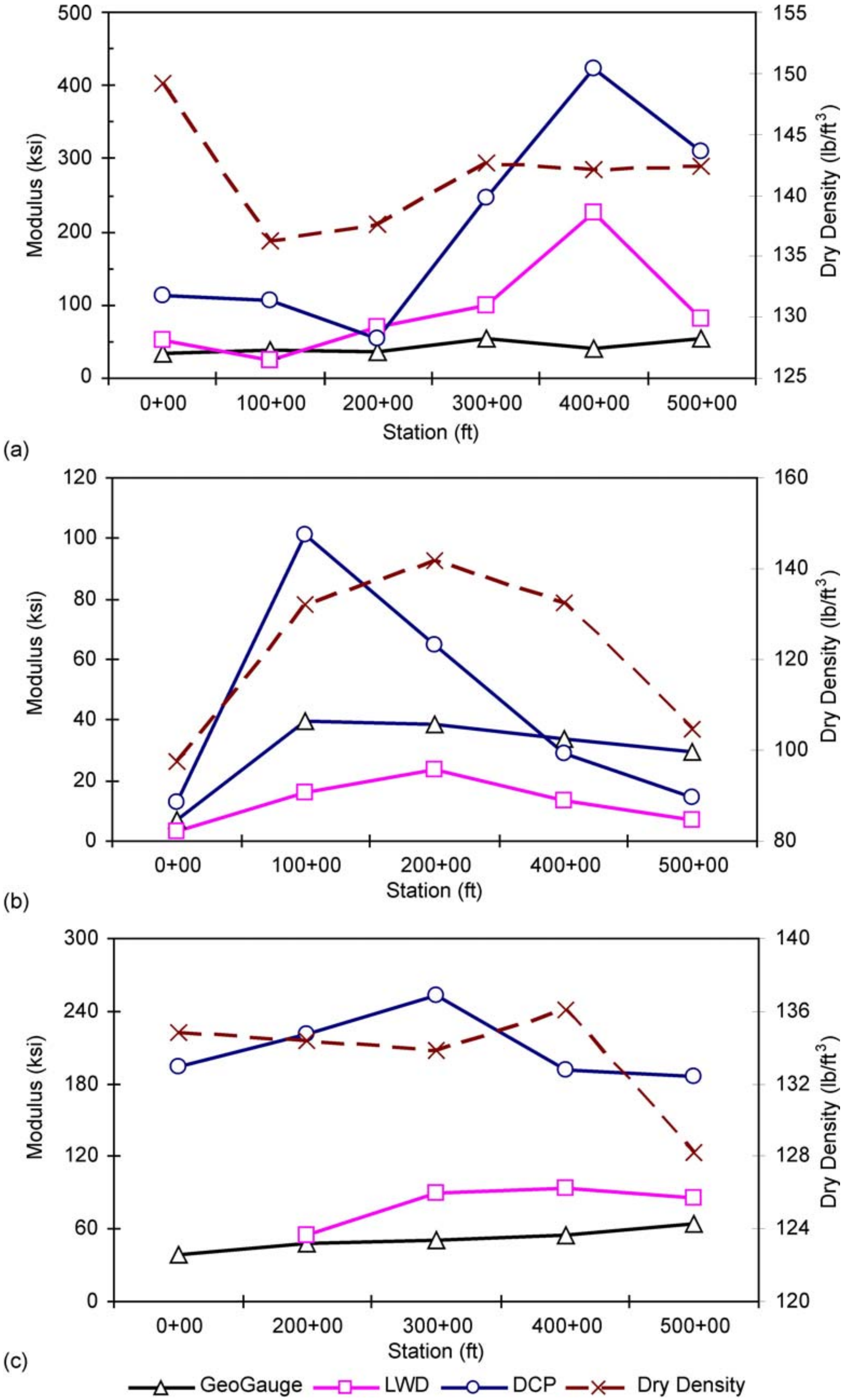

Figure 8. Comparison of Stiffness Modulus with Dry Density for Gravel Roads: (a) Route 782, (b) Route 785 (c) Route 797

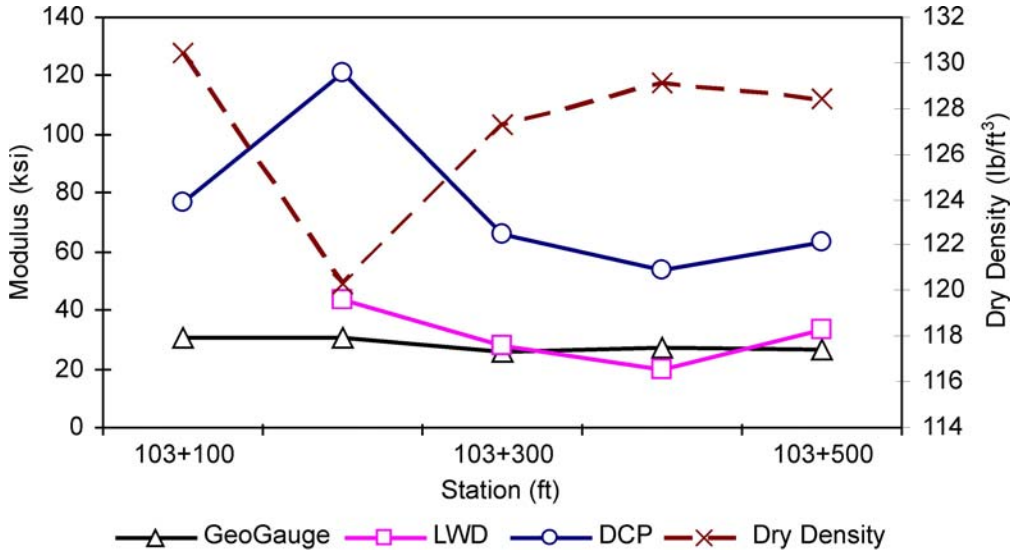

Figure 9. Comparison of Stiffness Modulus with Dry Density for Base Layer on Route 15

Effect of Moisture Content on Stiffness Modulus

The relationship between moisture content and soil stiffness moduli for subgrade, gravel road surfaces, and base aggregate is illustrated in Figures 10 through 12. In all cases, there was no clear trend in moisture content variation for LWD and GeoGauge stiffness moduli except for Route 3, where the correlation (R^2 = 0.31) for the LWD was poor. There was a strong to moderate influence of moisture content on the DCP stiffness modulus for all the projects considered in this study. The following can be deduced based on the comparison of moisture content and stiffness modulus:

- DCP soil stiffness varies inversely with moisture content; i.e., a higher moisture content is associated with a lower stiffness and vice versa.
- The correlation (R^2 = 0.97) between DCP stiffness and moisture content is high.
- The trend in LWD stiffness and GeoGauge stiffness values over the project length appears to be similar to that of density variation.
- The effect of moisture on field LWD and GeoGauge moduli is not readily apparent or consistent. This could be the result of the relatively lower number of moisture content tests performed compared to the number of stiffness test locations.

In all cases, the higher the moisture content, the lower the DCP stiffness modulus, as was expected. The lack of correlation between moisture content and device (LWD and GeoGauge) stiffness suggests the need for additional laboratory testing under controlled conditions.

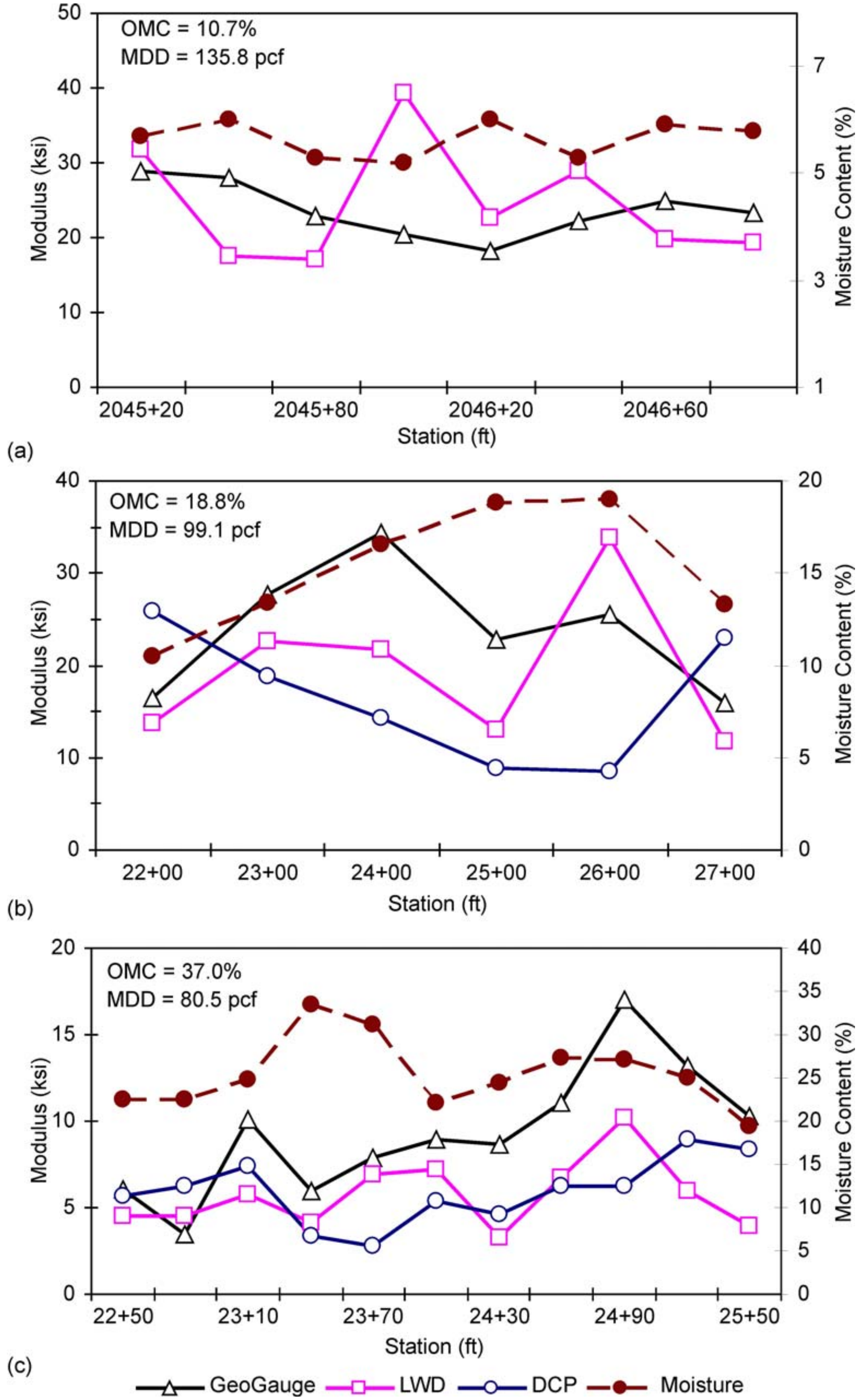

Figure 10. Effect of Moisture on Stiffness Modulus for Subgrade Soil: (a) Route 3, (b) Route 644, (c) Route 743

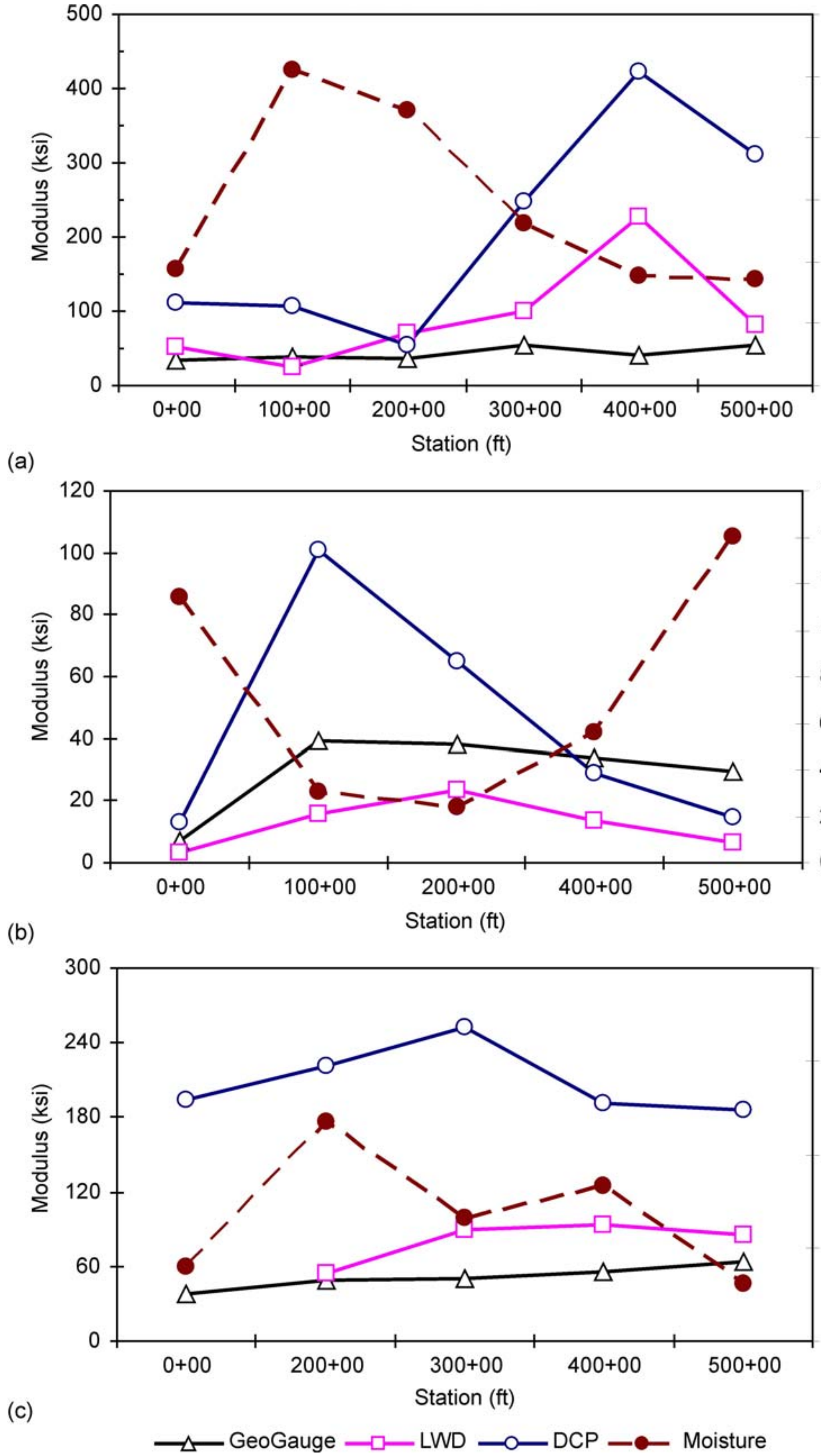

Figure 11. Effect of Moisture on Stiffness Modulus for Gravel Roads: (a) Route 782, (b) Route 785, (c) Route 797

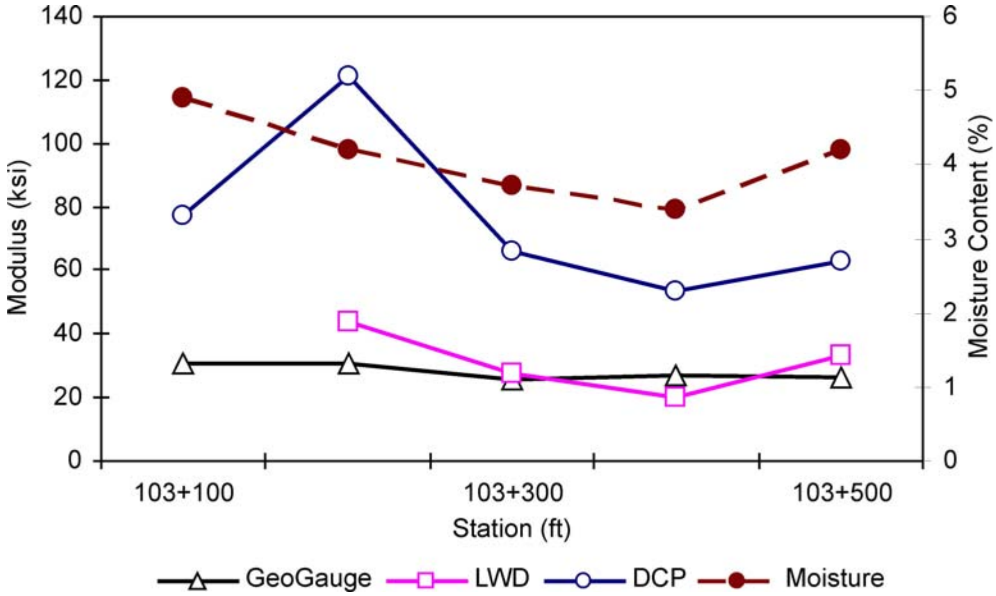

Figure 12. Effect of Moisture on Stiffness Modulus for Base Layer on Route 15

Spatial Variability of Stiffness Modulus

Stiffness modulus values calculated from all three devices have shown very high spatial variability as is obvious in Figures 7 through 9. Although there could be some real variability in the construction quality, within such a short section (200 to 500 ft), this high variability would be questionable. Therefore it would be more of a device-specific measurement variability than an actual material/construction quality. The mean and variability values for each project along its length are summarized in Table 12. In all cases, a high spatial variability in modulus values was observed for all three stiffness gauges. In most cases, the DCP measurements showed relatively higher modulus values compared to those of either the LWD or GeoGauge. In addition, the average GeoGauge stiffness was closer to the LWD data than to the DCP data.

The high spatial variability in measured stiffness together with the lack of correlation among mean stiffness values measured with the different devices used is clear and is in

Table 12. Spatial Variability of Soil Stiffness Modulus

Project	No. of Locations Tested	Soil Stiffness Measurements									Layer Tested
		Mean (ksi)			Standard Deviation (ksi)			Coefficient of Variation (%)			
		Geo	LWD	DCP	Geo	LWD	DCP	Geo	LWD	DCP	
Route 3	20	23	24	-	3	10	-	14	42	-	Subgrade
Route 644	6	24	19	17	7	8	7	30	43	44	
Route 743	11	9	6	6	4	2	2	40	34	32	
Route 15	5	28	31	76	2	10	26	8	32	35	Base
Route 782	6	43	92	209	9	71	142	21	77	68	Gravel road
Route 785	6	29	12	47	12	7	34	42	63	73	
Route 797	5	51	81	209	9	18	28	18	22	13	

Geo = GeoGauge, LWD = lightweight deflectometer, DCP = dynamic cone penetrometer, NDG = nuclear density gauge.

agreement with some earlier studies (Petersen et al., 2007a). Further examination of Figures 7 through 9 indicates agreement among the three stiffness devices at low values of measured stiffness. Table 13 shows the 85th percentile values for all measurements by the three devices.

Even though no good correlation was found among the three devices when all the data were compared, there appeared to be some correlation between the devices based on the 85th percentile values, as shown in Figure 13. The LWD stiffness modulus showed very good correlations with both the GeoGauge and DCP with an R^2 of 0.85 and 0.80, respectively. The 85th percentile modulus values for the GeoGauge and DCP also compared quite well ($R^2 = 0.73$). The results suggest the possibility of using the 85th percentile value to monitor compaction with any of the three devices.

The relative ranking of pavement sections based on the 85th percentile moduli are presented in Table 13. Three subgrade sections were ranked separately from the four aggregate base/gravel roads. The rankings (1 = lowest modulus, 4 = highest) based on the 85th percentile values were similar for the three devices compared. Given this similarity, the results indicate the potential for using certain modulus values obtained with the devices for pavement design. Further studies may be needed to evaluate the implications of the 85th percentile modulus obtained with the devices used in this study.

Table 13. Ranking of Pavement Layers Using 85th Percentile Value of Soil Stiffness Modulus[a]

Project	Soil Modulus (ksi) and [Rank]			Layer Type
	DCP	GeoGauge	LWD	
Route 3	-	20.2 [3]	14.9 [3]	Subgrade
Route 644	8.7 [2]	16.8 [2]	11.7 [2]	
Route 743	4.0 [1]	6.0 [1]	4.1 [1]	
Route 15	62.7 [3]	25.4 [2]	27.3 [2]	Aggregate base
Route 782	54.9 [2]	31.8 [3]	48.4 [3]	Existing gravel road
Route 785	13.6 [1]	17.8 [1]	6.0 [1]	
Route 797	168.6 [4]	38.2 [4]	60.7 [4]	

[a] DCP = dynamic cone penetrometer; LWD = lightweight deflectometer; - = no data available.

Results of Laboratory Investigation of Effect of Moisture on Stiffness Modulus

As previously discussed, a very high degree of spatial variability was observed in measured stiffness modulus obtained by all three devices. The field data suggested moisture content could be one of the factors causing the high spatial variability. Since field moisture content data were obtained at very limited locations in the field, the researchers decided to conduct limited soil testing in the laboratory under comparatively well-controlled conditions of moisture and density. The results are presented in Figure 14.

A close examination of the NOVA soil (AASHTO A-7-5) indicated that increasing the degree of saturation from 70% to 93% and the dry density from 87 to 91 lb/ft^3 have very little effect on GeoGauge and DCP modulus although they both followed the expected trend of decreasing modulus with increasing moisture content. An entirely different response to moisture content and density was observed in the case of the LWD-measured modulus. Below an 85%

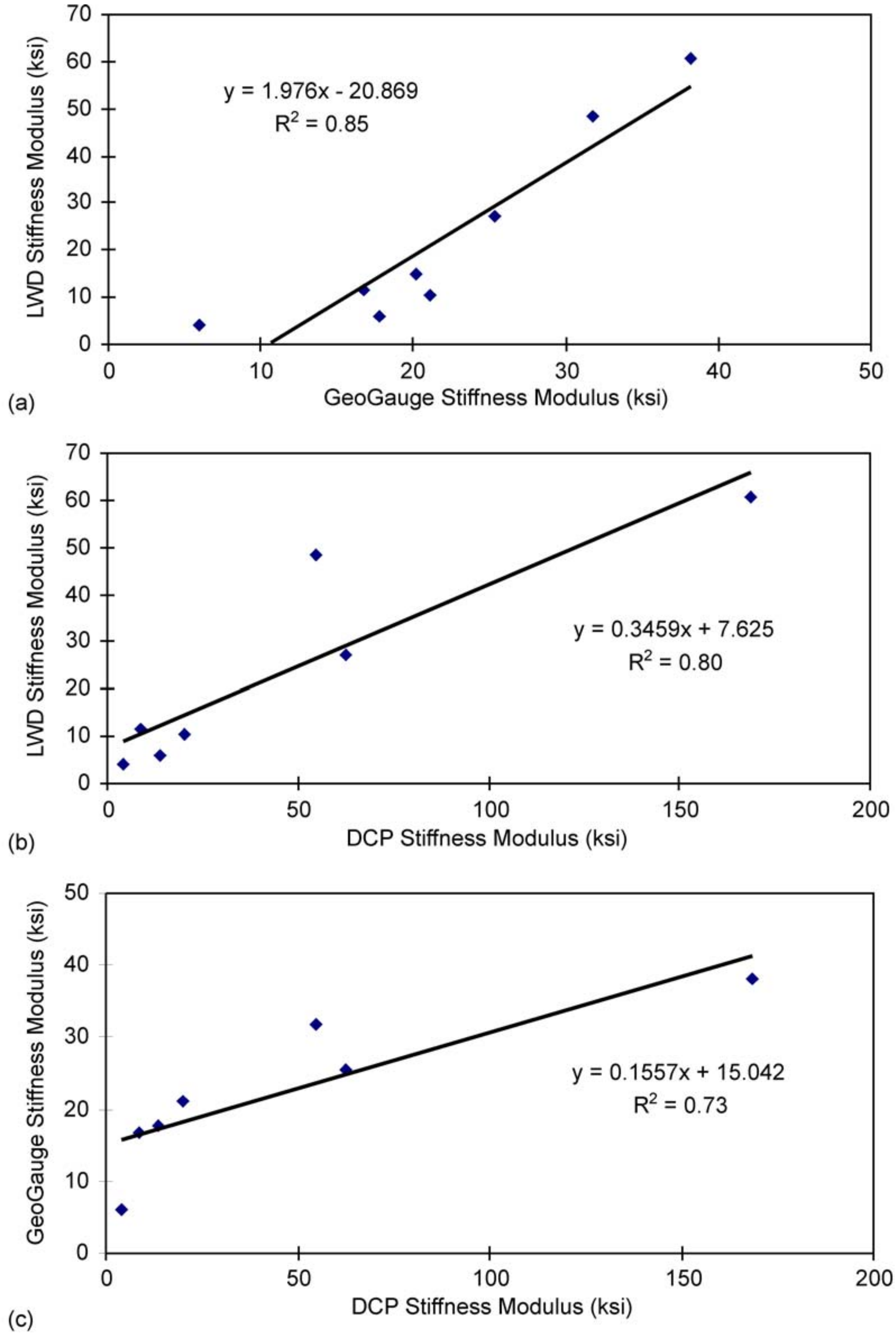

Figure 13. Comparison of 85th Percentile Stiffness Modulus

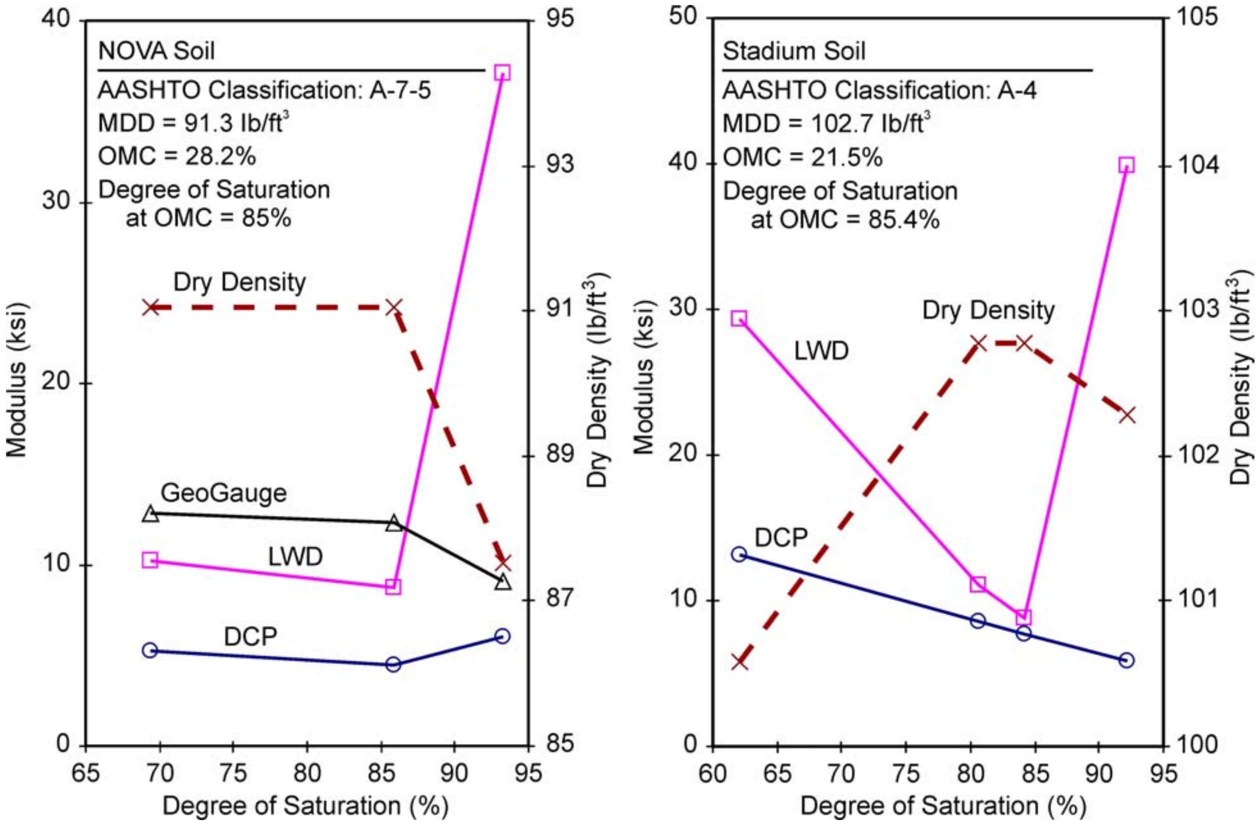

Figure 14. Effect of Moisture (Degree of Saturation) on Soil Stiffness Modulus in a Laboratory Setup. NOVA = Northern Virginia; AASHTO = American Association of State Highway and Transportation Officials; MDD = maximum dry density; OMC = optimum moisture content; LWD = lightweight deflectometer; DCP = dynamic core penetrometer.

degree of saturation, the effect of moisture content on the LWD modulus was negligible but followed the expected trend. However, the LWD modulus was quadrupled from 8.7 ksi to 37 ksi when the saturation level was more than 85%. One reason for such a high modulus might be that soils approaching 100% saturation develop high pore pressure when subjected to impact/ transient type loadings such as those applied during LWD testing. Because of the low permeability of A-7-5 soil and the very short duration of impact load, high pore pressure could have manifested as a high modulus, but in reality, the soil is actually weak

Very dry soils can also exhibit high stiffness because of the presence of capillary suction. Therefore, the UVA soil (AASHTO A-4) was tested at various moisture contents but the same dry densities to simulate the effect of both pore pressure and suction. Very high moduli were observed at the driest state (16.4% moisture content) because of the effect of soil suction and at the wettest state (23.0% moisture content) because of the development of pore water pressure. The results shown in Figure 14 confirmed the hypothesis that pore water pressure as well as soil suction could be the reason for the high variability in the LWD modulus. These results are significant as they could help explain some of the high variability in modulus values measured by the LWD under field conditions.

The results illustrate the importance of measuring soil moisture content along with the LWD modulus for quality control. The results also illustrate why dry density alone may not be enough to control compaction. For instance, at the same dry density of about 102.5 lb/ft^3, the A-4 (stadium) soil had modulus values that were 50% different depending on whether the soil was compacted wet or dry of the optimum. It is important to observe that modulus values measured by the DCP are not adversely affected by the moisture content. The decrease in the DCP modulus with increasing levels of saturation (or moisture content) is expected as the test involves penetration; increased moisture will provide increased lubrication.

CONCLUSIONS

- *All seven tested pavement sections exhibited high spatial variability in the measured stiffness modulus.* The COV values varied from 13% to 68% for the DCP-measured modulus, 8% to 42% for the GeoGauge modulus, and 22% to 77% for the LWD modulus. This high spatial variability is one of the major obstacles in using such devices for construction QC/QA. Further investigation is needed.

- *Modulus values measured by the three devices do not appear to be correlated.*

- *Despite high spatial variability, an 85th percentile value of the measured stiffness by the various devices for the entire test section showed a good correlation among the three devices.* This conclusion suggests the possibility of using the 85th percentile value for compaction control in the field, although further investigation is needed to address the high modulus values associated with extreme moisture contents.

- *None of the devices showed any consistent influence of dry density on the measured stiffness. It is important to note that the dry densities also did not vary significantly.*

- *Moisture content had a significant effect on the measured stiffness values for all three devices, especially the LWD.* There is no convenient way of incorporating such effects in the measured stiffness values, so further investigation is needed to establish this effect.

- *From the limited laboratory testing, the high LWD moduli could be attributable to the effect of pore water pressure buildup during testing (on the wet side of optimum) or to the presence of high soil suction (on the dry side of optimum).* Up to a 5-fold increase in measured LWD moduli was observed in the soils tested in the laboratory at various level of saturation. The effect of saturation on GeoGauge and DCP moduli was, however, comparatively low.

RECOMMENDATIONS

1. *VDOT's Materials Division should not use the LWD for QC/QA of pavement subgrade and bases until further research has determined the causes of the high spatial variability in measured soil modulus observed in this study.*

2. *VDOT’s Materials Division should use the LWD to gather more data to be analyzed for further evaluation to determine factors to control/consider in using the LWD test for construction QC/QA.*

3. *The Virginia Transportation Research Council (VTRC) should consider further investigation of the LWD to determine the effect of moisture content on measured modulus values. Once this investigation is complete, VDOT’s Materials Division and VTRC should develop a specification for using the LWD for construction QC/QA for base and subgrade based on VTRC findings from further research.*

SUGGESTIONS FOR FURTHER RESEARCH

The high variability in LWD moduli was found to be related to the development of pore water pressure during testing and the presence of soil capillary suction. Additional studies are needed to evaluate fully the effect of saturation/moisture on LWD moduli before the LWD can be adopted for routine testing by VDOT. Therefore, it is recommended that VTRC and VDOT’s Materials Division perform additional well-controlled laboratory testing to evaluate further the effect of soil saturation on LWD moduli along with field verification.

BENEFITS AND IMPLEMENTATION PROSPECTS

Stiffness modulus–based testing using the LWD offers several important advantages over density/moisture content methods of controlling compaction. Determination of fundamental material properties such as the soil modulus could be obtained from the LWD. The modulus properties are the basis for the new MEPDG pavement design. Another advantage of the LWD is the lower operating cost and lower health risk compared to those for the conventional nuclear density and moisture content devices. In addition, alternative materials and designs could be evaluated using results from stiffness-based devices such as the LWD. However, based on data obtained during this study, no recommendation can be made regarding the use of the LWD for routine compaction control for pavement layers for the following reasons: (1) the poor correlations between LWD-determined modulus and soil properties such as density and moisture content, (2) the little to no correlation between LWD moduli and the GeoGauge or DCP moduli, and (3) the high spatial variability in LWD-obtained stiffness moduli.

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