Intelligent Compaction Control of Highway Embankment Soil

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ABSTRACT

Mechanistic pavement design procedures based on elastic layer theory require characterization of all pavement layer materials including subgrade soil. This paper discusses the subgrade stiffness obtained from a new compaction device called the Intelligent Compaction (IC) roller on highway embankment projects in Kansas. Three test sections on two routes were compacted using a single, smooth steel drum Bomag Variocontrol (BVC) intelligent roller that compacts and at the same time, measures stiffness values of the compacted soil. Traditional compaction control measurements like density testing, in-situ moisture content, soil stiffness measurements using Geogage, surface deflection tests using Light Falling Weight Deflectometer (LFWD) and Falling Weight Deflectometer (FWD), and penetration tests using a Dynamic Cone Penetrometer (DCP), were also done. The results show that the IC roller was able to identify the locations of lower soil stiffness in the spatial direction. In general, IC roller stiffness showed sensitive to the field moisture content. No universal correlation was observed among the IC roller stiffness, Geogage stiffness, backcalculated subgrade soil moduli from the LFWD and FWD deflection data, and the California Bearing Ratio (CBR) obtained from the DCP tests.
INTRODUCTION

During last two decades, pavements have been designed using several rational design procedures. Design of pavements using these new tools requires detailed inputs on material response and damage properties. Example of such a tool is the newly developed Mechanistic-Empirical Pavement Design Guide (M-EPDG) of the National Cooperative Highway Research Program (NCHRP) (1). Foundation layer modulus, strength, and permeability are considered as the most critical material response parameters under repeated traffic load. Pavement performance is highly influenced by the above mentioned subgrade characteristics as well as by the ease and permanency of compaction. Subgrade compaction increases strength, decreases permeability, and reduces undesirable settlement. Current compaction quality control methods are fully based on the results of the laboratory compaction tests. The in-situ dry density of the soil is measured after compaction and compared with the laboratory maximum dry density. A number of methods such as, sand cone, rubber balloon and nuclear gage are used to measure the in-situ density. The in-situ moisture is also measured by the nuclear gage and other measurement methods, and controlled.

Intelligent Compaction Control

FHWA (2) defined the intelligent Compaction (IC) technology as “Vibratory rollers that are equipped with a measurement/control system that can automatically control compaction parameters in response to materials stiffness measured during the compaction process. The roller must also be equipped with a documentation system that allows continuous recordation, through an accurate positioning system, of roller location and corresponding density-related output, such as number of roller passes and roller-generated materials stiffness measurements.” The Intelligent Compaction (IC) is made possible because of the ability of a vibratory roller to first sense the material response of soil under loading, to process this information and compare it to the input requirements, and then to “decide” how to adjust compaction parameters to most efficiently compact the material. Since none of these features are available on conventional vibratory rollers, IC represents a major innovation in soil compaction technology (2). Currently, this technology is marketed by BOMAG from Germany, AMMANN from Switzerland, and DYNAPAC from Sweden. CATERPILLAR has also a system available for demonstration (3).

Stiffness Measured During Intelligent Compaction

“Material Stiffness” is the conceptual basis for intelligent compaction (2). During this compaction process, the stiffness is measured with a vibratory roller equipped with an accelerometer-based measuring system. The stiffness (roller vibratory modulus) is calculated continuously (30 to 60 times per second) as a function of the acceleration of the roller drum (or force) and the deformation of the compacted soil while the vibratory roller moves down the roadway. The soil-drum-interaction-force ($F_B$) is calculated by the following equation:

$$F_B \approx -m_d \ddot{x}_d + m_a r_a \Omega^2 \cos(\Omega t) + \left( m_f + m_d \right) g$$

(1)

where,

$m_d$ = mass of the drum (kg);
$x_d$ = vertical displacement of the drum (m);
\( \ddot{x}_d \) = acceleration of the drum (m/s^2);
\( m_f \) = mass of the frame (kg);
\( m_u \) = unbalanced mass (kg);
\( r_u \) = radial distance at which \( m_u \) is attached (m);
\( m_u r_u \) = static moment of the rotating shaft (kg.m); and
\( \Omega = 2 \cdot \pi \cdot f \); \( f \) = frequency of the rotating shaft (Hz).

The force acting on the positive direction (downward) has a plus sign and the inertia force \( m_d x_d \) shows negative value with respect to the corresponding coordinate. If the subsoil is described as a spring and dashpot system, the equation of soil-drum-interaction-force can also be written by:

\[ F_B \approx k_B x_d + d_B x_d \]  

By setting equation (1) equal to equation (2), the soil stiffness \( k_B \) can be obtained since all other parameters are known except the damping ratio which is considered 20 percent according to the manufacturer. Alternatively, the slope of the plotted force-settlement curve on the loading portion can be considered as the dynamic stiffness of the material being compacted.

![FIGURE 1 Soil reaction vs. roller amplitudes (after 4).](image)

Bomag Corp., one of the manufacturers of IC rollers, has developed a compaction quality measure, vibration modulus, \( E_{VIB} \) (MN/m^2). Soil stiffness, \( k_B \), is used as the basis for calculation of the vibration modulus. Since the modulus is a true independent soil parameter, the following relationship between \( k_B \) and \( E_{VIB} \) is proposed based on the Hertz and Lundberg theories:

\[ k_B = \frac{E_{VIB} \cdot L \cdot \pi}{2 \cdot (1 - \nu^2) \cdot \left[ 2.14 + \frac{1}{2} \cdot \ln \left( \frac{\pi \cdot L \cdot E_{VIB}}{(1 - \nu^2) \cdot 16 \cdot (m_f + m_d) \cdot R \cdot g} \right) \right]} \]  

where, \( L \) is the drum width, \( \nu \) is Poisson’s ratio, \( \ln \) is natural logarithm, \( m_f \) and \( m_d \) are the masses contributed by the frame and the drum of the roller, \( R \) is the radius of the drum, and \( g \) is the acceleration due to gravity. Knowing \( k_B \), Equation (3) gives \( E_{VIB} \).
The vibration modulus, $E_{\text{VIB}}$, is based upon the gradient of the force-displacement characteristics curve during the compression (loading) phase. The compression curve will be flat when the stiffness of the soil is low. The slope of the curve will increase with increasing material stiffness (Figure 1).

PROBLEM STATEMENT

Improper compaction control of highway embankment soils may result in bridge approach settlement, rapid increase in pavement roughness, etc. Current quality control and quality assurance testing devices, such as, nuclear gage, the dynamic cone penetrometer, the geogage, the light falling weight deflectometer are typically used to assess less than one percent of the actual compacted area (5). Also, each of these testing devices measures parameters unique to the device. Moreover, FHWA (2) has identified the following limitations of the conventional compaction and the compaction control process: (1) Density and density-related material properties can not be measured after the compaction process is complete; (2) Density measurement from a small number of spots may not the representative of the density of the entire lot; (3) Conventional compaction methodology does not allow any or very little instantaneous feedback for the project personnel; and finally (4) Overcompaction can occur and hence, can reduce the density that has already been achieved in the previous passes. A previous research project in Kansas has shown that current compaction control procedures result in highly variable stiffness values of the finished subgrade (6). This problem of variable stiffness of the pavement foundation layer has been addressed by the European countries using Intelligent Compaction Control (ICC). Intelligent Compaction (IC) technology has the potential to optimize and significantly improve the conventional compaction process. More details on ICC can be found elsewhere (2, 4, 7-10).

OBJECTIVE

The main objective of this study was to evaluate the soil stiffness measured by IC roller and its correlation with other stiffness and/or modulus values obtained from Geogage and Light Falling Weight Deflectometer (LFWD) and Falling Weight Deflectometer (FWD) deflections, and Dynamic Cone Penetrometer (DCP) data on compacted subgrade. Variation of the IC roller measured stiffness with the field moisture content and compaction levels was also analyzed.

TEST SECTION AND IC ROLLER DESCRIPTION

Two pavement reconstruction projects, one on US-56 and one on I-70, were selected for this study. The US-56 project had two 328 ft (100 m) sections. The first section was a “proof” section that had already been compacted by a conventional roller. IC roller stiffness measurements were made after one pass of the roller. The other section was a “growth” section that was compacted by the IC roller using multiple passes and densities were “built” up. The I-70 section had only one 328 ft (100 m) “growth” section. The target density and corresponding moisture content of the “growth” test sections were those required by the project special provisions. No proof rolling was performed on any of these test sections.

Both projects have sandy (SP or A-3) soils. Other relevant soil characteristics are shown in Table 1.
TABLE 1 Test Section Soil Characteristics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing # 200 Sieve (%)</td>
<td>4.2</td>
<td>6.8</td>
<td>8.4</td>
</tr>
<tr>
<td>Coefficient of Uniformity, $C_u$</td>
<td>2.1</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Coefficient of Curvature, $C_c$</td>
<td>1.25</td>
<td>0.67</td>
<td>1.6</td>
</tr>
<tr>
<td>Soil Classification (AASHTO)</td>
<td>A-3</td>
<td>A-3</td>
<td>A-3</td>
</tr>
<tr>
<td>Plasticity</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
</tr>
<tr>
<td>Avg. In-situ Moisture content (%)</td>
<td>6.4</td>
<td>5.6</td>
<td>8.98</td>
</tr>
<tr>
<td>Optimum Moisture Content (OMC), (%)</td>
<td>10.4</td>
<td>10.2</td>
<td>11.7</td>
</tr>
<tr>
<td>Maximum Dry Density, MDD, (kg/m$^3$)</td>
<td>1916.0</td>
<td>2012.0</td>
<td>1838.8</td>
</tr>
</tbody>
</table>

The IC roller used in this study was a Bomag VARIOCONTROL (BVC) single drum vibratory roller (Model BW 213 DH-4 BVC) as shown in Figure 2. The roller had a gross weight of 31,976 lbs (14,505 kg) and the weight on the single axle, steel drum was 20,283 lbs (9,200 kg). The working width was 83.9 in. (2130 mm). The speed of the roller was 0 to 8.1 mph (0-13 kmph). The vibration frequency was 1,680 vpm (28 Hz) and the amplitude was 0 to 0.094 in. (0-2.4 mm). The centrifugal force produced was 83,215 lbs (365 kN).

The BVC roller instantly and continuously adjusts amplitude and compaction energy (10). The adjustment is made possible because of the Bomag vibration system that generates linear vibration of the roller drum. The direction of this vibration is progressively adjusted between horizontal and vertical directions using a bi-axial accelerometer. The transmitted compaction energy is influenced by the adjustment of the direction. The vertical direction gives the maximum energy available from the roller. At the commencement of compaction, this accelerates the compaction process and improves depth effect. The horizontal direction gives the minimum energy available from the roller. This improves compaction close to the surface and reduces loosening. The energy required for the compaction of soil is defined by the soil itself, its layer thickness, the foundation layer, and its degree of stiffness as well as the resulting soil stiffness. The operator can pre-select six minimum values of Bomag IC roller vibration modulus, $E_{VIB}$ in MN/m$^2$ ($E_{VIB}$ = 45, 80, 100, 120 MN/m$^2$ and maximum). During compaction, soil stiffness in terms of $E_{VIB}$ and speed are continuously measured and displayed. When the preset minimum stiffness value is reached or at maximum compaction, BVC system reduces compaction forces and a green light on the $E_{VIB}$ display indicates the end of compaction (10).

In this study, $E_{VIB}$ data was continuously collected over the test sections. On the “proof” section on US-56, BVC stiffness data was collected after one pass of the roller. For the “growth” sections, $E_{VIB}$ data was collected for each pass of the roller.

FIGURE 2 BVC roller compaction on a test section on US-56 near Hugoton, Kansas.
TESTING AND DATA COLLECTION

Density and Moisture Measurements

The in-situ density measurements were done by a nuclear gage. Soil samples were collected at 16.5 ft (5 m) intervals on all sections. The soil samples were tested for gradation, Atterberg limits (unsuccessfully) and moisture-density relationships in the laboratory. Soil samples were also collected for in-situ moisture content determination by the gravimetric method in the laboratory. Typical results have been tabulated in Table 1.

Stiffness, Deflection, and Cone Penetration Tests

The Geogage, Falling Weight Deflectometer (FWD), Light Falling Weight Deflectometer (LFWD) and Dynamic Cone Penetrometer (DCP) measurements were made at 16.5 ft (5 m) intervals. For the US-56 “proof” section, tests were done after one pass of the BVC roller. For the “growth” sections, tests were done after the final pass of the BVC roller.

Geogage

The soil stiffness gage or Geogage is a portable, nondestructive, and nonnuclear device that was used to measure the soil stiffness. It was 0.8 ft (250 mm) in height, rested on a 0.9 ft (280 mm) diameter base, and weighed about 22 lbs (10 kg). The base was a rigid ring-shaped foot on the soil surface. The applied force and the displacement-time history were measured by two velocity sensors. According to the manufacturer, the geogage vibrates and produces small changes in vertical force with displacement within the 6,000 to 12,000 vpm (100 to 200 Hz) frequencies. The in-situ soil stiffness was measured at each frequency and then finally, the average value was recorded. It measured the stiffness up to 0.7 to 1 ft (220 to 310 mm) of depth from the contact surface. The geogage stiffness can also be used to determine the Young’s modulus (11).

Falling Weight Deflectometer (FWD)

The Dynatest model 8000 FWD system was used in this study to obtain the in-situ deflection data. The impulse force was created by dropping a target mass of 2500±200 lbs (1134±91 kg) from a certain height. This load level was recommended by George (12) for bare subgrade testing using an FWD. The load was transmitted to the subgrade through a load plate with a diameter of 18 in. (457 mm) to provide a load pulse in the form of a half sine wave with a duration of 25 to 30 ms. The load magnitude was measured by a load cell. Deflections were measured using seven sensors mounted on a bar that was lowered on to the pavement surface automatically with the loading plate. One of the sensors was located at the center of the plate while the other six were located at a radial distance of 12 in. (305 mm) center to center. The measured deflections at different stations were used to backcalculate the modulus of the subgrade soil. There are some general techniques that match the measured deflections with those calculated from theory. Example computer programs that make use of this technique include EVERCLAC 5.0, MODCOMP and MODULUS 6.0. In this study, EVERCALC 5.0 was used to backcalculate the subgrade modulus from the in-situ deflection data. In most cases, full deflection basin was used. In several instances, the seventh sensor data was ignored since the
deflection recorded by this sensor was more than the sixth sensor. In a few cases, the whole basin was discarded when the root-mean square (RMS) error in backcalculation was deemed too high. The first sensor deflection was also used to backcalculate the subgrade soil elastic modulus from the Boussinesq equation shown later.

**Light Falling Weight Deflectometer (LFWD)**

Recently hand-held, falling weight deflectometer devices have become available for surface deflection measurements. The Prima 100 LFWD device was used to evaluate the in-situ soil modulus in this study. The device consisted of four major parts: sensor body, loading plate, buffer system, and the sliding weight. The sensor body enclosed both the load cell and the geophone. The loading plate, buffer system and the sliding weight were attached to the sensor body. A 12 in. (300 mm) diameter steel loading plate, which also doubled as the sensor body, was used in this study. The LFWD device measured both force and deflection. The elastic modulus of the subgrade soil was calculated from the surface deflection using the following Boussinesq equation:

\[
E_{LFWD}(0) = \frac{k \cdot \left(1 - \nu^2\right) \cdot \sigma_o \cdot a}{d_o}
\]

(4)

Where,

\[
E_{LFWD} = \text{LFWD modulus (MPa)};
\]

\[
k = \frac{\pi}{2} \quad \text{and } 2 \text{ for rigid and flexible plate, respectively};
\]

\[
d_o = \text{deflection at center (\(\mu m\))};
\]

\[
\sigma_o = \text{Applied stress (kPa)};
\]

\[
\nu = \text{Poisson’s Ratio}; \text{ and}
\]

\[
a = \text{plate diameter (mm)}.\]

In this study, a rigid plate was assumed during modulus calculation from the Boussinesq analysis.

**Dynamic Cone Penetrometer (DCP)**

Dynamic Cone Penetrometer was initially developed in South Africa as an in-situ pavement evaluation technique for continuous measurement with the depth of pavement layers and subgrade soil parameters (13). Since then this device has been used extensively in South Africa, United Kingdom, US, Australia and many other countries because it is simple, economical, and less time consuming than most other available methods. The DCP used in this study was provided by Managing Technology, Inc., Overland Park, Kansas to KDOT in the early nineties. The KDOT DCP consisted of a slender steel rod with a cone tip at the end. The cone tip was made of hardened steel and was angled at 30E with a diameter at its head of 0.8 in. (20 mm). The hammer which slid down the steel rod had a height of 23 in. (575 mm) and weighed 18 lbs (8 kg). The unit had two aluminum blocks and a reference beam that aided in measuring the penetration depth during testing. For subgrade evaluation in this study, the DCP was penetrated
down from the top of the compacted subgrade. During testing, the number of blows vs. depth is recorded. The "DCP value" was defined as the slope of the blow vs. depth curve (in mm per blow) at a given linear depth segment.

**Correlation between DCP and CBR:** The California Bearing Ratio (CBR) test measures the static penetration resistance of a soil as a function of penetration of a cylinder prior to reaching the ultimate shearing value of the soil. The CBR is defined as a percentage determined by the ratio of the resistance in psi at 0.1 in (2.5 mm) penetration of the soil under test to the resistance of a standard, well graded, crushed stone at the same penetration (2.5 mm), and then multiplied by 100. This standard penetration stress is usually taken to be 1,000 psi (6,895 kPa).

In order to assess the structural properties of the pavement subgrade, the DCP values are usually correlated with the CBR of the pavement subgrade soil (13):

\[
\log CBR = 220 - 0.71 \times (\log DCP)^{1.5} \\
\text{(R}^2 = 0.95, N = 74)
\]

where the DCP is in mm per blow.

This relationship was verified for a wide range of pavement and subgrade materials (13). Additional laboratory and correlation work conducted at the University of Kansas (14) and by the U.S. Army Corps of Engineers (Waterways Experiment Station) (15) generally supported the relationship described in Equation (5), but indicated considerable data scatter. It was recommended the DCP limit of 1.0 in./blow (25 mm/blow) be correlated to a CBR of 8 for the silty/clay soils although the actual DCP value of the soil was way above this limit (14).

**RESULTS AND DISCUSSIONS**

**BVC Stiffness on US-56 “Proof” and I-70 “Growth” Sections**

BVC stiffness (\(E_{VIB}\)) measurements were made after a single pass on a 328 ft (100 m) “proof” section on US-56 that has been compacted by a conventional vibratory roller. Other BVC stiffness measurements were taken on a 328 ft (100 m) “growth” section on I-70 that has been compacted by the multiple passes of an IC roller. The results are shown in Figure 3. On the US-56 proof section, mean BVC stiffness (\(E_{VIB}\)) was 9 ksi (62 MPa) and it varied from 4 ksi (30 MPa) to 18 ksi (120 MPa). On I-70, the mean \(E_{VIB}\) was 6 ksi (40 MPa), and it varied from 4 to 9 ksi (30 to 60 MPa).

As the figure indicates - there were a number of soft spots along these small stretches of the embankment. Due to continuous measurement of the soil stiffness, it was possible for the IC roller to identify these locations.
FIGURE 3 Spatial variation of BVC stiffness on (a) US-56 proof and (b) I-70 growth.
Variation of BVC Stiffness with Moisture Content

Subgrade soil is susceptible to moisture variation after construction of the highway pavement. Briau d and Seo (7) have indicated that the soil at lower moisture content will have higher modulus values. This effect is more pronounced for the clay-type soil. On the other hand, density gives the compactness of the soil particles and determines how they are arranged in a given volume. But, unfortunately there is no correlation between the soil density and modulus, and the same density can be obtained for at least two different moisture contents (on either side of the standard Proctor compaction curve). That is why it is not possible to control soil compaction on the basis of the dry density alone. Figure 4 shows the relation between the BVC stiffness and the in-situ moisture content for the test sections on US-56 and I-70. The trends in these graphs clearly indicate that the BVC stiffness was somewhat sensitive to the field moisture content. Higher moisture content resulted in lower BVC vibration modulus.

![Graph](image-url)

**FIGURE 4** Variation of BVC stiffness with in-situ moisture content on (a) US-56 “proof” and (b) I-70 “growth” section.
Variation of BVC Stiffness With Compaction Level

The relationship between the in-situ dry density (obtained after compaction and expressed in terms of the maximum dry density from the standard Proctor test), and BVC stiffness was also examined. This was done due to the fact that the current practice of embankment compaction control in Kansas is based on the percent compaction obtained from the maximum dry density (MDD) value in the standard Proctor test. Figure 5 shows the relationship between the BVC stiffness and percent compaction obtained from the two sections on US-56 and I-70.

FIGURE 5 Relationship between BVC stiffness and percent compaction for (a) US-56 “proof” and (b) I-70 “growth” sections.
The US-56 results show that lower BVC roller stiffness was obtained for both very high and very low percent compaction. Although the I-70 test section showed higher levels of percent compaction, the trend was almost similar to that observed on the US-56 test section. This finding is very significant since it indicates the need for developing the “target” stiffness for the IC rollers for a specific type of soil. When the preselected stiffness value is entered prior to the compaction, the IC roller automatically controls the compaction process until the target stiffness value is obtained. At that point, the roller reduces or eliminates the compactive effort on subsequent passes. If these target values are low, the resulting density will be too low where as high target values will result in overcompaction. The results of this study tend to prove this point.

Correlation Among BVC Stiffness, Geogage Stiffness, LFWD Modulus, FWD Modulus and CBR/DCP

FHWA (2) reported that some European and Asian countries now use compaction specifications that contain modulus-based compaction control. In those specifications, minimum target modulus must be obtained in addition to the target moisture content and percentage of the Proctor density. The countries that have switched to modulus-based compaction control have typically compared their roller modulus with the field plate loading test modulus. The specifications vary from one country to another but they only vary in their minimum target modulus values depending on traffic, material type, and subgrade soil classification. For example, typical values of roller stiffness in one European specification have been reported to be 6.5 ksi (45 MPa) and 18 ksi (120 MPa) for low traffic roads and freeways, respectively (7). In the United States, the plate modulus test (or plate loading test) is not used by all states as a standard acceptance tool. However, Geogage, Dynamic Cone Penetrometer (DCP), light falling weight deflectometer (LFWD) and falling weight deflectometer (FWD) have become popular tools for subgrade evaluation. Table 2 shows the test conditions for various tests done on the projects. The table also shows the mean stiffness and moduli obtained from the IC roller and other tests. It is to be noted that all tests were done at different vertical pressure. It is well known that the subgrade soil is stress dependent –the soil modulus varies with the deviator stress and to some extent, confining pressure. For sandy soils, the modulus increases with increasing deviator stress. Thus the layer modulus changes with depth. This is potentially a source of problem when comparing stiffness and modulus results from different tests. In this study, efforts were made to keep the applied vertical stresses of FWD and LFWD similar.

Table 3 tabulates the summary of the IC roller stiffness and other stiffness and moduli results obtained in this study. IC roller stiffness and Geogage stiffness were the outputs of these pieces of equipment. Boussinesq’s equation was used to backcalculate the soil elastic modulus from both LFWD and FWD in-situ deflection data. FWD modulus was further calculated using the EVERCALC 5.0 backcalculation software using the full deflection basin from all seven or six sensors. The CBR/DCP modulus was calculated from the correlation between CBR and the resilient modulus.
TABLE 2 Applied Vertical Stresses and Moisture Content During IC Compaction and Testing

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Test</th>
<th>Applied Vertical stress, $\sigma_d$ (kPa)</th>
<th>Field Moisture Content $w$ (%)</th>
<th>OMC $w$ (%)</th>
<th>Average Stiffness/Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-56 “proof”</td>
<td>IC Roller</td>
<td>92.6-277.8</td>
<td>6.2 – 9.9</td>
<td>10.4</td>
<td>61.7</td>
</tr>
<tr>
<td></td>
<td>Geogage</td>
<td>25.0</td>
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<td>7.96</td>
</tr>
<tr>
<td></td>
<td>LFWD</td>
<td>130.9 – 162.5</td>
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<td>64.1*</td>
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<tr>
<td></td>
<td>FWD</td>
<td>67.6 – 116.5</td>
<td></td>
<td></td>
<td>73.3*</td>
</tr>
<tr>
<td>I-70 “growth”</td>
<td>IC Roller</td>
<td>92.6-277.8</td>
<td>6.2 – 9.9</td>
<td>11.7</td>
<td>40.5</td>
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<tr>
<td></td>
<td>Geogage</td>
<td>25.0</td>
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<td>4.9</td>
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<tr>
<td></td>
<td>LFWD</td>
<td>118.3 – 136.4</td>
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<td></td>
<td>26.4*</td>
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<tr>
<td></td>
<td>FWD</td>
<td>52.4 – 102.73</td>
<td></td>
<td></td>
<td>29.8*</td>
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</tbody>
</table>

* from Boussinesq equation

Figure 6 illustrates the variation of various stiffness and moduli obtained at different test locations on the US-56 “proof” and I-70 “growth” sections. The US-56 “growth” section did not have any LFWD data. Thus, this section was not considered in this analysis. Results in Table 3 indicate that on the US-56 section, the variation in stiffness and/or modulus values is much higher. The highest variation is indicated by both the IC roller stiffness and the LFWD-derived modulus. The trend of data in Figure 6(a) shows a good correlation between the Geogage stiffness and the LFWD backcalculated modulus on the US-56 “proof” section. On this section, the mean stiffness and moduli values obtained from the IC roller, LFWD and FWD (Boussinesq’s equation) are also somewhat close.

However, the above trend is not evident on the I-70 “growth” section though the summary results in Table 3 show that the stiffness and modulus values were much less scattered on this section. As expected, the mean modulus values from LFWD and FWD were similar. However, as illustrated in Figure 6(b), no definite correlation is evident among BVC stiffness, Geogage stiffness, and LFWD and FWD backcalculated moduli.
TABLE 3 Summary of Stiffness and Moduli Results

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Parameter</th>
<th>Mean (MPa)</th>
<th>Std. Dev. (MPa)</th>
<th>Coeff. Of Var. (%)</th>
<th>Range (MPa)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-56 “Proof”</td>
<td>BVC Stiffness</td>
<td>61.7</td>
<td>23.2</td>
<td>37.5</td>
<td>90.0</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Geogage Stiffness</td>
<td>7.96</td>
<td>2.2</td>
<td>27.4</td>
<td>10.96</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>LFWD Modulus*</td>
<td>64.1</td>
<td>24.1</td>
<td>37.6</td>
<td>91.3</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>FWD Modulus**</td>
<td>86.5</td>
<td>29.7</td>
<td>34.4</td>
<td>135.9</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>FWD Modulus *</td>
<td>73.3</td>
<td>19.2</td>
<td>26.2</td>
<td>87.8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>CBR/DCP Modulus***</td>
<td>129.6</td>
<td>28.3</td>
<td>21.8</td>
<td>98.8</td>
<td>21</td>
</tr>
<tr>
<td>I-70 “Growth”</td>
<td>BVC Stiffness</td>
<td>40.5</td>
<td>7.7</td>
<td>19.1</td>
<td>30.0</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Geogage Stiffness</td>
<td>4.91</td>
<td>1.1</td>
<td>23.1</td>
<td>5.3</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>LFWD Modulus*</td>
<td>26.4</td>
<td>7.2</td>
<td>27.4</td>
<td>28.1</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>FWD Modulus**</td>
<td>29.1</td>
<td>6.6</td>
<td>22.7</td>
<td>26.2</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>FWD Modulus *</td>
<td>29.8</td>
<td>6.4</td>
<td>21.3</td>
<td>23.8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>CBR/DCP Modulus***</td>
<td>97.3</td>
<td>8.2</td>
<td>8.4</td>
<td>34.2</td>
<td>21</td>
</tr>
</tbody>
</table>

* from Boussinesq equation; **from backcalculation; *** from correlation

The correlation among the soil stiffness obtained from the IC roller and Geogage, and the subgrade soil moduli obtained from the LFWD, FWD, and DCP (with CBR correlation) data was also examined statistically. Correlation tables were developed using the SAS statistical software (16). Results in Table 4 for the US-56 “proof” section tend to confirm the observation in Figure 6(a). The table shows about 78% dependency of Geogage in-situ stiffness on the LFWD stiffness at 95% confidence level with a p-value less than 0.0001. The Geogage stiffness also has a good correlation with the modulus obtained from CBR in the DCP test. However, results in Table 5 for the I-70 section show about 32% dependency of the Geogage stiffness on the LFWD modulus at 95% confidence level with a p-value equal to 0.1607. None of the test results seems to have a strong correlation with the BVC stiffness on this section. Further testing may be necessary to develop such a correlation. It may be mentioned that the BVC roller stiffness has been successfully correlated with the plate loading test results in Europe. It appears that larger plated helps to test a large soil sample that could be considered somewhat representative of the soil subgrade.
FIGURE 6 Spatial variation of BVC, Geogage, LFWD and FWD stiffness on (a) US-56 “proof” and (b) I-70 “growth” section.
### TABLE 4 Correlations among BVC and Geogage Stiffness, LFWD and FWD Moduli, and CBR on US-56 “Proof” Section

<table>
<thead>
<tr>
<th></th>
<th>BVC</th>
<th>Geogage</th>
<th>LFWD</th>
<th>FWD (Backcalculated)</th>
<th>FWD (Boussinesq equation)</th>
<th>CBR/DCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BVC</td>
<td>1.0</td>
<td>-0.35</td>
<td>-0.39</td>
<td>-0.19</td>
<td>-0.21</td>
<td>-0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12*</td>
<td>0.096*</td>
<td>0.43*</td>
<td>0.36*</td>
<td>0.04*</td>
</tr>
<tr>
<td>Geogage</td>
<td>1.0</td>
<td>0.78</td>
<td>0.24</td>
<td>0.83</td>
<td>0.0002*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;0.0001*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFWD</td>
<td>1.0</td>
<td>0.11</td>
<td>0.63</td>
<td>0.86</td>
<td>0.0001*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.68*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>1.0</td>
<td>0.36</td>
<td>0.18</td>
<td>0.47</td>
<td>0.033*</td>
<td></td>
</tr>
<tr>
<td>(Backcalculated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>1.0</td>
<td>0.12*</td>
<td>0.45*</td>
<td>0.47</td>
<td>0.033*</td>
<td></td>
</tr>
<tr>
<td>(Boussinesq equation)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBR/DCP</td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* p-value

### TABLE 5 Correlations among BVC, Geogage, LFWD and FWD Moduli, and CBR on I-70 “Growth” Section

<table>
<thead>
<tr>
<th></th>
<th>BVC</th>
<th>Geogage</th>
<th>LFWD</th>
<th>FWD (Backcalculated)</th>
<th>FWD (Boussinesq equation)</th>
<th>CBR/DCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BVC</td>
<td>1.0</td>
<td>0.39</td>
<td>-0.001</td>
<td>-0.03</td>
<td>-0.05</td>
<td>0.05</td>
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<tr>
<td></td>
<td></td>
<td>0.085*</td>
<td>0.99*</td>
<td>0.93*</td>
<td>0.82*</td>
<td>0.83*</td>
</tr>
<tr>
<td>Geogage</td>
<td>1.0</td>
<td>0.32</td>
<td>0.037</td>
<td>0.98*</td>
<td>0.75*</td>
<td>0.73*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.16*</td>
<td>0.89*</td>
<td>0.98*</td>
<td>0.75*</td>
<td>0.73*</td>
</tr>
<tr>
<td>LFWD</td>
<td>1.0</td>
<td>0.008</td>
<td>-0.08</td>
<td>0.75*</td>
<td>-0.08</td>
<td>-0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.98*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>1.0</td>
<td>0.97</td>
<td>-0.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Backcalculated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>1.0</td>
<td>0.1</td>
<td>-0.26</td>
<td></td>
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</tr>
<tr>
<td>(Boussinesq equation)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CBR/DCP</td>
<td></td>
<td>1.0</td>
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<td></td>
</tr>
</tbody>
</table>

* p-value
CONCLUSIONS

Based on this present study, the following conclusions can be made:

- Due to continuous measurements of the in-situ stiffness of the subgrade soil under compaction, the intelligent compaction (IC) roller is able to identify the soft spots with lower stiffness in the spatial direction.
- The IC roller stiffness is somewhat sensitive to the field moisture content. Higher moisture content will result in lower roller stiffness.
- “Target” stiffness values need to be selected in intelligent compaction control because both very high and very low maximum densities may be achieved during compaction yielding lower IC roller stiffness.
- No good correlation was observed among BVC stiffness and other stiffness/modulus values obtained from the Geogage, LFWD, FWD and DCP test data.
- Correlation between the Geogage stiffness and the LFWD moduli was found to be significant for one section. However, no good correlation was found on another section.

RECOMMENDATION

Based on this study, the following recommendations are made:

- The subgrade soil stiffness is very sensitive to in-situ moisture content and IC roller has been proven to be a very effective tool to identify those soft spots. Thus the IC roller can be used for “proof rolling”.
- Plate loading test is known to have a very good correlation with the IC roller stiffness measurements. FWD tests can be performed on subgrade using a larger diameter plate (about 30 in or 762 mm).

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