EVALUATION OF INTELLIGENT COMPACTION TECHNOLOGY FOR DENSIFICATION OF ROADWAY SUBGRADES AND STRUCTURAL LAYERS

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16. Abstract

The overall goal of WHRP Study #0092-08-07 was to collect information and data on the use of intelligent compaction (IC) technology to allow the Wisconsin DOT to make an informed decision on any useful application of this technology. Three objectives were identified to meet the overall goal of the study: (1) identify the advantages and limitations of the IC technology; (2) determine the material types and conditions that might cause inaccurate decisions or output from the IC roller (e.g., the accuracy of the outputs regarding layer stiffness); and (3) provide recommendations to the Wisconsin DOT on the use and implementation of IC technology for pavement construction.

Field demonstration projects were planned and executed to collect data and information related to the use of IC rollers in Wisconsin. The demonstration projects confirmed that IC for soils is more advanced than for hot mix asphalt (HMA) layers. Level 2 and Level 3 soil IC rollers can be used almost immediately in Wisconsin. Unfortunately, there are many more issues or unanswered questions for compacting HMA layers than for unbound layers.

The two areas where IC rollers can have immediate positive benefits, especially for unbound materials, are: (1) as a testing device to continually map the stiffness of an area prior to placing both unbound and HMA materials to identify areas with weak supporting layers, and after the layer has been compacted, and (2) to develop stiffness-growth relationships to determine the rolling pattern and number of passes to achieve a specific stiffness level. The key technical issues include lift thickness, bridging localized construction defects , and the fact that the IC roller output is a composite value influenced by the supporting layers,. Additional pilot projects are recommended to increase contractor and agency personnel's confidence in using this technology.

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ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACE	Ammann Compaction Expert
CCC	Continuous Compaction Control
CCV	Compaction Control Value
CDS	Compaction Documentation System
CI	Compaction Indicator
CMV	Compaction Meter Value
COV	Coefficient of Variation
DCO	Dynapac Compaction Optimizer
DCP	Dynamic Cone Penetrometer
DOT	Department of Transportation
FFT	Fast Fourier Transform
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GPS	Global Positioning System
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
LL	Liquid Limit
LTPP	Long Term Pavement Performance (Program)
LWD	Light Weight Deflectometer
M-E	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MMA	Machine Milled Accelerometer
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NDT	Nondestructive Testing
ODMS	Onboard Density Measuring System
OMV	Osillo-Meter-Value
PC	Personal Computer
PID	Proportional integral derivative
PL	Plastic Limit
PSPA	Portable Seismic Pavement Analyzer
PWL	Percent Within Limits
QA	Quality Assurance
QC	Quality Control
RAP	Reclaimed or Recycled Asphalt Pavement
VFA	Voids Filled with Asphalt
WHRP	Wisconsin Highway Research Program

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CHAPTER 1 INTRODUCTION

1.1 Background

The quality of pavement construction depends on achieving adequate density throughout the supporting embankment and pavement layers. Historically, the level of compaction for soils and pavement layers has been specified as a function of the relative compaction or laboratory density. The objective of achieving a specified density is to ensure a minimum layer stiffness and strength of the upper layers and to reduce detrimental long-term material property changes.

In current practice, achieving adequate density is judged by either visual means through proof rolling (typical for embankments in Wisconsin) or discrete in-place density measurements made by nuclear density gauges or other devices. The roller pattern to achieve this target density is determined at the beginning of the project through a control strip and then used throughout the project length. However, many factors can change within the length of a project that can cause over-compaction (degradation of material) or not achieving the specified minimum density, requiring the area to be reworked or removed, or resulting in a penalty to the contractor. Contractor and agency personnel have concern over the relative compaction of lower layers because the stiffness of those layers influences the compaction of the upper pavement layers.

Intelligent compaction (IC) is a technology that monitors layer stiffness during compaction by instrumentation of the roller to measure its reaction to the material being compacted. IC gives the contractor the opportunity to monitor layer stiffness continuously during compaction, producing more uniformly compacted layers and allowing compaction modifications based on response outputs in real time. The output from this technology also provides documentation for owner and contractor management regarding material stiffness of all pavement layers.

This technology has been in existence for several years and provides real-time, in-place material stiffness data that the roller operator can use to make better decisions during compaction. The use of IC technology as a viable construction quality measure has increased over the past decade. More than 20 State and Federal agencies have sponsored demonstration or pilot projects to date. Multiple vendors (Bomag, Case/Ammann, Caterpillar, Dynapac, Sakai, and Volvo/Ingersoll Rand) sell IC rollers in the U.S. with varying outputs and controls for compacting soils. These manufacturers have fully equipped rollers, but some also have instrumentation kits that can be attached to existing vibratory rollers. Bomag, Caterpillar, and Sakai are the only vendors in the U.S. that currently are selling IC rollers for compacting hot mix asphalt (HMA) layers. Multiple documents provide a description of the operation, measurement systems, and outputs for the different IC rollers (Briaud and Seo, 2005; Mooney et al., 2007; Von Quintus et al., 2009; FHWA Intelligent Compaction website[1]).

[1] FHWA website for intelligent compaction is: http://www.intelligentcompaction.com/

IC technology has the potential to improve layer density, having a positive impact on pavement warranty and design-build contracts, as well as traditional contracts. Warranty contracts transfer more risk to the contractor. The higher the uncertainty regarding layer support, the higher the bid price as contractors begin to accept more risk for pavement performance through the warranty period.

In summary, implementation of IC technology has the potential to lower construction costs, improve overall quality, reduce variability, and enhance the service life of pavement systems by providing the contractor documentation of layer stiffness levels and minimizing the potential for de-compaction and degradation of all pavement layers. The Wisconsin Department of Transportation (DOT) has recognized the potential benefits of this technology and is taking steps to investigate the use of IC for constructing new pavements and rehabilitating existing roadways. In fact, the Wisconsin DOT is participating in the Federal Highway Administration (FHWA) pooled-fund demonstration project.[2]

1.2 Project Goal & Objectives

The overall goal of Wisconsin Highway Research Program (WHRP) Study # 0092-08-07 was to collect information on the use of IC technology to allow the Wisconsin DOT to make an informed decision on any useful application of this technology. The following three objectives were identified to meet the overall goal of the study:

1. Identify the advantages and limitations of the IC technology.
2. Determine the material types and conditions that might cause inaccurate decisions or output from the IC roller (e.g., the accuracy of the outputs regarding layer stiffness).
3. Provide recommendations to the Wisconsin DOT on the use and implementation of IC technology for pavement construction.

The goal of the project does not include a comparison and evaluation of different IC rollers, only an evaluation of the technology itself.

1.3 Scope of Report

This report documents the overall findings and results from the study, including a literature review of previous studies and demonstration projects and an analysis of data collected from three demonstration projects on the use of IC technology in Wisconsin. The literature review was designed around objective #1 and was used in planning the demonstration projects, while the demonstration projects were designed around objective

[2] FHWA Research Project DTFH61-07-C-R0032, "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials."

#2. The analysis of data collected within this project and from previous projects was designed around objective #3.

The report is divided into six chapters, including this introductory chapter. The following provides a summary of the information included in subsequent chapters:

- Chapter 2 provides an overview of previous studies and demonstration projects. Most of the information from this chapter was extracted from the literature review report submitted to the Wisconsin DOT in 2008. Information from Chapter 2 was used to plan the demonstration projects.
- Chapter 3 is an overview of the demonstration projects and provides information on the materials, equipment, and test methods used on each project. A work plan was prepared for each demonstration project noting the type and frequency of nondestructive and laboratory tests to characterize the materials included in the study.
- Chapter 4 discusses the test results from the application of the IC technology for compacting unbound layers. Chapter 5 presents and discusses the results for HMA layers. The analysis of the data collected from all demonstration projects was completed to identify and/or confirm some of the limitations and benefits previously reported on the use of IC technology in Wisconsin.
- Chapter 6 summarizes the findings and conclusions from the study, as well as the recommended implementation plan for the Wisconsin DOT regarding IC.

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CHAPTER 2 OVERVIEW OF INTELLIGENT COMPACTION

IC was observed by U.S. Government, industry, and academia personnel during a 2002 European Scan trip to identify improved compaction technologies. The use of IC technology as a viable construction quality measure has increased over the past decade. More than 20 State and Federal agencies have sponsored demonstration projects to date. Additional demonstration projects are being conducted under the current FHWA pool-fund study.[3]

The purpose of this chapter is to provide a summary on the history and background of IC in the United States.[4] This historical information was used to answer the following basic questions about the technology and in planning the demonstration projects that are discussed in Chapter 3:

- How mature is the technology for compacting unbound materials and HMA mixtures?
- Does the increased purchase cost and maintenance of the IC rollers have an increased benefit that offsets those costs in the long term?
- Are there any technical issues and concerns that need to be overcome in using the technology to its fullest extent?
- Do the results from the initial demonstration projects suggest that agencies and contractors should continue to pursue this technology?

2.1 Intelligent Compaction (IC) ─ Defined

A general definition of IC is that it is a system of hardware, software, and instrumentation installed on rollers with the purpose of improving the compaction process, and/or increasing the density and uniformity of flexible pavements. The following was extracted from the Intelligent Compaction website:

> Intelligent Compaction (IC) refers to the compaction of road materials, such as soils, aggregate bases, or asphalt pavement materials, using modern vibratory rollers equipped with an in-situ measurement system and feedback control. Often, Global Positioning System (GPS) based mapping is included, and software that automates documentation of the results. By integrating measurement, documentation, and control systems, the use of IC rollers allow for real-time corrections in the compaction process. IC rollers also maintain a continuous record of color-coded plots that include number of roller passes, roller-generated material stiffness

[3] FHWA Research Project DTFH61-07-C-R0032, "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials."
[4] Most of the information from this chapter was extracted from the literature review report submitted to the Wisconsin DOT in 2008 (Von Quintus and Helwany, 2008).

measurements, and precise location of the roller.

Specifically, accelerometers are placed on the roller to measure its reaction to the material being compacted. This gives the contractor and roller operator the opportunity to monitor layer stiffness continuously at the time of compaction, producing more uniformly compacted pavement layers and allowing real-time compaction modifications based on response outputs. The output from this technology also provides documentation for owner and contractor management to quantify the stiffness of all pavement layers, or at least to obtain an estimate of pavement stiffness.

2.2 Methodology and Principle of Operation

IC technology is applicable to vibratory rollers, although some manufacturers are studying ways to adapt the technology to static drum rollers. All IC rollers essentially use a combination of three parameters—amplitude, frequency, and speed—to modify the compactive energy delivered by a roller of specific mass and diameter, just like a standard vibratory roller. The difference is that the IC roller provides feedback to the roller operator, in real time, regarding the resistance of the material to the compactive energy being delivered by the roller.

The principle behind IC rollers is that compactive effort is applied using the dynamic force created by the weight of the roller and rotating eccentric masses in the roller drum, and at the same time the material's responses to the vibratory impulses are measured using an accelerometer affixed to the drum. Measurements from the accelerometers and/or machine energy are used to calculate an index parameter related to modulus, stiffness, or bearing capacity. This information is then used by the control system of some rollers to determine whether to increase or decrease compaction energy by adjusting the internal, mechanical parameters of the roller automatically—primarily adjusting the magnitude or direction of the amplitude. Other rollers do not adjust the compactive energy during rolling and are simply a continuous testing machine used to map the stiffness of an area. Whether these rollers should be considered IC rollers is debatable, but they have been included in previous demonstrations.

IC rollers provide the capability to monitor a response value of the material continuously during the compaction process, to adjust compactive effort during rolling, and to develop color-coded mapping of the layer being compacted. These capabilities have the potential to revolutionize the compaction equipment industry by allowing for fundamental changes in the compaction process relative to a contractor's quality control (QC) tool and an owner's acceptance procedure.

2.3 IC Systems and Equipment

Most IC rollers can be grouped into two general categories: the Onboard Density Measuring System (ODMS) patented by Pennsylvania State University for rolling HMA mixtures and the Continuous Compaction Control (CCC) system that is applicable to both bound and unbound layers. Both systems offer real-time pavement quality measurement and use accelerometers to measure parameters of the compactor's vibratory signature. Other sensors are used to gain supplemental information about the pavement and to estimate pavement quality via layer stiffness values. IC vendor-specific information is discussed later in this chapter.

2.3.1 Onboard Density Measuring System

The ODMS offers density measurements in real time at a rate of one per second during the compaction process, thereby affording the contractor and roller operator the opportunity to recognize and correct compaction problems immediately, while maintaining a permanent record of the entire compaction process.

The ODMS was developed from the rather simple idea that, the denser the material that the vibratory roller is rolling over, the more excited the vibratory response of the roller. This response is measured by an onboard computer connected to a machine milled accelerometer (MMA) attached to the frame of the roller just inside the roller's damping mechanism. The computer receives the signal from the MMA and uses a Fast Fourier transform (FFT) to decompose a sequence of values into a frequency domain, producing a power spectrum such as the one seen in Figure 1. The computer then integrates the power spectrum into an algorithm that calculates the HMA density at 1-second intervals and transports them via radio signal to interested project personnel at a remote computer.

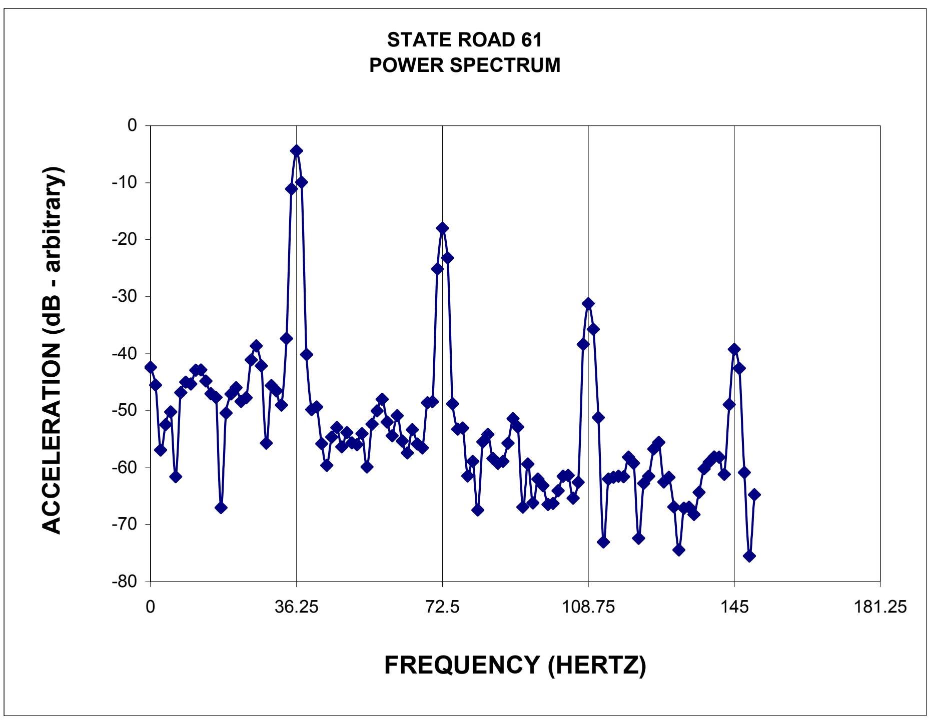

Figure 1. Typical Power Spectrum Produced by the ODMS

Two major aspects of the ODMS separate it from other acoustics-based density gauges. It is the only acoustics-based density gauge that takes into account physical parameters other than the vibratory response of the roller. The developers of this system state that it is a direct measurement of density in pounds per cubic foot (pcf) and is not a relative density reading (Minchin, 1999; Minchin et al., 2001; Minchin et al., 2005). That statement, however, is debatable. Measurements with this system have been compared to point-specific in-place densities measured on cores recovered immediately after rolling, and relatively good correspondence was found between the ODMS densities and core densities on the few projects included in the field validation study (Minchin and Thomas, 2003). The following was extracted from NCHRP Report #626 to summarize the ODMS principle of operation (Von Quintus et al., 2009).

> As the HMA mat is compacted with each successive pass of the vibratory roller, the density level rises, and the effective stiffness increases. The theory behind the system is that the acceleration level of the vibratory response is affected in a repeatable manner. The fundamental relationships between the displacement, the velocity, and the acceleration of a mechanical system or vibration parameters are both unique and convenient.
>
> The displacement is written as Δ(t). The velocity of the vibration (V) is the derivative of the displacement (Δ) as a function of time; therefore, velocity can be written as:

$$V(t) = \frac{d\Delta(t)}{dt} \qquad (1)$$

> Acceleration is defined as the rate of change in velocity at a given point in time. Acceleration is the derivative of velocity; therefore, the acceleration can be written as:

$$a(t) = \frac{dV}{dt} = \frac{d^2\Delta}{dt^2} \qquad (2)$$

> Thus, these relationships can be derived, as shown in the following equations:

$$Displacement = \Delta(t) = A(\sin(\omega t)) \qquad (3)$$

$$Velocity = V(t) = \frac{d\Delta}{dt} = wA(\cos(\omega t)) \qquad (4)$$

$$Acceleration = a(t) = \frac{dV}{dt} = \frac{d^2\Delta}{dt^2} = \omega^2 A(\sin(\omega t)) \qquad (5)$$

> Where:
>
> A = Amplitude
> t = Time

ω = Circular frequency (in radians / sec.)

As shown in Figure 2, the concept of mat stiffness and the presence of damping induced by the mat were introduced. The assumption that the mat contains these properties is symbolized by the traditional spring, shown as stiffness, K, and dashpot, shown as damping, C. The acceleration, a(t), of the compacting vibrations for this study depends on mat stiffness, K, and the damping, C. At very low frequencies, stiffness K is the dominant physical factor affecting a(t). This is shown by equation 6:

$$F_{damping} = CV = CA\omega \sin(\omega t) \qquad (6)$$

Where:

V = Velocity of the vibration

Equation 6 shows how dependent the damping force is on the frequency. Since the frequencies of the vibratory components studied are in a sufficiently low range, the damping, C, can be initially ignored. This theory is a continuation of the original hypothesis, discussed earlier. Mathematically, it can be stated that:

Acceleration, a(t) = f(Stiffness, K)

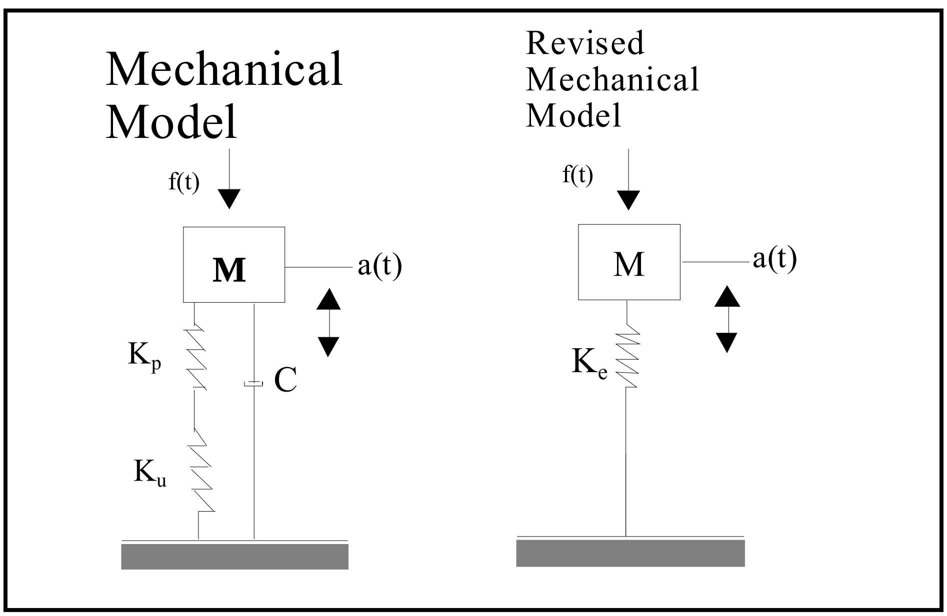

Figure 2. Illustration of the ODMS Mechanical Model

As material under the roller becomes denser, the reduction of air voids adds structure to the material, resulting in higher densities and mat stiffness. The theoretical relationship for stiffness can be expressed as a function of HMA density, so acceleration can be expressed as a function of density.

Acceleration a(t) = f(Density)

The parameters that have a large impact on the accuracy of the system include the temperature and thickness of the HMA mat, the vibratory frequency and amplitude of the compactor, and the strength of the underlying pavement structure.

2.3.2 Continuous Compaction Control System

The Geodynamik CCC system is a well-established method for stiffness assessment and control of 100 percent of an area of material being compacted by vibrating or oscillating rollers. The method is based on the use of a roller-integrated compaction meter that treats the roller drum as a dynamic loading object. The vibration of the roller drum is measured with an accelerometer, the output signal of which is analyzed using a microprocessor. The result is then presented to the roller operator as a numerical value and/or a graphical symbol indicating the achieved material stiffness. The numerical values are stored for later retrieval using a personal computer (PC). This makes it possible to generate various charts and reports for QC documentation.

The CCC system produces a compaction meter value (CMV), which is a dimensionless term that estimates the compaction state of a material. The CMV absolute value varies with the material's rigidity. The system consists of an accelerometer, a processor, a compaction or compacto-meter, and a frequency meter. Both meters are fed information by the accelerometer.

The accelerometer detects the drum's vertical vibrations and transforms them into electric signals. The signals are amplified, filtered, and then sent to the processor via a cable. In the processor, the signals are analyzed and the CMV is calculated. This CMV signal is then sent to the compacto-meter and to the compaction documentation system (CDS).

CMV is a measure of how much the vibration signal differs from a pure sinusoidal signal. The reason the vibration signal differs from a sinusoidal signal is because the drum hits the ground. If the ground is hard, the impact will be very short in duration and strong, and consequently, the distortion of the signal from the sensor will be large. In principle, about 25 to 40 load tests per second are obtained. To level out the CMV variations from impact to impact, the processor builds up a moving average that is valid over a given period of time. The overall effect is that the CMV values that the processor sends at a given time is the average of the load test results for the last half second.

Compaction Meters

The compaction meter for use with oscillatory rollers was developed based on the measured horizontal acceleration of the center axis of the drum (Sandstrom, 1993). This method of estimating compaction can be considered equivalent to a continuous dynamic loading test of the ground while the drum rolls. The compacto-meter analyzes loading tests with vertically directed loads, as the oscillometer uses horizontally directed oscillating loads.

As in the case of a dynamic plate-load test, the blows from the cylindrical drum can be used as a load test of the material. This idea was evaluated in numerous field tests that employed test rollers as well as production rollers equipped with accelerometers. It was found that the ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency was significant for the compaction level achieved. It also can be shown that the force amplitude, F, of the blows is proportional to the first harmonic of the vertical acceleration of the drum.

The displacements during the blow can be approximated by the amplitude of the double integral of the fundamental acceleration component. Therefore, it is relevant to express a "cylinder deformation modulus," E_c, as the ratio of the force and the corresponding displacement as:

$$E_c = c_1 \frac{F}{s} = c_2 \frac{A_{2\Omega}}{(\frac{A_{\Omega}}{\omega^2})} \tag{7}$$

Where:

ω = Fundamental angular frequency of the vibration.
A_{Ω} = Amplitude of vertical drum acceleration at the fundamental (operating) frequency Ω.
$A_{2\Omega}$ = Drum acceleration amplitude of the first harmonic.
c_1, c_2 = Constants

Analogous to the definition of E_c, the CMV is defined as:

$$CMV = 300 \frac{A_{2\Omega}}{A_{\Omega}} \tag{8}$$

Where the constant has been chosen to give a full scale reading of 100.

The measured CMV will vary from roller to roller, and the roller parameters (especially the frequency) have to be kept constant and equal to the parameters used during calibration. A roller operated at a standardized setting, is similar to a Falling Weight Deflectometer (FWD) for the assessment of surface stiffness. The advantages of using a "standardized" roller as a measuring tool are that complete coverage of the area is obtained and the result can be displayed to the roller operator instantaneously. The instantaneous CMV under the drum normally is shown on the display unit located in the roller cabin. Comparing this CMV with a recommended or calibrated CMV-minimum, the operator is able to see where sufficient compaction levels have been reached and where additional passes are needed. Calculating the CMV has the same issues and boundary limitations as the FWD where multiple support layers exist, with the exception that one reading is recorded for each impact rather than multiple values to describe a deformed basin.

Oscillometer

The CCC system also has an oscillometer. The oscillometer is a patented roller-integrated compaction meter for oscillating rollers. It can be mounted on all types of oscillating rollers. The oscillometer consists of an accelerometer, a processor, an I-sensor (a proximity transducer that produces an electric pulse whenever a metallic object passes by), an oscillo-meter-value (OMV) meter, a roll-speed meter, and an oscillation frequency meter.

The operation of the oscillometer is based on the indirect measurement of the reaction force in the horizontal direction brought about as a result of the drum's contact with the ground. This reaction force accelerates the whole roller horizontally. An A-sensor registers this horizontal acceleration and transforms it into an electrical signal. This signal is then filtered, amplified, and sent to a processor unit via a cable.

When the drum is operated at frequencies above the resonance, and there is no slip between drum and soil, the amplitude of this signal is a function of soil stiffness as well as the roller parameters. This stiffness value, called OMV, is quite insensitive to moderate variations in the excitation frequency. When there is slip between drum and soil, the signal processor of the oscillometer uses a special algorithm to calculate the OMV. This calculation is based solely on the time intervals during which the soil and the drum move together without slipping.

The friction between the material and the oscillating drum is not large enough to keep the drum and the material in contact during the whole oscillation. There is always some gliding between the drum and the ground. The processor takes this into consideration and uses only that part of the signal where the gliding does not occur. The values produced by this process correspond to the reaction force that would have existed if the friction were large enough to prevent gliding between the drum and the ground.

The analysis includes the computation of the maximum reaction force into the material during oscillation of the drum. This reaction force increases with increasing rigidity of the ground in a specific way, provided all the other factors affecting the whole system are kept constant (which, in reality, is an incorrect assumption). The estimate of stiffness is a function of the CMV and OMV values.

2.4 IC Roller Modules and Features

As noted in the previous section, most IC systems consist of multiple components, as shown in Figure 3: an accelerometer, a speed sensor, a data processor, and a display unit. An additional sensor is included on HMA IC rollers for measuring temperature. The accelerometer is located close to the roller drum axis in order to measure the vertical component of drum acceleration. The compaction meter values are stored in the roller cabin on a graphical display that represents the area being compacted. To obtain information on where the roller is situated along a strip, an inductive speed sensor is mounted on the rear axis. This sensor is connected to the display unit in the roller cabin, thereby continuously updating the roller's position. Most IC rollers now include a global positioning system (GPS) module to track the system's location during compaction operations.

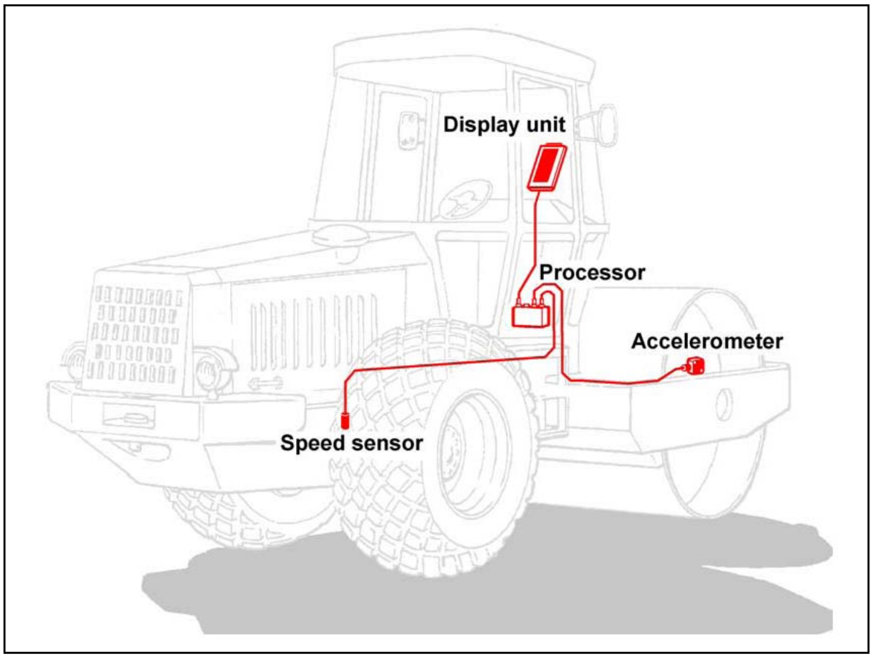

Figure 3. Geodynamik Compaction Documentation System

The Geodynamik Compaction Indicator (refer to Figure 4) uses an LED-matrix and a mini-display. The LED-matrix indicates (in a simple and easy readable way in green color) where compaction results have been reached or exceeded and (in red color) where additional passes are needed. Some vendors use a variable color display corresponding to different index values. On the display unit, the roller operator can read the CMV directly under the roller drum. The roller speed, the vibration frequency, and the distance traveled from the starting line also are displayed.

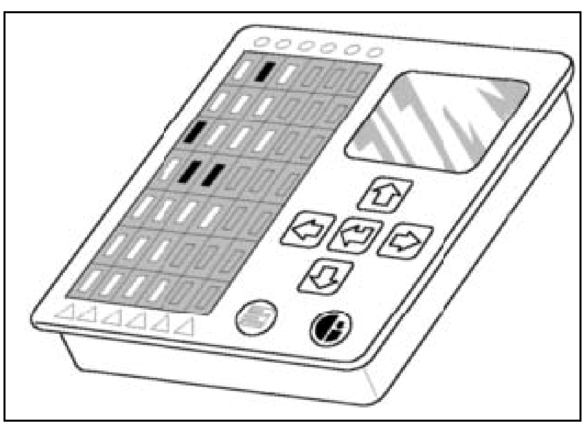

Figure 4. Geodynamik Compaction Indicator Display Unit

For this report, the authors use a three-level description of IC rollers based on how they have been used or referred to in other studies:

1. Location-specific roller – Rollers include GPS equipment and other sensors to collect ancillary or supplemental data, including HMA surface temperature, speed, etc. Level 1 rollers do not meet the IC definition and are not considered intelligent rollers.
2. Stiffness testing roller – Rollers include level 1 features with accelerometers attached to the oscillating drum for estimating stiffness. Level 2 rollers do not meet the specific definition of IC and are not considered intelligent rollers.
3. Variable/adjustable energy – Rollers include level 1 and level 2 features and a response feedback feature for varying the energy from the roller being transmitted to the material based on the measured response from the accelerometer. Level 3 rollers meet the IC definition and are considered intelligent rollers.

2.5 Integrated Response Values

This section explains the various roller-determined dynamic measurement values in use today, namely compactor indicator or index (CI), compaction meter value (CMV), Omega value, vibration modulus (E_{vib}), and roller-determined stiffness (k_s).

2.5.1 Geodynamik Compactor Indicator

As a byproduct of the development of IC rollers, Geodynamik developed a mathematical model to calculate a stiffness parameter, *G*, and a plastic parameter, *p*, based on the recorded acceleration of the roller drum and the instantaneous position of the eccenter weights. The result, primarily used for controlling a roller, also can be presented as a stiffness value for the material being compacted. The stiffness modulus *G* can easily be recalculated to an E-modulus for convenient comparison with standard spot-test results. In recent years, there has been some development along similar lines in Switzerland and Germany, and compaction meters based on these concepts have been introduced in the market.

Common to all these methods is that the contact force between drum and material is calculated from the recorded drum acceleration and the eccenter phase. The movement of the drum in a vertical direction is calculated by integrating the acceleration twice. Other compaction meters on the market are based on a model where the contact zone is treated as an elastic contact between a flat, elastic half-space and a horizontal cylinder having infinite stiffness. The load/displacement relationship for this contact zone is nearly linear, and the zone cannot exhibit any irreversible deformation. A load/displacement cycle (refer to Figure 5) will be an ellipse, or a truncated ellipse if the drum lifts off the surface. For most materials, however, a failure zone—eventually leading to plastic deformation—develops as the cylindrical drum surface loads the soil surface.

The contact area is initially zero when the cylinder first makes contact and expands as the drum moves downwards and contact force increases. A typical load/displacement cycle—

when the drum lifts off from the ground and a fairly large amount of plastic deformation takes place—is shown in Figure 6. The inclination of the loading part (A to B in Figure 5) cannot be used directly as a measure of the E-modulus of the soil because the total displacement consists of contributions from both plastic and elastic effects.

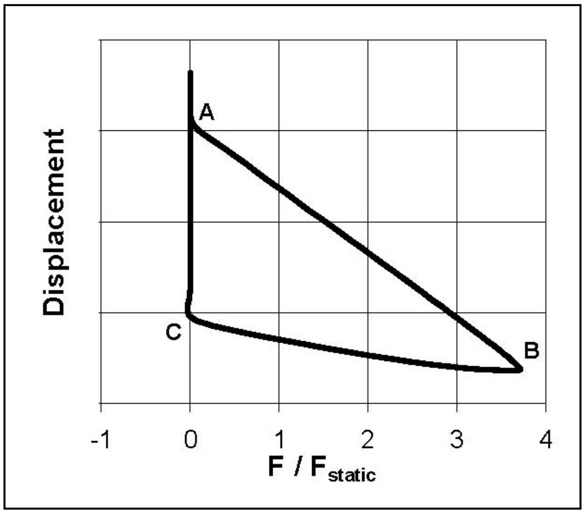

Figure 5. Calculated Load/Displacement Cycle for Soil with Linear Drum/Soil Interface

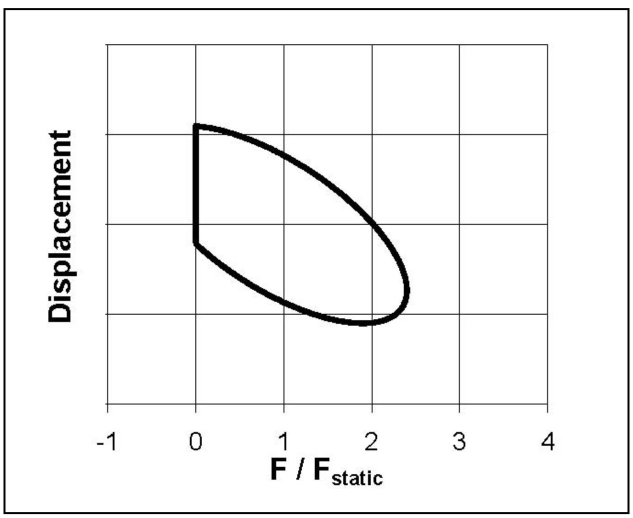

Figure 6. Calculated Load/Displacement Cycle for Soil with Elastic and Plastic Deformation

2.5.2 Compaction Meter Value

Initial research showed that various indices incorporating drum acceleration amplitude and the amplitude of its harmonics (i.e., multiples of the excitation frequency) can be correlated with the soil compaction and underlying stiffness, as mathematically defined in section 2.3.2. As such, the *CMV* was proposed (Thurner et al., 1980) and is computed as:

$$CMV = C\frac{A_{2\Omega}}{A_{\Omega}} \quad (9)$$

Where A_{Ω} is the amplitude of vertical drum acceleration at the fundamental (operating) frequency **Ω**, and $A_{2\Omega}$ is the drum acceleration amplitude of the first harmonic, i.e., twice the eccentric excitation frequency (refer to Figure 7). *C* is a constant established during site calibration (*C* = 300 is often used; refer to equation 8). The ratio of $A_{2\Omega}/A_{\Omega}$ is a measure of nonlinearity.

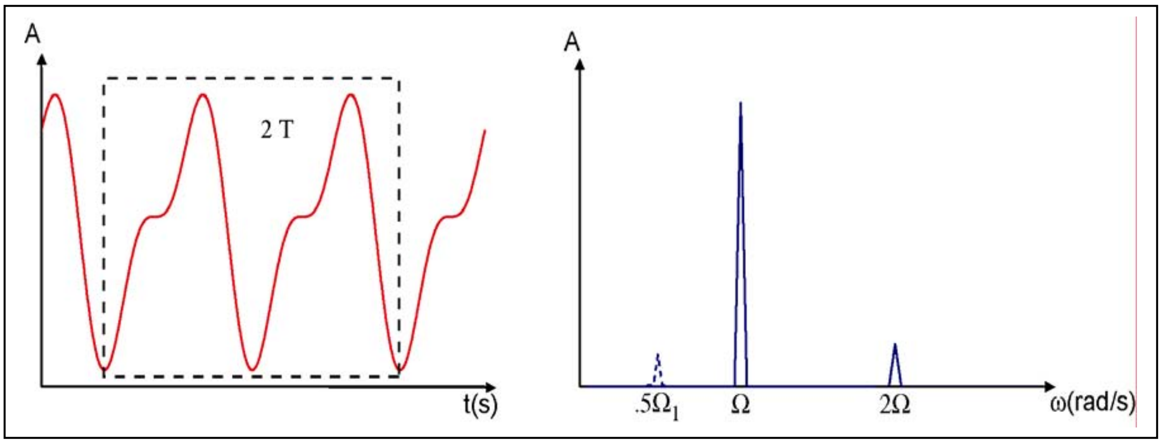

Figure 7. Method to Determine CMV Involves Spectral Analysis (right) of Two Cycles of Vertical Drum Acceleration Time History Data (left)

In a truly linear roller-soil system, a roller with an excitation frequency of 30 Hz would produce a 30 Hz drum acceleration response and $A_{2\Omega}/A_{\Omega}$ would equal zero. Because the roller-soil system is nonlinear (soil is non linear elastic-plastic, partial loss of contact occurs, contact surface varies nonlinearly during each cycle of loading), the drum acceleration response is distorted and not purely sinusoidal. Fourier analysis can reproduce a distorted waveform by summing multiples of the excitation frequency. Therefore, the ratio $A_{2\Omega}/A_{\Omega}$ is a measure of the degree of distortion or nonlinearity. *CMV* is determined by performing spectral analysis of the measured vertical drum acceleration over two cycles of vibration (refer to Figure 7).

The relationship between *CMV* and soil density, stiffness, and modulus is empirical and is influenced by roller size, vibration amplitude and frequency, forward velocity, soil type, and stratigraphy underlying the soil being compacted (Sandstrom and Pettersson, 2005; Mooney et al., 2007). Therefore, the use of *CMV* in CCC systems requires careful calibration. Calibration instructions for the system are very detailed, and the calibration procedure continues until no considerable rise in compaction occurs or when a double jump occurs for the first time. After the compaction for purposes of calibration is finished, most vendors recommend a step-by-step procedure to complete the calibration process. The associated relationships developed during calibration must be strictly adhered to during subsequent site measurement.

2.5.3 Omega Value

Developed by Bomag and incorporated into the Terrameter system, the Omega value provides a measure of the energy transmitted to the soil. The concept is illustrated by the schematic of the roller compactor and the forces acting on the drum in Figure 8. Here, F_s is the force transmitted to the soil and Z_d is the drum displacement. F_s is determined by summing the static force (roller weight), drum inertia and eccentric force; frame inertia is ignored. The accelerometer provides the drum acceleration time history. The Omega value is determined by integrating F_s and Z_d time history over two consecutive cycles of vibration:

$$Omega = \left(-m_d \ddot{Z}_d + \left(m_d + m_f\right)g + m_o e_o \Omega^2 \right) \dot{Z}_d \, dt \quad (10)$$

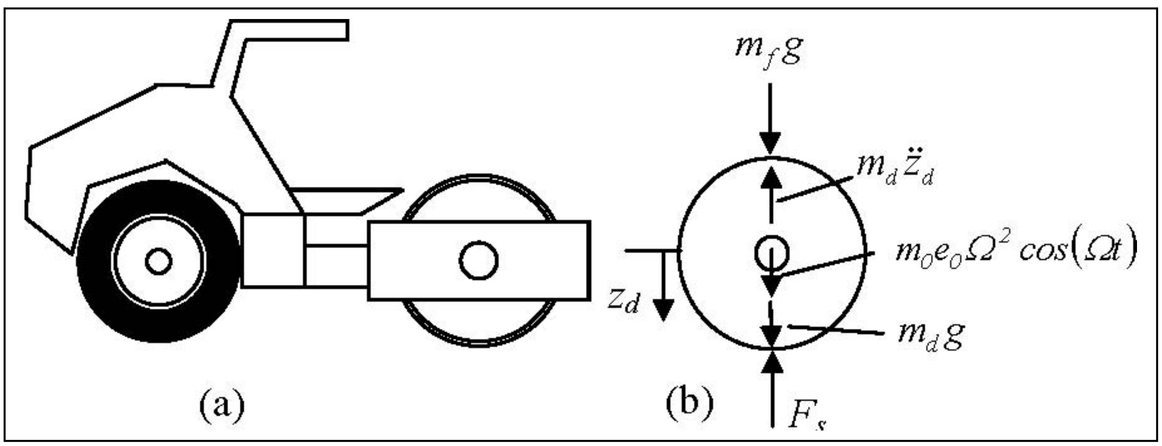

Figure 8. One-Degree-of-Freedom Lumped Parameter Model Representation of Vibratory Compactor

2.5.4 Vibration Modulus Value (E_{vib})

The output value measured by Bomag, E_{vib} (Kröber et al. 2001), is a parameter that combines the effect of vibration and cylinder assembly on elastic half-space theory. The drum/soil assembly is modeled as shown in Figure 8, where m_d and m_f are the drum and frame masses, Z_d and $\ddot{Z}_d$ are the drum displacement and acceleration, $m_o e_o$ is the eccentric mass moment, and Ω is the excitation frequency.

Bomag employs constant frequency compaction with Ω= 32 Hz. In addition, F_s is the drum/soil contact force and g is the acceleration of gravity. Bomag employs two accelerometers to measure vertical drum acceleration (frame inertia is neglected). Phase lag is calculated and enables the determination of the contact force, F_s, per equilibrium of forces shown in Figure 8. The drum displacement is computed from the measured drum acceleration. The combination of F_s and Z_d data yields contact force-drum deflection curves from which soil stiffness can be extracted. Figure 9 illustrates the loading portion of the F_s-Z_d response and the loading dynamic secant stiffness k employed by Bomag's E_{vib} measurement value.

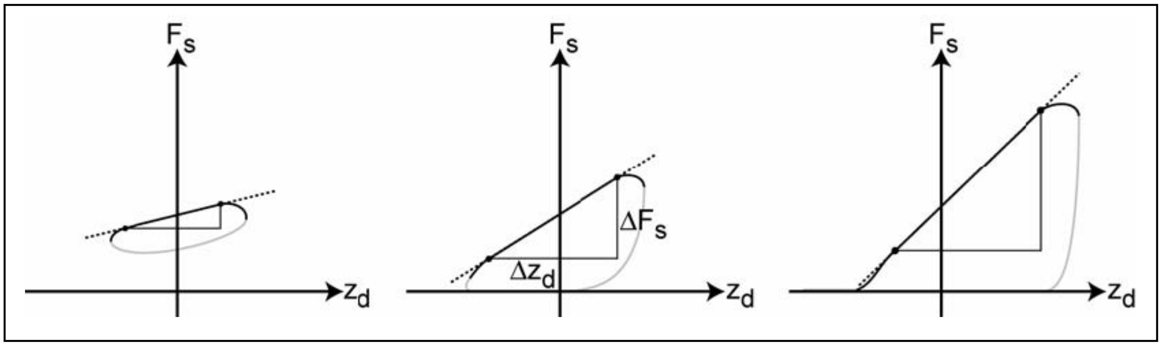

Figure 9. Contact Force – Drum Displacement Behavior, *Fs=FB* (after Kröber et al., 2001)

To relate the measured F_s-Z_d behavior and stiffness k to vibration modulus E_{vib}, Lundberg's theoretical solution for a rigid cylinder resting on a homogeneous, isotropic elastic half-space is used (refer to Figure 10). Lundberg's theory is a static solution and relates F_s, Z_d, drum length L and diameter R, to Poisson's ratio v and Young's modulus E of the half-space, through the following equation:

$$Z_d \frac{2\left(1-\upsilon^2\right)}{\pi E}\left(\frac{F_s}{L}\right)\left(1.8864 + Ln\frac{L}{b}\right) \tag{11}$$

Where b is the contact width that is given by:

$$b = F_s\sqrt{\frac{16R\left(1-\upsilon^2\right)}{\pi EL}} \tag{12}$$

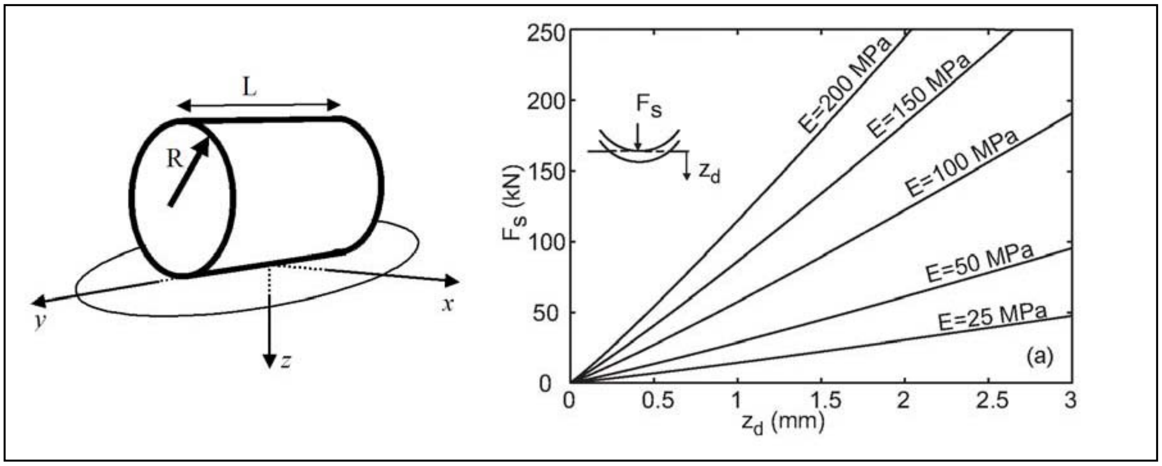

Figure 10. Relationship Between Contact Force and Drum Displacement per Cylinder on Elastic Half-Space Theory

2.5.5 Soil Stiffness (k_s)

Ammann introduced a roller-determined soil stiffness parameter k_s in the 1990s. Ammann considered the lumped parameter model to represent the vertical kinematics of the soil-drum-frame system. The soil is represented with a Kelvin-Voigt spring-viscous dashpot model which determined the drum inertia force and eccentric force time histories via measurement of drum acceleration and eccentric position (frame inertia neglected). The drum displacement amplitude Z_d is determined via spectral decomposition and integration of the measured peak drum accelerations (Anderegg and Kaufmann, 2004).

The resulting F_s-Z_d response is illustrated in Figure 11 for continuous contact and partial uplift behavior. Solving the equation of motion for k_s when the drum velocity is zero yields the following solution, where the parameters have been previously defined (Anderegg and Kaufmann, 2004):

$$k_s = \omega^2 \left[m_d + \frac{m_o e_o \cos(\phi)}{Z_d} \right] \tag{13}$$

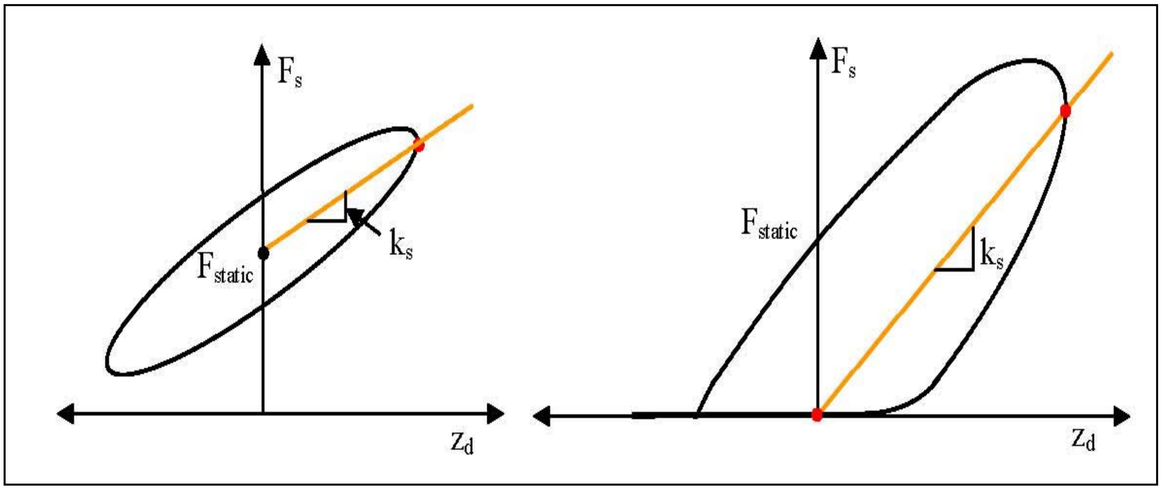

Figure 11. Illustration of k_s Contact (left) and Partial Loss of Contact Behavior

The Ammann constant, k_s, is the ratio of F_s to Z_d and is computed when the drum is at the bottom of its trajectory and Z_d is at its maximum. The k_s constant represents a composite static stiffness (spring constant) for the soil and is valid to the degree to which the Kelvin-Voigt model is a good approximation for soil. The spring-dashpot model has been shown to be effective in representing foundation-soil system behavior and roller-soil system behavior.

2.6 IC Roller Vendors

Multiple vendors now build and sell IC equipment with varying outputs and controls. These include Bomag, Sakai, Case-Ammann, Caterpillar, Dynapac, and Volvo/Ingersoll Rand. These vendors have fully equipped rollers but also have instrumentation kits that can be attached to existing vibratory rollers. Von Quintus et al. (2009) provided a brief description of the operation, measurement system, and outputs for the different IC systems and rollers. This part of the report reviews equipment used in some of the demonstration projects and FHWA pool-fund study.

2.6.1 Bomag

Bomag has two IC systems: Vari-Control for soil rollers and Asphalt Manager for HMA rollers. The two systems are similar in that the exciter mechanism is contained in a housing that can be rotated through an arc of 90 degrees (via a slewing motor) to change the direction (vector) of the drum's force. As the material stiffness measuring system senses that compaction is increasing, the drum's force (which remains constant, because amplitude and frequency remain constant) is automatically vectored from a primarily vertical orientation to a primarily horizontal orientation.

Both Bomag systems, in their automatic mode, allow the operator to pre-set maximum compaction force levels, and in their manual mode, the systems allow the operator to select from six exciter positions (force values) to match material characteristics. The value Bomag uses to report measured material stiffness is the "vibration modulus," or E_{vib}, which is measured in Mega-Newtons per square meter (MN/m^2).[5] Bomag's Asphalt Manager System also monitors mat temperature and allows parameters to be set in order to alert the operator when critical temperatures are approaching. The Bomag Varicontrol System was set up to run with a GPS-based documentation system (refer to Figure 12).

Asphalt Manager was introduced in 2001 and combines variomatic technology with a new method for HMA compaction and testing to provide an assessment during the compaction process (refer to Figure 13). Bomag's system first calculates the stiffness of the HMA and then ties the stiffness to a density, producing a reading of how much the density of the mat has increased in pounds per cubic foot (Bomag, 2003; Kloubert, 2002). Bomag advertises the Asphalt Manager as a total HMA compaction management system. The density measurement is only one component of that, and it is a descendent of the original Hypac Terrameter.

Bomag reports that the dynamic stiffness value calculated by the Asphalt Manager, termed E_{vib}[MN/m^2], can be used as a measure for the level of compaction under uniform subgrade stiffness and under consideration of the HMA temperature. E_{vib} and the Marshall density have been shown to be related to one another.

Figure 12. Bomag Vari-Control IC Roller

5 One Mega-Newton is equivalent to about 224,800 pounds of force.

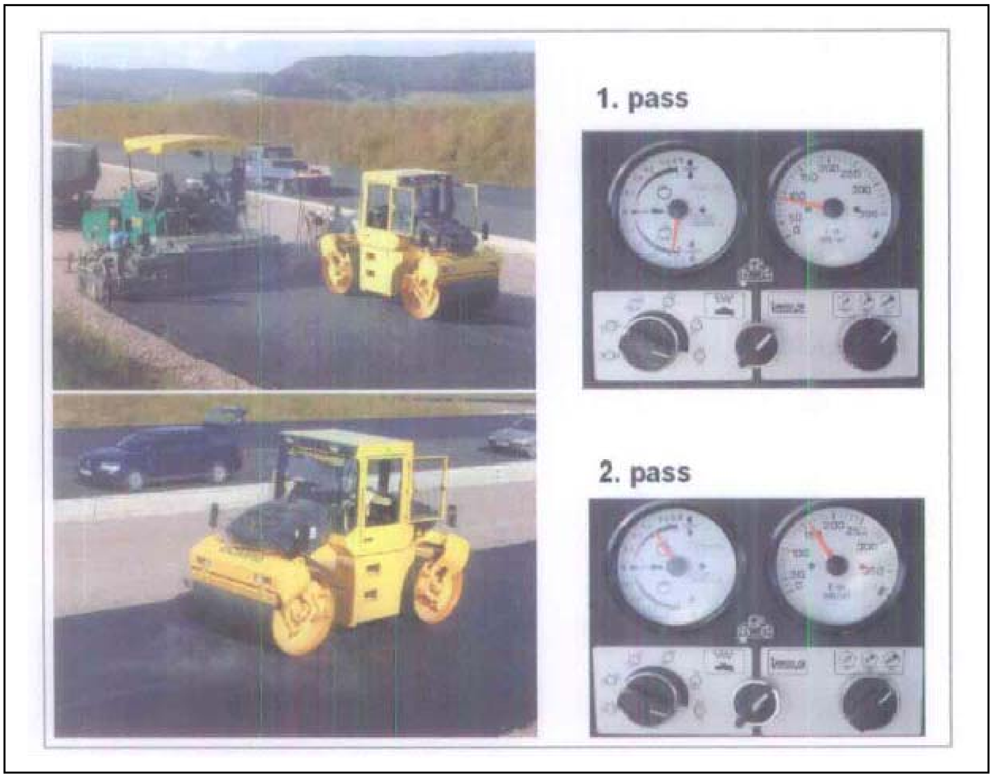

Figure 13. The Asphalt Manager from Bomag

The contact force between the HMA and roller drum, together with the vibration path, is determined by acceleration measurements taken on the vibrating roller drum. When calculating the contact force over the vibration path of the drum, each rotation of the eccentric produces a loading and unloading curve in which the enveloped area defines the compaction work done.

As with the plate bearing test used in soils, the dynamic stiffness of the HMA is calculated using the load curve. The cylindrical shape of the drum and the changing contact area of drum and HMA is thereby taken into account. The physical measurement value of HMA stiffness is the vibration modulus, E_{vib} (Bomag, 2003).

The roller operator reads the E_{vib} value on an analogue display. Since HMA stiffness is temperature-related, the surface temperature is sensed by an infrared measuring unit underneath the cab and also displayed on an analogue gauge. Site experience shows that temperature sensitivity of the E_{vib} value is between 100 and 150°C (212 and 302°F) and is therefore within reasonable limits. The effect of increasing compaction is very distinct and provides an assessment of the compaction progress. Compaction measurements using a nuclear density gauge show a direct correlation between the E_{vib} vibration modulus and density; given a uniform and stable base under the HMA layer and taking the mat temperature into account.

2.6.2 Sakai

Sakai IC vibratory rollers utilize an accelerometer-based technology to measure the stiffness of soils, crushed aggregate materials, and HMA layers (Figure 14). As compaction increases with increased roller passes, the drum accelerations increase and various frequency components are created according to the machine/ground condition interaction. The sensor calculates a relative value termed Compaction Control Value (CCV), which is based on the detected amplitude spectrum at the various frequency components. The higher the CCV, the higher the stiffness (refer to Figure 15).

Figure 14. Sakai IC Rollers for Unbound Materials and HMA Mixtures

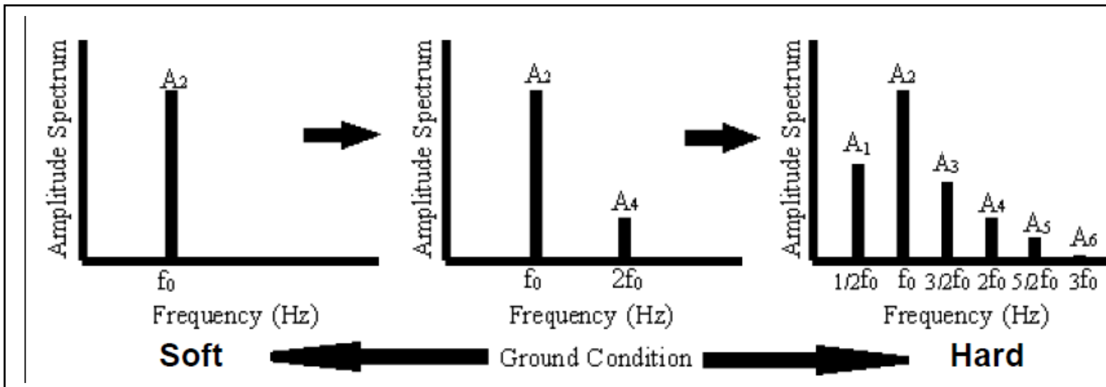

Figure 15. Graphical Representation of the Compaction Control Value Used by Sakai

The CCV sensor gives a dimensionless relative value that typically increases with compaction and is reported to correlate with conventional single point density measurement devices as well as mechanistic testing equipment. The Compaction Information System (CIS) displays records all compaction data at the same time, providing the roller operator and inspection personnel with a real-time visual representation of the following measured data:

- CCV includes accelerometer/controller with the “standard” LED display panel

- CIS includes PC display/software/sensor(s)
- GPS options: Leica, Topcon, Trimble, Starfire, others

2.6.3 Ammann

Case-Ammann defines its IC system, the Ammann Compaction Expert (ACE), as an electronic measuring and control system that automatically adjusts the amplitude and frequency of a vibratory roller to suit material characteristics (refer to Figure 16). Thus, areas with lower load-bearing capacity are compacted with high effective amplitude, and hard areas are compacted with low effective amplitude.

Amplitude is adjusted "as flyweights in the exciter system twist against each other," and frequency is adjusted "to the resonance of the ground." Similar to the vibration-modulus value determined by the Bomag system, the ACE system determines "dynamic ground-bearing capacity" by equating the drum's action to a "plate-loading" test, in which a circular pad is pressed into the soil with a known force, and then the resulting deformation (or subsidence) in the material is measured. Ammann reports this measurement as the "k_B" value, which is measured in MN/m.

When the ACE system is used on an HMA vibratory roller, the first strip is compacted with the ACE system switched on, and a first k_B value is determined (in relation to the subsoil) that can be memorized by the system. An infrared temperature gauge in the ACE asphalt system can prevent operation when the mix is "too hot, too cold, or when the material is in a critical temperature sensitive (tender) zone."

Figure 16. Ammann IC Roller

2.6.4 Dynapac

The Dynapac Compaction Optimizer (DCO) system automatically adjusts the drum's amplitude "from zero up to a maximum, depending on the state of compaction." The DCO system should be operated in the automatic mode with maximum force values selected, but the system does allow manual operation, and in that mode, provides the selection of six amplitudes or force values.

The Dynapac IC soil roller measures and reports a "dynamic stiffness value," identified as the CMV. As described earlier, the CMV is a well accepted and proven indicator of the soil's relative state of compaction. The company's IC HMA roller does not use accelerometers to measure material stiffness, because Dynapac research indicates that this approach is potentially unreliable.[6]

2.6.5 Caterpillar

Caterpillar calls the IC system for its soil machines a "continuously variable amplitude" system, which can automatically adjust the drum's amplitude from zero to a maximum — a maximum that stays comfortably away from the double jump (refer to Figure 17).[7] But along with variable amplitude, the Caterpillar IC system also employs three frequency settings, one of which the system will select automatically depending on the amplitude range in which the drum is operating. Adjusting the drum's force by varying the amplitude provides an advantage because the zero amplitude setting allows the exciter system to remain spinning at all times. This means that the machine does not need to continually expend the tremendous energy required to restart the exciter's weights each time the machine reverses direction.

Restarting the vibratory mechanism requires a significant amount of the engine's horsepower, and it requires that the exciter's hydraulic drive system run at near relief pressure until full momentum is achieved. All of this has the potential of allowing the use of smaller engines that use less fuel. Caterpillar's IC soil machine features a GPS-based documentation system as standard equipment. The machine adjusts drum force by infinitely varying amplitude from zero to a pre-set maximum, and the system automatically selects from three frequency settings to match the amplitude band.

Tables 1 and 2 provide a summary of the features in IC rollers for soils and HMA materials, respectively (www. intelligentcompaction.com, accessed in October 2010).

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[6] Information provided by Ingmar Nordfelt, research manager for compaction and paving techniques at the Dynapac International High Comp Center in Karlskrona, Sweden.
[7] Information provided by Robert Ringwelski, advanced product development manager.

Figure 17. Caterpillar IC Roller

Table 1. Summary of Features in IC Rollers for Soils

Vendor	**Bomag**	**Caterpillar**	**Dynapac**	**Sakai**
Model	VarioControl	NA	DCA-S (GPS)	ExactCompact
Auto-Feedback	Y	Y	Y	N
Measurement System	Y	Y	Y	Y
Output	Evib	CMV	CMV	CCV
Measurement Unit	MN/m^2	None	None	None
GPS Capability	Y	Y	Y	Y
Documentation System	BCM 05 Office and Mobile	AccuGrade	DCA	NA
Development Status	In production	In production	In production	Under development
Availability	Current	Current	Current	Current

Table 2. Summary of Features in IC Rollers for HMA

Vendor	Bomag	Caterpillar	Dynapac	Sakai
Model	Asphalt Manager	AccuGrade Compaction	DCA-A	Exact Compact
Auto-Feeback	Y	N	Y	N
Measurement System	Y	Temperature and Pass Count	Y	Y
Output	Evib	Temperature	CMV	Sakai CCV
Measurement Unit	MN/m^2	deg C	Unitless	Unitless
GPS Capability	Y	Y	Y	Y
Documentation System	BCM 05 Office and Mobile	AccuGrade	DCA	Aithon MT-R software
Development Status	In production	Available as special order*	In production	In production
Availability	Current	Special order	Current	Current

2.7 Demonstration Projects

IC rollers have been used on various demonstration projects and case studies throughout the U.S. The Minnesota DOT, FHWA, and National Center for Asphalt Technology (NCAT) have sponsored demonstrations and workshops on the use of IC rollers. Other agencies where case studies have been completed include Alabama, Florida, Iowa, Maine, Oklahoma, Virginia, Texas, and Wisconsin, to name a few. FHWA also has developed a strategic plan (Horan and Ferragut, 2005) to implement IC technology within the U.S., which includes a systematic procedure to encourage State agencies and industry to expedite the implementation process. Agencies including Iowa, Louisiana, Minnesota, New Jersey, North Carolina, and Virginia are conducting field and laboratory studies to evaluate IC technology and to develop specifications for pilot projects (White and Cackler, 2007; Petersen et al., 2006; Maupin, 2006).

In 2005, the Minnesota DOT demonstration at the Minnesota Road Research test track (MnROAD) used the Bomag system and other nondestructive testing (NDT) devices (Dynamic Cone Penetrometer [DCP], Geogauge, lightweight deflectometer [LWD]) to determine the relationship between the IC roller response output and independently measured soil properties. In general, it was found that the moisture content in the soil greatly influenced the compaction process and the modulus measurement, as expected. The study suggested future demonstration projects on “real-world” construction projects, which are being completed under the FHWA pool-fund study. Other demonstration projects have followed this use of additional point-specific NDT testing. The completed pool-fund projects were located in Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, New York, and Texas, andadditional projects were planned in 2010 for North Dakota, Pennsylvania, Virginia, and Wisconsin.[8]

IC rollers (Bomag, Caterpillar, Case/Ammann, and an instrumented vibratory roller) were used in National Cooperative Highway Research Program (NCHRP) Project 10-65 for controlling and accepting HMA mixtures and unbound pavement layers. The IC response output parameters were compared to modulus and density values measured by traditional density measuring devices and other NDT devices (Von Quintus et al., 2009). The type of materials included crushed aggregate bases, high and low plasticity clays, and HMA base mixtures. Overall, the IC rollers detected dense and less dense areas, and their output was found to correlate with other NDT density and modulus values. However, the IC rollers bridged some localized weak areas or anomalies (soft spots, segregation, etc.) in both HMA and unbound aggregate layers.

Figure 18 compares the modulus values before and after IC rolling, as measured by different NDT devices. As shown, most of the modulus values consistently increased after IC rolling. Figure 19 compares the coefficient of variation of the average modulus values before and after IC rolling. The variability in the modulus values decreased in some, but not all, lots. This observation was unexpected because one of the major benefits of IC technology is to identify soft areas so that more compaction can be applied to those areas.

Densification curves were prepared and used to evaluate changes in the measured responses of the IC roller to increases in density of the HMA layer. Figure 20 compares the density and Bomag's E_{vib} readings, while Figure 21 is an example of the densification curves. The contractor's compaction operation included the use of two rollers to achieve the same density as the IC roller, confirming that the IC technology can be more efficient. Figure 21 also shows the benefit of using E_{vib} to determine when the correct number of passes has been used to reach the required density. This additional information during lift compaction would be a benefit to roller operators to ensure that an adequate density or stiffness of the material has been reached.

Seismic testing has also been used to measure the layer modulus at the same points used to prepare the densification curves. The average seismic modulus measured along an HMA control strip was 269 ksi, as compared to an average value of 239 ksi without the use of the IC roller. The seismic tests suggest an increase in the stiffness of the mixture, in addition to the increase in density. The one major issue that has yet to be resolved is correctly taking into account the effect of decreases in temperature on the increase in E_{vib} during compaction of the HMA lift or changes in moisture content of unbound layers, both critical for making the "right" decision.

[8] The reports, testing plans, and other information for the completed and scheduled projects can be obtained from the FHWA website for Intelligent Compaction: http://www.intelligentcompaction.com/.

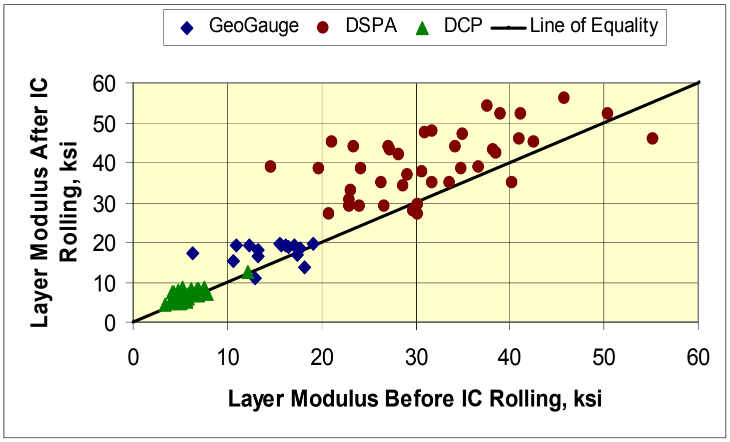


Figure 18. Modulus Values Before and After IC Rolling of an Embankment Soil

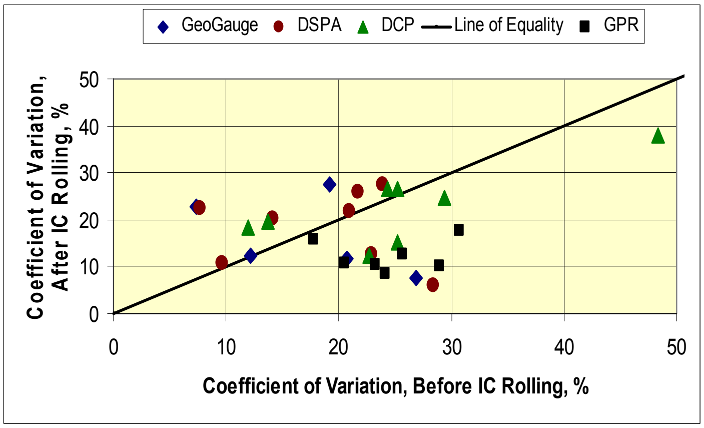


Figure 19. Embankment Uniformity Before and After IC Rolling

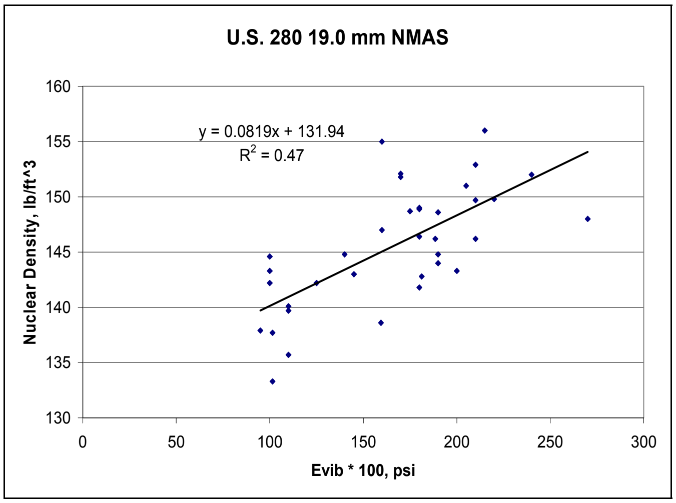


Figure 20. Nuclear Density Readings Compared to IC Roller E_{vib} Values

Figure 21. Densification Growth Curves—IC Roller Values Compared to NDT Results

NCHRP initiated Project 21-09 in 2006 to determine the reliability of IC systems and to develop quality assurance (QA) specifications for the application of IC in the compaction of unbound materials. The field study included an evaluation of three IC systems for soils—Case/Ammann, Bomag, and Caterpillar (Mooney et al., 2007). Findings from the study suggested that smooth drum rollers were more reliable than pad or sheep-foot rollers. A change in displacement amplitude of the roller proved to have a larger effect on soft clays than on granular materials. Conversely, initial results from the FHWA pool-fund study now suggest that the pad-foot rollers for clay soils can be used with success. Soils properties, such as modulus and penetration index, are correlated to roller output for both fine-grained (moderate to high plasticity clay soils) and coarse-grained soils, as well as for crushed stone aggregate materials (similar to the NCHRP 10-65 findings; Von Quintus et al., 2009). Work being undertaken by Iowa State University and FHWA should result in the development of construction specifications for embankments and granular bases.

In summary, nearly all previous studies have concluded that the use of IC rollers has many advantages and should be pursued as a contractor's QC tool to monitor the compaction of pavement materials and to identify soft spots or weak areas along a project. Most studies have focused on the effect of increasing material compaction or density on the IC measured response and have reported good correlations between the IC output and density-modulus for a specific material and project. Fewer studies have focused on the effects of temperature, moisture, material condition, and varying subsurface conditions on the responses and output from the IC measurement systems, in terms of reducing the risk of making an incorrect decision during construction. Temperature of HMA, moisture content of unbound layers, and support conditions of the underlying layers are important factors related to the IC roller's output.

2.8 Implementation and Use of IC Technology

It is hypothesized that IC produces a more uniform product than standard compaction methods since IC rollers continuously alter the amount of energy being transferred to the material based upon a target value for the roller-specific compaction-related parameter. Research has shown that thicker lifts of material can be compacted more efficiently using IC technology. These factors contribute to IC's ability to streamline the compaction process, which has the potential to translate into significant cost savings for the contractor.

Real-time geospatial location combined with verification of lift compaction makes it possible to assure complete coverage of the compaction area throughout the construction process. The IC roller's control system helps to achieve a more uniform subgrade and upper pavement layers, which contribute to increased pavement service life. This also helps to eliminate the chance of costly damage to the roller and aggregate fracture. The roller output of in-place layer modulus provides a vital link to mechanistic-empirical (M-E) based pavement design procedures. IC roller data can be easily mapped and stored for later use in forensic analysis and used during long-term pavement management.

Finally, an important benefit of IC is that it should reduce or eliminate the need for point-specific sand cone and nuclear density testing. DCP, LWD, non-nuclear density gauges, and other nondestructive tests are better suited for QA in conjunction with IC. Furthermore, these tests can be conducted in a fraction of the time required for sand cones. NDT, in conjunction with IC, has the potential to improve the efficiency of QA for construction projects significantly.

Even more significantly, these NDT devices increase jobsite safety. Testing personnel will no longer be required to subject themselves to the dangers of conducting sand cones and/or nuclear density tests. Tests can be conducted quickly with minimal danger to personnel, and construction delays will be lessened, as mechanistic test results are available immediately and are less affected by the vibrations of passing heavy equipment traffic.

2.9 Summary

Numerous agencies have sponsored demonstration and research projects. Most of these studies concluded that IC should be pursued and are in support of furthering this technology. FHWA, NCHRP, and Minnesota DOT have driven much of the initial research work. FHWA's pool-fund study currently includes 12 participating agencies, including Wisconsin DOT. These and other agencies have active and completed research efforts that deal with IC of soils and other materials. IC technology also plays a prominent role in M-E based pavement design implementation efforts, because of the real-time modulus feedback from the instrumentation.

The literature review and results from the earlier demonstration projects provided data and information for the following questions that were a part of the scope of work and for planning the field demonstration projects in Wisconsin.

- *Does IC lead to better and more uniform compaction than conventional compaction methods?*

  Most studies have shown an increase in uniformity of the layer being compacted, while a few have shown a decrease in uniformity. It is unclear whether a level 3 roller was used in all of these studies. In some projects, the feedback process was done manually by the operator rather than electronically by the processor. As such, variability of compacted layers with and without the use of IC rollers should be checked during the demonstration projects.

- *Is the effectiveness of this technology influenced by material parameters, such as subgrade type, moisture content in unbound layers, granular layers versus embankments, and HMA mixtures (fine versus coarse-graded materials)?*

  Most studies have noted that IC is an effective technology for judging when a layer has been compacted adequately. A few studies, however, have noted concern from the influence of the underlying layers and subgrade in making that judgment. Insufficient data were found to determine the impact of variable volumetric and support conditions on the measured response of level 2 and level 3 rollers. The demonstration projects should be selected and planned so that areas can be designated with varying fluid contents, component properties, and/or temperature to confirm that IC rollers can detect physical or volumetric changes in the material.

- *Are draft specifications and output criteria ("trigger values") developed by other agencies applicable for use in Wisconsin?*

  Although specifications have been developed and used in Europe, no U.S. agency has included IC in their specifications or defined criteria for use in day-to-day construction practice for HMA or unbound materials. The Minnesota DOT has developed a pilot specification and is developing the criteria, but to-date no specification is used in day-to-day practice for acceptance. Contractors are using IC rollers in their day-to-day practice to identify soft areas and other anomalies for their warranty type projects.

- *How mature is the technology for compacting unbound materials and HMA mixtures?*

  IC entails the use of sensing equipment that estimates material strength, density, stiffness, or modulus based on compaction equipment behavior. Its use on subgrade is at a more mature stage than its use on HMA layers. There are simply more unanswered questions for compacting HMA layers than for unbound layers.

The impact of mix cooling, tender mixtures, and rolling in the temperature-sensitive zone with the intermediate or finish rollers are challenges that must be overcome prior to full-scale implementation for HMA mixtures. As such, the field demonstration projects should be selected to include HMA mixtures with a different temperature state during compaction and/or tender mixtures.

- *Are there any technical issues and concerns that need to be overcome in using the technology to its fullest extent?*

  Most IC studies have assumed that increasing layer stiffness is proportional to an increase in density and material quality, but that is not necessarily the case. Other factors can cause an increase in stiffness while resulting in a decrease in pavement quality or performance. This is validated in the data analyses discussed in chapter 5. For example, lower temperatures and increasing mineral filler during production of HMA mixtures will result in an increase in modulus without increasing density, while lower water content and increasing plastic fines can cause an increase in stiffness without necessarily increasing density. To overcome this challenge, the calibration procedures included in NCHRP Report #626 will be employed in the field demonstration projects (Von Quintus et al., 2009).

  More importantly, for this study, stiffness and density are considered different properties that can have opposite effects on pavement quality or performance. However, as density increases during compaction, everything else being equal, the stiffness generally increases. To evaluate material quality, other field test devices and laboratory tests will be used to measure the in-place volumetric and stiffness properties of the material included in the field demonstration projects. There have been relatively few field and theoretical studies to determine the importance of the measured response parameters and confirm that the measured response relates to changes in density and stiffness of the material being compacted.

  Some of the technical concerns (the influence of moisture in unbound materials and temperature in HMA mixtures) in using the technology related to this issue are being addressed through calibration and data adjustment based on regression analyses to account for varying fluids content, gradation, and/or temperature.

- *Does the increased purchase cost and maintenance of the IC rollers have an increased benefit that offsets those costs in the long term?*

  IC is promoted as useful in creating uniformly stiff subgrades; identifying weak or soft spots in subgrade; and, depending on calibration and data analysis, providing real-time modulus, stiffness, or density data. It also promises QC and acceptance applications that improve on current methods of in-place, point testing because it provides qualitative data for the entire coverage area of compaction, not just at incremental points that are used to estimate specific properties for the entire lot or site.

Cost-benefit analyses, however, have not been completed to address this question, and it is expected that the Wisconsin field demonstration projects will be unable to answer this question directly. Data will be collected during the field demonstration projects to address the question indirectly.

- *Do the results from the initial demonstration projects suggest that agencies and contractors should continue to pursue this technology?*

  All of the agency-sponsored studies concluded that IC should be pursued and are in support of furthering this technology. On the other hand, some contractors that have used the technology in day-to-day practice do not see a benefit in the use of IC to reduce their risks of being penalized by the owner agency, especially related to HMA layers. Most contractors that have purchased IC rollers use the devices to identify soft or weak spots and still rely on point specific QC tests along the roadway for either new construction or rehabilitation.

In summary, the true test of the IC system is whether it saves time (fewer passes), improves uniformity of the layer, and produces accurate, consistent readings that can be used in a decision-making process by the contractor and owner. The Wisconsin DOT demonstration projects were planned and developed to provide an expanded database to confirm the response measurements of the IC rollers to stiffness and density increases and identify limitations of the equipment.

CHAPTER 3 FIELD DEMONSTRATION PROJECTS

Chapter 3 describes the demonstration projects, IC rollers used on each project, and field and laboratory tests used for measuring material properties. This chapter is grouped into three parts: an overview of all demonstration projects, a summary of the properties for the unbound and HMA materials included in those projects, and a description for the nondestructive tests used to measure the in-place properties of materials compacted with the IC rollers. The roller response and in-place material properties (including a comparison of the measured properties) are included in Chapters 4 and 5. These two chapters also include a more detailed discussion on the use of the IC rollers for compacting the materials in terms of changing density and stiffness values with number of IC roller passes.

3.1 Overview of Projects and Materials

Table 3 lists the demonstration projects, IC rollers used on each project, nondestructive field test methods, and laboratory test procedures.[9] Initially, five projects were planned: two with unbound materials covering a range of aggregate materials and embankment soils, two with different HMA mixtures, and one that included both unbound and HMA materials. Two other projects were considered and visited but were not selected because of scheduling, site assess, and material availability issues. The material properties for all materials and layers included in the demonstration projects are provided in the next subsection of this chapter.

The first project was planned near the end of the 2008 construction year and included both unbound layers (crushed stone, fine and coarse-grained soils) and HMA to evaluate the use of IC rollers for compacting the entire flexible pavement─embankment to wearing surface. Unfortunately, this project had to be abandoned because the amount of HMA mixture to be paved in 2008 was less than a week's worth. In addition, most of the embankment soils already had been placed prior to being able to mobilize the soil IC, sheep-foot roller for the project. The next three projects were completed successfully, as shown in Table 3. The fifth project was dropped because the Wisconsin DOT decided to delay this project by one year; this project became a demonstration project included in the FHWA pool-fund project.

Although two of the original projects were dropped, the remaining three projects included a suitably wide range of materials and soils. The HMA demonstration project was confined to one HMA mixture, but a change in mixture did occur during production. The change in mixture properties was found to be more important than using a second mixture without any major change in properties occurring during mixture production and placement.

[9] Work plans were prepared for each demonstration project noting the type and frequency of other nondestructive and laboratory tests to characterize the materials included in the study. These work plans were used to coordinate with the contractor and Wisconsin DOT region personnel.

Table 3. Summary of Demonstration Projects

Project ID	Materials	IC Rollers[10]	Field Tests	Laboratory Tests
Burlington; Realignment of SR 48	Project was abandoned because IC roller could not be mobilized at the end of the 2008 construction season and there was too little HMA paving.			
Reconstruction & Widening of STH 80; north of Highland	• High Plasticity Clay • Granular Embankment • Crushed Stone Base • RAP Base • HMA[11]	• Sakai	• Nuclear gauge (density & water content) • Dynamic Cone Penetrometer • Geogauge	• Moisture-Density Relationship • Atterberg Limits • Gradation • Resilient Modulus
Reconstruction Realignment of STH 18; west of Jefferson	• Low Plasticity Clay • Sandy Embankment • Crushed Stone Base	• Sakai • Bomag	• Nuclear gauge (density & water content) • Dynamic Cone Penetrometer • Geogauge	• Moisture-Density Relationship • Atterberg Limits • Gradation • Resilient Modulus
Rehabilitation & Overlay of USH 45; near Eden	HMA Overlay: • 12.5 mm, PG58-28 wearing surface[12] • 19 mm, PG58-28 HMA binder layer	• Sakai • Bomag • Caterpillar	• Non-Nuclear Density Gauge • Portable Seismic Pavement Analyzer • Infrared Camera	• Bulk specific gravity-cores • Maximum specific gravity of mixture • Dynamic modulus
Rehabilitation of I-39	Project was dropped because it was delayed to 2010 construction season. The rehabilitation project is a rubblization of PCC slabs with an HMA overlay. This Wisconsin project was selected for the FHWA pool-fund demonstration study.			

3.1.1 Reconstruction and Widening of STH 80

Five materials and two IC rollers originally were planned for use on the project. The focus of this project was mainly on pavement unbound materials that consist of subgrade soils (fine-grained low to high plasticity soils), crushed aggregate base, and reclaimed or recycled asphalt pavement (RAP) base. As listed in Table 3, only one IC roller was delivered to the project: a Sakai IC Level 2, smooth-steel drum roller. Two other IC roller vendors had been contacted but could not commit their rollers because of other

[10] All soil IC rollers used on the field demonstration projects were smooth-steel, single drums.
[11] The HMA mixture that was planned to be included within this project was omitted from this project because of the delays that occurred during heavy rains.
[12] The wearing surface for this project was excluded because rain delays changed the contractor's paving schedule during the week of the demonstration project.

scheduling issues. In addition, both a smooth-steel drum and sheep-foot drum were to be delivered to the project site for compacting the different materials. Unfortunately, a separate contractor had requested a demonstration of the IC roller with the sheep-foot drum on a separate project, and that contractor eventually purchased that IC roller.

The granular embankment was excluded from this project because of heavy rains that delayed paving on the project (refer to Figure 22). The revised paving schedule conflicted with other demonstration projects, so the HMA was excluded from this project.

Figure 22. Highland STH 80 Project; Granular Embankment Test Section, Saturated with Standing Water from Heavy Rains and Excluded from Demonstration Project

The following provides a summary of the different materials that were compacted and tested by the Level 2 Sakai IC roller:

- Crushed Aggregate Base: Two sections were designated for compacting and testing the crushed aggregate base material (refer to Figure 23). The contractor had already compacted the base layer but scarified the layer so that the material could be rolled and tested with the Sakai IC roller (refer to Figure 24). Density and stiffness growth curves were measured in a few areas.
- High Plasticity Clay Embankment (3 lifts): High plasticity clay removed from cut areas by scrapers was deposited within the test area, graded with a bulldozer, and compacted in two lifts above the original subgrade layer that had already been placed and compacted. The Sakai IC roller was used to further compact and map the stiffness of the first lift that had already been placed and compacted by the contractor using standard construction practice and equipment. The other two lifts were about 18 to 24 inches thick and compacted with the IC roller. Four

individual lanes were designated for compacting and testing the high plasticity clay embankment (refer to Figures 25 and 26). The in-place properties of each lift were measured with the NDT methods listed in Table 1. Density and stiffness growth curves were measured in a few areas for the second and third lifts.

- Granular Embankment: The granular embankment layer had been placed by the contractor and was scheduled to be compacted after the high plasticity clay embankment. However, heavy rains prevented this layer from being included in the demonstration project; the material was simply too wet to be compacted and tested (refer to Figure 22).
- RAP Base: The RAP base layer had been placed and compacted by the contractor (refer to Figure 27). The RAP base was not scarified and re-compacted similar to the crushed stone base, because paving was scheduled during the week of the demonstration project. The Sakai IC roller was used to test the stiffness of the layer along two lanes using two amplitudes, low and high, both before and after the heavy rain. These and other results will be discussed in the next chapter.

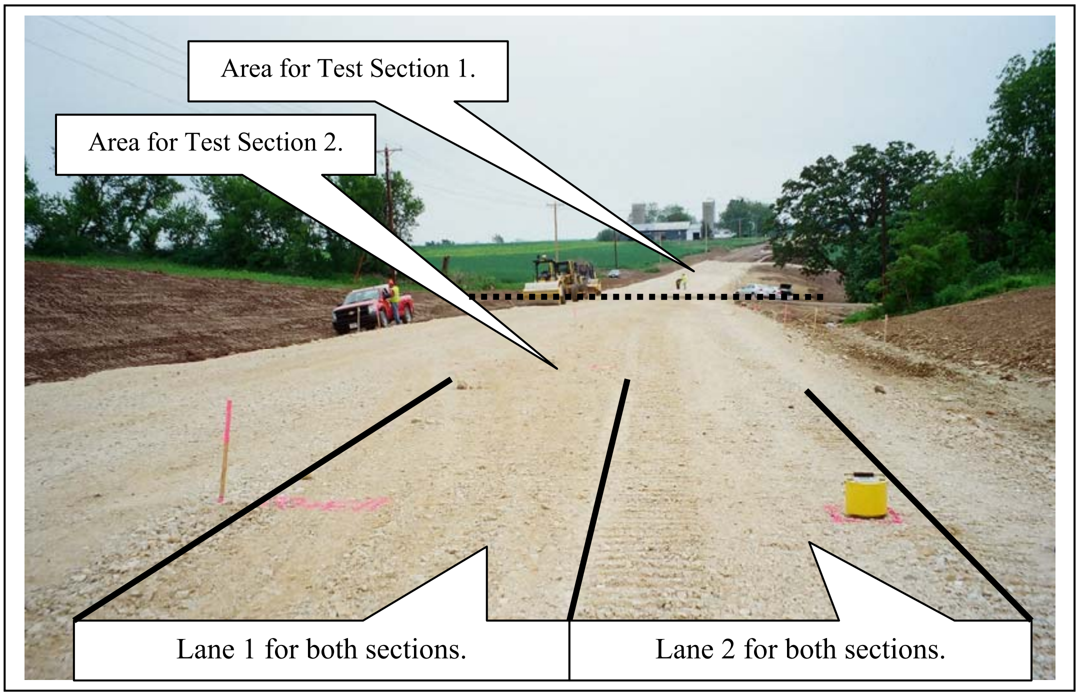


Figure 23. Highland STH 80 Project; Crushed Stone Base Test Sections

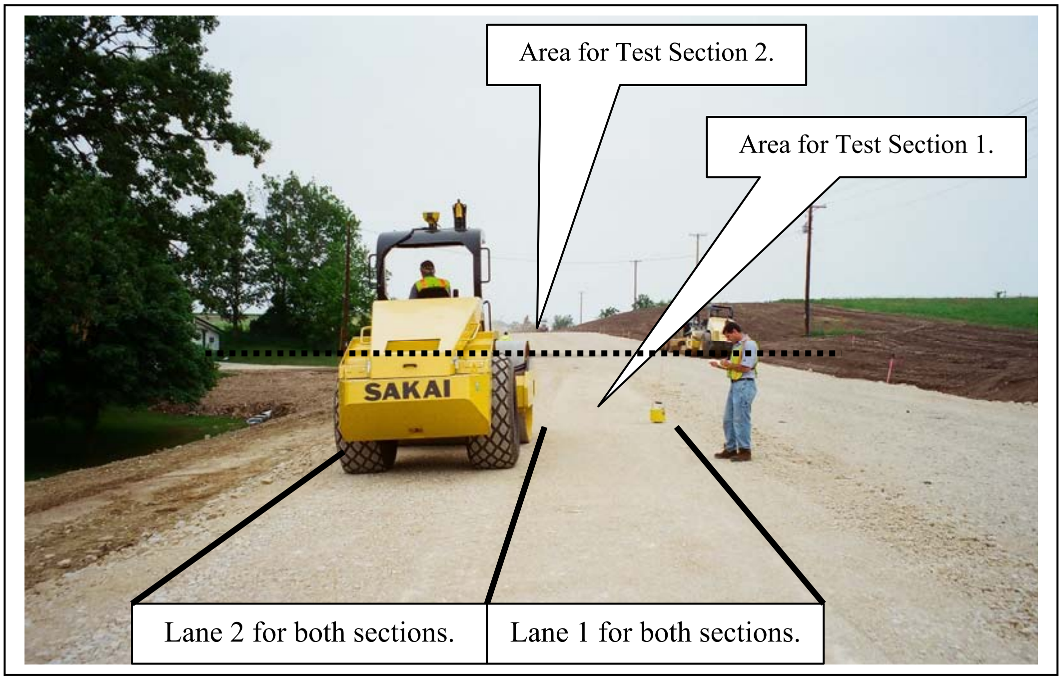


Figure 24. Highland STH 80 Project; Sakai, Level 2 IC Roller Compacting the Crushed Stone Base Material

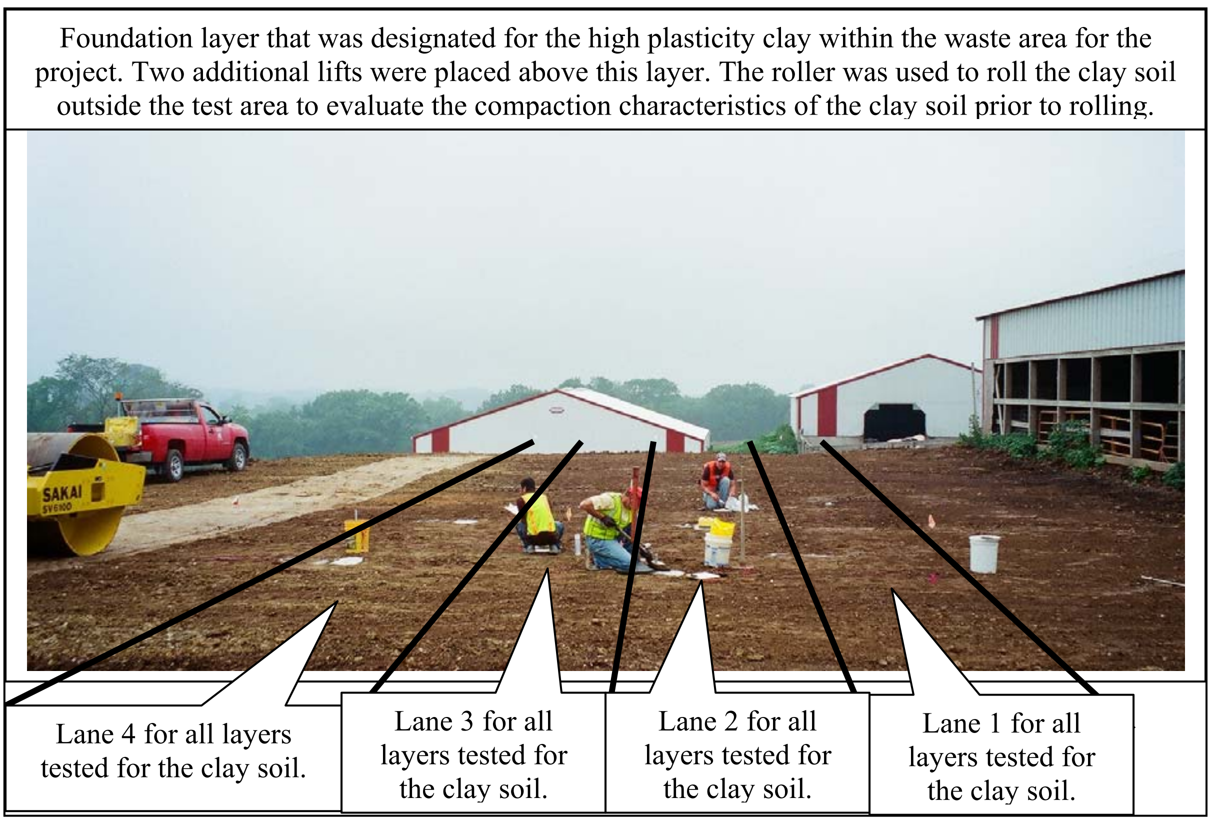
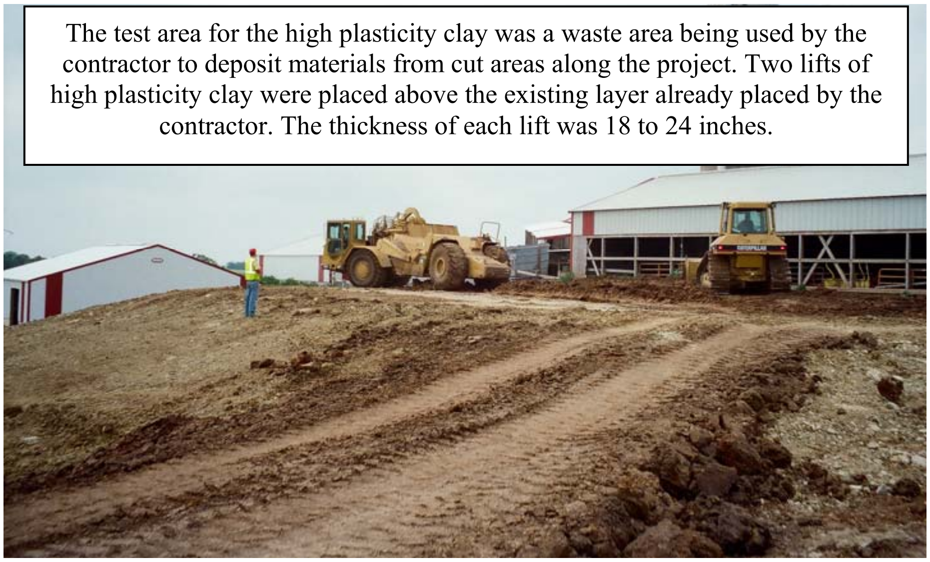


Figure 25. Highland STH 80 Project; Four Designated Lanes for Testing the In Place Properties of the High Plasticity Clay

First lift being placed after the foundation layer was compacted and tested.

The test area for the high plasticity clay was a waste area being used by the contractor to deposit materials from cut areas along the project. Two lifts of high plasticity clay were placed above the existing layer already placed by the contractor. The thickness of each lift was 18 to 24 inches.



Second lift placed and compacted with the Sakai single drum vibratory roller.

Figure 26. Highland STH 80 Project; High Plasticity Clay Embankment Test Area

Figure 27. Highland STH 80 Project; RAP Base Test Area

High plasticity clay, crushed aggregate base, and RAP samples were collected during construction. The crushed aggregate base was sampled from the quarry stockpile from which the material was obtained to construct the aggregate base course layer. The RAP sample was removed from the existing pavement layer. Three samples of the high plasticity clay were collected from each lift placed within the test site, including the clay foundation that had already been placed by the contractor. After compaction, the sand cone method was used to determine the relative compaction of each lift and material (moisture content and unit weight).

3.1.2 Reconstruction & Realignment of STH 18

Three materials and two IC rollers were used to compact the unbound materials and soils on this reconstruction/realignment project, as listed in Table 3. Both were smooth, steel single drum vibratory rollers. The Bomag satisfied a Level 3 IC roller, while the Sakai satisfied a Level 2 IC roller. Another vendor had been contacted but could not commit their IC roller because of scheduling conflicts.

Heavy rains occurred at the beginning of the week for this demonstration project. In fact, neither IC roller could make it to the designated test section for the low plasticity clay embankment (refer to Figure 28). The rolling and testing of the materials had to be delayed until the soil had dried sufficiently. Although the demonstration project had to be delayed, all materials were included in the project, as originally planned.

Figure 28. Jefferson STH 18 Project; Embankment Test Area After Heavy Rains

The following provides a summary of the different materials that were compacted and tested using the Level 2 Sakai and Level 3 Bomag IC rollers:

- Embankment Soil: An area was designated for compacting the low plasticity clay and silty sand embankment materials. This area was located in a bridge approach area where significant fill had already been placed and compacted using standard construction methods and compaction equipment. Additional lifts of embankment soils were placed in the areas with end dump trucks, spread and leveled with a bulldozer, and compacted (refer to Figure 29). Four lanes were located in the test area, two per IC roller (refer to Figures 30 and 31). Density and stiffness growth curves were measured on both embankment materials.
    - The first lift was the low plasticity clay. The thickness of this lift was approximately 18 to 24 inches that dried the surface.
    - The second lift was the silty sand; placed 12 to 18 inches in thickness. Water had to be added to the silty sand during the compaction process because high winds and temperatures dried the surface.
- Crushed Aggregate: The crushed stone consisted of two lifts placed along an access two-lane roadway (refer to Figure 32). Each lift was approximately 6 inches in thickness. The Bomag IC roller was used to compact each lift, across the entire roadway width (refer to Figure 33).

The low plasticity clay, silty sand, and crushed aggregate base were collected during construction. The aggregate base was sampled from the roadway during material placement. Three samples of the low plasticity clay and silty sand were collected within the test site after the materials had been placed by the contractor. After compaction, the sand cone method was used to determine the relative compaction of each lift and material (moisture content and unit weight).

Figure 29. Jefferson STH 18 Project; Placement and Spreading of the Embankment Soils

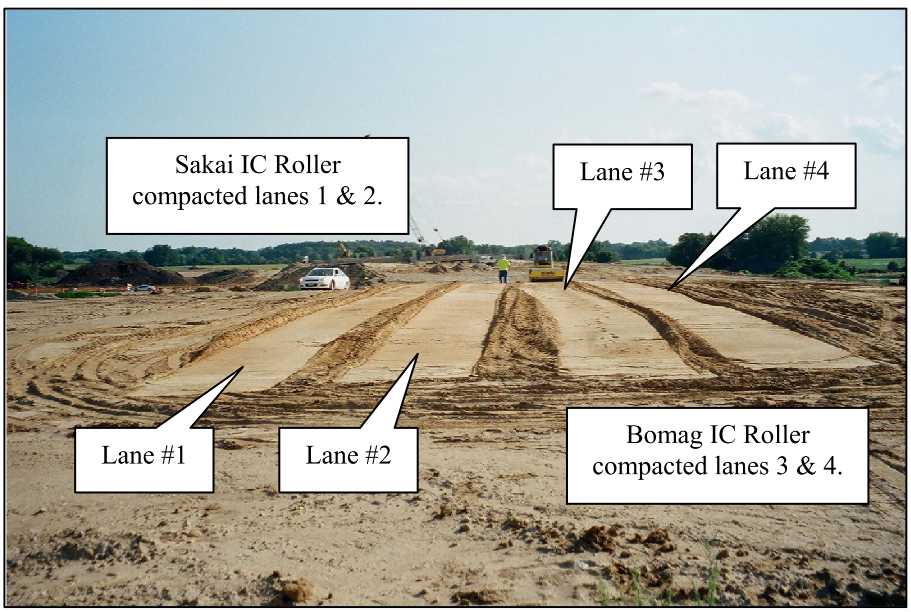


Figure 30. Jefferson STH 18 Project; Four Designated Lanes for Testing the In-Place Properties of the Low Plasticity Clay and Silty Sand Embankment

Figure 31. Jefferson STH 18 Project; Bomag and Sakai IC Rollers Used to Compact the Low Plasticity Clay and Silty Sand Embankment

Figure 32. Jefferson STH 18 Project; Placement and Spreading of the Second Lift of Crushed Aggregate Base (Both Lifts Were Included in Project)

Figure 33. Jefferson STH 18 Project; Crushed Aggregate Base, Both Lanes Included in Project

3.1.3 Rehabilitation and Overlay of USH 45

The rehabilitation of USH 45 near Eden was the third project completed (refer to Figure 34). Initially, two HMA mixtures and three IC rollers were planned for compacting and testing the HMA mixtures, as listed in Table 3. However, one of the mixtures was excluded from the demonstration project because of scheduling changes during construction created by wet weather during the beginning of the demonstration project. In addition, the Caterpillar roller did not have an accelerometer attached to the drum, so it only satisfied a Level 1 IC roller and was used to evaluate any improvement in the rolling pattern by the operator. The Sakai satisfied a Level 2 IC roller, while the Bomag satisfied a Level 3 IC roller (refer to Figure 35). Each IC roller was used as the primary or breakdown roller for about a half-day. These rollers were rotated down the roadway and were followed by an Ingersoll-Rand roller operated in the vibratory and static modes.

Bulk samples of the HMA mixture were taken at the plant during production for dynamic modulus testing. Cores also were taken is selected areas along the project. Bulk specific gravities were measured on these cores for calculating air voids and to develop correlations between the non-nuclear and nuclear density gauges and other field tests.

Figure 34. Eden USH 45 Project; HMA Paving

Figure 35. Eden USH 45 Project; IC and Other Rollers Used on the Project

3.2 Material Properties

A laboratory testing program was conducted to characterize the soil, aggregate base, RAP, and HMA materials included in the field demonstration projects (refer to Table 3). A summary of the tests is included in Table 4. All laboratory tests were conducted in accordance with the standard test procedures used by the Wisconsin DOT. A more detailed description of the laboratory test program and results from those tests is given in the following subsections by material type.

Table 4. Standard Laboratory Test Procedures Used to Characterize the Materials

Material Property	Standard Test Designation
Particle Size Analysis	AASHTO T 88/311: Particle Size Analysis of Soils/Grain-Size Analysis of Granular Soil Materials
Atterberg Limits	AASHTO T 89/90: Determining the Liquid Limit of Soils/Determining the Plastic Limit and Plasticity Index of Soils
Compaction Tests	AASHTO T 99/180: Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in) Drop/4.54-kg (10-lb) Rammer and a 457-mm (18in) Drop
Soil Classification	AASHTO M 145-91: Standard Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes
	ASTM D2487 - 93 Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)
Resilient Modulus	AASHTO T 307: Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials.
Dynamic Modulus	AASHTO PP-62

AASHTO = American Association of State Highway & Transportation Officials.

3.2.1 Unbound Materials and Soils

Subgrade soil, aggregate base, and RAP samples were tested to determine their physical properties, compaction characteristics, and stiffness properties. The laboratory testing to characterize the unbound materials and soils was conducted at the Geotechnical and Pavement Research Laboratory at the University of Wisconsin-Milwaukee.

3.2.3 Physical Properties and Compaction Characteristics

The physical properties measured in the laboratory to classify the materials consisted of grain size distribution (sieve and hydrometer analyses) and Atterberg limits (liquid limit, *LL,* and plastic limit, *PL*). Standard Proctor tests were used to determine the optimum moisture content ($w_{opt.}$) and maximum dry unit weight (γ_{dmax}) of the materials. The test results are included in the appendices—Appendix A includes the results from the moisture-density relationship tests, and Appendix B includes the gradation or grain size distribution test results. Tables 5 and 6 summarize the material properties measured from these tests.

Table 5. Compaction Characteristics of the Unbound Materials

Project ID & Material Type		**Relative Compaction**		**Compaction Properties**		
		Field Water Content, %	**Dry Unit Weight, pcf**	**Test Method**	**Optimum Water Content, %**	**Maximum Dry Unit Weight, pcf**
Subgrade, Embankment Soils						
STH 80; High Plasticity Clay	Existing; Lift #1	18.0	98.8	AASHTO T99, Method A	16.8	108.0
	Lift #2	22.7	102.3		14.5	111.0
	Lift #3	20.5	119.9		22.0	98.8
STH 18; Low Plasticity Soil	Lift #1	10.1	129.7	AASHTO T99, Method A	7.6	135.5
	Lift #2	3.1	123.2		10.9	111.3
Base Materials						
STH 80	RAP	3.3	123.7	AASHTO T180, Method A	6.8	125.5
STH 80	Crushed Stone	3.2	124.6	AASHTO T180, Method D	7.7	145.0
STH 18	Aggregate Base	5.6	139.1	AASHTO T180, Method D	6.1	143.5

Table 6. Physical Properties of the Unbound Embankment Soils

Project ID & Material Type		**Soil Classification**			**Plasticity Index**	**Plastic Limit**	**Gradation, % Passing**		
		USCS	**AASHTO**	**Group Index**			**#4**	**#40**	**#200**
STH 80, High Plasticity Soil	Existing, Lift #1	CL; Lean Clay with Sand	A-6; Clayey Soil	14	16.3	20.7	96.3	90.6	84.5
	Lift #2	CL; Lean Clay	A-6; Clayey Soil	11	11.9	24.1	94.5	90.2	85.2
	Lift #3	CH; Fat Clay	A-7-6; Clayey Soil	32	33.2	23.3	99.4	97.6	87.5
STH 18 Low Plasticity Soil	Lift #1	ML; Sandy Silt	A-4; Silty Soil	0	NP	0	---	---	37.3
	Lift #2	SP; Poorly Graded Sand	A-3 Fine Sand	0	NP	0	---	---	3.6

3.2.4 *Repeated Load Resilient Modulus*

A repeated load triaxial test was conducted to determine the resilient modulus of the subgrade soils in accordance with AASHTO T 307*: Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*. Each fine-grained soil was tested under three different conditions of unit weight and moisture content: (1) maximum dry unit weight and optimum moisture content, (2) a percent of the maximum dry unit weight and the corresponding moisture content on the dry side of optimum, and (3) a percent of the maximum dry unit weight and the corresponding moisture content on the wet side of optimum. The aggregate base and RAP materials were tested only at the in-place water content and dry density measured during construction. Results from the repeated load resilient modulus tests are included in Appendix C.

Several unsuccessful attempts were made to conduct the test on specimens prepared at a dry unit weight and moisture content on the dry and wet side of the optimum value. The 6-inch-diameter aggregate base specimens exhibited severe deformation and bulged during testing, as shown in Figure 36. Therefore, repeated load triaxial testing was conducted on smaller, 4-inch-diameter specimens for both the aggregate base aggregate and RAP materials.

Specimen Preparation

Test specimens were prepared in accordance with the AASHTO T 307 procedure, which requires five-lift static compaction. Special molds were used to prepare soil specimens by static compaction of five equal layers. This compaction method provided uniform compacted lifts while using the same weight of soil for each lift. Figure 37 shows the molds used to prepare the test specimens and compaction equipment.

After the soil sample was compacted to a specified unit weight and moisture content, it was placed in a membrane and mounted on the base of the triaxial cell. Porous stones were placed at the top and bottom of the specimen. Figure 38 shows the different steps within the test specimen preparation for the repeated load triaxial test.

Specimen Testing

The test was conducted using the Instron FastTrack 8802 closed loop servo-hydraulic dynamic materials test system at the University of Wisconsin-Milwaukee. This is a fully digital controlled system with adaptive control that allows continuous update of proportional–integral–derivative (PID) terms at 1 kHz, which automatically compensates for the specimen stiffness during repeated load testing. Figure 39 shows the dynamic materials test system used in this study.

The confining pressures and repeated loads (deviator stresses) used in the test program were the test sequences specified by AASHTO T 307 based on material type. The test specimens were first conditioned by applying 1,000 repetitions of the specified deviator stress (σ_d) and confining pressure. Conditioning eliminates the effects of specimen disturbance from compaction and specimen preparation procedures and minimizes the imperfect contact points between end platens and test specimen. The test specimen was then subjected to the stress sequences according to AASHTO T 307.

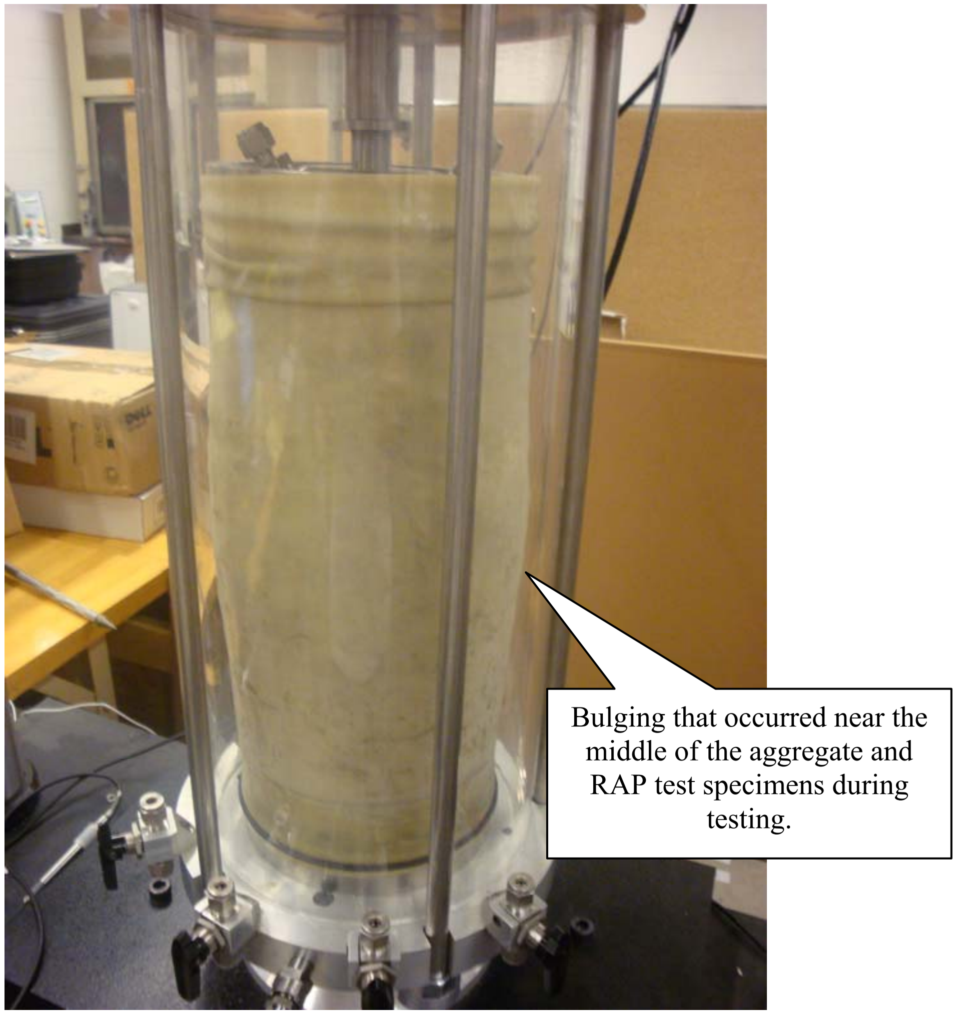


Figure 36. Aggregate Base Test Specimen Bulging During Repeated Load Testing

(a) Molds of different sizes

(b) Filling mold with one soil layer

(c) Applying static force to compact soil specimen

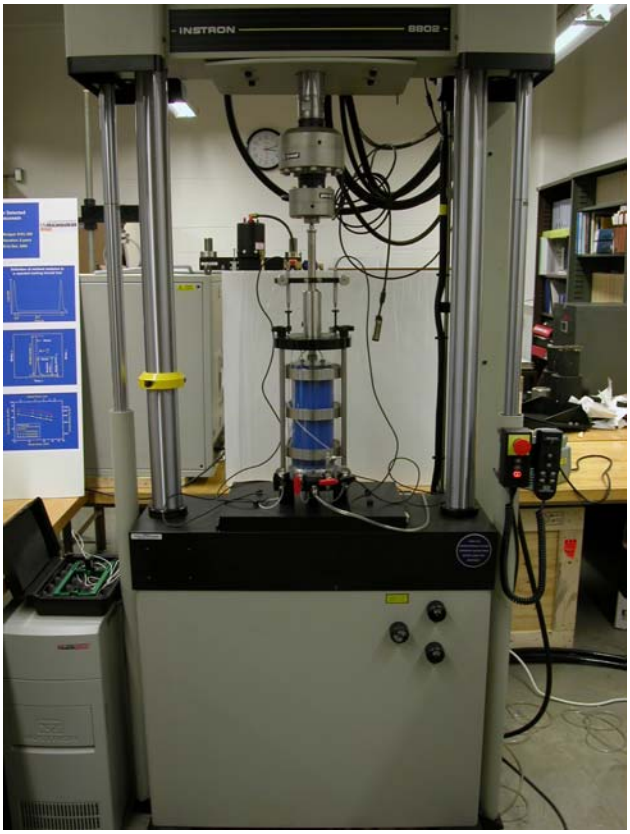
Figure 37. Preparing Test Specimens in Accordance with AASHTO T 307

(a) Compacted subgrade soil specimen

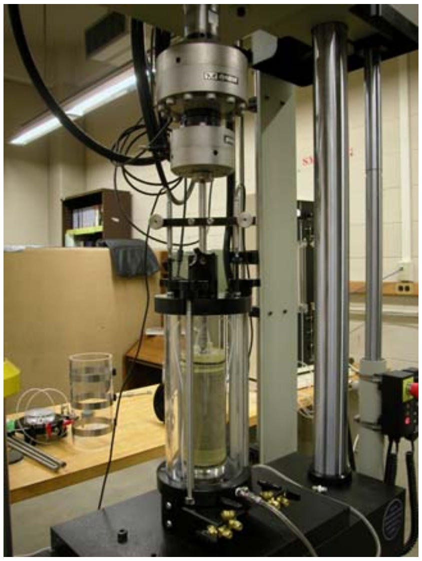
(b) Seating a specimen on the cell base and placing the top cap

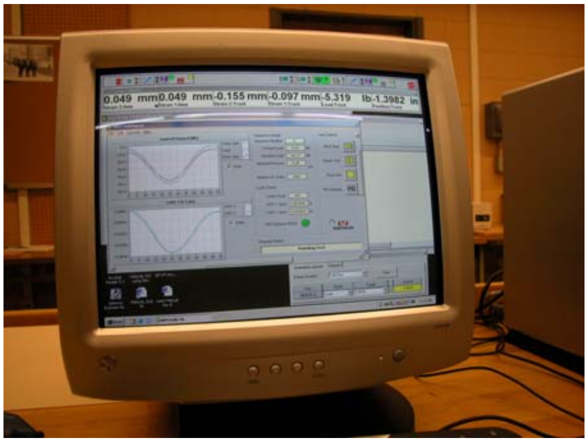
(c) Mounting the cell on the loading frame

Figure 38. Preparation of Test Specimens for the Repeated Load Triaxial Test



(a) Loading frame





(b) Triaxial cell (c) Control software

Figure 39. Servo-Hydraulic Closed-Loop Dynamic Materials Test System Used to Measure the Resilient Modulus of Subgrade Soils and Aggregates

3.2.5 HMA Mixtures

Most of the volumetric property test results were performed by the contractor (Payne and Dolan) during construction, as part of production QC testing. These tests included bulk specific gravity measured on cores recovered from the lift compacted by the IC rollers, maximum specific gravity of the mixture, gradation, and asphalt content. The other laboratory test performed on these mixtures was the dynamic modulus test, as listed in Table 3.

HMA sample preparation and dynamic modulus testing was carried out by Mathy Construction in Onalaska, Wisconsin. The dynamic modulus was measured on unconfined test specimens prepared and compacted to the in place air voids measured during construction. Dynamic modulus was measured at five test temperatures (14, 40, 70, 100, and 140°F) and six loading frequencies (0.1, 0.5, 1.0 5.0, 10.0, and 25.0 Hz). The test results are included in Appendix D.

3.3 Nondestructive Tests to Measure In-Place Properties

This section presents the NDT methods and equipment used to measure the in-place properties of the unbound materials and HMA mixes included in the demonstration projects. It also includes a brief evaluation and summary of the test results measured for each material and compares the results measured by different NDT devices.

3.3.1 Unbound Materials and Soils

Impact Penetration Test─DCP

The manual DCP was used to estimate the in-place stiffness of the unbound materials in accordance with ASTM D6951 (refer to Figure 40). The sequence of drops and penetration readings were modified based on the in-place material strength and layer thickness being evaluated at each project site.

Figure 40. DCP Test and Equipment, and Example of Calculated Resilient Modulus from the Penetration Rate with Depth

For each point, the test was begun by using one seating drop from full height. The penetration was recorded for the seating drop. The penetration was then recorded after each drop or successive drops (depending on the material's strength) throughout the layer thickness and into the supporting layer. One DCP test was performed at each designated test point, which was located based on the results from the Geogauge and nuclear density gauge.

The penetration rate was used to calculate the resilient modulus for each test point in accordance with equation 14. Figure 40 includes an example showing the calculated resilient modulus with test depth for one of the high plasticity clay lifts included in the Highland project. Table 7 lists the average elastic modulus for each area tested. The average penetration rates through the test layer or lift were used to calculate the average elastic modulus at each designated test point.

$$E_R = 17.6\left(\frac{292}{(DPI)^{1.12}}\right)^{0.64} \tag{14}$$

Where:

E_R = Resilient modulus, MPa.

DPI = Penetration rate or index, mm/blow.

Table 7. Summary of DCP Test Results; Estimate of Elastic Modulus

Project	Material	Section or Test Condition	Elastic Modulus, psi	
			Mean Value	COV, %[13]
Highland STH 80 Project	High Plasticity Clay Embankment	Initial Lift; no IC	2.36	9.9
		Initial Lift; with IC	2.66	11.5
		2nd Lift	1.21	12.1
		3rd Lift	1.60	33.4
	Crushed Stone	Test Section 1; Center	10.84	6.2
		Test Section 1; Edge	11.93	24.2
		Test Section 2; Center	9.94	11.2
		Test Section 2; Edge	10.04	8.7
	RAP Base	Near Centerline	10.04	4.3
		Near Shoulder	9.84	2.2
Jefferson STH 18 Project	Low Plasticity Clay Embankment; 1st Lift	Lanes 1 & 2; no IC	2.64	33.0
		Sakai Lanes: with IC	2.63	14.8
		Lanes 3 & 4; no IC	2.04	20.1
		Bomag Lanes	2.40	13.8
	Silty Sand Embankment; 2nd Lift	Sakai Lanes	1.73	21.2
		Bomag Lanes	2.17	38.2
	Crushed Stone Base	1st Lift	5.87	6.8
		2nd Lift	---[14]	---

[13] COV = Coefficient of Variation
[14] The DCP shaft fractured during the test sequence along the 2nd lift and could not be repaired at the test site.

Steady-State Vibratory Test—Geogauge

The Geogauge was used to measure the elastic modulus of the unbound materials and soils in accordance with the procedure recommended by the manufacturer and NCHRP Report #626 (Von Quintus et al., 2009).

The Geogauge should be calibrated to the project materials and conditions to improve on its accuracy, because of the potential influence from the supporting materials. This calibration requires that laboratory repeated load resilient modulus tests be performed on each unbound layer for judging the quality of construction. Repeated load resilient modulus tests were performed, but after the field testing had been completed. Thus, this section presents the unadjusted values measured for each material and project. The adjusted Geogauge modulus readings are presented and discussed in Chapter 4.

The test procedure is almost identical to that followed by an operator of a nuclear density gauge, except that the Geogauge operator spreads a thin layer of sand on the pavement surface to set the instrument on before taking the reading (see Figure 41). The following summarizes the testing sequence.

Figure 41. Humboldt Geogauge

1. The operator clears the surface to be tested with a small broom or other device to remove loose surface particles (see Figure 41).
2. A thin layer of moist sand is placed to fill in surface voids to ensure that the ring under the gauge is in contact with at least 75 percent with the test surface. Moist sand should be used because the gauge vibrations will cause dry sand particles to relocate under the gauge and disturb the reading. The layer of moist sand should only be thick enough to fill the surface voids of the material being tested.
3. The Geogauge is placed on the test point, and a light pressure and rotation of the Geogauge is used to ensure good contact with the test surface.
4. The test is initiated. It is important that the Geogauge not be touched and that the test not be conducted during excessive vibrations from nearby equipment (such as a vibratory roller or other heavy equipment). The Geogauge displays the elastic modulus value and other parameters. These readings can be stored in the device and downloaded to a computer at a later date, or the operator can record the measured elastic modulus for each test.
5. The Geogauge is lifted from the surface and the operator inspects the surface of the sand to ensure adequate coupling with the surface. If the Geogauge is improperly coupled with the surface, erratic readings can be obtained.
6. The Geogauge is then replaced in a different area or location on the sand surface and seated. A common sequence is to locate the Geogauge within different quadrants of a 12-inch-diameter circle. The test sequence is repeated until the required number of tests at the same point has been completed.

Triplicate tests were performed at most designated test points for each project and material. In some cases, more clustered tests were performed because of higher variability. Table 8 summarizes the average elastic modulus values measured by the Geogauge for each material and project.

In-Place Density & Water Content Tests—Nuclear Density Gauge

A troxler nuclear density gauge was used to measure the in-place density and water content during the compaction process at the designated test points for the Geogauge and DCP. Tables 9 and 10 list the average dry densities and water contents for each material and project after it had been compacted with the IC rollers, respectively, and in some cases, after compaction with the non-IC rollers being used by the contractor.

Table 8. Summary of Geogauge Test Results; Estimate of Elastic Modulus

Project	Material	Section or Test Condition	Elastic Modulus, psi	
			Mean Value	COV, %
Highland STH 80 Project	High Plasticity Clay Embankment	Initial Lift; no IC	14.09	14.5
		Initial Lift; with IC	14.74	18.6
		2nd Lift	5.27	45.9
		3rd Lift	10.4	17.7
	Crushed Stone	Test Section 1; Center	18.67	14.8
		Test Section 1; Edge	18.08	17.6
		Test Section 2; Center	16.21	12.5
		Test Section 2; Edge	13.98	5.7
	RAP Base	Near Centerline	27.27	9.8
		Near Edge	22.28	6.1
Jefferson STH 18 Project	Low Plasticity Clay Embankment; 1st Lift	Lanes 1 & 2; no IC	8.02	11.3
		Sakai Lanes; with IC	8.70	35.2
		Lanes 3 & 4; no IC	8.28	26.2
		Bomag Lanes; with IC	10.30	40.0
	Silty Sand Embankment; 2nd Lift	Sakai Lanes	7.18	9.6
		Bomag Lanes	7.62	27.1
	Crushed Aggregate Base	1st Lift	15.65	10.0
		2nd Lift	16.63	6.8

Table 9. Summary of Dry Densities Measured with a Nuclear Density Gauge

Project	Material	Section or Test Condition	Dry Density, pcf	
			Mean Value	COV, %
Highland STH 80 Project	High Plasticity Clay Embankment	Initial Lift; no IC	108.3	1.8
		Initial Lift; with IC	109.7	2.6
		2nd Lift	103.5	2.1
		3rd Lift	103.8	7.6
	Crushed Stone	Test Section 1; Center	139.5	1.6
		Test Section 1; Edge	139.6	2.4
		Test Section 2; Center	136.5	1.2
		Test Section 2; Edge	134.5	1.0
	RAP Base	Near Centerline	127.8	1.9
		Near Shoulder	127.5	1.5
Jefferson STH 18 Project	Low Plasticity Clay Embankment; 1st Lift	Lanes 1& 2; no IC	122.7	1.9
		Sakai Lanes	126.0	9.7
		Lanes 3 & 4; no IC	120.5	2.8
		Bomag Lanes	124.5	3.0
	Silty Sand Embankment; 2nd Lift	Sakai Lanes	115.4	3.2
		Bomag Lanes	111.5	3.6
	Crushed Aggregate Base	1st Lift	136.1	0.6
		2nd Lift	133.0	1.9

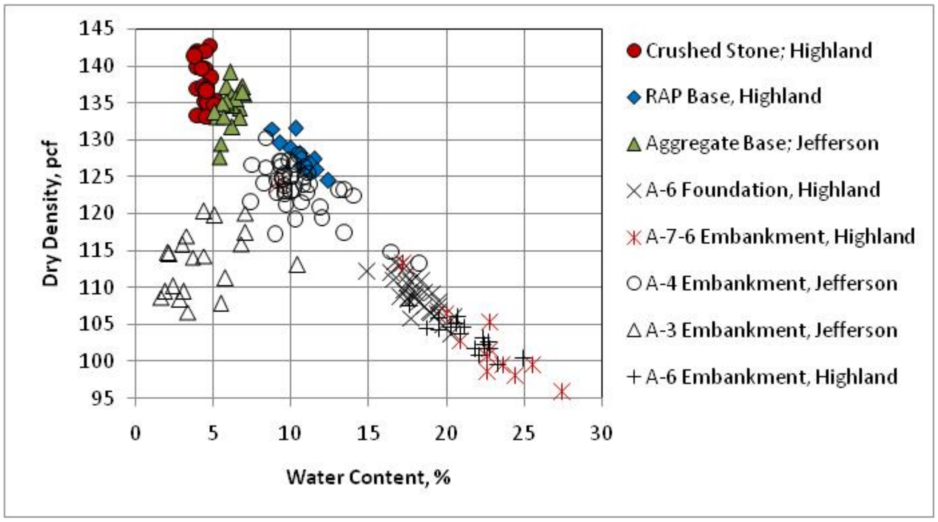
Table 10. Summary of Water Contents Measured with a Nuclear Density Gauge

Project	Material	Section or Test Condition	Water Content, %	
			Mean Value	COV6.0, %
Highland STH 80 Project	High Plasticity Clay Embankment	Initial Lift; no IC	18.28	6.0
		Initial Lift; with IC	17.95	7.6
		2nd Lift	21.2	8.6
		3rd Lift	21.6	21.7
	Crushed Stone	Test Section 1; Center	4.22	6.9
		Test Section 1; Edge	4.48	8.9
		Test Section 2; Center	4.56	8.7
		Test Section 2; Edge	4.60	7.0
	RAP Base	Near Centerline	10.67	9.3
		Near Shoulder	10.80	8.7
Jefferson STH 18 Project	Low Plasticity Clay Embankment; 1st Lift	Lanes 1 & 2; no IC	11.7	25.2
		Sakai Lanes; with IC	10.4	25.5
		Lanes 3 & 4; no IC	10.46	13.0
		Bomag Lanes; with IC	9.69	8.2
	Silty Sand Embankment; 2nd Lift	Sakai Lanes	3.96	47.5
		Bomag Lanes	4.67	56.1
	Crushed Aggregate Base	1st Lift	6.49	5.2
		2nd Lift	5.75	8.1

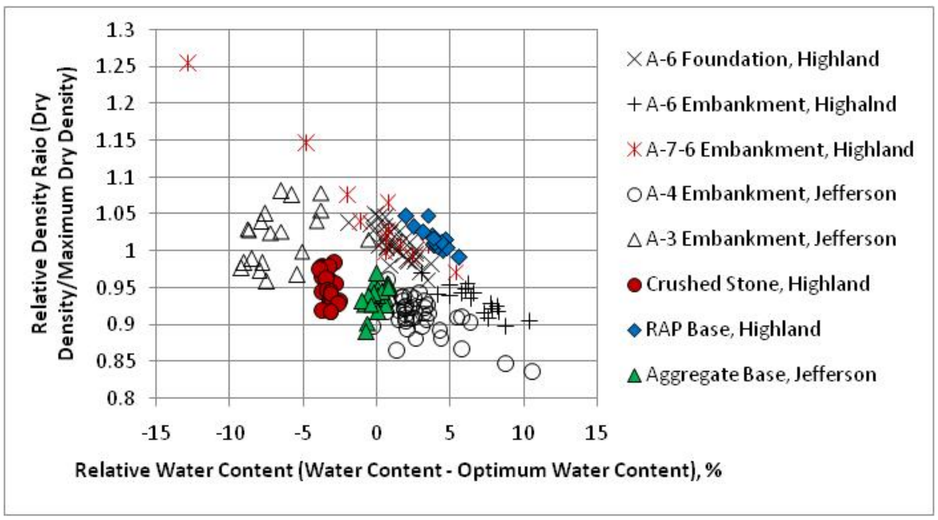
Comparison of In-Place Properties

Limited sand cone density tests were conducted on each of the projects to confirm the density and moisture content readings from the nuclear density gauge. Results from the sand cone tests are included in Appendix A, along with the moisture-density relationships. The density and water content derived from the sand cone tests were found to be significantly different and highly variable from the nuclear density gauge test results; no correlation was found. Thus, the results from the nuclear density gauge were used without making any corrections to the readings.

The in-place dry density of unbound aggregate layers and embankment soils is heavily influenced by its water content. Figure 42.a shows a comparison between water content and dry density for all unbound materials included in the demonstration projects. As shown, the dry density decreases with increasing water content across all materials, except for the A-3 (silty sand) embankment. The A-3 embankment was the only layer that began to dry during the compaction process enough so that water had to be added during rolling. Figure 42.b also shows a comparison between water content and dry density, but relative to the optimum water content and maximum dry density (values were included in Table 5).



(a) Actual In Place Values



(b) In Place Values Relative to Optimum Values

Figure 42. Comparison Between In-Place Water Content and Dry Density

The following provides a summary of the volumetric data relative to the weather conditions during rolling and testing:

- The A-6 and A-4 embankment layers were placed and compacted after heavy rains. This helps explain the higher water content and lower dry density relative to the optimum values.
- The A-7-5 embankment layer was excavated and placed between rain storms, which could explain the wide range of moisture contents, relative to the optimum value.

- The RAP base layer was placed prior to any rains but was tested in place after the heavy rains that occurred during the week for the demonstration project, which helps explain the higher water content relative to the optimum value.
- The A-3 embankment layer was placed a couple of days after the heavy rains that occurred prior to the demonstration project. However, high winds and temperatures dried the surface layer. The crushed stone base layer also was placed, scarified, re-compacted, and tested prior to any rains. This helps explain the lower water contents relative to the optimum value for both layers.
- The aggregate base layer was compacted using a higher density specification than required for the other layers.

Yau and Von Quintus (2001) found that the dry density relative to the maximum dry density and water content relative to the optimum water content were important parameters for predicting the resilient modulus of some materials, especially coarse-grained materials. Figure 43 shows a comparison of dry density, water content, and wet density and Geogauge modulus. In general, as dry density increases, the stiffness or modulus increases, everything else being equal. Figure 44 shows a similar comparison but relative to the maximum dry density (relative dry density ratio) and optimum water content (relative water content). In general, the Geogauge modulus increases with an increase in dry density for the coarse-grained base materials. For the sandy and fine-grained embankment soils, other physical properties of the soils become important relative to stiffness.

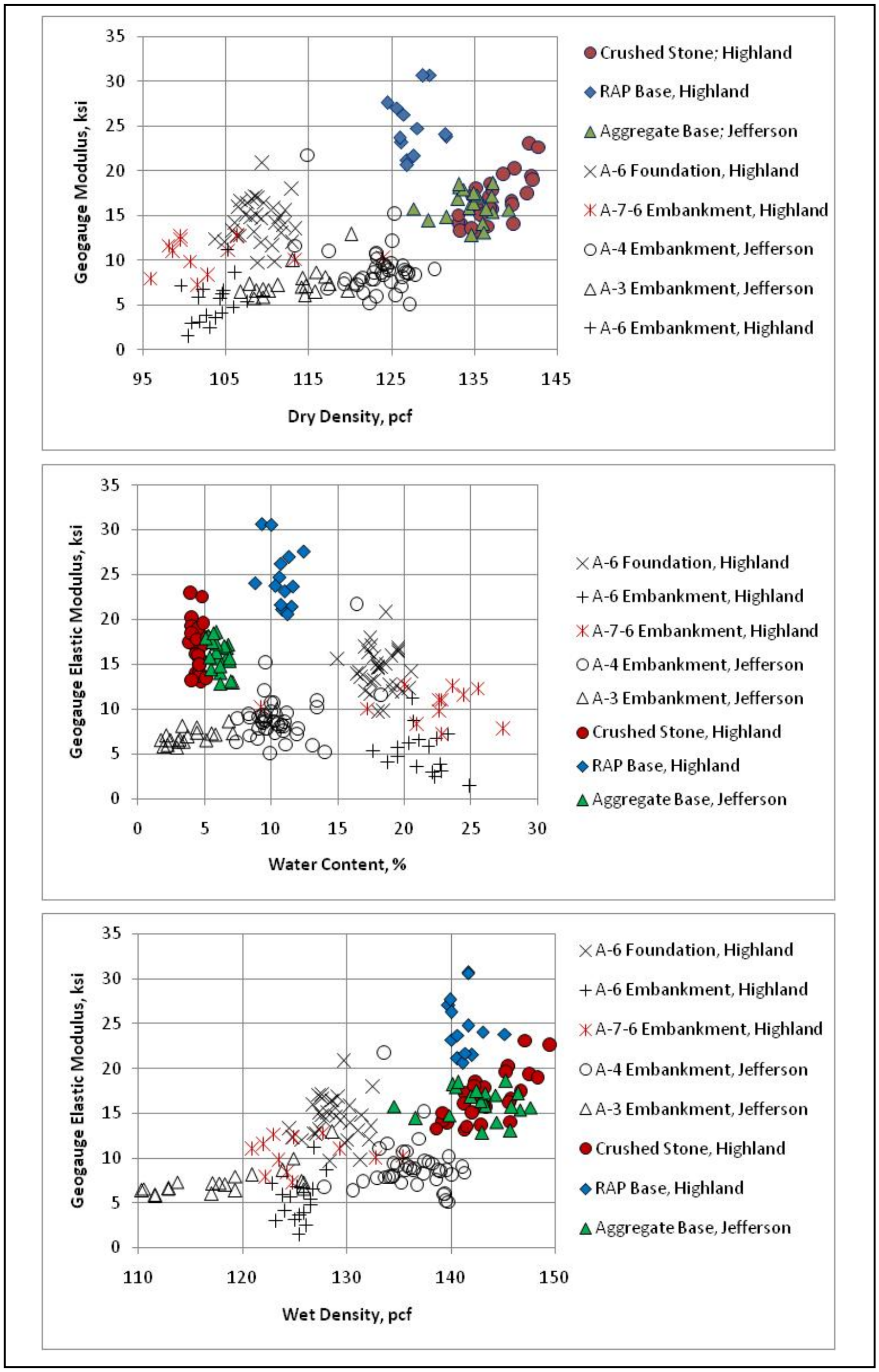
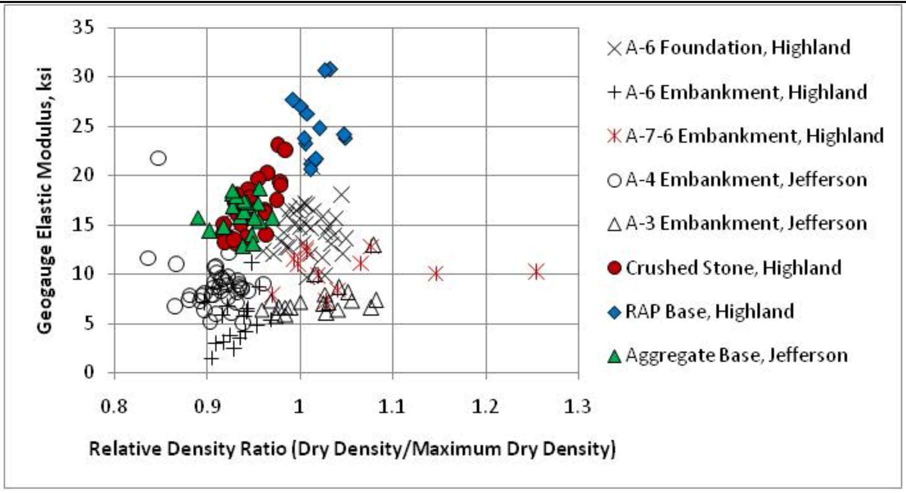
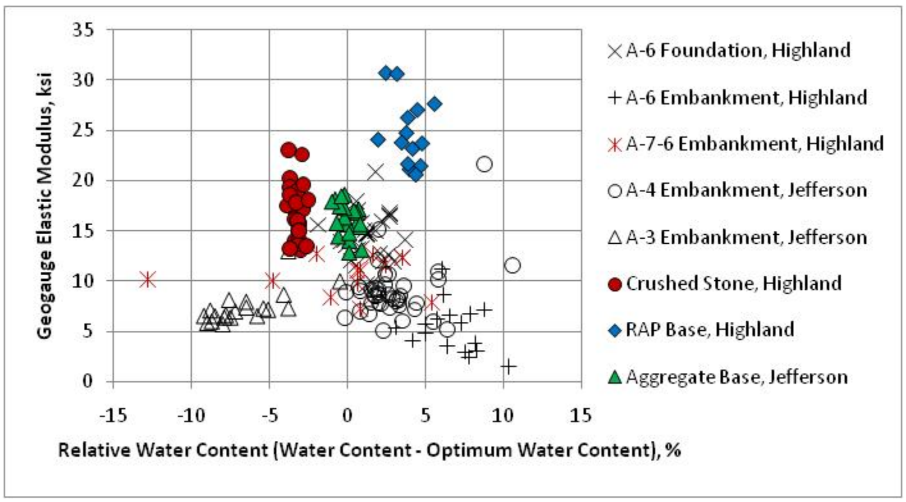


Figure 43. Comparison Between In-Place Dry Density, Water Content, and Wet Density and Geogauge Elastic Modulus



(a) Relative Density Ratio Versus Geogauge Modulus



(b) Relative Water Content Versus Geogauge Modulus

Figure 44. Comparison Between the Relative Density Ratio and Relative Water Content and Geogauge Elastic Modulus

3.4.2 HMA Materials

Seismic Test–Portable Seismic Pavement Analyzer (PSPA)

The PSPA was used to measure the seismic modulus of the HMA materials in accordance with the procedure and software developed by Dr. Nazarian for the Texas DOT and NCHRP Report #626 (Von Quintus et al., 2009).

The device consists of a stand linearly connected by a stiff arm to a source and two receivers connected by a wire to a computer (refer to Figure 45). The source contains a hammer which is dropped several times at regular intervals. The receivers, containing quartz-crystal accelerometers, measure the acceleration of the Rayleigh waves induced by the dropping of the hammer and report the resulting electrical charge to the data acquisition system. An FFT transforms the electrical charge or data into the frequency domain.

Figure 45. PSPA Being Used to Test the USH 45 HMA Overlay

The data interpretation program that comes with the PSPA uses the measured values to provide the output in the form of the mean Young's modulus to a particular depth. The spacing of the receivers determines the depth of measurement. The system initially converts the readings of the load pulse and response to a seismic modulus of the material.

Because the modulus of HMA mixtures is affected by temperature and frequency, the seismic modulus is internally adjusted to account for these conditions. The internal adjustments are included in the software and initially based on global default values. However, these default adjustments can be determined in the laboratory by measuring the seismic modulus on test specimens prepared during the mixture design process, on bulk mixture compacted to the density or air void level expected during construction, or on field cores recovered during construction. Global default values initially were used to calculate the seismic modulus at a load frequency of 5 Hz for the field demonstration projects.

Measuring the seismic properties in different directions increases the perceived variability of the device. The variability can be reduced slightly by always taking the readings in one direction. For this project, three to five readings were taken at each test point in multiple directions. Table 11 lists the average seismic modulus values measured within each test section at the points where densities were measured. Table 11 also includes the coefficient of variation (COV) of the in-place stiffness measurements. The variation along the project was typical of most projects, with the exception of Sections 1 and 6.

Table 11. Summary of PSPA and Non-Nuclear Density Test Results

Section Identification			IC Roller	PSPA Seismic Modulus, ksi		PaveTracker Adjusted Density, pcf	
				Mean	COV, %	Mean	COV, %
1	9/30/09	Southbound	Caterpillar	448[15]	10.59	143.2	2.62
2	9/30/09	Northbound	Sakai	226	26.57	143.5	2.53
3	9/30/09	Northbound	Sakai	151	19.26	144.1	1.08
4	9/30/09	Northbound	Bomag	144	19.28	144.5	1.79
5	9/30/09	Northbound	Sakai	135	19.73	142.8	1.79
6	10/01/09	Northbound	Bomag	154	53.44	145.6	1.88
7	10/01/09	Northbound	Sakai	141	26.97	145.1	1.26

Non-Nuclear Density Test—PaveTracker

A non-nuclear density gauge was used to measure the density of the HMA mixtures: the PaveTracker. The PaveTracker is a lightweight device for measuring the uniformity of HMA mixtures (refer to Figure 46). The measurements are practically instantaneous when the device is placed on an HMA surface. Areas of segregation, lower density levels along longitudinal joints, or otherwise non-uniform areas can be detected.

[15] The PSPA readings for the first section were made the following day after paving; whereas, all other readings were made the same day of paving.

Figure 46. Non-Nuclear Density Gauge – The PaveTracker

The PaveTracker is used exactly like nuclear density gauges, but is a non-nuclear device. The PaveTracker also has an on-board, real-time system that takes the density readings and keeps a record of them for future use, allowing the device to be integrated into the paving process. The tests are performed in accordance with the manufacturer's recommendations and NCHRP Report #626 (Von Quintus et al., 2009).

Four density readings were made directly over each marked test point, and three additional reading were made at 90 degree deviations around the test point with the edge of the gauge's base adjacent to the test point. Table 11 summarizes the average in-place HMA densities for each section tested.

Repeatability with the non-nuclear gauges was reported to be good in NCHRP Report #626 (Von Quintus et al., 2009). As an example, the COV of cluster readings taken at each point was 1.32 percent, and 99 percent of the test points had a COV of less than 5 percent. This is similar to the results from a study sponsored by Wisconsin DOT on the evaluation of non-nuclear density gauges (Schmitt et al., 2006, Rao et al., 2007). As listed in Table 11, the COV values determined for this demonstration project are similar to those measured on many other projects.

The densities listed in Table 11 are adjusted values that account for the bias between the non-nuclear and nuclear values (refer to Figure 47). This adjustment process was completed in accordance with NCHRP Report #626 and the procedure used by Schmitt, et al. (2006) in the Wisconsin study. Bulk specific gravities were measured on cores extracted from the HMA overlay and were used within this adjustment and calibration process.

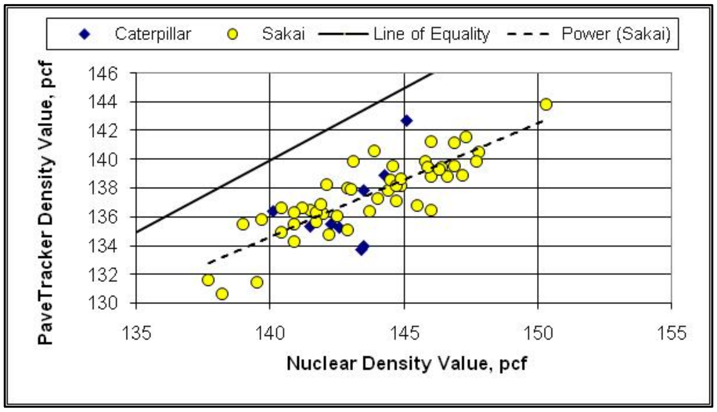


Figure 47. Comparison of HMA Densities Measured with the Nuclear and Non-Nuclear Density Gauges

Thermal Imagery Test—Infrared Camera

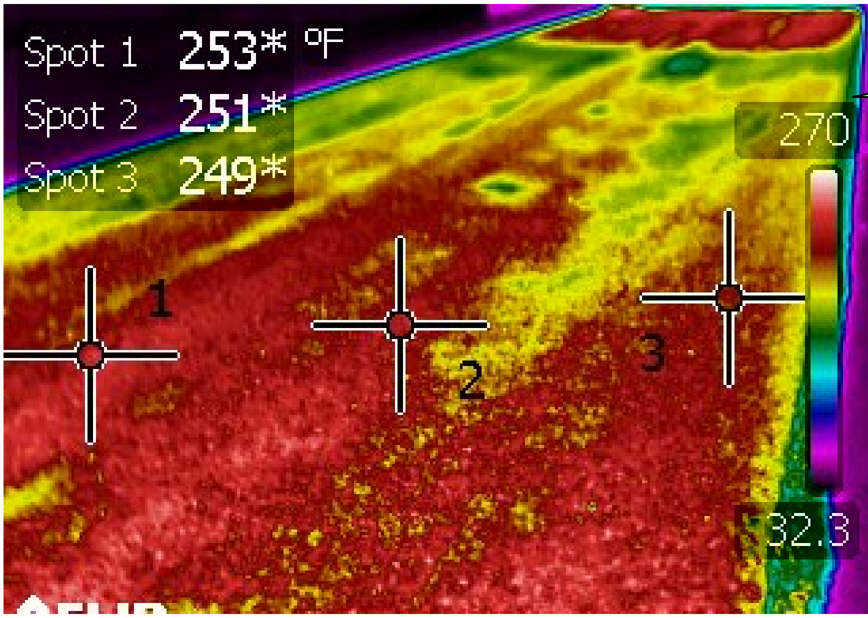
Infrared is a particular implementation of thermography in which an infrared camera is used to detect the infrared radiation emitted by a material surface. With appropriate calibration for material properties and background radiation, this radiation can be converted into a direct measurement of temperature of the material surface.

Infrared thermography has been used to detect segregation in newly placed HMA, as well as to detect stripping and debonding between HMA layers due to discontinuity in the temperature caused by the difference in voids between two areas. Studies have shown that changes in infrared data are significantly related to changes in HMA properties, such as air void content and gradation.

These cameras provide a cursor that displays numeric temperature values on the image (refer to Figure 48). Using the infrared camera, pavement surface locations with temperature anomalies have to be manually marked on the pavement surface while the image is being viewed, since the camera has no distance scale. The contractor's infrared camera was used on the project to identify and locate areas with different surface temperatures. These areas were marked to determine whether the IC rollers could detect a change in temperature via different stiffness readings from the roller display unit.

Comparison of In Place HMA Properties

Other studies have reported conclusively that HMA stiffness and densities are related; everything else being equal, as density increases, stiffness increases. Figure 49 shows a comparison of the densities and PSPA values measured on the USH 45 overlay. As shown, there is a general increase in stiffness with increasing density, but the two properties were found not to be highly correlated for this project. Other mixture properties are probably influencing the measured values. In fact, material changes occurred during production that affected the mix stiffness but not the contractor's ability to get density. This issue will be discussed further in Chapter 5.



Localized Cold Spot

Example of image showing a thermal anomaly; cold spot due to delay in trucks arriving at site.

Example of image showing uniform temperature distribution across the mat placed by paver.

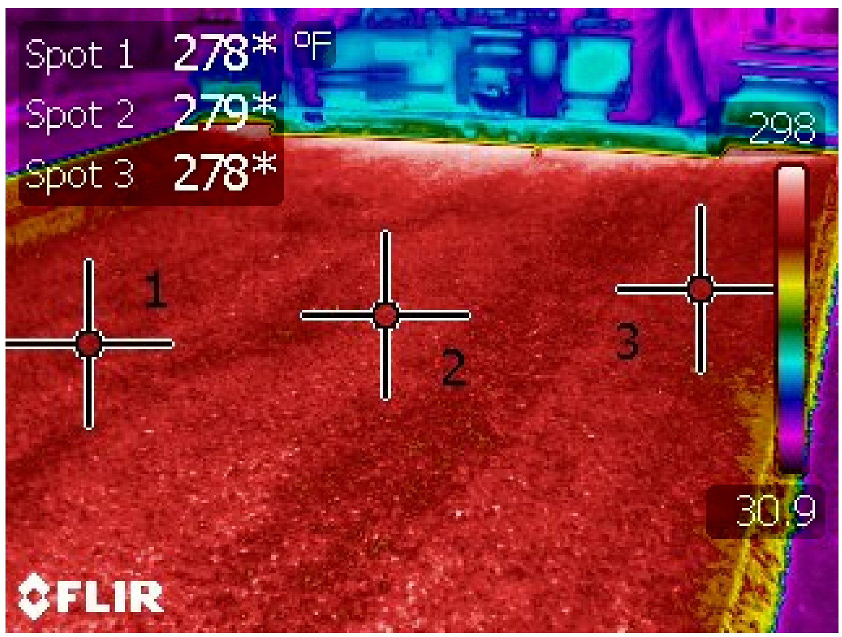


Figure 48. Images from Infrared Camera to Locate Temperature Differences

NOTE: PSPA values for section #1 were taken the day after paving while the PSPA values for all other sections were taken the day of paving.

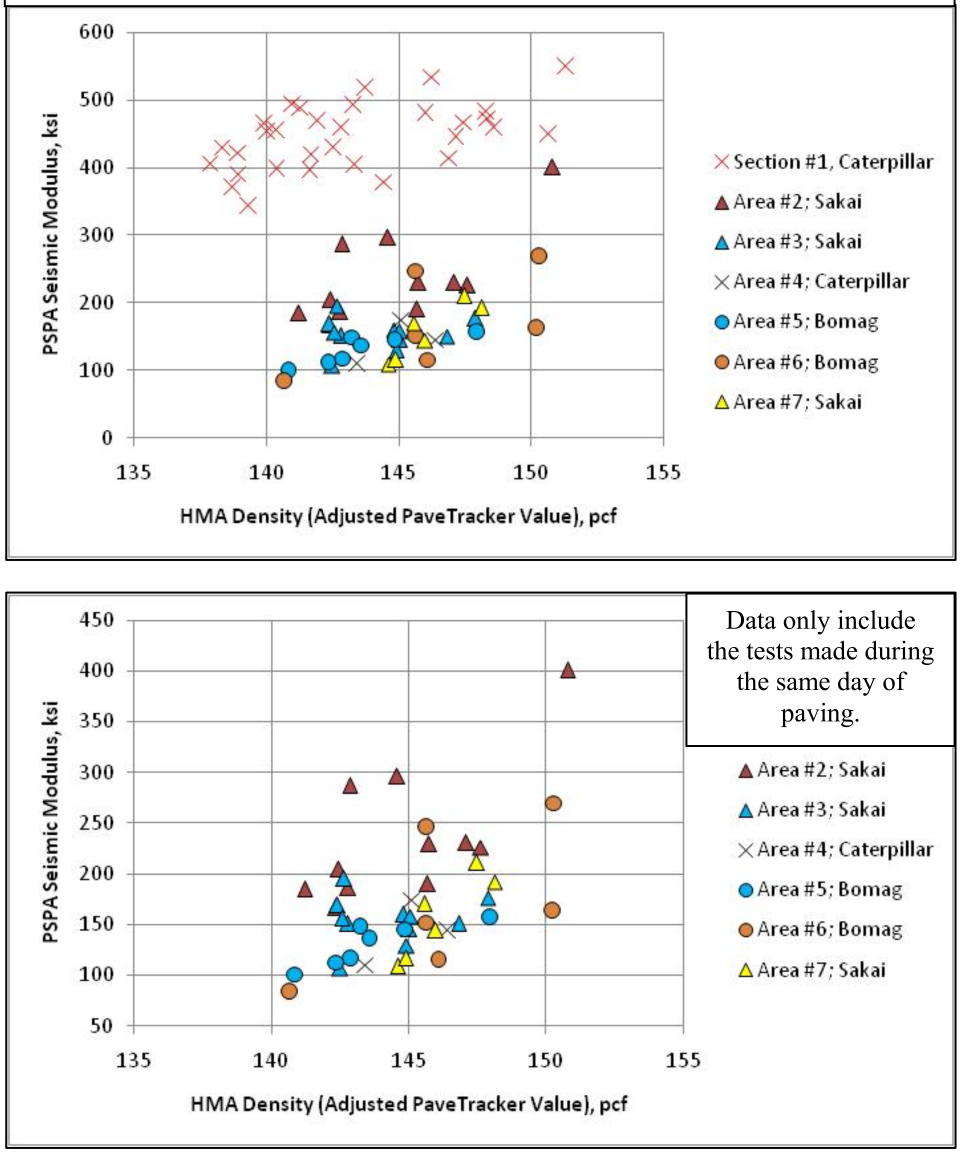


Figure 49. Comparison of HMA Density (Non-Nuclear Density Gauge) and Stiffness (PSPA Readings)

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CHAPTER 4 UNBOUND MATERIAL – LAYER STIFFNESS

This chapter discusses the application and use of IC technology on selected demonstration projects in Wisconsin for monitoring the compaction process of unbound layers. Data collected from all demonstration projects were analyzed to identify and/or confirm some of the limitations and benefits previously reported on the use of IC technology.[16] This chapter is grouped into five sections relative to the use of IC rollers: (1) relationship between the IC roller response and other material properties, (2) density and stiffness growth relationships, (3) uniformity of material stiffness, (4) identification of stiffness anomalies (weak or soft spots) influencing the roller response, and (5) interpretation of IC roller responses related to design values.

4.1 Relationship Between IC Roller Responses and Other Properties

The in-place layer properties that are important relative to the IC response values are density-moisture content relationship of the layer being compacted and modulus of the supporting layers. Chapter 3 included a comparison of the volumetric properties and Geogauge values. Trends in the data were observed between the volumetric properties and stiffness, but other properties (like gradation) have a significant effect on stiffness (Yau and Von Quintus, 2001). These other properties were not measured at each test point and represent confounding factors in relating volumetric properties to stiffness. This section provides a comparison of the IC response measurements and in-place material properties measured with the Geogauge and other devices.

4.1.1 Stiffness Gradient and NDT Devices

As described in Chapter 3, two different pieces of equipment were used to measure the in-place stiffness of unbound materials and soils: the DCP and Geogauge. The DCP was used as an alternate device based on recommendations included in NCHRP Report #626 (Von Quintus et al., 2009) and to estimate the elastic modulus of the supporting layer. The DCP also was used to evaluate stiffness gradients through the surface layer. Figure 50 shows an example of the DCP stiffness gradient through the aggregate base course and into the embankment layer along the Jefferson project. As shown, the select granular embankment was found to be stiffer than the bottom of the crushed stone base at one of three test points, and one of three points was found to be softer. These gradients can be important in comparing different devices that measure an average or composite stiffness to different depths.

Figure 51 includes a comparison of the elastic modulus values estimated with both devices. As shown, the DCP average modulus values are significantly less than those

[16] Electronic files from the Bomag IC roller were not provided; only strip charts of the E_{vib} values were provided for each project. The Sakai IC roller provided electronic files but no hard copies of the data during rolling operations.

estimated by the Geogauge. The reason for this large difference is unknown and was unexpected, but it probably is related to the higher water content (above the optimum value) for the highly plastic clays and sandy silt, and the low water content for the poorly graded sand— all of which can result in low shear strength for these materials.[17] Thus, all IC roller responses were compared to the Geogauge and laboratory measured values (resilient modulus). Results from the DCP were used only to evaluate differences between test areas and projects that had variable support conditions.

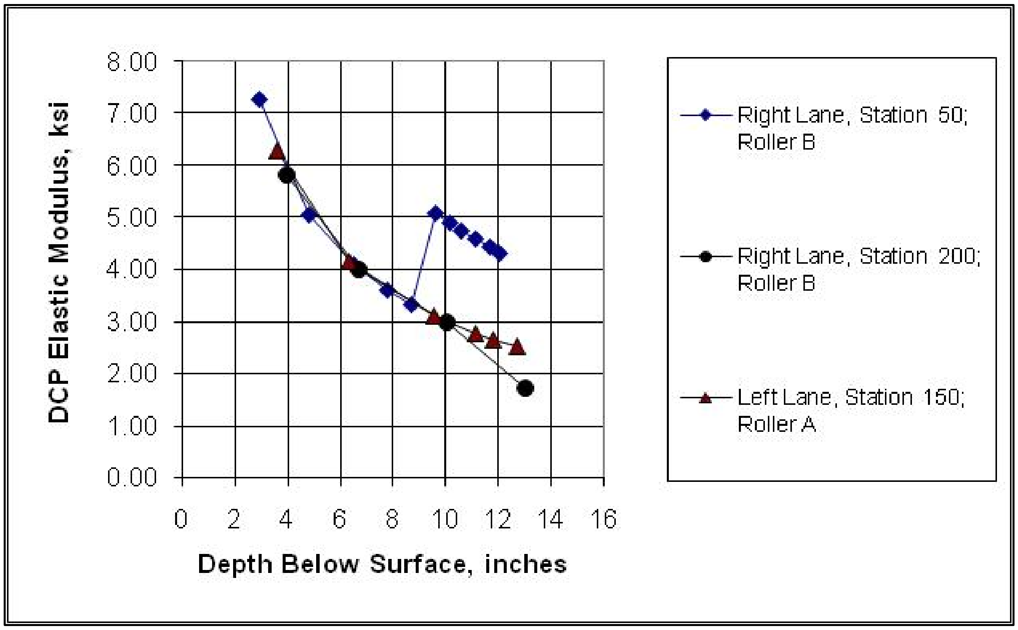


Figure 50. Elastic Modulus Gradient through the 8-inch Crushed Aggregate Base and into the Embankment Layer, as Measured by the DCP (Jefferson Project)

[17] This comment or hypothesis is based on the authors' experience from other projects. The compression-modulus is greater for these materials than estimated with the DCP under these volumetric conditions.

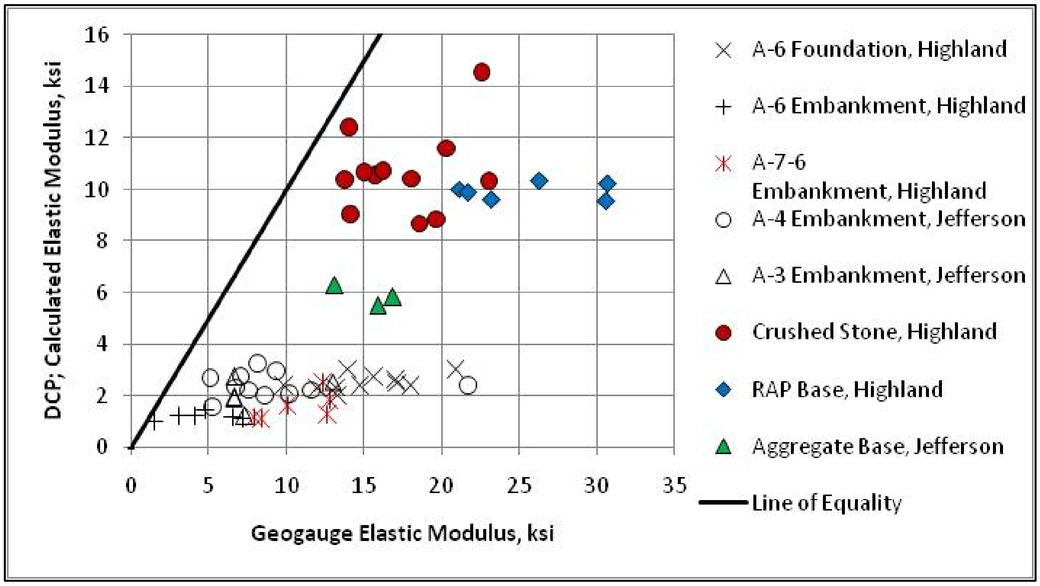


Figure 51. Comparison of the In-Place Modulus Estimated with the DCP and Geogauge

4.1.2 Modulus Adjustment Factors – Laboratory to Field Measured Values

One of the stated benefits of using IC rollers is that the output parameter can be used to confirm pavement design values. The IC roller response is a field measured value, while most pavement design procedures, including the Mechanistic-Empirical Pavement Design Guide (MEPDG), require the use of laboratory measured material properties for characterizing each layer (ARA, 2004). The question becomes: is the IC output parameter equivalent to a laboratory measured resilient modulus, or is there bias between the IC output parameter and laboratory measured value to ensure that the modulus of the compacted layer exceeds the value used in design?

As an example, the in-place modulus backcalculated from FWD deflection basin data has to be adjusted to represent a laboratory measured value. This adjustment factor is the C-factor included in the 1993 *AASHTO Guide for Design of Pavement Structures*. The C-factor was evaluated and found to be structure dependent using most of the test sections included in the FHWA's Long Term Pavement Performance (LTPP) program (Von Quintus and Killingsworth, 1998). In addition, NCHRP Report #626 found that the Geogauge value needs to be adjusted to represent laboratory resilient modulus values for some soils and recommends that this adjustment factor be included as part of a calibration procedure for most nondestructive tests, including IC rollers. Thus, both the IC roller response and Geogauge values were compared to laboratory measured resilient modulus values to determine the applicability of this adjustment factor.

Laboratory repeated load resilient modulus tests were performed on each unbound material, as discussed in Chapter 3, and the test results are presented in Appendix C. Resilient modulus values were estimated for the individual test sections using the average stress state calculated under the IC roller. Figure 52 compares the laboratory resilient modulus values (compaction stress state) and the average Geogauge values measured within a test area or lane (all materials grouped together and by material type). As shown, the Geogauge elastic modulus increases as the laboratory resilient modulus increases. Table 12 compares the adjustment factors from NCHRP Report #626 and those determined from the Wisconsin demonstration projects. As shown, the ratios are similar, except for the fine-grained clay soils.

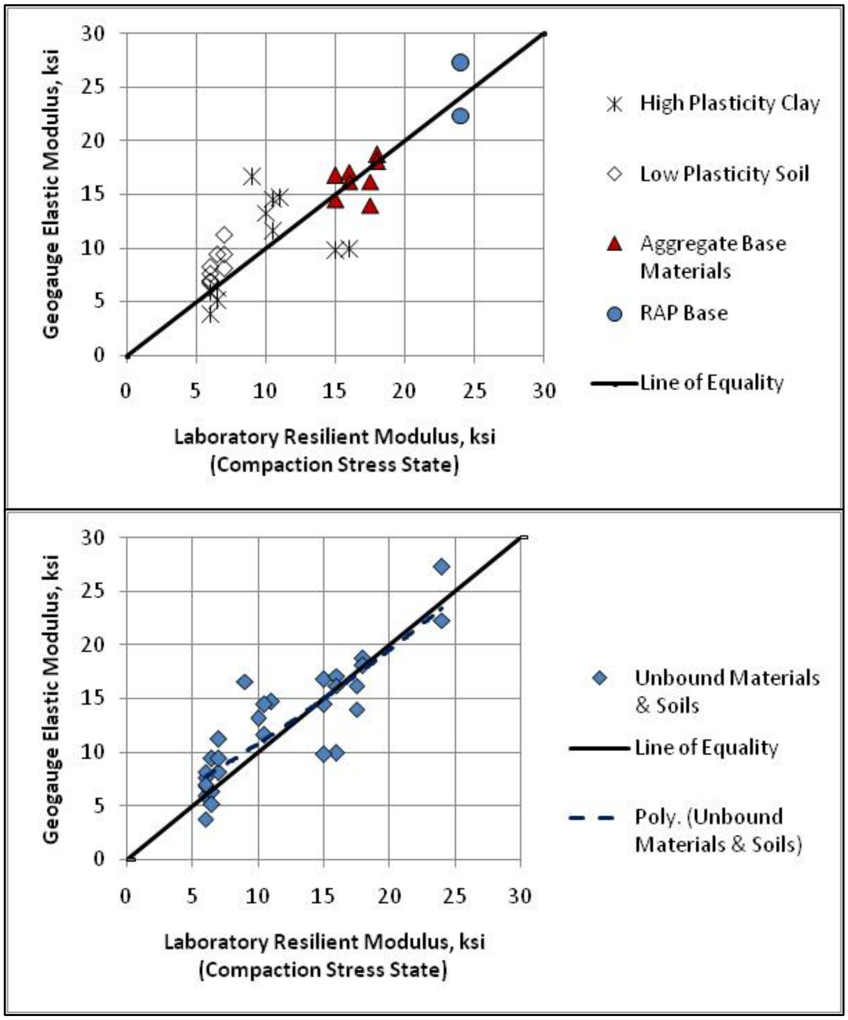


Figure 52. Comparison of Resilient Modulus Measured in Laboratory at the Compaction Stress State and Elastic Modulus Measured with the Geogauge

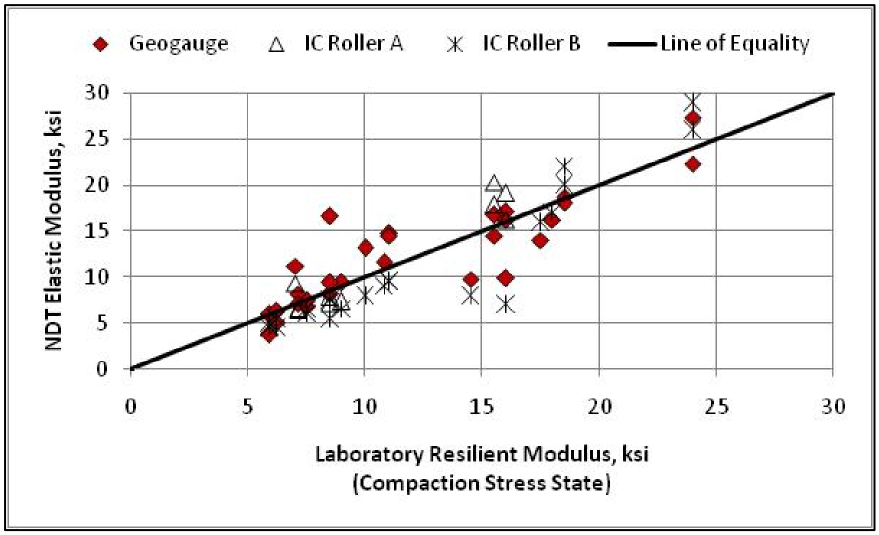
Table 12. Adjustment Factors (Ratios) Between Laboratory (Resilient Modulus) and Geogauge Measured Values

Material Type		**NCHRP Report #626**	**Demonstration Projects**	
			Mean	**COV, %**
Fine-Grained Clay Soils	High Plasticity	0.454	1.05	35.1
	Low Plasticity		0.88	20.7
Sand	Poorly Graded	---	0.99	9.9
Soil-Aggregate Mixture		1.06	---	---
Crushed Aggregate Base		1.02	1.04	10.3
RAP Base		---	0.98	14.3
The adjustment factor or ratio is defined as: $\frac{M_R(Laboratory)}{E(Geogauge)}$				

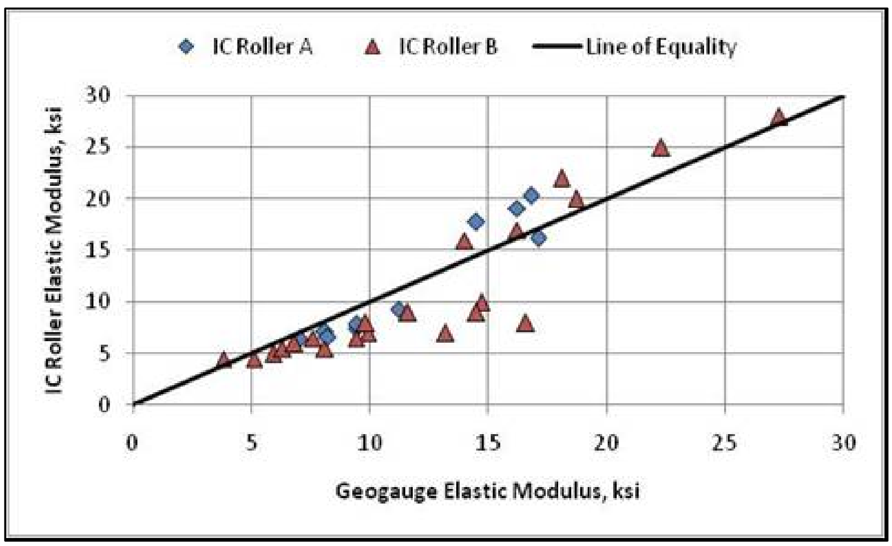
For fine-grained soils, the field adjustment factor included in NCHRP Report #626 was reported to be correlated to the amount of material passing the #200 sieve (there were sufficient data to show the trend in the data, but not to develop any conclusive relationship). The adjustment factor for the high plasticity clay soils for the Wisconsin demonstration projects was found to vary from 0.5 to 1.6. The reason for the higher adjustment ratios from the Wisconsin demonstration projects is unknown. It is expected that the laboratory repeated load resilient modulus test could be a factor related to this difference in results. For this study, only the Geogauge values for the high plasticity clay embankment layers were adjusted to laboratory equivalent resilient modulus values under the IC rollers. The other materials were near unity, so no adjustment was made. The following summarizes the adjustment factors for the high plasticity clays with variable volumetric conditions:

- A-6 foundation that was near the optimum water content with a percent compaction of about102 percent; adjustment factor of 0.69, which is within the range of values measured and reported in NCHRP Report #626.
- A-6 embankment layer that was near complete saturation with a percent compaction of about 93 percent; adjustment factor of 1.19.
- A-7-6 embankment layer that had a wide range of water contents with a percent compaction of about 105 percent; adjustment factor of 1.34.

Figure 53 shows a comparison of the Geogauge and IC roller elastic modulus values to the laboratory measured values, while Figure 54 includes a similar comparison except using the adjusted Geogauge values and grouped by material type. As shown, the IC roller values are similar to the laboratory measured resilient modulus values for the stress state under the IC roller. Thus, the Geogauge and IC roller response values were used to evaluate material behavior and increase in stiffness with number of roller passes.

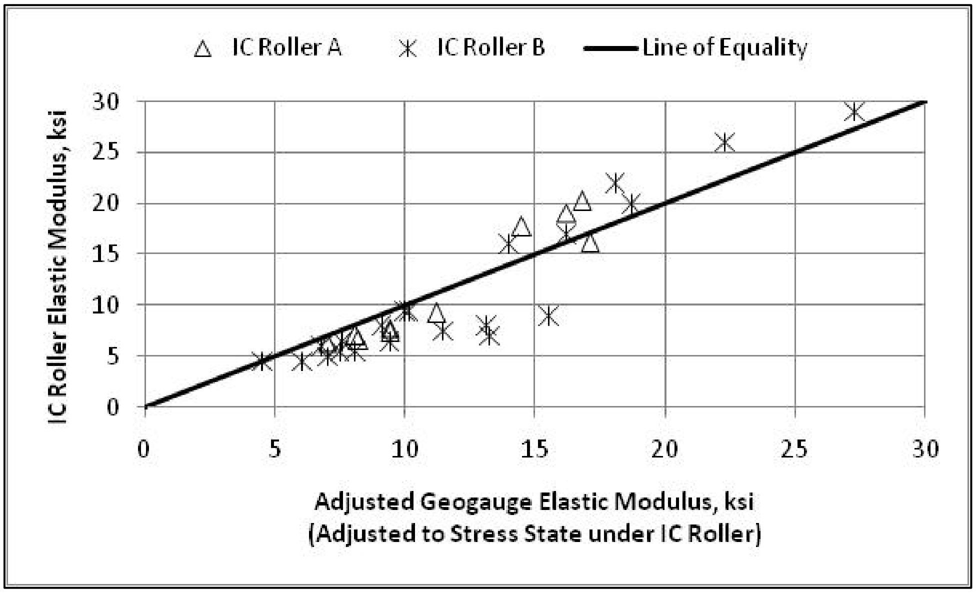


(a). Comparison Relative to Laboratory Resilient Modulus Values

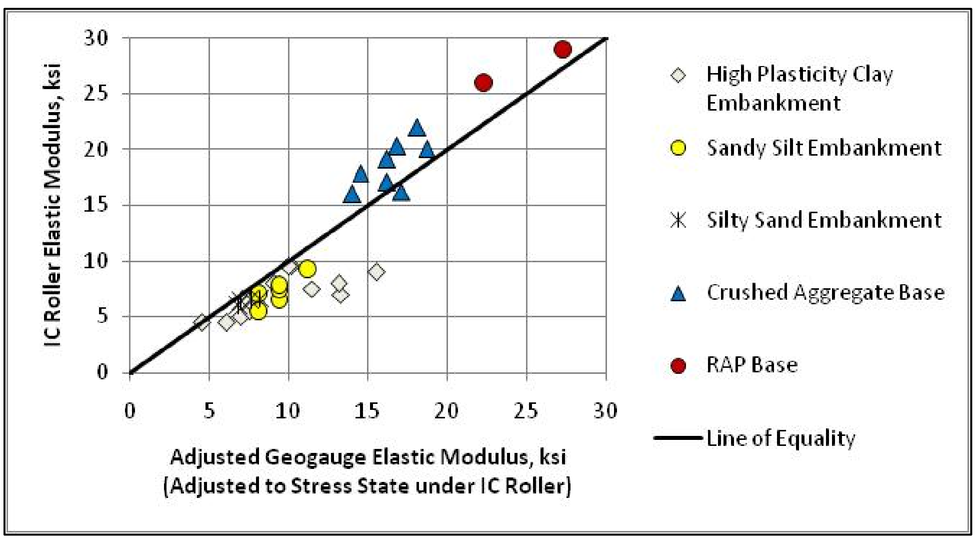


(b). Comparison Grouped by Different IC Rollers

Figure 53. Comparison of Geogauge and IC Roller Elastic Modulus Values



(a) Data Grouped by Type of IC Roller



(b) Data Grouped by Material Type

Figure 54. Comparison of Adjusted Geogauge and IC Roller Elastic Modulus Values

4.2 Density-Stiffness Growth Relationships

One of the benefits of using IC rollers is to determine the minimum number of roller passes to achieve the maximum stiffness of the layer and if continued rolling will damage the materials. Different points were used in multiple test areas to monitor the increase in material density and stiffness with number of roller passes. The remainder of this section discusses the density-stiffness growth relationships measured for the different materials included in the demonstration projects. Anomalies were identified on some of the projects, which are discussed in detail for the respective material.

4.2.1 Crushed Stone and Aggregate Base

Figure 55 shows a typical change in dry density and stiffness with increasing roller passes (2^{nd} lift of the crushed aggregate base layer). Many of the density-stiffness growth relationships, regardless of material type, were similar to this relationship. As shown, four passes will achieve the maximum stiffness of the material for the site conditions along the Jefferson project, while the density continued to increase for some test points. The density-stiffness growth relationship for the 1^{st} lift of the crushed aggregate base layer is shown in Figure 56.

Along the Highland crushed stone base test section, dry density was found to slightly increase with IC roller passes, while the stiffness measured with the Geogauge was found to decrease (refer to Figure 57). This observation contradicts previous findings and does not seem reasonable. A possible explanation for this anomaly is related to the low water content of the in-place crushed stone and lower layers (prior to the heavy rains that occurred during the latter part of this demonstration project). The select granular embankment has an appreciable amount of fines and can be stiff when dry.

The crushed stone base along the Highland project was scarified to a depth of about half its thickness and re-compacted with the Sakai Level 2 IC roller. The original plan was to operate the Sakai IC roller in high amplitude for the first couple of passes and then decrease the amplitude after the maximum density and stiffness had been achieved. After the first couple of passes, it was observed that the density did not significantly increase and the elastic composite modulus from the Geogauge and IC roller response decreased at multiple test points.

It was hypothesized that the high amplitude initially used to compact this area increased the density of the crushed stone surface but adversely affected the lower portion of the crushed stone base and underlying select granular embankment (reducing the stiffness or de-compacting that layer). The Geogauge elastic modulus is a composite value that represents the material from the surface to a depth between 9 to 12 inches below the surface. The response of the IC roller also slightly increased and decreased in different areas after the first pass, and then basically remained the same because its response is also influenced by the change in stiffness of the supporting layers. Based on the Geogauge and IC roller responses from the first couple of passes, the amplitude was decreased to protect the supporting materials from further damage.

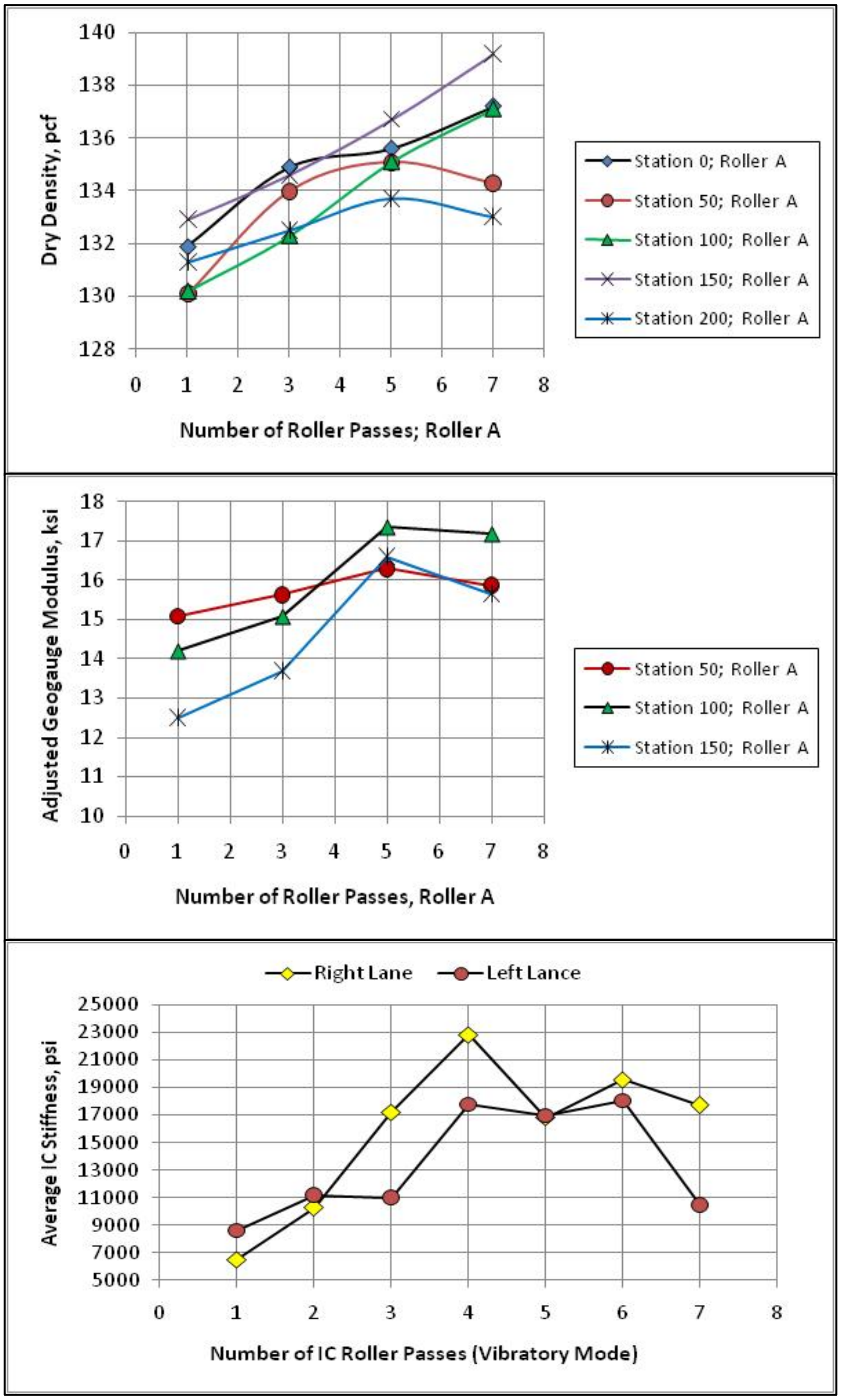


Figure 55. Density-Stiffness Growth Relationship for Crushed Aggregate Base; 1st Lift (Jefferson Project)

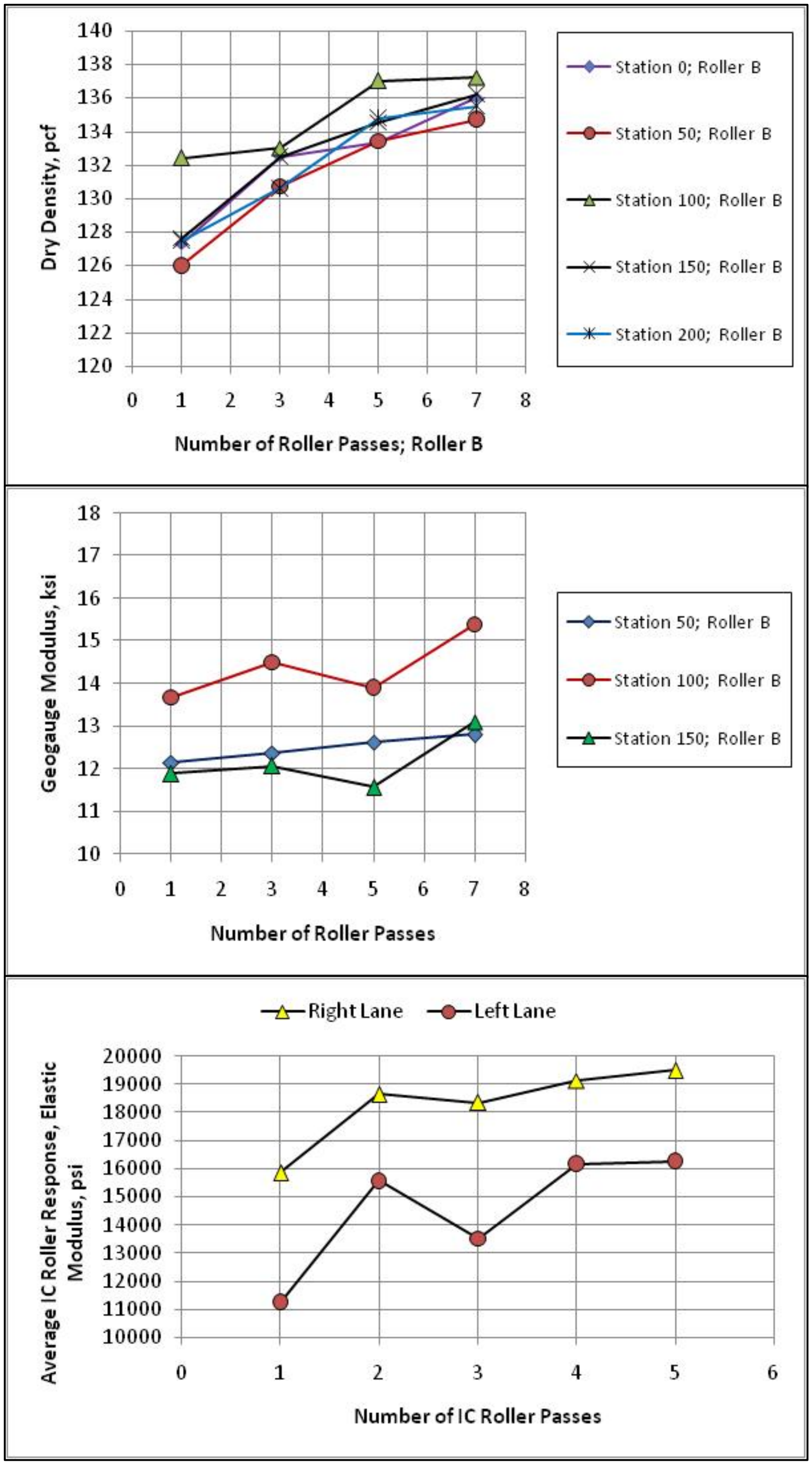
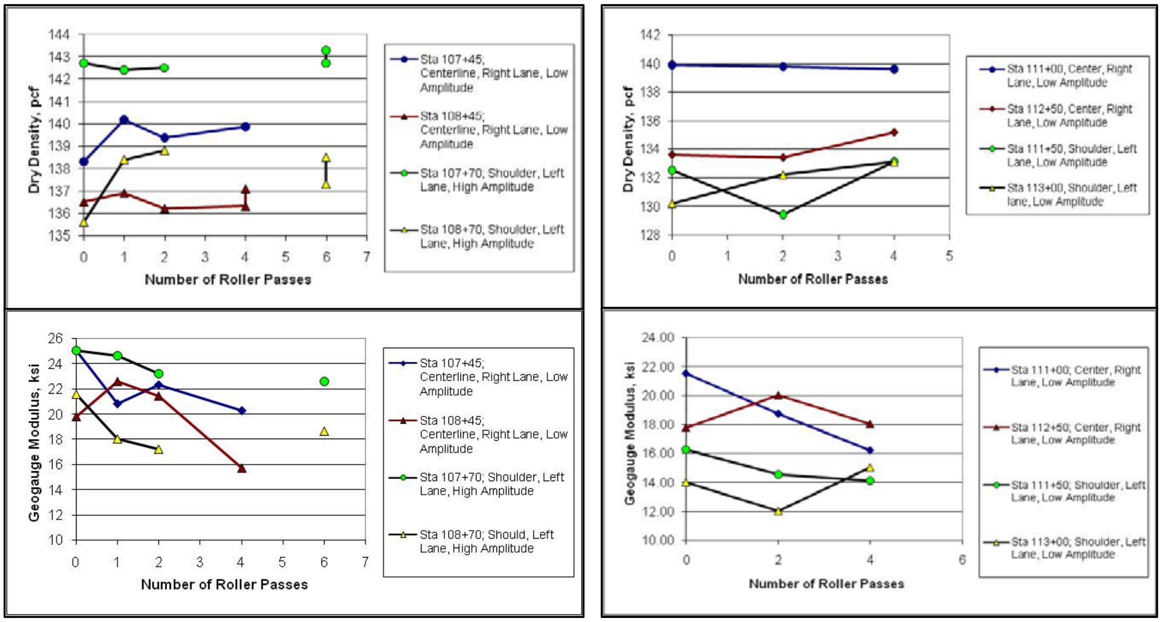


Figure 56. Density-Stiffness Growth Relationship for Crushed Aggregate Base; 2nd Lift (Jefferson Project)

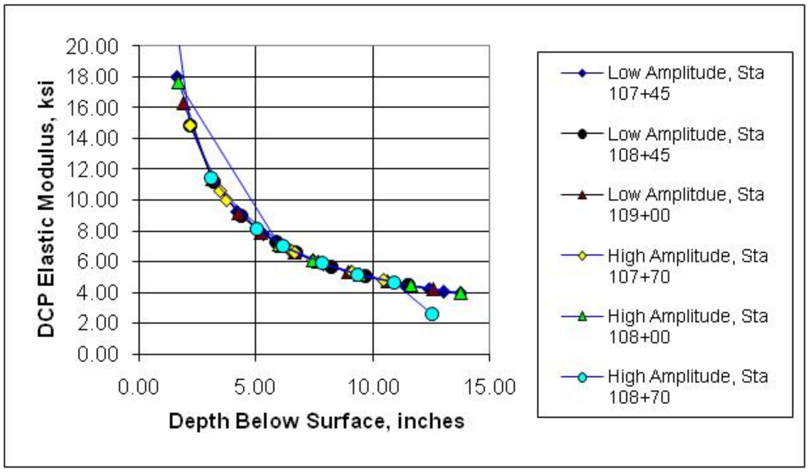


(a). Section 1 (a). Section 2

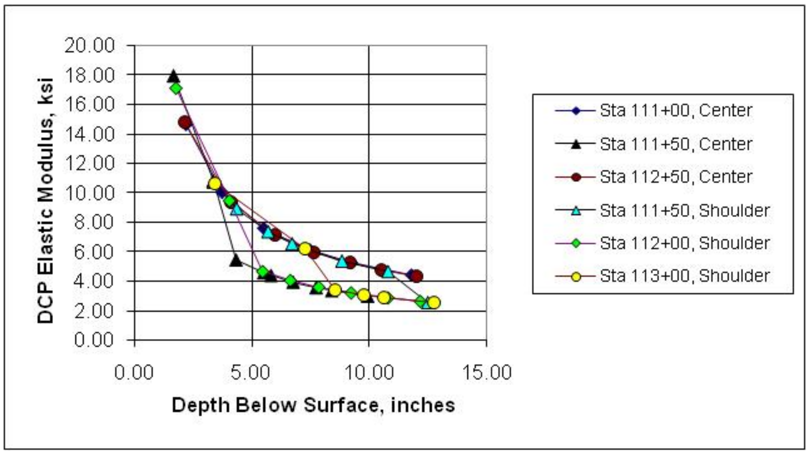
Figure 57. Highland Project; Density-Stiffness Growth Curves for the Crushed Stone Base

For the final pass, the amplitude of the Sakai IC roller was decreased to the lowest setting for mapping the stiffness of the crushed stone base layer. After IC rolling, the DCP was used to measure the modulus of the crushed stone and the top part of the granular base layer. Results from the DCP tests are shown in Figure 58. As shown, the DCP elastic modulus for the lower portion of the crushed stone base and below the crushed stone is low, especially for select granular materials that have been adequately compacted. Although this observation is considered an anomaly, it does show the value of using the IC roller response to make decisions in real-time about material behavior and densification.

Density-stiffness relationships were not measured for the RAP base material that the contractor had already placed along the Highland project. This layer was ready for paving which had been scheduled for the latter part of this demonstration project, so scarifying that layer was not an option.



Test Section #1



Test Section #2

Figure 58. Highland Project; Elastic Modulus Calculated from the DCP Penetrometer Rate Readings within and through the Crushed Stone Base Layer

4.2.2 High Plasticity Clay

Only a few density-stiffness growth relationships for the high plasticity clay embankment were prepared because of the rains that occurred during this demonstration project.

Figure 59 shows the density-stiffness growth relationship for the A-6 foundation layer (1st lift) that had already been placed and rolled by the contractor using a standard single smooth-steel drum roller. As shown, the dry density slightly increased, while there was a significant increase in the Geogauge elastic modulus and IC roller response for the first two to four passes. The sixth pass of the Sakai IC roller resulted in a decrease in the stiffness of the embankment for all test points being monitored for the density-stiffness relationship.

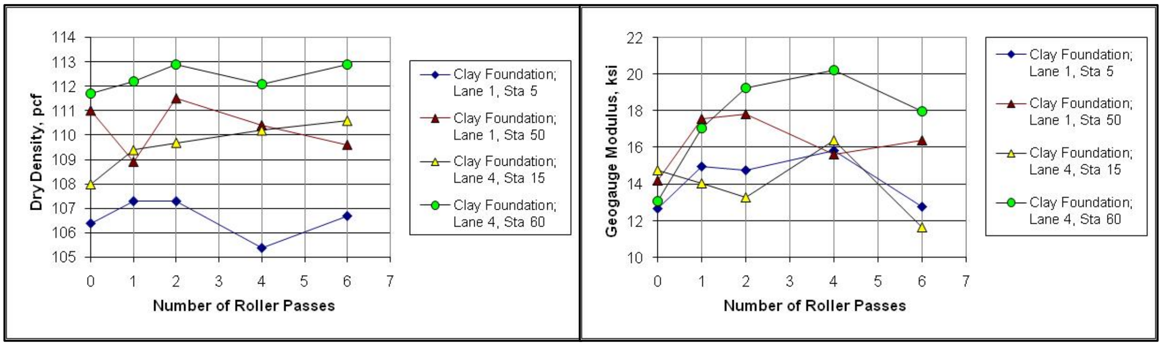


Figure 59. Highland Project; Density-Stiffness Growth Curves for the A-6 High Plasticity Clay Foundation (1st Lift)

Figure 60 shows the density-stiffness growth relationship that was prepared for the 3rd lift of the embankment (A-7-6 clay). As shown, the density of the A-7-6 embankment layer increases with number of roller passes, but the Geogauge elastic modulus basically remained unchanged after the first couple of passes of the roller. The Sakai IC roller responses had a similar trend—they increased through the first four passes and then decreased-increased between successive passes.

A possible reason for this observation is that the high plastic clay was found to have a highly variable water content (above and below the optimum value) and began to exhibit lenses and cracks at the surface (refer to Figure 61). It is believed that the cracks and interface between these lenses resulted in lowering the Geogauge modulus but not the nuclear density readings. A similar observation was made at the NCAT test track during the compaction and in-place testing of a high plasticity soil (Von Quintus et al., 2009). The use of a sheep-foot roller would have prevented this condition along the Highland project. Unfortunately, a sheep-foot roller was unavailable, as discussed in Chapter 3.

The density-stiffness growth relationship for the 2nd lift of the A-6 high plasticity clay embankment was not measured because the material was wet, near saturation and heavy rains were in the forecast.

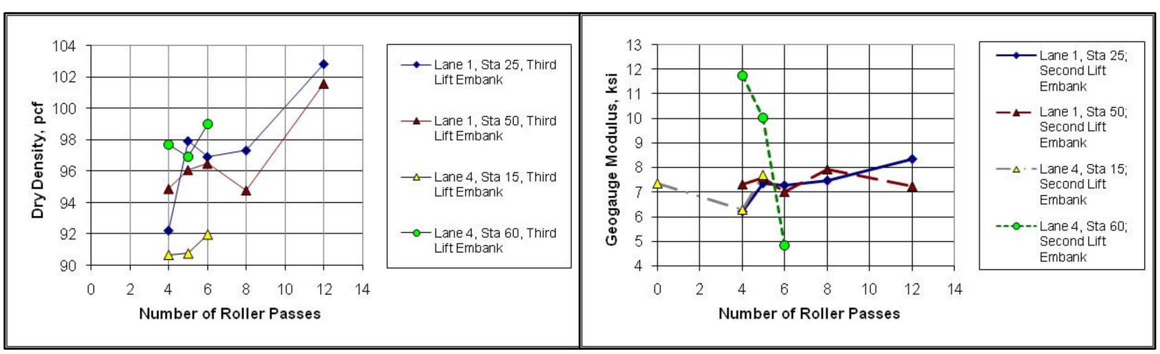


Figure 60. Highland Project; Density-Stiffness Growth Curves for the A-7-6 High Plasticity Clay Embankment (3rd Lift)

Figure 61. Condition of the Surface of the High Plasticity Clay Embankment during the Compaction Process (Highland Project)

4.2.3 Low Plasticity Clay

Figure 62 shows the stiffness-growth relationship measured with the IC roller response for the sandy silt or A-4 embankment (1st lift) placed at the Jefferson project. Density-stiffness relationships were not measured for the sandy silt embankment using point NDT because of the heavy rains that occurred prior to arriving at the site.

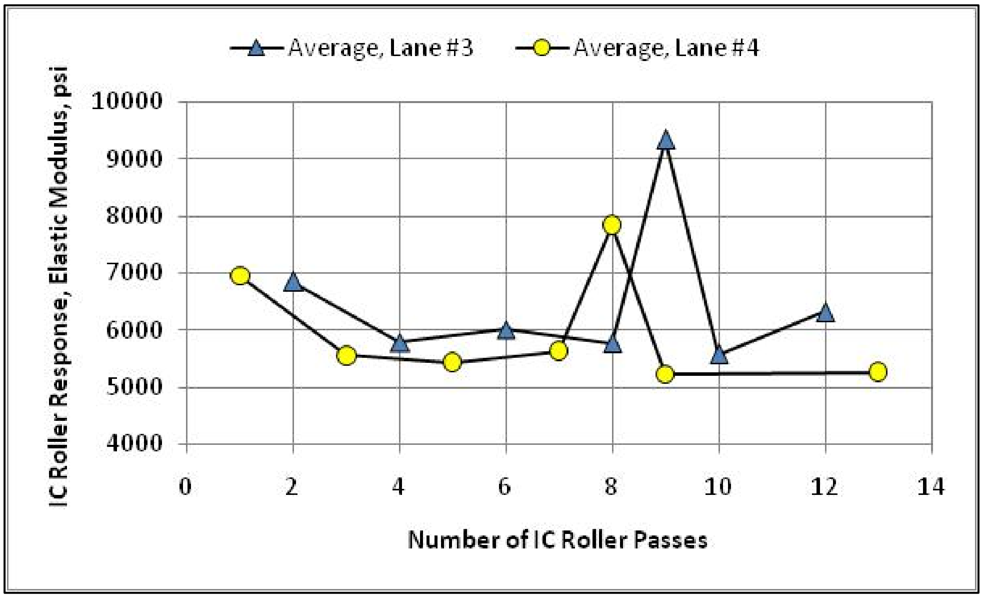


Figure 62. Density-Stiffness Growth Relationships for the Sandy Silt, A-4 Embankment, 1st Lift (Jefferson Project)

As noted above, this lift had already been placed and rolled by the contractor using a standard single smooth-steel drum roller. As noted in Chapter 3, the area used for the demonstration was a large fill section between two bridges. The IC roller response did not indicate any increase in stiffness of the test lanes with over 14 passes of the roller. One possible explanation for this observation is that the contractor's rolling pattern already achieved the maximum density and stiffness appropriate for the site conditions and properties of this soil. Another possible explanation for this observation is that the water content of this lift during IC rolling was near saturation. The reason for the large number of passes in each lane of this area was to determine the effect of using different operational modes (automatic and manual with different vectors) on the stiffness of the material. The different modes of operation did not appear to have any impact on the stiffness of the material.

Figure 63 includes the density-stiffness growth relationship for the poorly graded sand or A-3 embankment layer, the 2nd lift that was placed along the Jefferson project. As shown, the maximum density and stiffness were achieved at 5 to 10 passes. One reason for the higher number of passes is that the surface of the poorly graded sand became too dry for using vibratory rollers. The poorly graded sand was being displaced by both vibratory rollers (Sakai and Bomag), so water was added to continue the compaction operation. In addition, the amount of sand in the A-3 embankment increased from Lane #1 to #4. The increasing sand content in Lane #4 is believed to explain the wide range in IC elastic modulus between successive passes of the roller.

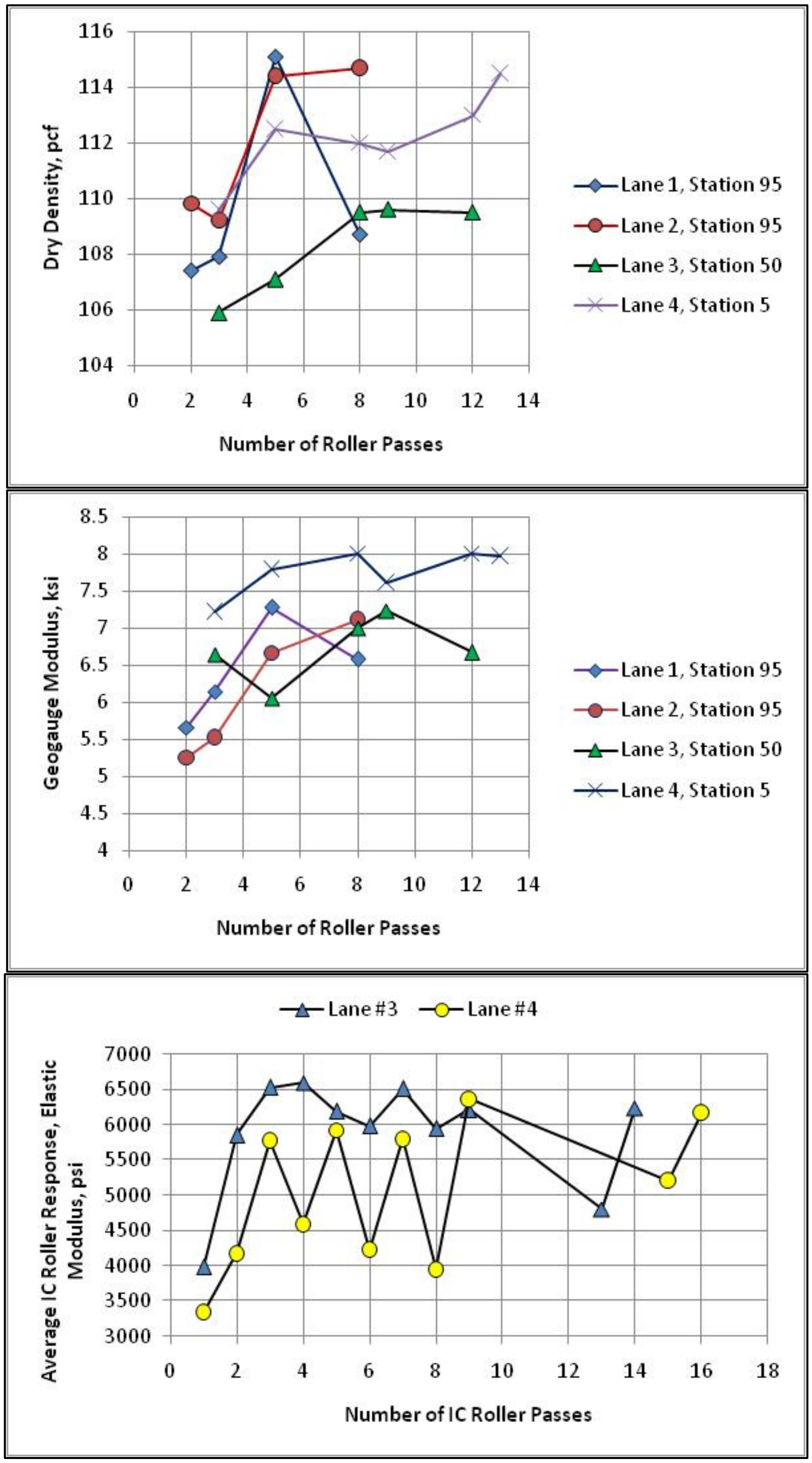


Figure 63. Density-Stiffness Growth Relationships for the Poorly Graded Sand, A-3 Embankment, 2^{nd} Lift (Jefferson Project)

4.2.4 Summary

Although anomalies were identified from the density-stiffness growth relationships, the demonstration projects showed the value of using the IC rollers to identify those anomalies and to investigate or explain them, and more importantly, to change the rolling pattern to eliminate any damage to previously compacted layers and improve the compaction process or rolling pattern to increase density and stiffness of the layers.

4.3 Layer Stiffness Monitoring – Uniformity and Increased Density

The field demonstration projects were used to determine the benefit of monitoring layer stiffness using the IC rollers in terms of changing density or stiffness to reduce variability with the fewest number of roller passes. Two conditions were used to make these comparisons—use of the contractor's standard rollers and pattern (defined as prior to IC rolling) and use of the IC roller (defined as after IC rolling). Three parameters were used to determine the benefit: density measured with the nuclear gauge, Geogauge composite elastic modulus, and DCP stiffness gradient. The following summarizes the findings relative to material uniformity:

- Figure 64 provides a comparison of the in-place dry density prior to and after IC rolling. For this project, the in-place dry density was improved by using the IC rollers, while the variability in density values decreased. It should be noted that on other sections the contractor's standard compaction operation adequately achieved the required density with about the same or less variability.
- Figure 65 provides a comparison of the DCP results in terms of elastic modulus with depth of testing. As shown, the magnitude of the elastic modulus values increased and the variability decreased in the test area or lane. Conversely, there were other test sections where the amount of variability increased, as shown by Figure 66. It is expected that the use of the Level 3 IC rollers that vary the amount of energy depending on the roller's response actually can increase the variability, especially when there are stiffness anomalies just below the layer being compacted.

Figure 67 summarizes the COV for the densities and Geogauge elastic modulus values. Across all projects there is a slight increase in variability when using the IC rollers, in comparison to the standard rollers that were used by the contractor. Other studies, however, have shown a decrease in material variability with the use of IC rollers (Von Quintus et al., 2009). Increased variability can be important, especially under a Percent Within Limits (PWL) type of specification.

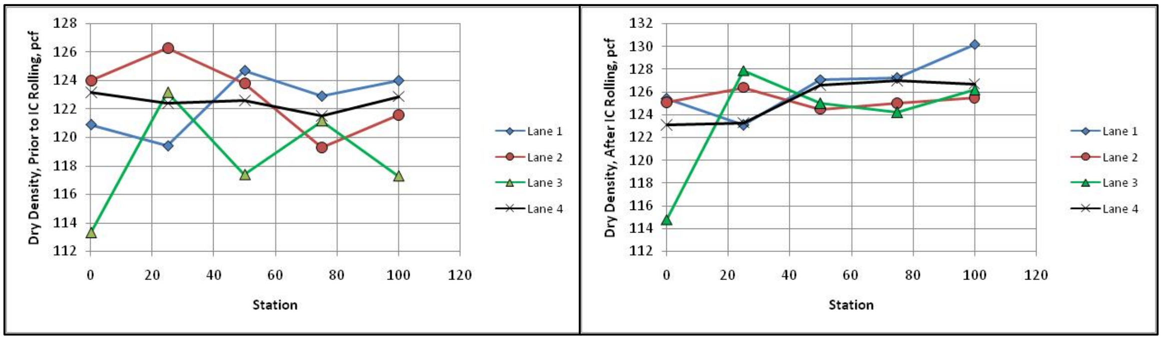


Figure 64. Jefferson Project; Comparison of the Dry Densities Prior to (Standard Rollers) and After IC Rolling

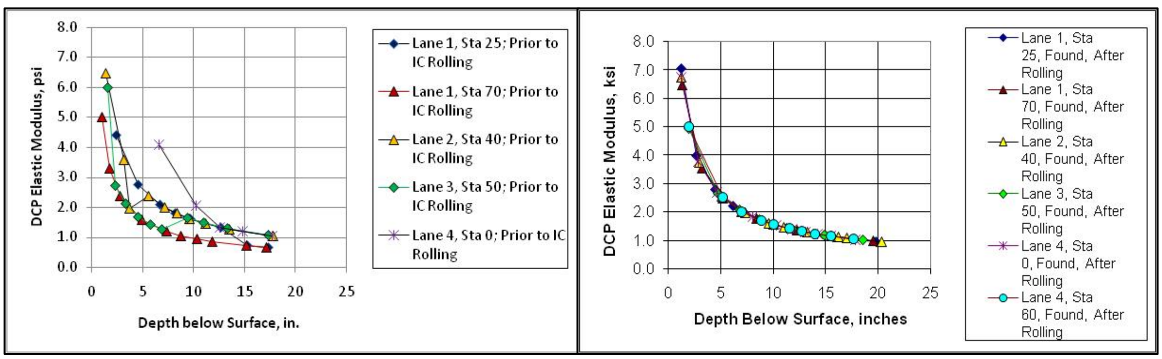


Figure 65. Highland Project; Comparison of the Elastic Modulus Calculated from the DCP Test Results Prior to (Standard Rollers) and After IC Rolling

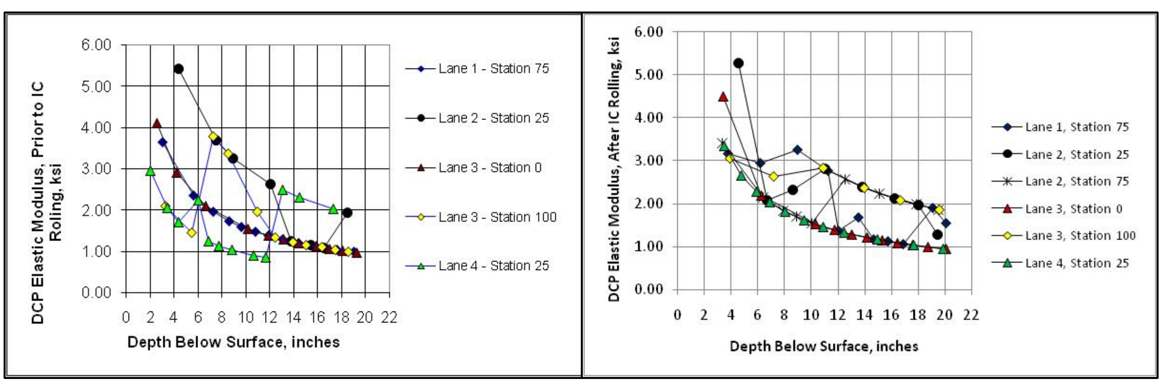


Figure 66. Jefferson Project; Comparison of the Elastic Modulus Calculated from the DCP Test Results Prior to (Standard Rollers) and After IC Rolling

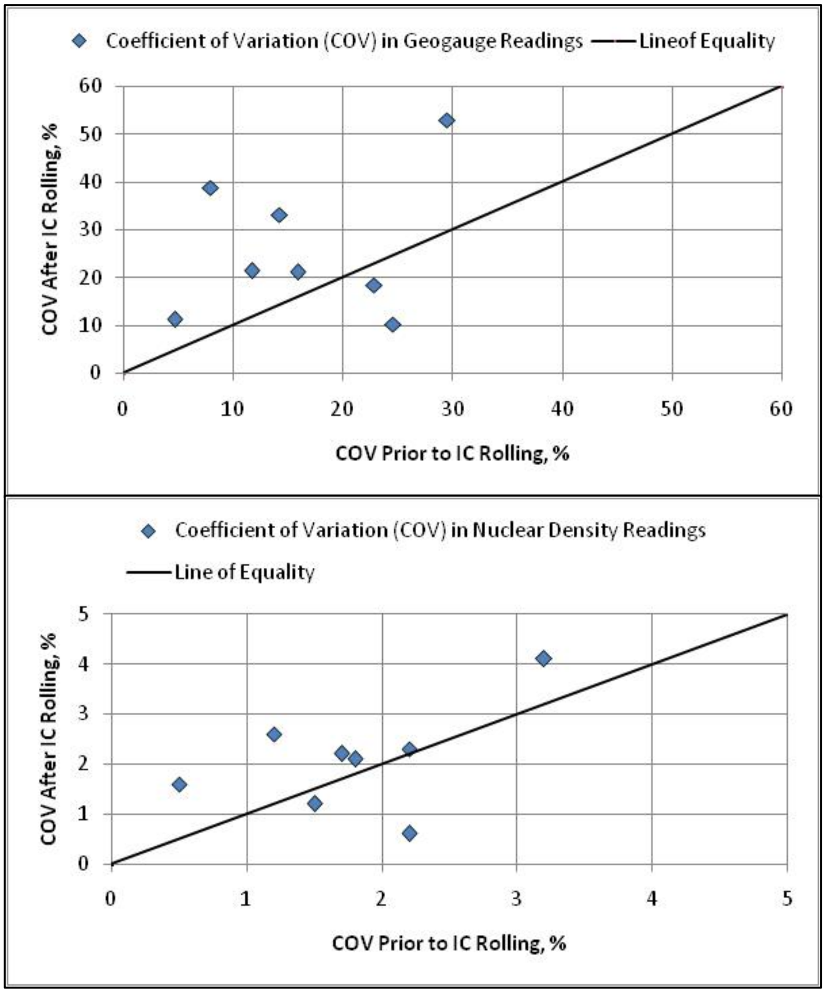


Figure 67. Comparison of Layer Variability Prior to and After IC Rolling

4.4 Identification of Stiffness Anomalies & Damage – Soft Spots

One of the most important benefits of IC rollers is the ability to identify stiffness anomalies in underlying layers and damage to the surface layer from over-rolling. The Jefferson project clearly demonstrated this benefit. The following summarizes the observations from the IC roller responses using the Bomag Level 3 IC roller to compact and test the first and second lifts of the crushed aggregate base:

- Figure 68.a shows the Bomag's E_{vib} values measured during the first pass. As shown, the E_{vib} values are lower as expected. In addition, there are definite soft areas in the foundation that were not originally identified using standard point test methods. The IC roller can be used as a continuous testing device to identify these weak areas and segment the project into areas with similar IC roller response values.

- Figure 68.b shows the E_{vib} values after the second pass. As shown, the average E_{vib} value has increased from 16.5 ksi (first pass) to 20.3 ksi. In addition, the weaker areas are more pronounced and easily identified because the stiffness of the crushed aggregate base is increasing above the soft areas, so more energy is being transmitted into the lower layers. The E_{vib} values above the soft areas remain about the same (shown as the minimum E_{vib} value in the figure), because the E_{vib} is a composite value influenced by the stiffness of supporting layers. The E_{vib} values above the areas with the stronger subsurface layers are increasing, because more energy in going into the crushed aggregate base.
- Figure 68.c shows the E_{vib} values after the fourth pass. As shown, the average E_{vib} value has increased to 22.8 ksi. The E_{vib} values above the weaker areas are still about the same as for the first pass. This demonstrates the effect of soft spots along the project on the roller responses. Weak areas should be removed and replaced or improved through some stabilization process to improve of the uniformity of the compacted layer and to eliminate the influence of the underlying support layers for interpreting the IC roller response values.
- Figure 68.d shows the E_{vib} values after the seventh pass. As shown, the average E_{vib} value decreased to 17.7 ksi. The results suggest de-compaction or damage to the crushed aggregate base layer. In fact, Figure 69 shows the surface condition of the crushed aggregate base in areas above the weak and other areas of the roadway. Surface cracks and crushed aggregate began to be observed between the sixth and seventh pass. These cracks and the amount of crushed aggregate were in the crushed aggregate base were greater above the weaker areas, but they were not restricted to the weaker areas.
- Figure 70 shows the E_{vib} values for the adjacent lane (left lane) along this roadway. The maximum average E_{vib} value along the left lane was 18.0 ksi and occurred during the sixth pass. The changes in IC roller response values (E_{vib} values) were similar to those measured along the right lane (Figure 68), except that the average E_{vib} values are lower and there was a greater reduction in E_{vib} values during the seventh pass (Figure 70.d, as compared to Figure 68.d).

The average E_{vib} values began to increase with continued passes but remained less than the average maximum stiffness of 22.8 ksi that was measured during the fourth pass of the IC roller. Thus, the contractor continued with the compaction operation in other areas using five passes. The strip charts were not printed during the rolling operation for the final passes of the roller.

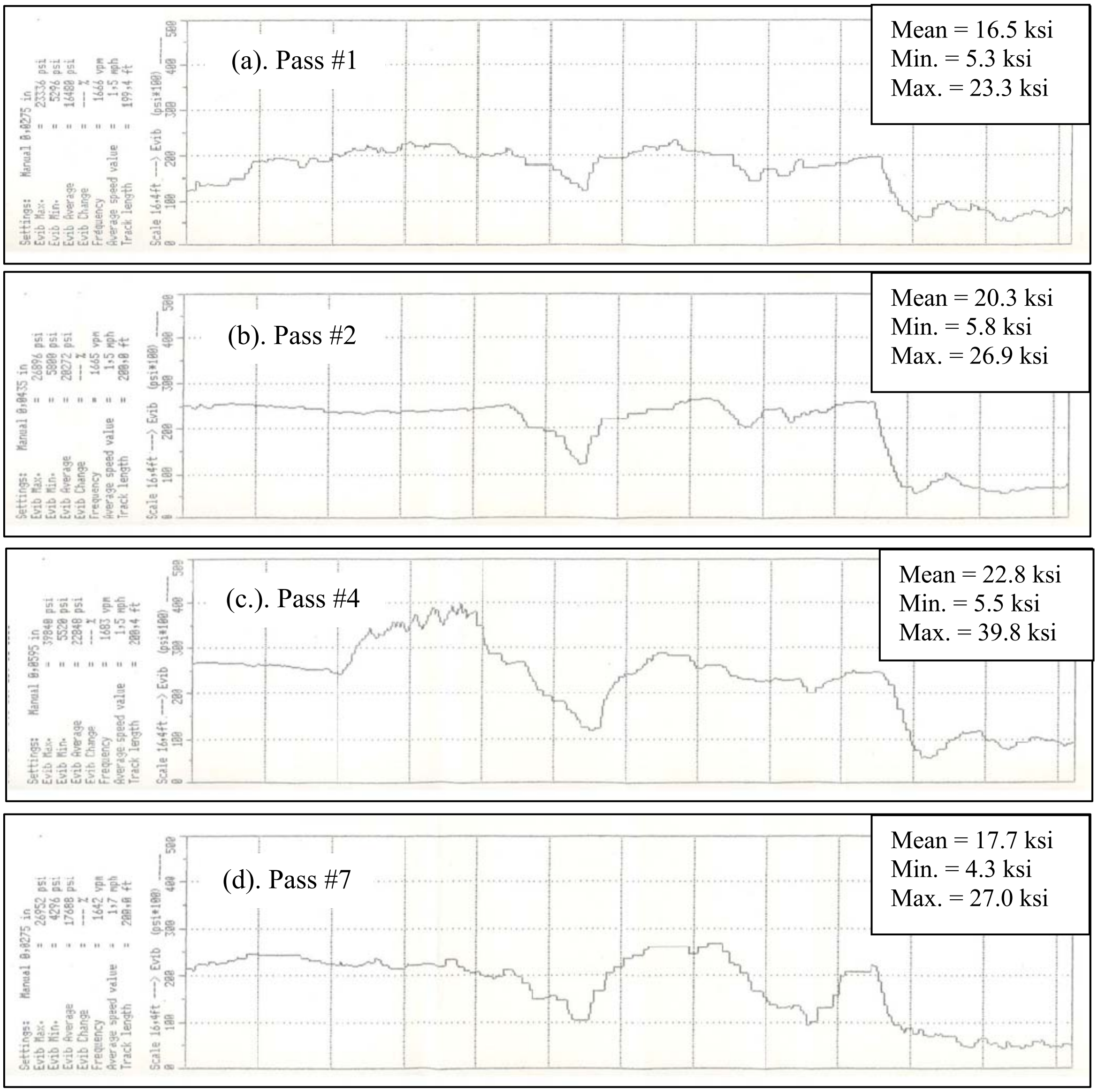


Figure 68. Charts from the Bomag IC Roller Showing the E_{vib} Values for Different Roller Passes; Jefferson Project; Crushed Aggregate Base, Right Lane, 1st Lift

Figure 69. Jefferson Project; Photographs of the Crushed Aggregate Base Surface Showing the Cracks and Crushed Aggregate

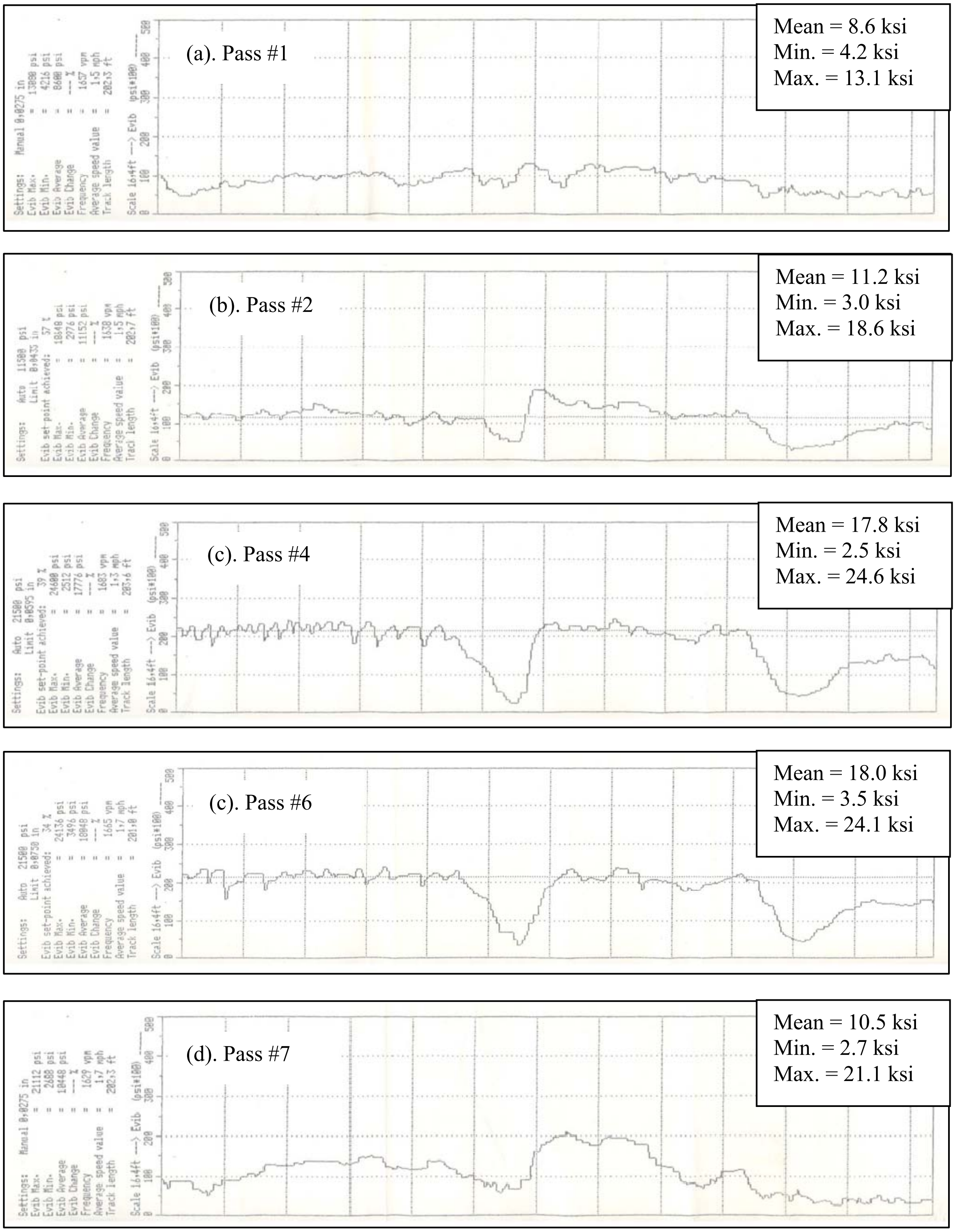


Figure 70. Charts from the Bomag IC Roller Showing the E_{vib} Values for Different Roller Passes; Jefferson Project; Crushed Aggregate Base, Left Lane, 1st Lift

Figures 71 and 72 show the E_{vib} strip charts for the second 6-inch lift of crushed aggregate placed along the right and left lanes, respectively. Only five passes of the IC roller were used for compacting the second lift. Limiting the number of roller passes to five significantly limited the amount of cracks and crushed aggregate. Similar IC roller responses were measured for all lifts and lanes compacted with the Bomag IC roller.

Figure 71. Charts from the Bomag IC Roller Showing the E_{vib} Values for Different Roller Passes; Jefferson Project; Crushed Aggregate Base, Right Lane, 2nd Lift

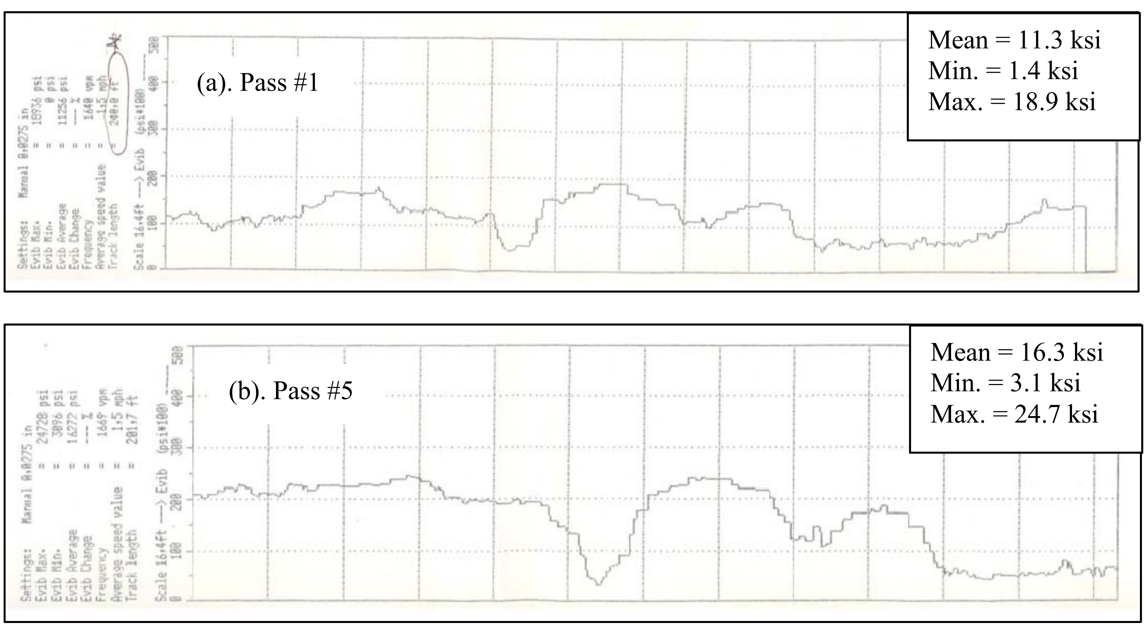


Figure 72. Charts from the Bomag IC Roller Showing the E_{vib} Values for Different Roller Passes; Jefferson Project; Crushed Aggregate Base, Left Lane, 2nd Lift

Another benefit of the IC rollers is to use them as a continuous testing device to map the stiffness prior to beginning the compaction operation of an additional layer. This benefit can be important on warranty-type projects, if the primary contractor was not responsible for placing or preparing the foundation.

Figure 73 shows the use of the IC roller in a testing mode to map the stiffness of an area for the sandy silt, A-4 embankment of the Jefferson project. Figure 30 in Chapter 3 shows the layout of the lanes in reference to Figure 73. As shown, the stiffness of the supporting foundation prior to placing an additional embankment layer is fairly uniform with no weak or soft spots. The amount of variability is also fairly low, even though the lanes are short. Figure 74 shows the stiffness map for Lanes 3 and 4 in the same area after the A-3, poorly graded sand embankment was compacted. As shown, the average values are uniform and the average E_{vib} value for Lane 4 was increased after placing the A-3 embankment, while the E_{vib} value for Lane 3 remained unchanged after compaction.

One physical condition that was not identified by the IC roller response was the testing to map the RAP base layer along the Highland project. As noted above, this layer previously had been placed and compacted by the contractor and was ready for paving. The Sakai IC roller was used to map the area in relating the IC roller response to the other NDT-measured properties. The roller was used to test a small section of the RAP base after the high plasticity clay had been compacted and tested, the day prior to the heavy rains that occurred. The roller was operated in high amplitude prior to the test section that had been designated for testing without any noticeable effect on the RAP base layer. The density and moisture content tests using the nuclear density gauge showed that the moisture content of the RAP base and below this layer significantly increased after the heavy rain.

The day following the heavy rains, the IC roller began the mapping process in high amplitude mode. After mapping a short distance, short transverse cracks were observed behind the roller (refer to Figure 75). The IC roller response did not indicate any substantial change in stiffness over this short distance. Once the cracks were visually observed, the roller was stopped. The roller setting was then decreased to low amplitude to map the area. No cracks were observed in the RAP base under the low amplitude setting, so the entire test area was mapped. The Sakai IC roller response did not identify any significant weak or soft spots within this area. Thus, it was concluded that the higher water contents in the RAP base and other layers were consistent throughout the area.

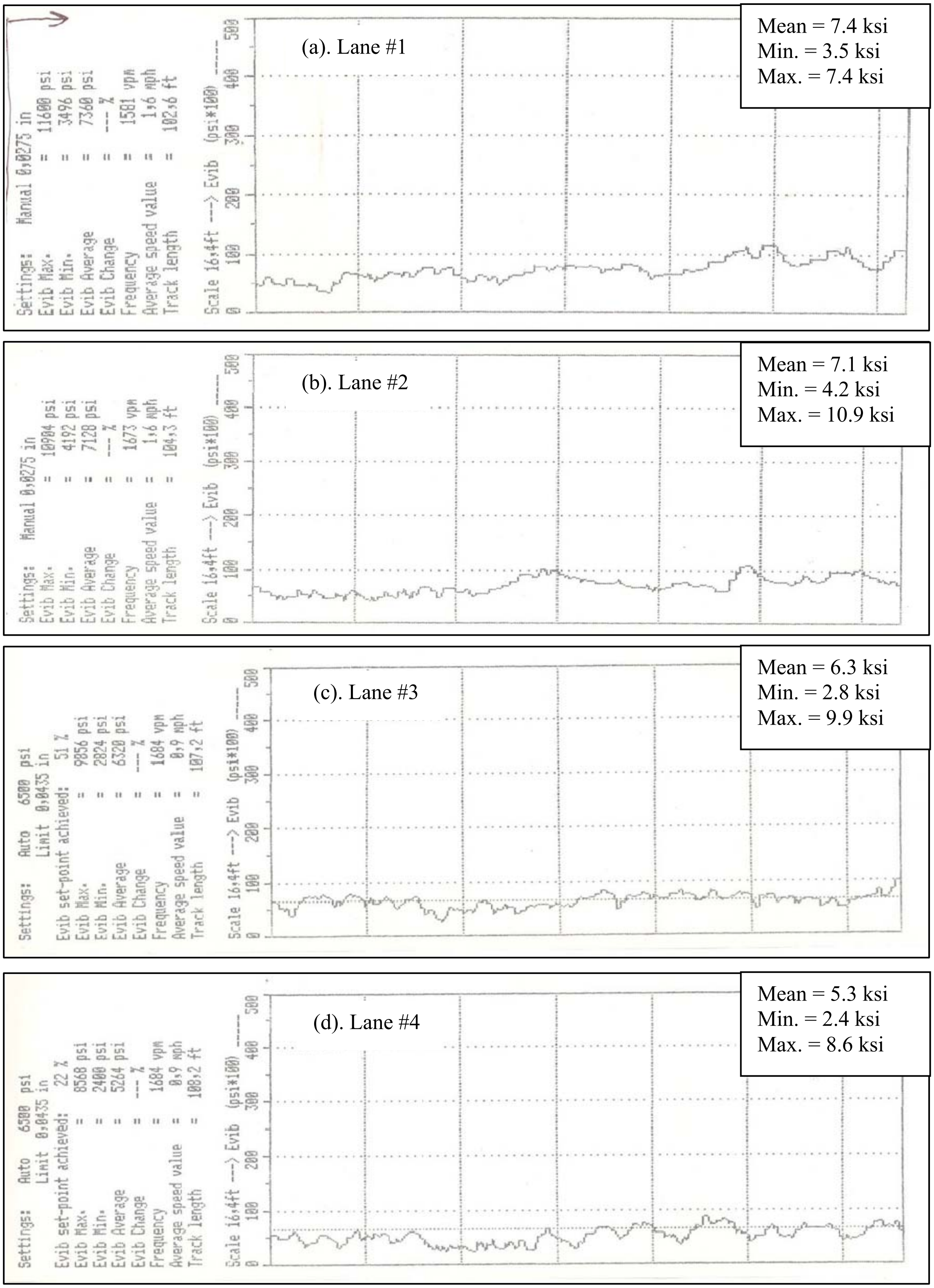


Figure 73. IC Roller Response Used to Map the A-4, Sandy Silt Embankment; Jefferson Project

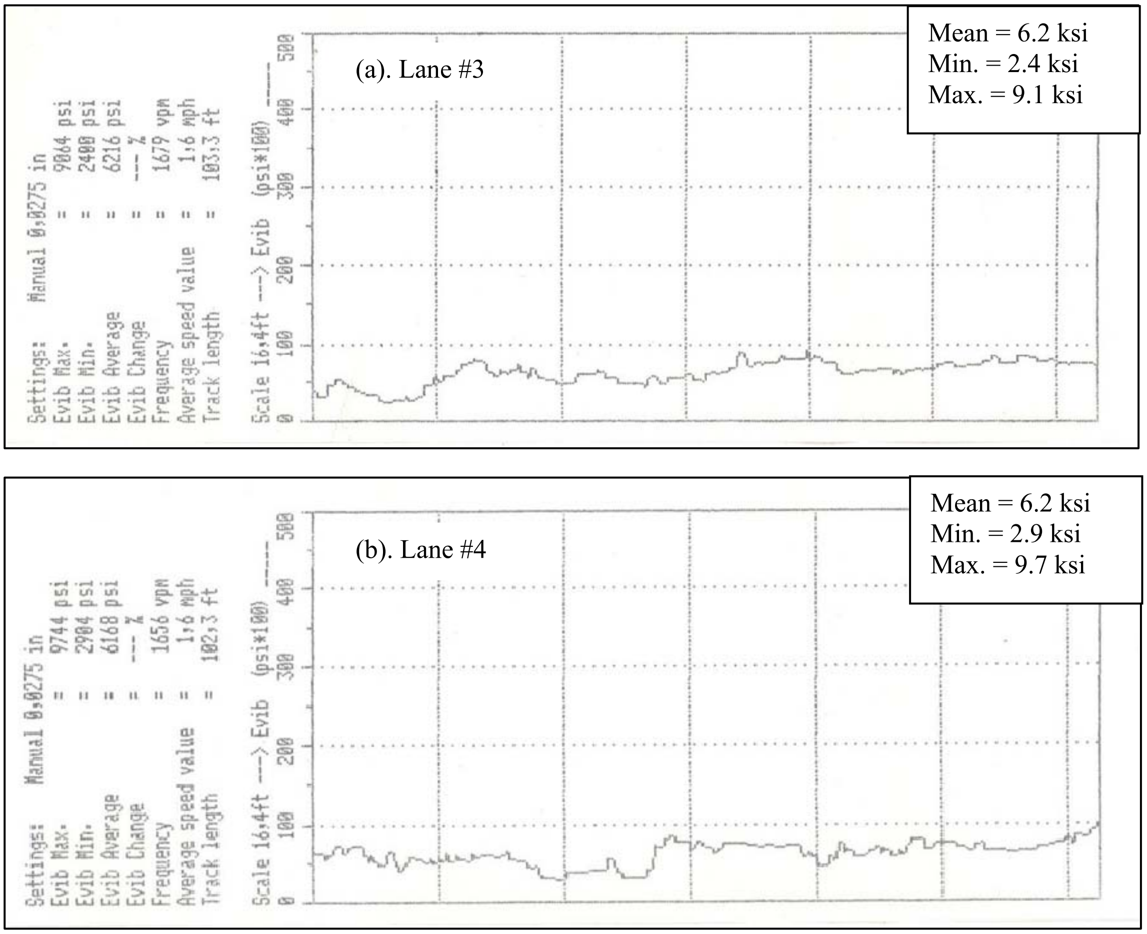


Figure 74. IC Roller Response Used to Map the A-3, Poorly Graded Sand Embankment; Jefferson Project

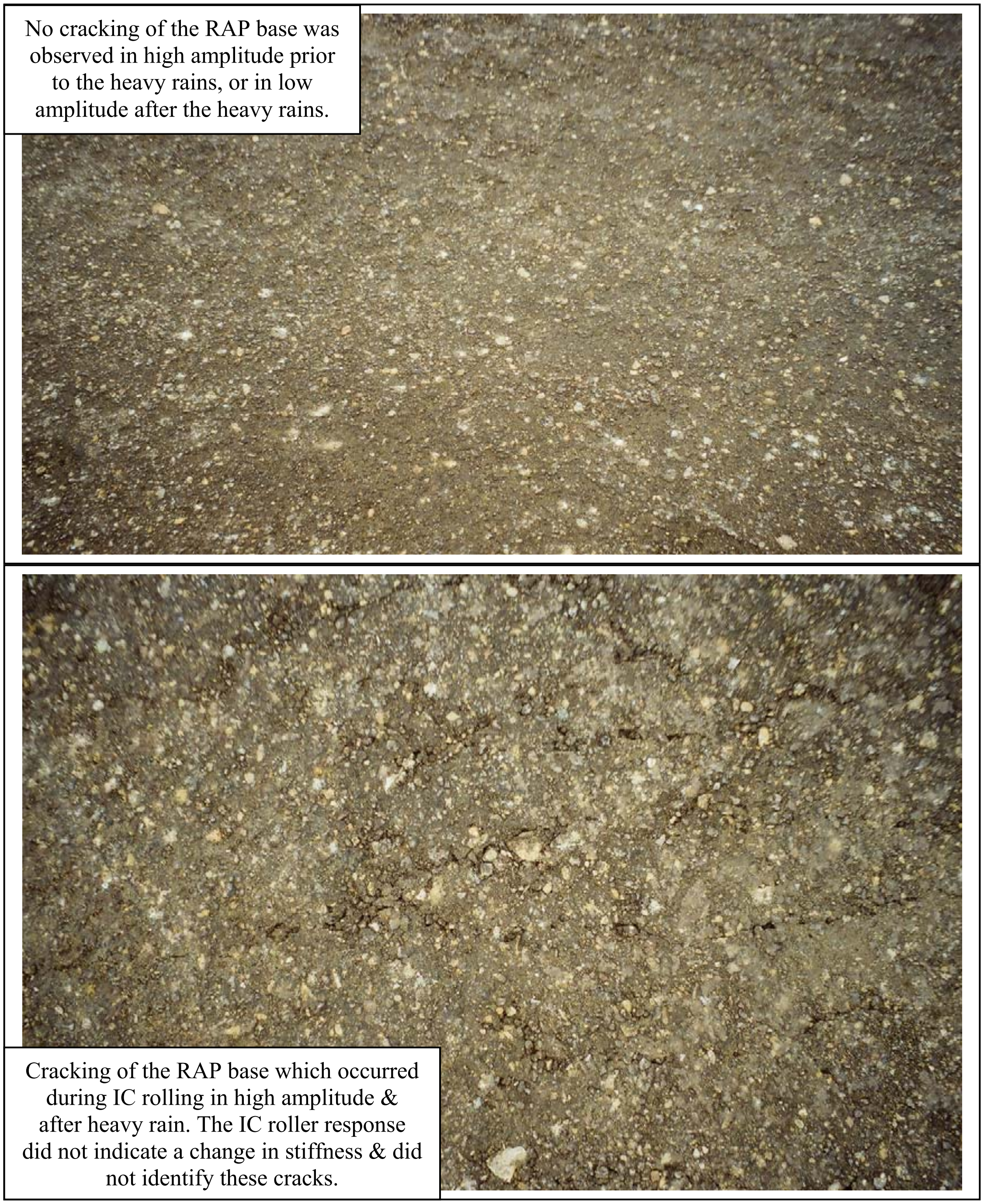


Figure 75. RAP Base, Highland Project; Cracks that Occurred in the RAP Base Under High Amplitude Operation of the IC Roller

4.5 Interpretation of Results for Judging Acceptability

The purpose of this section is to interpret the IC roller and NDT responses in terms of deciding whether pavement design assumptions have been satisfied. Acceptability is used in this case as exceeding the modulus used in design. The procedure recommended in NCHRP Report #626 was followed and is summarized below:

1. Perform repeated load resilient modulus tests to determine the stress sensitivity of the material (refer to Appendix C). Results from the resilient modulus tests are used to determine the average value to be used in pavement design, as well as in setting the target value for judging whether the design assumptions have been met. It is assumed that the stress sensitivity of the material is constant for different density-water content combinations within typical construction variability.
2. Determine the average resilient modulus value used in design for each material, using the average stress state expected under the pavement.
3. Determine the average resilient modulus value using the stress state under the rollers. This value is used for setting the target value for evaluating the acceptability of the material during construction.
4. Measure the modulus of the material during compaction using the IC roller response and Geogauge. Determine the average value within each test area or lot.
5. Adjust the Geogauge and IC roller elastic modulus or the target laboratory resilient modulus to eliminate bias between laboratory and field measured modulus values. Table 13 summarizes the adjustment ratios used for judging the acceptability of the layers.
6. The field measured values should exceed the construction target value for the design assumption to have been exceeded.

Table 13. Adjustment Ratios; Laboratory to Field Modulus Values

<table>
<tr><th rowspan="2">Material Type</th><th rowspan="2">Specific Material/Soil Included in Demonstration Projects</th><th colspan="2">Geogauge</th><th colspan="2">IC Roller</th></tr>
<tr><th>Test Area</th><th>Value Suggested for Use</th><th>Test Area</th><th>Value Suggested for Use</th></tr>
<tr><td rowspan="3">High Plasticity Soil</td><td>A-7-6 Embankment</td><td>1.34</td><td rowspan="3">0.7</td><td>1.77</td><td rowspan="5">1.2</td></tr>
<tr><td>A-6 Foundation</td><td>1.19</td><td>1.17</td></tr>
<tr><td>A-6 Embankment</td><td>0.69</td><td>1.25</td></tr>
<tr><td>Low Plasticity Soil</td><td>A-4 Sandy Silt</td><td>0.88</td><td>0.9</td><td>1.20</td></tr>
<tr><td>Sandy Soils</td><td>A-3 Poorly Graded Sand</td><td>0.99</td><td>1.0</td><td>1.15</td></tr>
<tr><td rowspan="2">Aggregate Base</td><td>Crushed Aggregate</td><td>0.98</td><td rowspan="3">1.0</td><td>0.86</td><td rowspan="3">0.9</td></tr>
<tr><td>Crushed Stone</td><td>1.09</td><td>0.98</td></tr>
<tr><td>RAP Base</td><td>RAP Base</td><td>0.98</td><td>0.88</td></tr>
</table>

Table 14 summarizes the average design value, target construction value, and field measured value, and whether the in place material exceeds the design assumption. The following defines the information included in Table 14:

- Design Resilient Modulus. The pavement structure planned for construction was used to estimate the stress state in the embankment and/or aggregate base layers for the appropriate material using the repeated load resilient modulus tests included in Appendix C. For design, it is generally assumed that the material will be compacted at the optimum water content to 95 to 100 percent% of the maximum dry density. This value is used in design to determine the layer thickness requirements above the layer in question. The average value from the resilient modulus tests at the optimum water content and maximum dry unit weight was entered in the Table 14.
- Construction Resilient Modulus. As stated previously, the stress state was estimated under the IC roller during compaction. This stress state was used to determine the resilient modulus value from the repeated load resilient modulus tests included in Appendix C. The construction resilient modulus can be lower or higher than the design resilient modulus depending on the stress sensitivity of the material (stress hardening versus stress softening materials). This value becomes the target value for estimating whether the in-place material exceeds the design resilient modulus because of the difference in stress states. The average value from the resilient modulus tests was entered in the Table 14.
- Geogauge Elastic Modulus. This is the adjusted Geogauge modulus and represents the average value measured after compaction with the IC roller. The adjustment factor or ratio eliminates the bias between the laboratory and field measured values (refer to Table 13).
- IC Roller Elastic Modulus. This is the adjusted elastic modulus estimated from the IC roller response parameter and represents the average value within an area. The adjustment factor or ratio eliminates the bias between the laboratory and field measured values (refer to Table 13).
- Compaction. This is the percent compaction value determined from the in place dry density and maximum dry unit weight included in Appendix A for the appropriate material.

Results from the Geogauge and IC rollers were found to be above the construction target resilient modulus value for 3 of 8 test areas (acceptable areas), 2 of 8 were borderline; and 3 of 8 were below the target value (rejected areas). For the areas that were rejected, all could be explained by volumetric properties that deviated from the standard practice. All of these were planned or caused by weather events—none were related to improper operations of the contractor.

Table 14. Summary of Results and Decision from Field IC Tests

Material	**Resilient Modulus, ksi**		**Elastic Modulus, ksi**		**Comment Related to Control & Acceptance**
	Design	**Construction**	**Geogauge**	**IC Roller**	
A-6 Clay Foundation	11.8	10.6	10.3	10.4	Compaction = 101.6% Design assumption is borderline. Reason for low stiffness – water content was above optimum value.
A-6 Clay Embankment	16.5	16.0	3.7	5.9	Compaction = 93.2% Design assumption not satisfied; layer rejected by both Geogauge & IC roller. Reason for low stiffness – water content was well above the optimum value.
A-7-6 Clay Embankment	16.0	15.2	7.3	9.6	Compaction = 105.1% Design assumption not satisfied; layer rejected by both the Geogauge & IC roller. Reason for low stiffness – water content was highly variable during compaction.
A-4, Sandy Silt Embankment	11.0	9.0	8.6	9.1	Compaction = 92.4% Design assumption is borderline. Density is low because water content of material was well above optimum value.
A-3 Poorly Graded Sand Embankment	7.0	7.0	7.4	7.4	Compaction = 101.9% Design assumption exceeded; layer is acceptable.
Crushed Aggregate Base	12.0	15.8	16.2	16.5	Compaction = 93.8% Design assumption exceeded; layer is acceptable.
Crushed Stone Base	12.0	18.0	16.8	16.9	Compaction = 94.9% Design assumption not satisfied; layer rejected by both the Geogauge & IC roller. Reason for low stiffness – Material re-compacted in dry condition using low amplitude to prevent damage to supporting layers.
RAP Base	15.0	24.0	24.8	24.8	Compaction = 101.7% Design assumption exceeded; layer is acceptable. The layer was wet during testing, but the IC roller did not identify the wet supporting layer because the higher water contents are uniform over the area tested.

Note: The construction target modulus value is determined from the design value. The design assumption is satisfied when the Geogauge or IC roller elastic modulus value is greater than the target construction value. On the other hand, the design assumption is not satisfied when the Geogauge or IC roller elastic modulus value is less than the target construction value.

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CHAPTER 5 HOT MIX ASPHALT LAYERS

This chapter discusses the application and use of IC technology on selected demonstration projects in Wisconsin for monitoring the compaction process of HMA layers. The data collected from the demonstration project were analyzed to identify and/or confirm some of the limitations and benefits previously reported on the use of IC technology.[18] This chapter is grouped into five sections relative to the use of IC rollers: (1) relationship between the IC roller response and other material properties, (2) density and stiffness growth relationships, (3) uniformity of material stiffness and density, (4) identification of stiffness anomalies influencing the roller response, and (5) interpretation of IC roller responses related to design values.

5.1 Relationship Between IC Roller Response and Other Properties

The in-place HMA mixture properties and pavement features that are important relative to the IC response values are temperature, asphalt content, gradation, and aggregate physical properties, as well as the composite stiffness of the supporting layers. None of these properties were included in the test program on a point by point basis, but average values were available for the different lots included in the study. The HMA mixture was sampled during paving and the volumetric properties measured as part of the contractor's QC plan.

Tables 15 and 16 summarize the volumetric properties of the HMA mixture placed during this demonstration project. As shown, the contractor observed a slight change in the mixture properties within lot 14; voids filled with asphalt (VFA) increased, air voids of laboratory compacted specimens decreased, and maximum specific gravity (the Rice value) decreased. Although these changes are not considered significant, the HMA mixture definitely exhibited a change in stiffness during the compaction operation. The PSPA stiffness decreased 33 to 40 percent from the beginning of lot 14 (Section 2) to the end of the demonstration project (Section 7). This change in mixture stiffness is significant and indicates a change in the mix itself.

[18] Electronic files from the Bomag IC roller were not provided; only strip charts of the E_{vib} values were provided from each test area. The Sakai IC roller provided electronic files but no hard copies of the data during rolling operations.

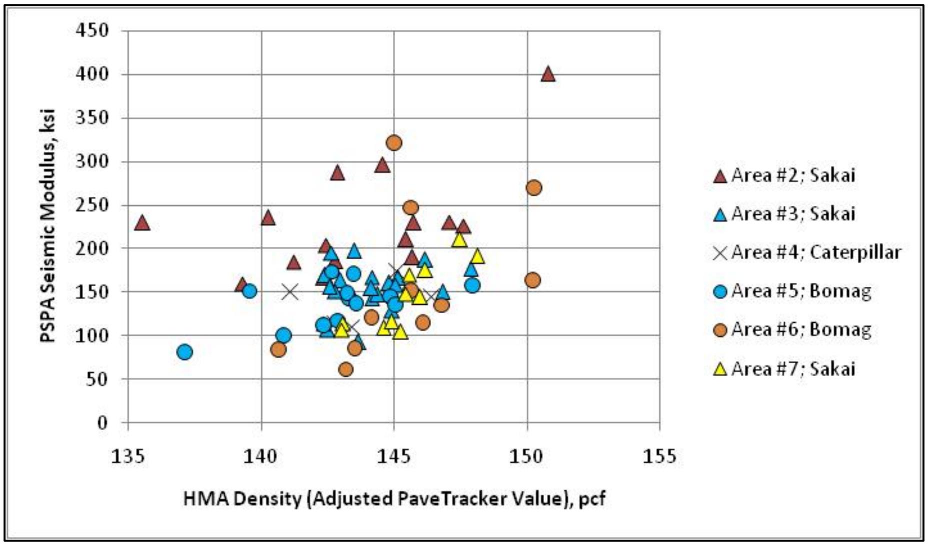
Table 15. HMA Gradation Properties; 19-mm Mixture

Date	Lot	Gradation, Percent Passing Sieve Size				
		9.5 mm	4.75 mm	1.18 mm	0.60 mm	0.075 mm
Job Mix Formula		*73.4*	*57.8*	*34.7*	*25.9*	*4.4*
9/29/2009	13-1	73.7	56.2	32.0	24.0	4.8
9/29/2009	13-2	76.2	58.4	33.1	24.1	4.2
9/29/2009	13-3	76.9	59.8	34.2	24.6	4.6
9/30/2009	14-1	76.4	56.6	32.0	23.2	4.4
9/30/2009	14-2	76.8	56.3	31.6	22.7	4.0
9/30/2009	14-3	75.9	56.9	32.9	24.6	4.9
9/30/2009	14-4	75.3	57.7	33.8	24.9	5.4
10/01/2009	15-1	76.7	56.4	31.5	23.1	4.5
10/01/2009	15-2	77.7	60.8	33.8	24.5	4.4
10/01/2009	15-3	72.5	54.4	31.6	23.1	4.2
10/01/2009	15-4	77.3	59.0	32.9	24.3	4.9

Table 16. HMA Volumetric Properties; 19-mm Mixture (Laboratory Compacted)

Date	Lot	Specific Gravity		Air Voids, %	Voids in Mineral Aggregate, %	Voids Filled with Asphalt, %
		Bulk	Rice			
Job Mix Formula		*2.483*	*2.586*	*4.0*	*13.5*	*70.4*
9/29/2009	13-1	2.447	2.542	3.7	14.5	74.5
9/29/2009	13-2	2.421	2.537	4.6	15.4	70.1
9/29/2009	13-3	2.421	2.525	4.1	15.4	73.4
9/30/2009	14-1	2.442	2.545	4.0	14.7	72.8
9/30/2009	14-2	2.439	2.541	4.0	14.8	73.0
9/30/2009	14-3	2.444	2.534	3.6	14.6	75.3
9/30/2009	14-4	2.444	2.536	3.6	14.6	75.3
10/01/2009	15-1	2.442	2.541	3.9	14.7	73.5
10/01/2009	15-2	2.483	2.530	4.1	13.5	73.0
10/01/2009	15-3	2.440	2.535	3.7	14.7	74.8
10/01/2009	15-4	2.439	2.534	3.7	14.8	75.0

Chapter 3 included a listing and comparison of the average PaveTracker density and PSPA values (refer to Table 11). Figure 76 shows the relationship between density (measured with the PaveTracker, nuclear gauge, and cores) and the PSPA modulus measured during the same day of paving. As shown, no trend was found in the data, even though density has an effect on the dynamic modulus. In fact, density (or air voids) is an input to the MEPDG for calculating dynamic modulus (ARA, 2004). Thus, the in-place density (or percent compaction) did not explain the significant decrease in mixture stiffness.



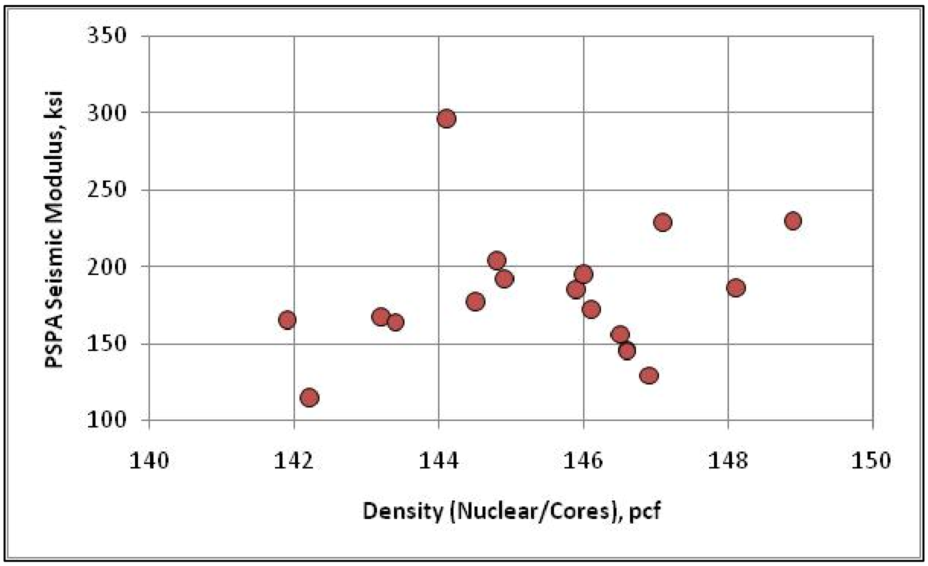


Figure 76. Comparison of HMA Density and PSPA Modulus

Figure 77 shows the surface of the HMA mixture after IC rolling near the beginning of lot 14 and at the end of lot 14. As shown, the mixture started to exhibit tenderness within lot 14 (between Sections 2 and 3). The reason that stiffness and density are not related is that the finish roller operator noticed the change in mixture response during intermediate and finish rolling and delayed final rolling until the mix cooled sufficiently so that the roller marks would be removed and mix checking (resulting in a reduction in density) would not occur.

The IC roller responses were recorded for the Level 3 Bomag and Level 2 Sakai roller. As reported in Chapter 3, an accelerometer was not installed on the Caterpillar roller. Thus, the Caterpillar roller was used only to evaluate any change in the rolling pattern of the operator from using the IC roller.

(a). Surface of HMA Mixture Near the Beginning of the Demonstration Project; No Mix Tenderness or Checking Observed

(b). Surface of HMA Mixture Near the End of Lot 14; Mix Tenderness and Checking Observed

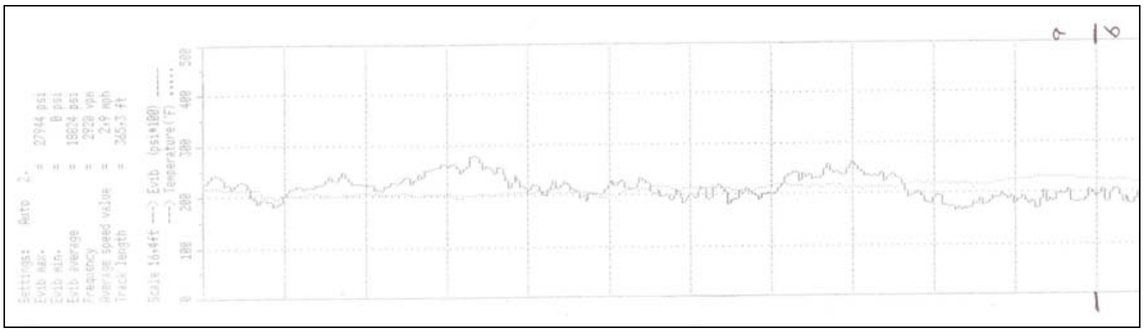
Figure 77. Surface of HMA 19-mm Lift After IC Rolling

Figure 78 shows an example of the charts that were printed after each rolling zone was completed, while Table 17 summarizes the average, maximum, and minimum E_{vib} values from two runs or rolling zones. Two points can be extracted from the data summarized in Table 17:

1. The magnitudes of the E_{vib} elastic modulus values are significantly lower than dynamic modulus values measured in the laboratory at comparable temperatures and loading frequencies. It is expected that these low values are more representative of the composite stiffness of the section, rather than just the HMA mixture being compacted. More importantly, Table 17 includes the E_{vib} values for the final pass near the edge of the roadway for each area. As shown, these values are significantly lower than for the center; there is a much larger decrease in

stiffness between the center and edge condition than from the start to the end of paving. It is expected that the mix properties do not change this much from the center to edge and the smaller values are more related to lower support from the underlying layers, as well as along a confined or unconfined edge.

2. The E_{vib} values show a continuous decrease in the magnitude of the average value from the beginning to the end of this paving segment. This is consistent with a continuous decrease in PSPA values, as discussed in Chapter 3. However, these differences are small in relation to the differences measured with the PSPA and may be an indication of a consistent decrease in the stiffness of the supporting layers. The PSPA sensors were spaced so that the measurements of seismic modulus were confined to the surface (2 to 3 inches in depth below the surface).



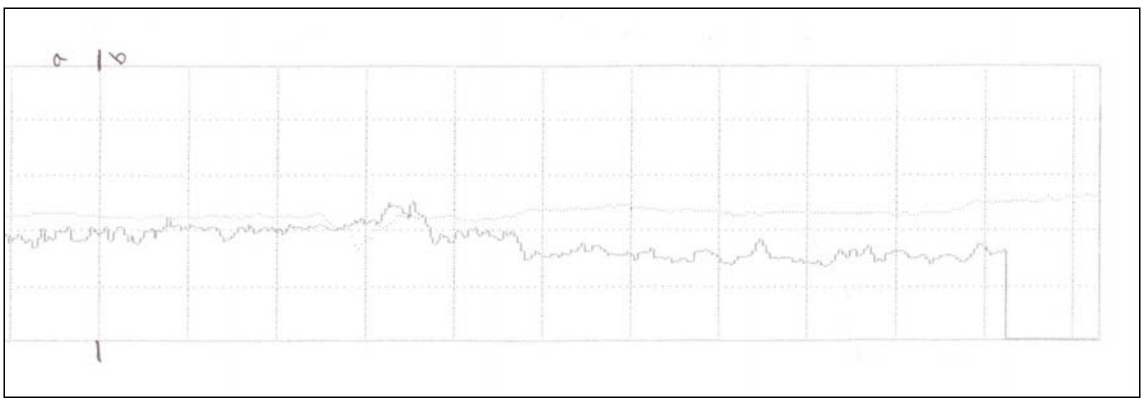


Figure 78. E_{vib} Values for the Last Pass in One Rolling Zone

Table 17. Summary of E_{vib} Values for Four Rolling Zones

Location	**E_{vib}, psi**		
	Average	**Maximum**	**Minimum**
1-Center	18,384	27,800	10,600
2-Center	18,824	27,944	10,000
3-Center	17,432	27,872	10,000
4-Center	16,432	26,824	10,000
1-Edge Pass	17,232	32,648	10,000
2-Edge Pass	14,968	22,224	10,000
3-Edge Pass	13,728	23,512	10,000
4-Edge Pass	21,064	34,120	10,000

Figure 78 shows that the E_{vib} values are fairly consistent along most of this rolling zone, but they suddenly decrease towards the end of the rolling zone. This decrease is believed to be related to a change in underlying support conditions. The other IC roller showed similar results for the average elastic modulus values along specific rolling zones. Thus, it was difficult to determine the reason for these changes during the paving-compaction operation.

More importantly, the elastic modulus values measured with the IC rollers did not exhibit a clear and consistent decrease in mixture stiffness that was identified by the PSPA. One possible reason for this observation is that the IC rollers were alternated down the roadway; each roller compacted the HMA mixture for about 3 to 4 hours. This difference in IC roller responses during the same day and between days is a confounding factor in trying to identify gradual changes in mixture stiffness considering the variability of the underlying pavement layers.

5.2 Modulus Adjustment Factors – Laboratory to Field Measured Values

As stated in Chapter 4, most pavement design procedures require the use of laboratory measured material properties for characterizing each layer, including HMA layers. Dynamic modulus tests were performed on laboratory compacted test specimens, and the results are presented graphically in Appendix D. As for the unbound materials, NCHRP Report #626 found that the PSPA value needs to be adjusted to represent laboratory measured dynamic modulus values. The purpose of the adjustment factor is to remove bias between the laboratory and field measured stiffness values. The assumption for removing that bias is that the field mixture is of the same quality as the laboratory produced material. Two adjustment ratios are provided in NCHRP Report #626; 0.89 for HMA mixtures that are easily compacted or exhibit tenderness, and 1.34 for coarse-graded, harsh mixtures that are difficult to compact.

Table 18 summarizes the average dynamic modulus values for the reference and in-place temperatures and estimated frequency of the PSPA. As shown, the average dynamic modulus is higher near the beginning of the demonstration project and lower after the first part of lot 14. This decrease in dynamic modulus from the start to the end of the project is considered insignificant.

Table 18. Summary of Laboratory Dynamic Modulus

HMA Mixture	Lot Identification	Average Dynamic Modulus, ksi	
		Reference Temperature & PSPA Frequency	In-Place Temperature & PSPA Frequency
E3: 19 mm, PG58-28 Binder Layer	14-2	560	320
	14-4	550	295
	15-2	520	290

Table 19 summarizes the adjustment factors between the laboratory and field measured stiffness values. As shown, the adjustment factors for the Wisconsin demonstration project are much greater than those reported in NCHRP Report #626, even for harsh mixtures, with the exception of Section 2. Most of the mixture placed in Section 2 was prior to mix tenderness and checking being observed during compaction.

After the HMA mixture began to exhibit tenderness and checking, the adjustment ratios increased significantly (refer to Table 19). The PSPA seismic values decreased significantly, while the laboratory dynamic values decreased but much less than what was measured with the PSPA. The opposite was observed on mixtures that were included in NCHRP Report #626 (the laboratory dynamic modulus decreased much greater than the PSPA values). The reason for this discrepancy is unknown, but possible explanations are discussed further in Section 5.5.

Table 19. Adjustment Factors (Ratios) Between Laboratory (Dynamic Modulus) and PSPA Measured Values

Section Identification		**Roller**	**NCHRP Report #626**	**Demonstration Project**	**Percent Compaction**
2	9/30/2009	Sakai	1.34 (For harsh coarse graded mixtures; values ranged from 0.92 to 1.69)	1.42	91.1
3	9/30/2009	Sakai		2.12	91.3
4	9/30/2009	Bomag		2.05	91.6
5	9/30/2009	Sakai		2.19	90.5
6	10/01/2009	Bomag		1.88	92.3
7	10/01/2009	Sakai		2.06	92.0
		Average		1.95	---

NOTES:
1. Lot #1 from the Wisconsin demonstration project was excluded from this listing because the seismic modulus values were measured the day after paving; while the values for the other lots were measured the same day of paving.
2. The percent compaction values included above do not represent lot averages. The location of the density and stiffness tests were selected based on mixture behavior under the IC roller and in cold spots identified by the Infrared camera to determine whether the IC roller response would identify the anomalies.
3. The adjustment factor or ratio for HMA mixtures is defined as: $\frac{E^*(Laboratory)}{E_{Field}(PSPA)}$

5.3 Density-Growth Relationship

The PaveTracker was used to develop density-growth curves for the 19-mm mixture using two of the three IC rollers (see Figure 79). In general, the density increased 15 to 20 percent, and both IC rollers exhibited similar density-growth relationships. After the development of the density-growth relationship, the contractor's rolling pattern was two passes of the IC roller, followed by one pass of the intermediate roller and one or more passes of the finish roller to ensure any roller marks were removed. The intermediate and finish roller were used to further increase the density and remove any roller marks left by the vibratory IC roller.

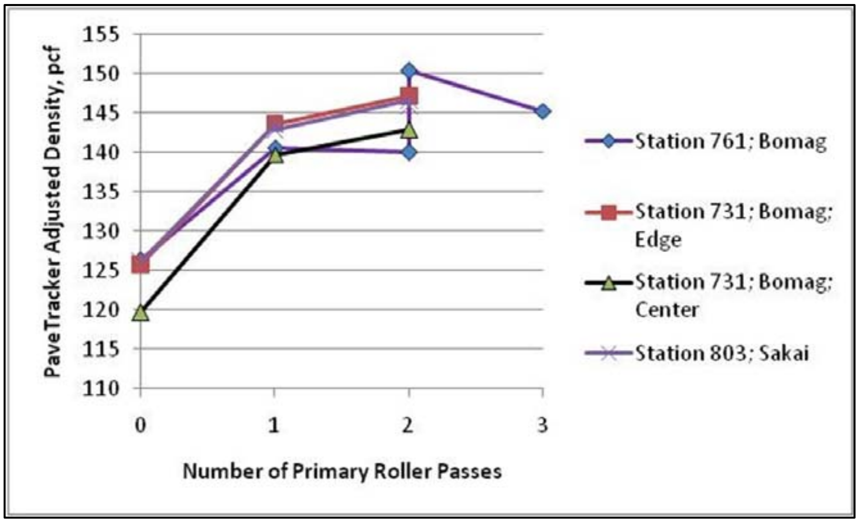


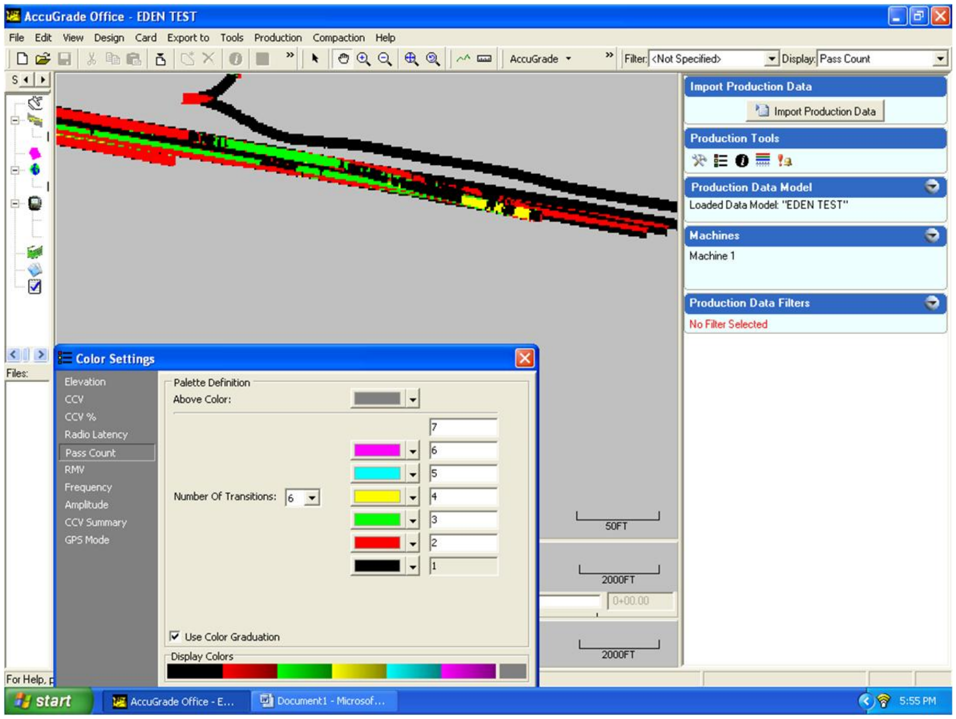
Figure 79. Density-Growth Relationship for the 19-mm HMA Mixture

The PSPA was not used to develop similar stiffness-growth relationship because of the elevated mixture temperature. The mixture was simply too soft to obtain a reasonable stiffness reading with the PSPA. This is a limitation of the PSPA, rather than a potential problem with the mixture.

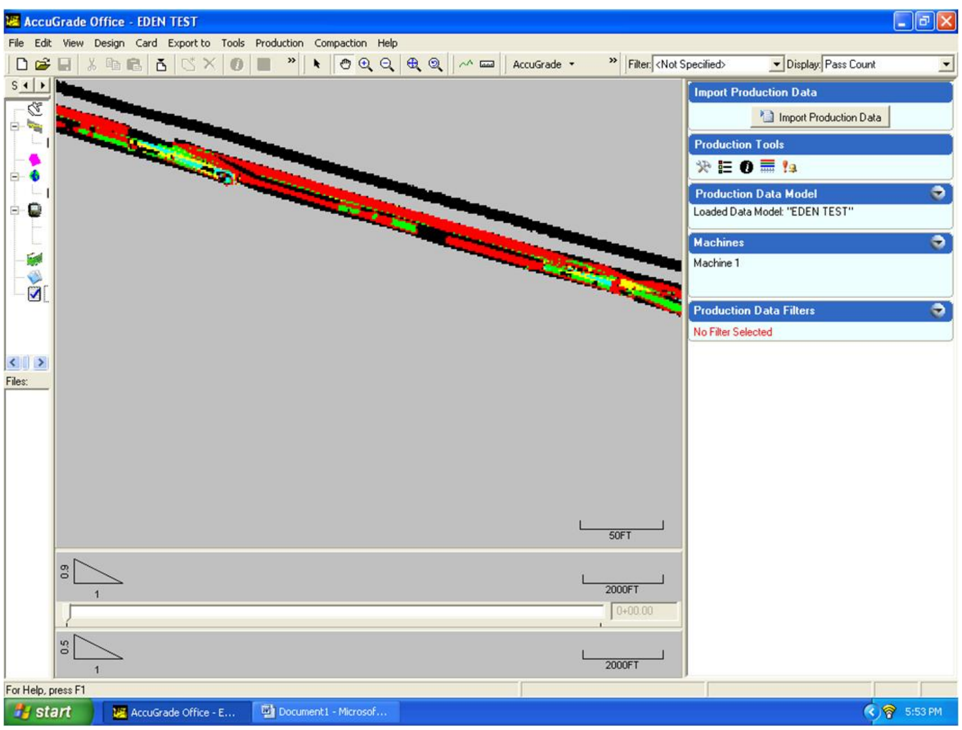
The IC rollers also were used to develop stiffness-growth relationships for this mixture. Although the stiffness did increase, the magnitude of increase was less than 10 percent for both rollers. More importantly, the increase in magnitude appeared to be influenced by the supporting layers, similar to the findings for unbound materials. Thus, the increase in IC roller response parameter is an increase in the composite modulus or stiffness of the pavement section, not just the HMA.

5.4 Layer Stiffness Monitoring – Uniformity and Increased Density

All three IC rollers were used to evaluate coverage of the mat with the designated roller pattern. At the beginning of the demonstration project, the IC roller operator was not sufficiently overlapping every pass or continuing through the entire compaction zone from beginning to end, so some areas had only one pass of the IC roller. Figure 80.a shows the visual display for the initial compaction zone from the Caterpillar IC Level 1 roller and clearly shows that there were areas with only one pass of the IC roller.



(a). Near the Beginning of the First Section; Compaction Zone #1



(b). Compaction Zone #3

Figure 80. Color Image of the Number of Passes of the Caterpillar Level 1 IC Roller Near the Beginning of the Demonstration Project

The lengths of roadway with only one pass substantially decreased as the operator became familiar with using the display unit on the Sakai and Caterpillar rollers. Figure 80.b shows the visual display for compaction zone #3. It was obvious that the color-coded image showing the number of passes over the entire mat was a benefit to the operator. However, the density data from the contractor's QC plan before the demonstration project did not show a reduction in variability by using the IC rollers. A possible reason for this observation is that these areas were narrow or relatively short in length, so the probability of taking a density reading and cores from these areas is very small.

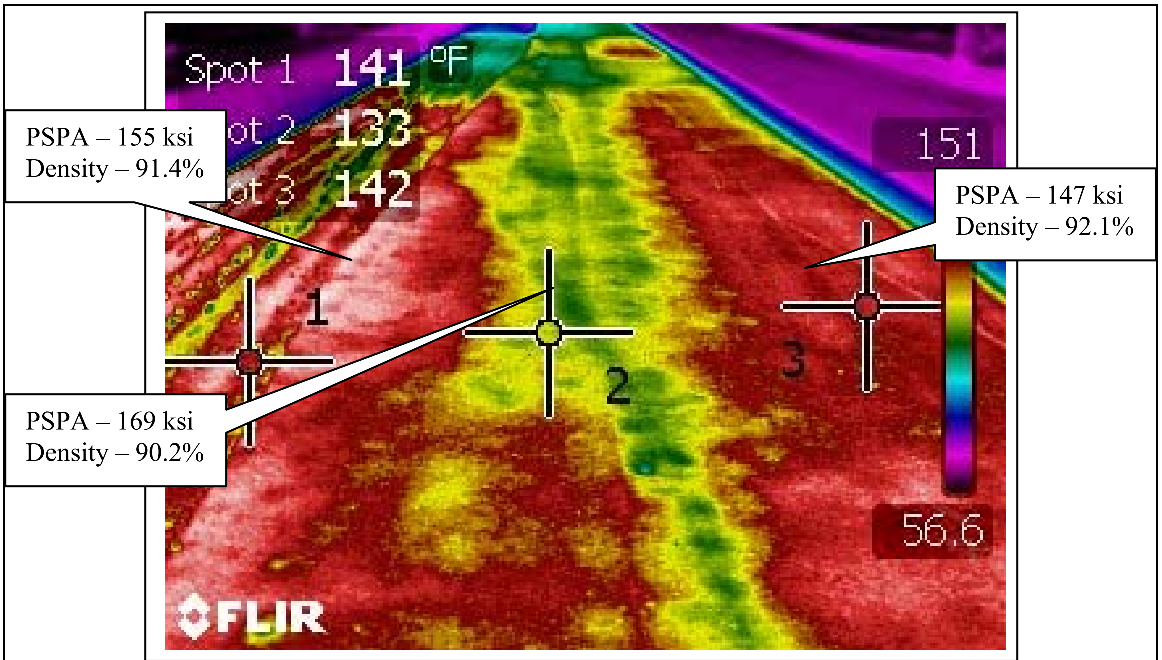
5.5 Identification of Stiffness Anomalies & Mix Tenderness

The contractor's infrared camera was used to measure the surface temperature of the mix and identify any cold spots during the paving operation. Cold spots generally exhibit higher stiffness values. A few such areas were found, primarily caused as a result of a delay in a consistent supply of trucks delivering mix to the paver. Most of the areas behind the paver had relatively uniform temperatures. Figure 81 shows areas with surface temperature differences. A few areas were marked for conducting PSPA, non-nuclear, and nuclear gauge tests and extracting cores.

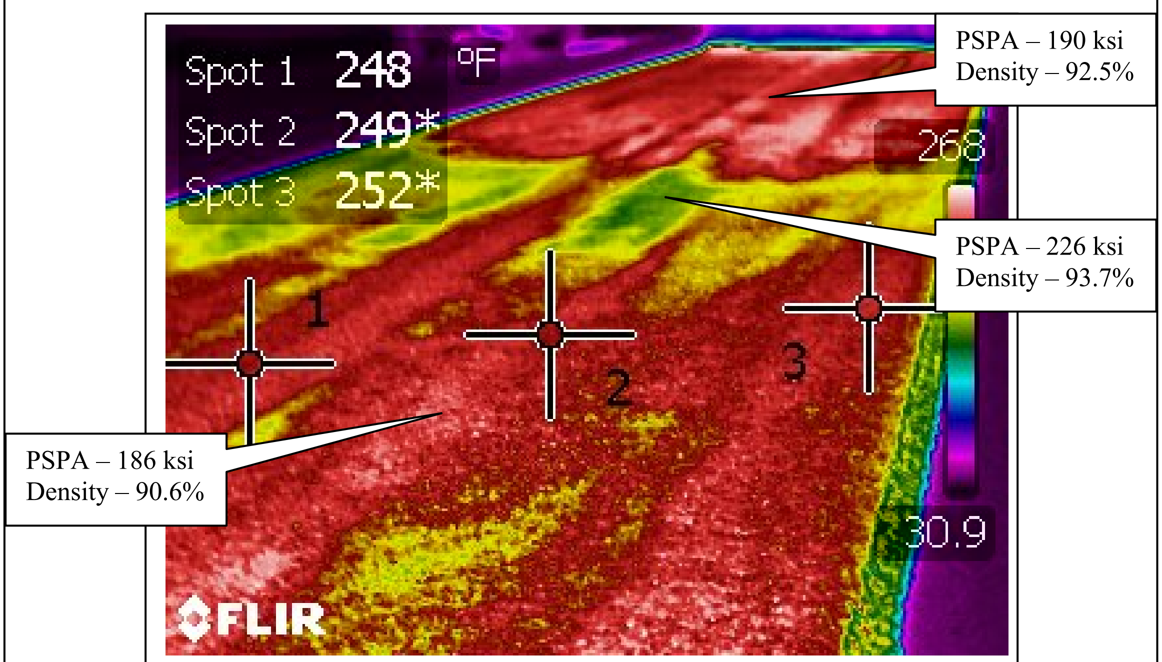
The IC roller's response was monitored as the roller travelled over the cold spot. However, no change could be identified as an increase in stiffness over the cold spot. Figure 82 shows an example of this observation. Two possible reasons for this observation are (1) the readings are averaged over an area, and (2) the change in stiffness is smaller than what can be detected by the roller instrumentation. In either case, the IC roller was unable to detect or identify these cold spots accurately during the compaction operation.

The PSPA device, nuclear density gauge, and non-nuclear density gauge also were used to test some of these areas (refer to Figure 81). The densities were found to be lower for most of these areas, but the PSPA seismic values were within the range of other modulus values within the test area. The PSPA readings were taken almost 4 hours after paving, so the mixture had cooled prior to testing. The difference in stiffness between 90 percent compaction and 94 percent becomes more difficult to identify accurately on a point by point basis because of other confounding factors.

The change that occurred during the demonstration project was illustrated in Figure 77. As noted in Chapter 3, the PSPA and finish roller operator were the first to recognize this change in mixture response. The mixture began to exhibit tenderness characteristics during the first day of the demonstration project. Figure 83 shows the checking and mix shoving that was observed along the project.



(a). Image Taken After IC Rolling, during PSPA Testing



(b). Image Taken Before IC Rolling, before PSPA Testing

Figure 81. Examples of Differences in Surface Temperatures in Localized Areas

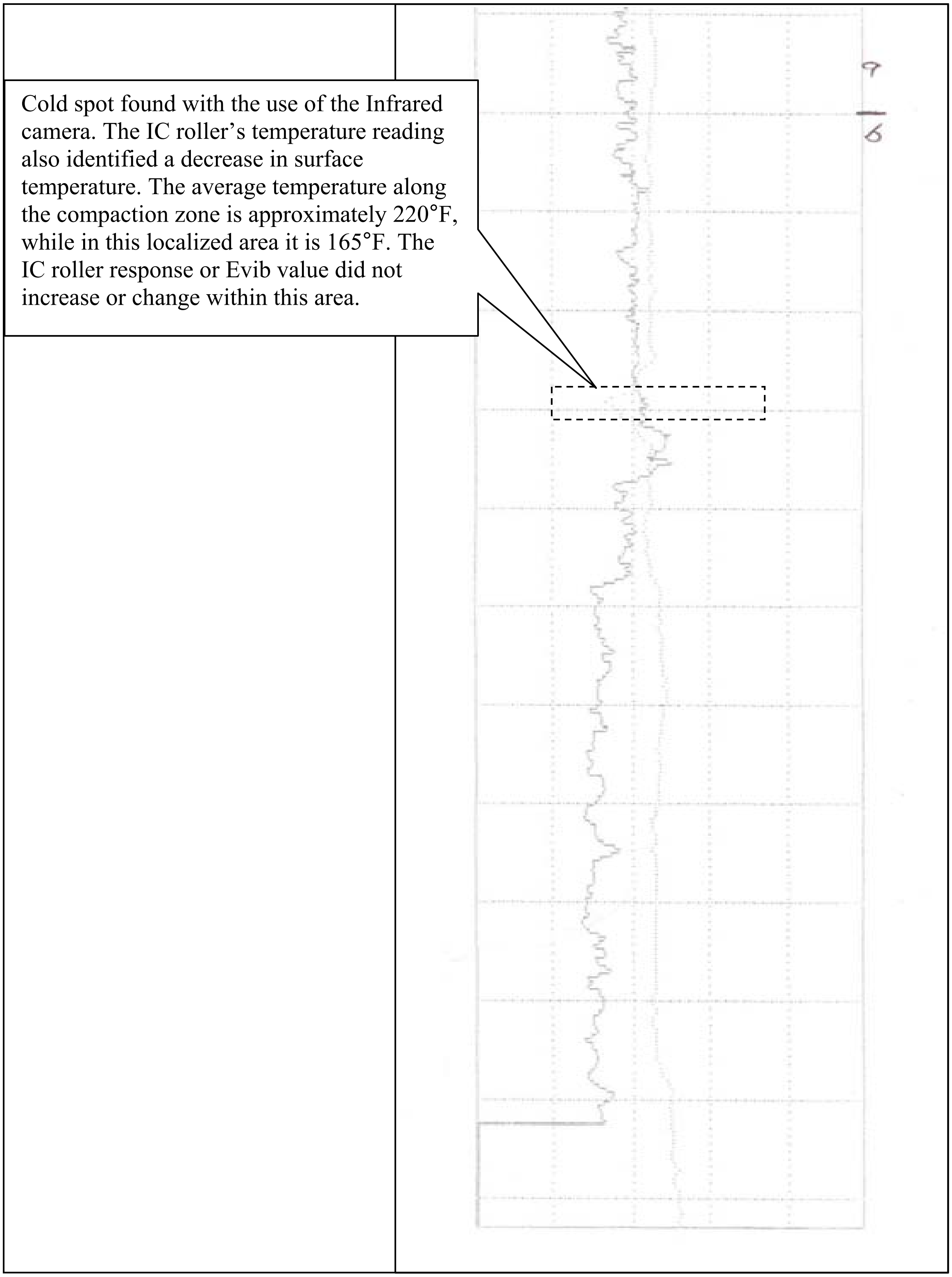


Figure 82. Example Chart from IC Roller Showing the E_{vib} and Temperature Readings

(a). Roller Marks & Mix Shoving Left by the IC Roller; Prior to Finish Rolling

(b). Cracks along Edge of IC Roller; After IC Rolling

(c). Checking (Short Transverse Cracks) in a Localized Area; after Finish Rolling. Areas Marked for Test Locations

Figure 83. Example of Shoving or Shearing Along the Edge of the Roller Drum and Mix Checking

The Contractor was able to meet the density requirement through this project because of the awareness of the finish roller operator. The finish roller operator delayed the final rolling until the mix had cooled so that density would continue to increase with further rolling. Continued rolling into the temperature sensitive zone can be detrimental to density. Figure 84 shows an example of the decrease in density when rolling is continued into the temperature sensitive zone (Von Quintus et al., 2009). Although delaying the final rolling was the proper decision to be made in terms of density, the final stiffness of the mixture is significantly less than measured by the PSPA prior to shoving, checking, and roller marks being observed on the mat. Another correct decision would have been to complete the compaction operation or final rolling prior to the temperature of the mix going into the temperature sensitive zone.

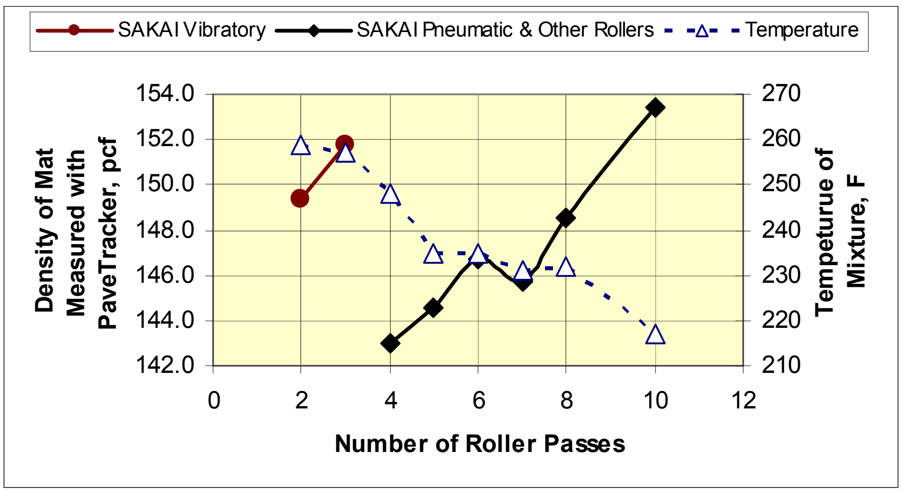
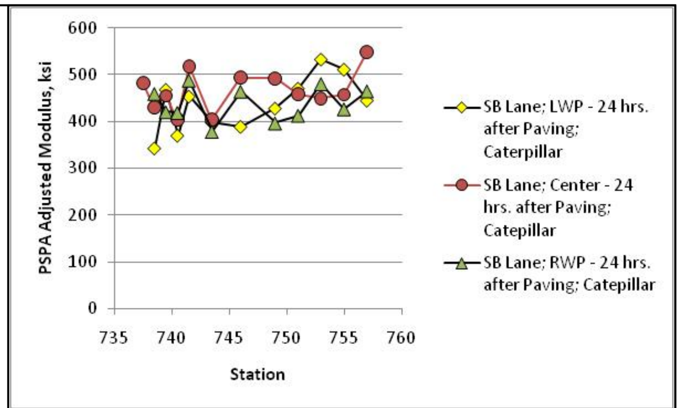


Figure 84. Example of a Decrease in Density Caused by Rolling in the Temperature Sensitive Zone for HMA Mixtures

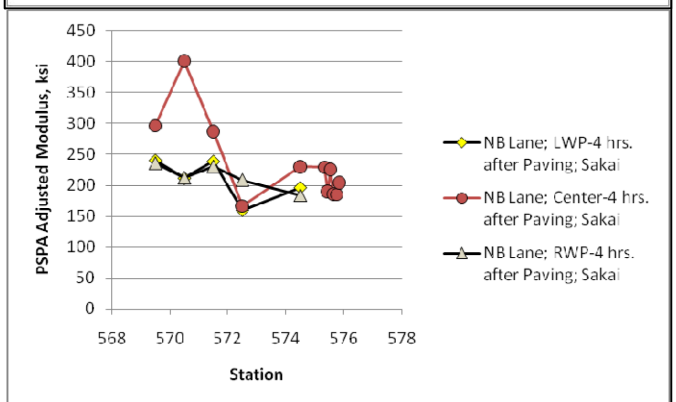
It is unknown what mix property changed during production to cause the stiffness to decrease. One possible explanation is that the moisture content in the mix may have been higher due to higher water contents in the aggregate stockpiles from the rains that occurred just prior to the demonstration project. Inadequately dried aggregate can result in tenderness of the mix during compaction, increase the temperature sensitive zone of the mix, and reduce the stiffness of the mix. If moisture is the cause, mix stiffness will increase over time unless the mixture is susceptible to moisture damage. This also would explain why the laboratory dynamic modulus tests did not result in low values from bulk mixture sampled during production. These tests were completed months after the project, and the test specimens were reheated in preparation for testing. If moisture was the issue, the reheating would have removed the excess moisture.

Figure 85 shows the average PSPA measurements taken at individual points along the project for selected test sections, while Figure 86 shows the E_{vib} values measured along the fourth test section. The PSPA values decreased by nearly 50 percent from one end of the fourth section to the other, while the E_{vib} values did not. Conversely, the PSPA and E_{vib} values did identify an area with higher mix stiffness in Section 6 (refer to Figure 87).

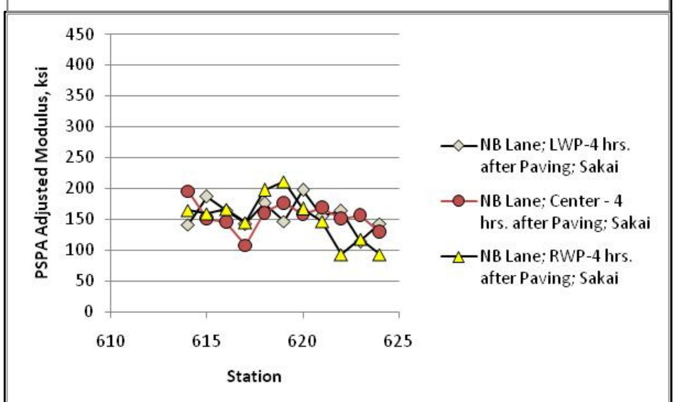
(a). First Section; Used to Estimate Bias for Testing Mixtures with PSPA at Least One Day After Paving & Testing with Other Devices



(b). Second Section; Used to Estimate Bias for Testing Mixtures with PSPA the Same Day of Paving & Testing with Other Devices; Contractor Reversed Direction from the Initial Section



(c). Third Section Used for Testing Mixtures with PSPA and Other Devices



(d). Fourth Section Used for Testing Mixtures with PSPA and Other Devices

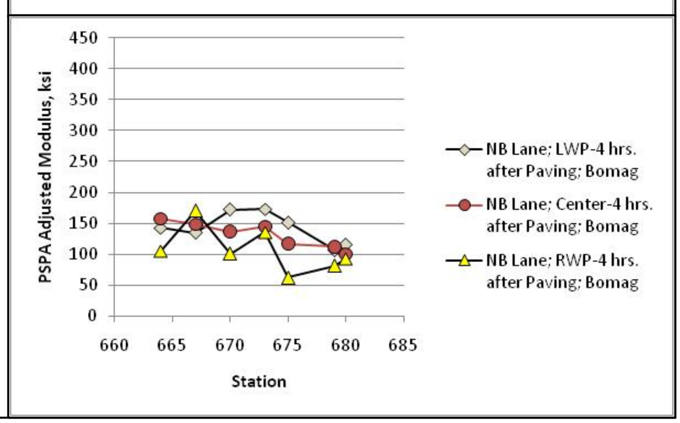


Figure 85. Average PSPA Measurements at Individual Points Along the Test Sections

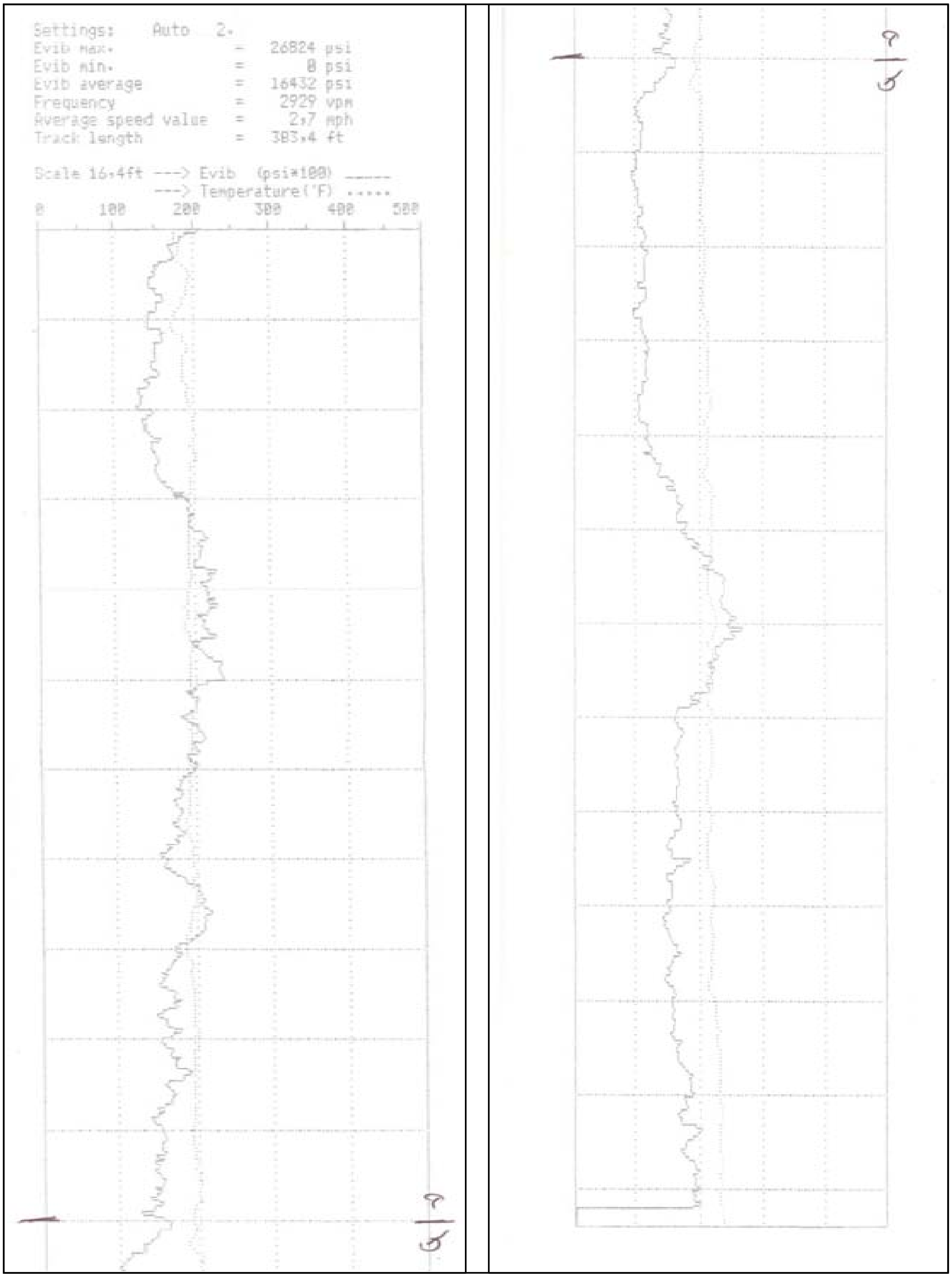


Figure 86. E_{vib} Values Measured Along the Fourth Test Section

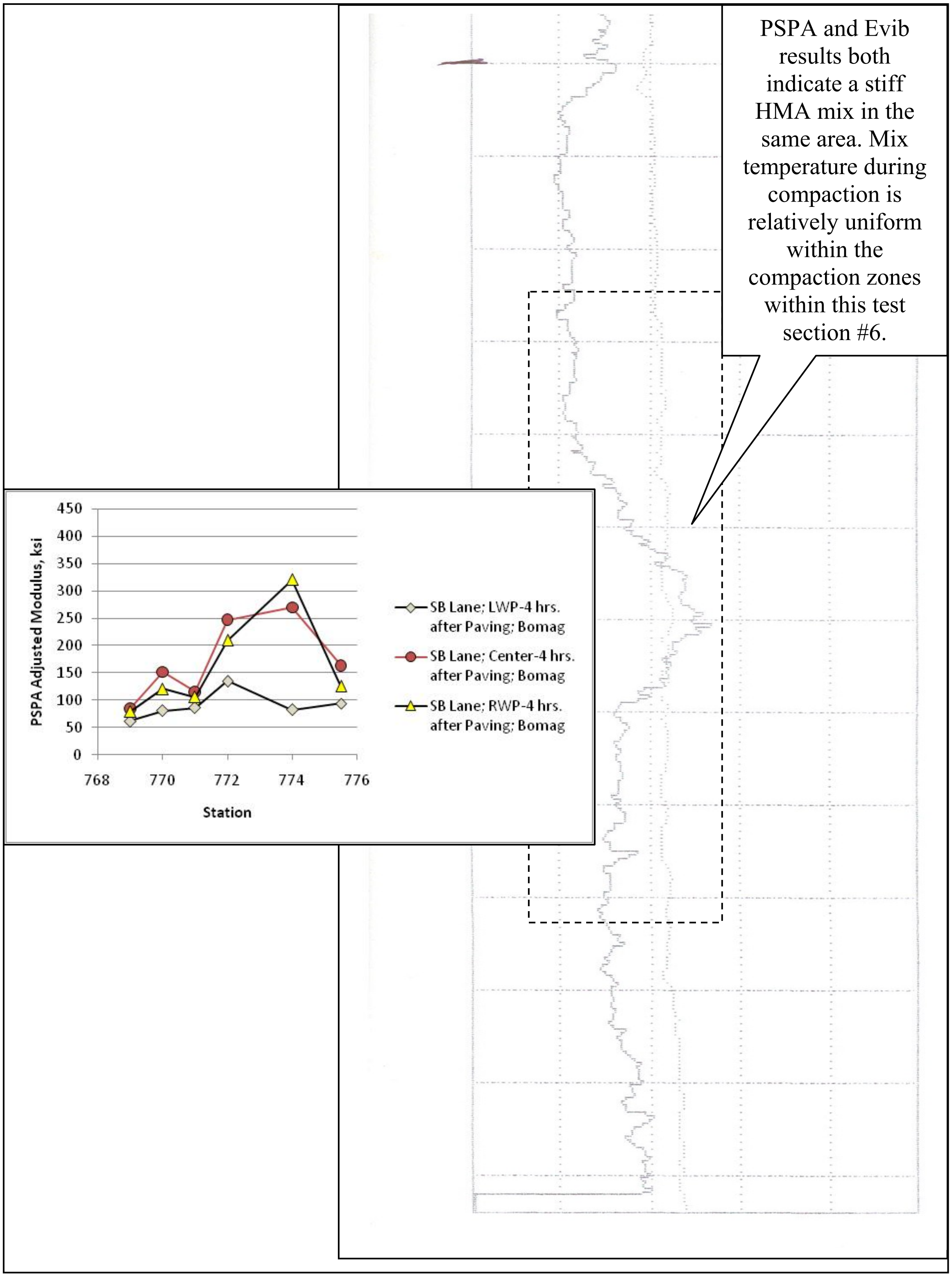


Figure 87. Comparison of PSPA and E_{vib} Measured Values in Section 6

5.6 Interpretation of Results for Judging Acceptability

This section presents an interpretation of the IC roller and NDT responses in terms of deciding whether pavement design assumptions have been satisfied. Acceptability is used in this case as exceeding the modulus used in design. The procedure recommended in NCHRP Report #626 was followed and is the same as summarized in the previous chapter for unbound materials.

The IC roller responses of elastic modulus were unable to identify any substantial change in the mixture throughout the demonstration project. The PSPA, however, did indicate a substantial reduction in mixture modulus from the laboratory measured values, even after adjusting to laboratory equivalent conditions. As such, Sections 2 through 7 would have been rejected because they did not meet the minimum design value determined from the laboratory dynamic modulus tests, as summarized below:

- Average design dynamic modulus (laboratory), short-term aging (refer to Table 18); 300 ksi
- Adjustment factors (eliminating bias between laboratory and field tests):
    - PSPA measurements, same day of paving (refer to Table 19); 1.40
    - PSPA measurements, next day of paving (more aging & asphalt absorption); 0.70
- Average PSPA adjusted seismic modulus values:

Test Section						
#1	#2	#3	#4	#5	#6	#7
314	316	211	202	189	216	197

The adjustment factors were based on mixture placed prior to exhibiting tenderness characteristics and determined from control strips (Sections 1 and 2 for different time periods). As shown, the design assumption was not met in Sections 3 through 7, so the mixture would have been rejected from a stiffness standpoint. Conversely, it was acceptable from the standpoint of density and other mixture volumetric properties.

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

Following is a summary of the findings and conclusions from this study, as well as recommendations regarding the future use of IC technology in Wisconsin. The conclusions (Section 6.2) are presented in terms of answering the questions that were listed at the end of Chapter 2.

6.1 Findings

All three types of IC rollers were found to be beneficial in compacting both unbound and HMA materials. However, contractors have been compacting pavement layers successfully (meeting the agency's specifications) for decades without the use of IC rollers. Therefore, the use of IC rollers must be evaluated in terms of improving on that process, and this section discusses both the benefits and limitations of IC rollers.

6.1.1 Benefits and Advantages

The benefits of IC that were identified from the field demonstration projects are listed below:

- The IC roller's display unit that shows a colored-coded image of the coverage within an area is beneficial to ensure the area received an adequate number of passes. It is especially useful for larger areas, such as parking lots, when multiple passes of the roller are required for a single coverage. This was demonstrated clearly on a couple of the projects. However, this benefit depends on the roller operator, and it may be less of a factor when the roller operator is properly trained and experienced. The benefit to the contractor is a permanent record of coverage with an adequate number of passes years after the project has been completed. The benefit to the agency is minimal, unless the variability in density and stiffness decreases. On the average, variability slightly increased for the unbound layers included in the demonstration projects.
- Mapping stiffness on a continuous basis before a layer/embankment is placed or after the layer has been compacted is a major benefit for both the contractor and owner. The benefit to the contractor (prior to the layer being placed) is in identifying soft or weak areas along a roadway that might need to be removed and replaced or stabilized for warranty-type projects. The benefit to the owner (after the layer has been compacted) is a permanent record of the composite stiffness for each lift. This positive feature of IC was demonstrated on each project to determine the variability or uniformity of support conditions and to segment an area with diverse stiffness prior to material placement.
- Another major benefit of the soil IC rollers is that the roller's output is correlated to laboratory measured resilient modulus values at comparable stress states. This was not the case for HMA IC rollers because the lift thickness of unbound layers is greater than for HMA layers. Lift thickness can be a confounding factor in terms of interpreting the IC roller's output for both unbound and HMA layers.

Although a bias was found between the soil IC elastic modulus and laboratory resilient modulus, this correspondence results in additional benefits for the soil IC rollers, which are listed below. Another reason for the poor correlation with the HMA stiffness estimated with the PSPA is that the finish roller can build or destroy the density and stiffness of the final mixture.

- The soil IC roller output can be used to determine the minimum number of passes to achieve maximum stiffness because its output is related to the laboratory measured resilient modulus values and point specific test results (Geogauge). In fact, the soil IC roller output can be used to develop stiffness-growth relationships in real time and continuously monitor that relationship over the project. The result is that fewer passes are needed to accomplish equivalent or better levels of stiffness in less time.
- Similarly, an important benefit is the capability to identify when stronger base materials are being over-rolled. The demonstration projects clearly showed a significant decrease in composite stiffness when the IC roller started damaging the crushed aggregate layers. This condition can be monitored continuously by the roller operator on a real-time basis to discontinue rolling in the vibratory mode when the roller's response output or composite elastic modulus values begin to decrease.
- Another beneficial feature of IC is that the magnitude of maximum amplitude that is used during the initial roller passes is higher when compared to some conventional rollers. This is made possible by measurement and control systems on IC rollers that optimize the compactive effort based on measured stiffness. This feature results in the ability to effectively compact deeper lifts of pavement materials of all types. There has been some evidence to confirm this with work on thick aggregate base materials in the U.S. The thick embankment lifts that were compacted within the demonstration projects also confirmed the IC roller's ability to compact thicker lifts.
- Results from the soil IC rollers are applicable to the new MEPDG, which the Wisconsin DOT is planning to implement. As such, the in-place composite values can be used to check or confirm material input parameters used for structural design, tying mixture and structural design parameters to construction. This benefit is a long-term goal and requires continued laboratory testing and comparison to the response outputs from different IC rollers under different site or support conditions and lift thicknesses.
- Soil IC roller responses and output can be used to determine the locations where point measurements are needed for final acceptance of the pavement layer. In other words, strategically locate the more time-consuming acceptance tests and reduce the number of tests without increasing the DOT's risk of making a wrong decision, similar to the process that Washington DOT has implemented with infrared cameras for HMA. Determining the test locations for the IC roller responses for the acceptance of HMA mixtures should be postponed until more data become available to account for the effect or confounding factors of temperature and stiffness of the supporting layers.

6.1.2 Limitations and Issues

Most previous studies have assumed that layer density is proportional to and can be determined through the IC roller output—stiffness. However, other factors can cause an increase in stiffness while resulting in a decrease in pavement performance. Stiffness and density should be considered two different properties that can have different effects on pavement performance. This density-stiffness relationship needs to be recognized by both contractor and agency construction personnel. The remainder of this section lists those limitations or issues that were identified during the demonstration projects.

- The foundation and supporting layers influence the IC roller response and output—elastic modulus. In other words, the IC roller response parameter is a composite stiffness that reflects the stiffness of the layer being compacted as well as the supporting layers. The output is not a direct measurement of the material's elastic modulus (resilient modulus for unbound layers and dynamic modulus for HMA). This issue can result in false readings or interpretation by the roller operator, as well as by agency personnel responsible for acceptance. This issue requires adjustment factors be developed to eliminate bias between laboratory (material specific) and field (composite) measured stiffness values, which depend on the site, lift thickness, and material condition. For the soil IC rollers, these adjustment factors do not deviate far from unity, so their implementation becomes more straightforward, at least for thicker lifts. That is not the case for the HMA IC rollers.
- Although not an actual limitation, the use of IC rollers does not eliminate the need for control strips for confirming the rolling pattern. Both rollers still require the use of control strips to develop layer/material adjustment ratios and confirm the minimum number of roller passes and roller settings (amplitude and frequency or amplitude direction for some rollers) to achieve maximum density and stiffness.

Soil IC Rollers

- The material's moisture content needs to be measured during the compaction operation because it can affect the adjustment ratio for some soils. It also has an obvious impact on the density and stiffness-growth relationship. Thus, use of the soil IC roller does not eliminate the need for other volumetric tests during construction.
- Lift thickness is a confounding factor with soil IC rollers. The Highland project included the use of a 3-to 4-inch crushed stone base layer, and stiffness-growth relationships could not be developed because of the stiffer supporting layers. The definition of thin lift construction in terms of IC is expected to be specific to the structure or supporting layer stiffness.
- Another limitation is that the soil IC rollers will not detect anomalies directly in the underlying layers, if those anomalies are uniform over the area being compacted. Thus, visual inspection and other volumetric tests will not be replaced by the soil IC roller.

HMA IC Rollers

- The most significant limitation of the HMA IC roller is that it is not the final roller being used to compact the mixture. The IC roller is followed by an intermediate and finish roller. The IC roller will not prevent the intermediate or finish rollers from being operated in the temperature sensitive zone and destroying the density created by the IC roller. This limitation is critical and limits the use of the IC roller for judging the acceptability of HMA mats. This issue was demonstrated clearly on the HMA demonstration project.
- Another critical limitation for the HMA IC rollers is that the roller response is heavily influenced by the supporting layers such that the composite stiffness measurement is significantly less than the values measured in the laboratory at comparable temperatures and loading frequencies. It is expected that the confounding factor of the supporting layers will become less important with thicker HMA lifts (greater than 4 inches in thickness), but that hypothesis needs to be confirmed.
- Another limitation of the HMA IC roller is that it did not detect cold spots by stiffness measurements itself and can bridge mat defects that are localized or narrow. For example, centerline segregation or worn out kick-back flights or paddles that do not push enough mixture under the paver's center drive box will not be detected. These construction issues still require visual inspection and point-specific tests for acceptance of the final product. Although these areas can be small, they can have a detrimental impact on pavement performance and service life.

6.2 Conclusions

The potential for IC technology to improve the in-place density of pavement materials has been documented from projects in Europe, Asia, and the United States. This study helped to answer critical questions regarding the conditions under which IC technology can provide data for making accurate decisions, as well as the potential for inaccurate decisions based on the output from IC rollers.

- *How mature is the technology for compacting unbound materials and HMA mixtures?*
  The demonstration projects confirmed that IC for soils is more advanced than IC for HMA layers. Level 2 and Level 3 soil IC rollers can be used almost immediately in Wisconsin. Unfortunately, there are many more unanswered questions for compacting HMA layers. The impact of mix cooling, tender mixtures, and rolling in the temperature sensitive zone with the intermediate or finish rollers are challenges that must be overcome prior to full-scale implementation for HMA mixtures.

- *Is the effectiveness or adequacy of this technology influenced by material parameters (such as material type, fluids content, etc.), and support conditions?* IC output is influenced by site conditions, lift thickness, and fluids content of the materials being compacted, among other factors. These demonstration projects, however, confirmed that IC is an effective technology for judging when an unbound layer has been compacted adequately. Results from the demonstration projects showed the influence of the underlying layers, subgrade, and volumetric condition in making judgment decisions, and contractor and owner personnel need to understand these factors. With proper use and training, however, the decision-maker has real-time data to make accurate decisions to provide long-term benefits, at least for the soil IC rollers.

- *Does IC lead to better and more uniform compaction than conventional compaction methods?*
  It has been reported that using IC for compacting pavement layers will result in a significant decrease in the variability or COV of density. Improved density of pavement materials has obvious benefits since poor in-place density has been identified as a major factor in premature pavement failures. Compaction processes that produce consistently high and more uniform density offer agencies and the traveling public a much better return on their investment of tax dollars with extended service lives and reduced maintenance costs.

  Variability was not reduced consistently on the demonstration projects. However, this observation does not imply that the technology will not be beneficial to the owner and contractor. On the average, the demonstration projects showed a slight increase in variability (coefficient of variation) with the use of IC rollers. This observation will become important to contractors operating under a PWL type of specification. Thus, there is still conflicting data regarding the use of IC to reduce variability or increase uniformity of the final compacted layer.

- *Are there any technical issues and concerns that need to be overcome in using the technology to its fullest extent?*

Density – Stiffness Relationship

Most IC studies have assumed that increasing layer stiffness is proportional to an increase in density and material quality, but that is not necessarily the case. Other factors can cause an increase in stiffness while resulting in a decrease in pavement quality or performance. For example, lower temperatures and increasing mineral filler during production of HMA mixtures will result in an increase in modulus without increasing density, while lower water content and increasing plastic fines can cause an increase in stiffness without necessarily increasing density.

Stiffness and density can have opposite effects on pavement performance. However, as density increases during compaction, everything else being equal, stiffness also increases. To evaluate material quality, other field test devices and laboratory tests should be used to measure the in-place volumetric and stiffness properties of the material, at least at the beginning of the project. This issue is considered the greatest challenge towards implementation of IC. To overcome this challenge, the calibration procedures included in NCHRP Report #626 can be employed in future projects.

Composite Elastic Stiffness, Representative of Support Layers

The IC response output is a composite value that depends on the stiffness of the supporting layers. In other words, the stiffness of the lower pavement layers and/or foundation affects the IC roller responses or measured stiffness of the layer being compacted. The difference between the composite elastic modulus (field measured value) and material specific modulus (laboratory measured value) must be understood so that construction personnel make the right decision in terms of compacting the material.

Lift Thickness

Lift thickness affects the adjustment factors to eliminate the bias between the composite elastic modulus from the IC roller and laboratory measured values. Insufficient data were collected from the demonstration projects to determine the effect of lift thickness by material type and support conditions. Thus, more data are needed.

Bridging Localized Anomalies or Construction Defects

Many forensic investigations have shown that smooth-steel drum vibratory rollers bridge narrow or localized anomalies and construction defects. This bridging issue is also applicable to IC smooth-steel drum rollers. Inspection by the contractor and owner personnel, as well as point specific tests, will still be needed on IC projects.

- *Do the results from the initial demonstration projects suggest that agencies and contractors should continue to pursue this technology?*
  All of the agency-sponsored studies reviewed concluded that IC should be pursued and are in support of furthering this technology. Conversely, some contractors that have used the technology in day-to-day practice do not see a benefit in the use of IC to reduce their risks of being penalized by the owner agency, especially related to HMA layers. Most contractors that have purchased IC rollers use the devices to identify soft or weak spots and still rely on point-specific QC tests along the roadway for new construction and rehabilitation. Results from the demonstration projects showed positive findings, so the IC technology should be pursued for future use.

- *Does the increased purchase cost and maintenance of the IC rollers have an increased benefit that offsets those costs in the long term?*
  IC is considered useful in creating uniformly stiff subgrades; identifying weak or soft spots in subgrade; and, depending on calibration and data analysis, providing real-time modulus, stiffness, or density data. It also promises QC and acceptance applications that improve current methods of in-place, point testing because it

provides qualitative data for the entire coverage area of compaction, not just at incremental points that are used to estimate specific properties for the entire lot or site.

However, cost-benefit analyses have not been completed to address this question. Insufficient data were collected from the field demonstration projects to answer this question directly. It is the opinion of the authors that contractors should not be required to use IC rollers for compacting both unbound and HMA layers. That decision should be left up to the contractor, unless the use of the rollers is to provide supplemental data for other purposes.

In summary, the true test of the IC system is whether it saves time (fewer passes), improves uniformity of the layer, and produces accurate, consistent readings that can be used in a decision-making process by the contractor and owner.

6.3 Recommendations for Implementation

It is recommended that the Wisconsin DOT continue to move forward with implementation of IC technology. The two areas in which this technology can have immediate positive benefits, especially for unbound materials, are listed below:

1. The Level 2 and 3 IC rollers can be used as a testing device to continually map the stiffness of an area prior to placing both unbound and HMA materials to identify areas with weak supporting layers, and after the layer has been compacted. Their use will not identify the cause of weak/strong areas.

   In addition, IC rollers can be used to segment the layer being compacted for determining the average stiffness values based on areas with different composite elastic modulus values. The Wisconsin DOT should consider one of the following for implementing this benefit in an accelerated manner:
   a. Lease an IC roller from one of the local vendors and complete the stiffness mapping itself.
   b. Issue an annual contract for completing the stiffness mapping of selected projects.

2. The soil IC rollers can be used to develop stiffness-growth relationships to determine the rolling pattern and number of passes to achieve a specific stiffness level. This recommendation is directed more towards contractors than the DOT.

The FHWA pooled-fund study and other studies completed to date have identified correlations between the IC response values and the volumetric and mechanistic properties measured at point locations. Some of the reported relationships have reasonable statistical correlation values, while others are fairly poor. However, no universal relationship has been found, even for a specific class of material.

Although the field demonstration projects have identified those conditions that can have a detrimental impact on the correlation between IC roller response output and point-specific tests, more pilot projects are needed to determine how the physical condition of the layer being compacted affects the IC response parameters, especially for HMA mixtures. Implementation of the results into practice will take time and will depend on the availability of these rollers in Wisconsin. Contractor and agency personnel need to be confident that the IC response parameters are providing meaningful data that can be used to make the correct decisions in real time.

The following are recommendations that the DOT should consider over time.

More Pilot Projects

- The field demonstration projects were developed to provide an expanded database to confirm the response measurements of the IC rollers to stiffness and density increases and identify limitations of the equipment. For the most part, that objective was accomplished, but more projects should be scheduled to increase the confidence of construction personnel in making correct decisions and to limit the possibility of misinterpreting the IC roller response.
- The testing plan for additional pilot projects should include the FWD, Geogauge, and PSPA. The FWD is used to measure the deflection basins in areas with different IC roller responses or elastic modulus values. The purpose of this testing is to confirm that the low and high composite modulus values from the IC roller's measurement system is a result of the supporting layers. The Geogauge is used to assist in developing the stiffness adjustment factors for unbound layers, and the PSPA is used to estimate the in-place stiffness of the HMA layer. Until more data become available, the calibration procedure included in NCHRP Report #626 and used in these demonstration projects should be followed.
- Electronic files from the Bomag IC roller were not provided; only charts of the E_{vib} values were provided for each test area. The Sakai IC roller provided electronic files but no hard copies of the data during rolling operations. Both are beneficial during compaction operations, especially for agency construction personnel, and it is recommended that the DOT request both types of information in future demonstration and pilot projects.

IC Roller Availability

- As there are only a limited number of IC rollers available in the U.S., scheduling use of the rollers with the vendors is an issue—hopefully, a short-term issue. The different vendors of this technology have been supportive in allowing agencies and contractors to use the equipment at no cost for the demonstration projects. However, vendors can only support so much work without funding. Change orders to existing construction contracts may be needed to meet the schedule demands of the vendors and projects. Merging state compaction requirements with existing field test capabilities in collecting IC data should be pursued, but the DOT should plan on reimbursing the vendors for their continued efforts.

Confirmation of Structural Design Input Parameters

- The MEPDG requires that laboratory measured modulus values be entered into the program. Assuming the DOT continues to move forward with the adoption of the MEPDG for pavement design, the use of the soil IC rollers will be beneficial to confirm the design assumptions. This is a long-range goal that requires additional laboratory tests and comparisons to the response outputs from different IC rollers. Adjustment factors will need to be developed to eliminate bias between the laboratory and IC measured composite modulus values. The values determined from these demonstration projects should be confirmed with additional demonstration or pilot projects.
- Laboratory measured values are needed to determine the adjustment factors on a project-specific basis. The Wisconsin DOT does not routinely perform HMA dynamic modulus tests or soil repeated load resilient modulus tests, and it is expected that the DOT will not purchase or maintain the laboratory test equipment to measure the dynamic modulus of HMA mixtures or the resilient modulus of unbound layers. That being the case, it is recommended that the DOT consider including the measurement of these parameters for major construction projects by one of the following:
  - Include the testing as part of the construction requirements and specifications. For this case, the contractors will be responsible for measuring these values. Whether the contractor purchases the test equipment or hires a testing laboratory or university would be left up to the contractor.
  - Establish a center within one of the universities for measuring these properties for use in design and construction acceptance. The center should be available to both agency and contractor personnel.
  - Issue an annual contract to a consultant or testing firm for measuring these properties on projects identified by the DOT.

IC Use Related to Acceptance

- The DOT should use the IC roller responses and output to determine locations where point measurements are needed for final acceptance of the unbound layer. In other words, strategically locate the more time-consuming acceptance tests and reduce the number of tests without increasing the DOT's risk of making a wrong decision.

IC Specifications

- New compaction specifications and field control procedures must be developed to take full advantage of IC capabilities. Continuing education on the background principles and actual project experiences will be required to make this happen. Fully understanding the differences between soils (and aggregates) with HMA IC roller output and how IC information compares to existing compaction tests and specifications is also important. Furthermore, procedures will be needed to address locations where IC data show that the desired compaction levels have not been met.

- The authors recommend caution in requiring that contractors use IC rollers on projects. The authors believe that an owner should not dictate to the contractor on how to achieve the end result in QA-type specifications—only “recipe type” specifications. It is suggested that the DOT sponsor future pilot projects on the use of IC technology to demonstrate the value to local contractors.

Training – Interpretation and Use of IC Technology

Training is an issue, as it is for implementing any new technology, for both contractor and owner personnel. This training issue goes beyond the DOT, because many local agencies (cities, counties, municipalities) follow the specifications and requirements of the DOT.

More importantly, vendors are taking different approaches in the development and implementation of IC technology for dual drum rollers used to compact HMA materials, which will result in varying levels of capabilities between vendors. This complicates the implementation effort of agencies trying to achieve the benefits of IC technology without making the specification too restrictive or specifying a specific IC system.

At this time, it is considered premature to develop a training program until the DOT has decided on the path of implementation and use of IC technology in Wisconsin. The Wisconsin DOT should consider teaming with the agencies in neighboring States (common contractors working for different agencies) to develop a training program, to offset some of the development costs.

An important training issue for contractors is the durability and long-term accuracy of electronic components when assessing frequency of repairs and calibration for implementation and use of this technology. Contractors must be able to determine the maintenance and service requirements of the equipment and components accurately so that they may eventually recover their investment costs. This information will be proprietary and difficult to obtain from the vendors; it likely will need to be obtained from other contractors who have experience using IC rollers.

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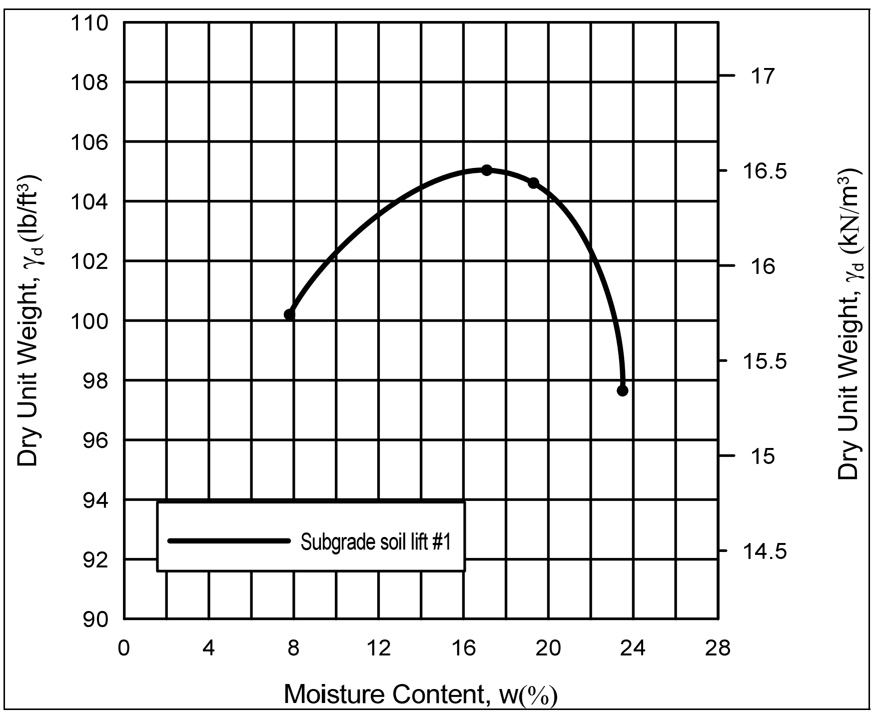
APPENDIX A
MOISTURE-DENSITY RELATIONSHIPS FOR UNBOUND MATERIALS

This appendix provides the test results from laboratory and field moisture-density tests. The first part of this appendix provides a graphical summary of the laboratory moisture-density relationships measured for the unbound materials and embankment soils for the demonstration projects. The second part provides the limited sand cone tests performed on the in-place soils.

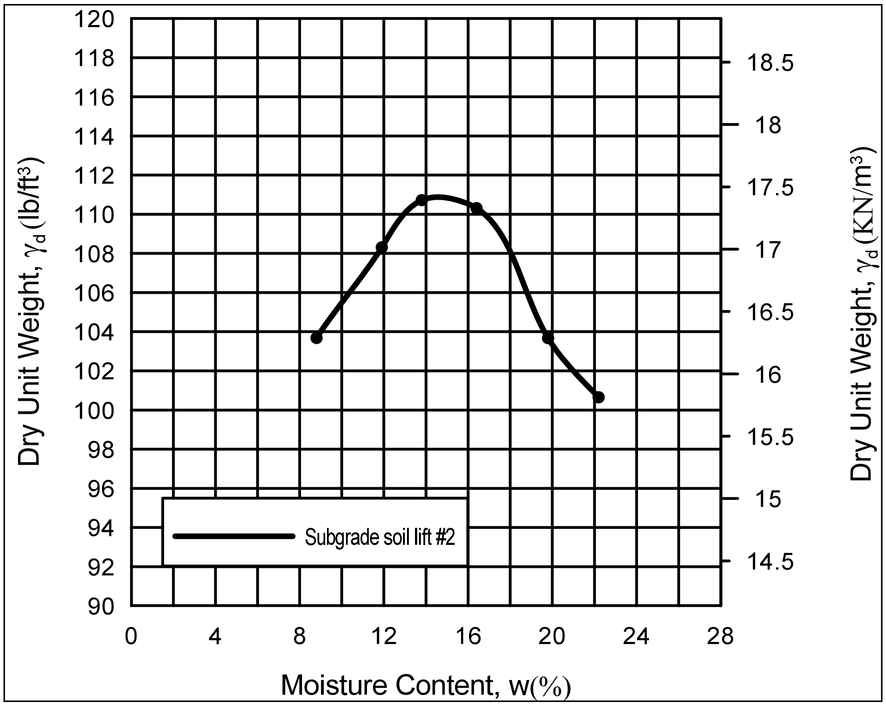
A.1 SH 80 Project Materials

A.1.1 High Plasticity Soil Embankment

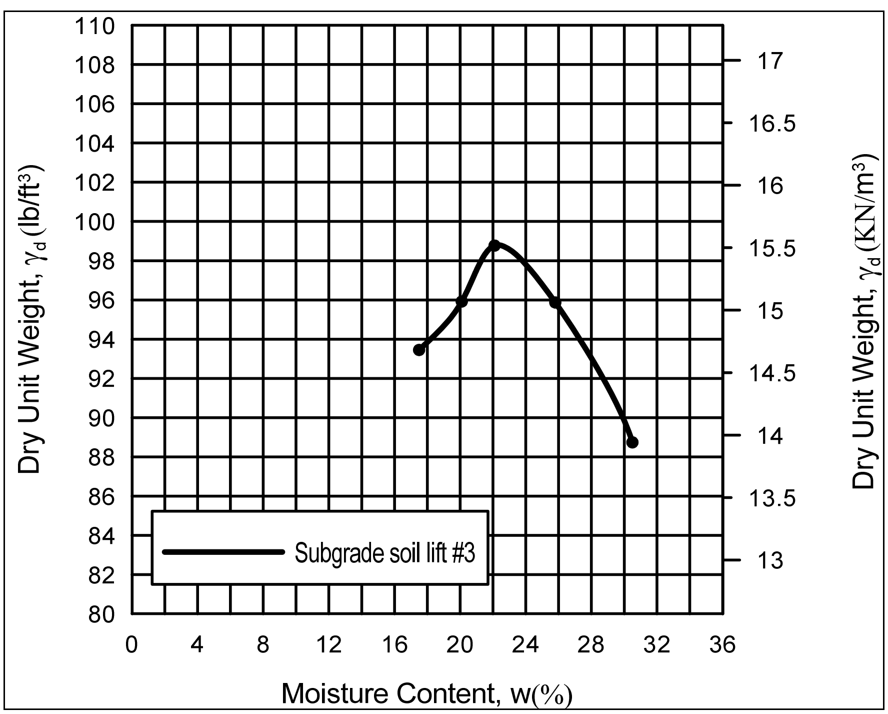
The following is a graphical presentation of the compaction characteristics (moisture-unit weight curve) for the A-6 high plasticity clay foundation, soil lift #1, for the existing soil layer.



The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the A-6 high plasticity clay embankment, soil lift #2.

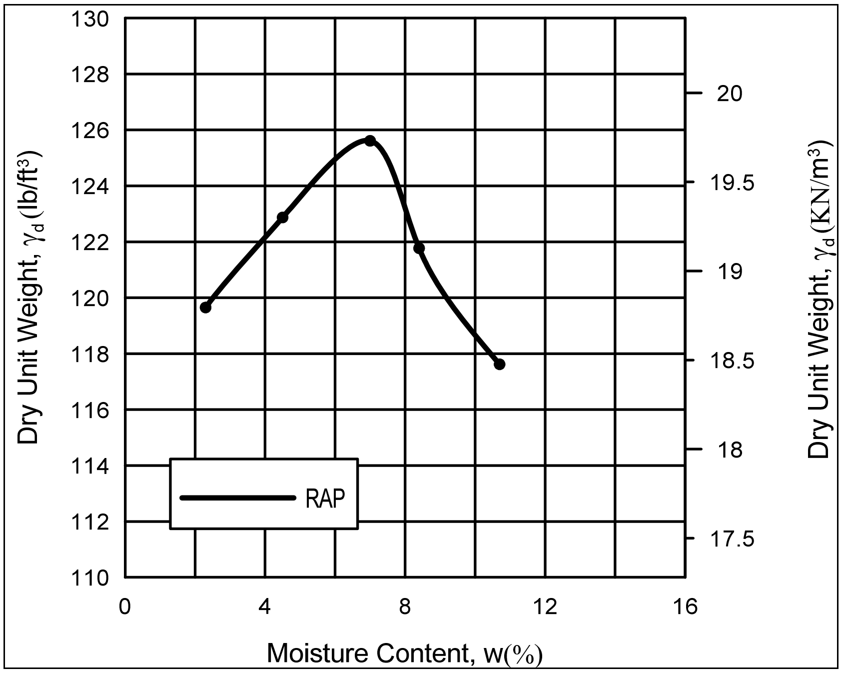


The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the A-7-6 high plasticity clay embankment, soil lift #3.



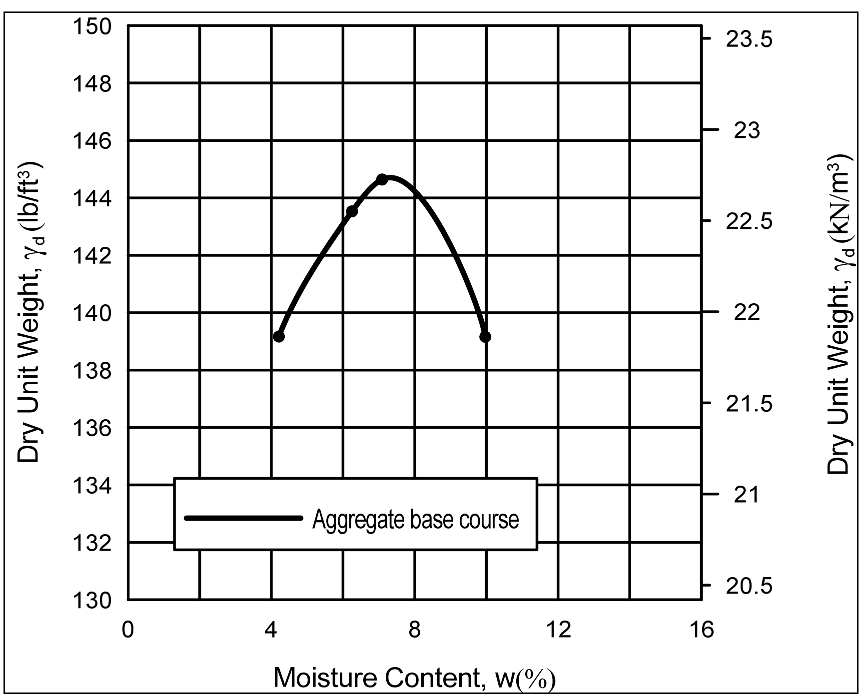
A.1.2 RAP Base Layer

The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the RAP base layer that was placed above the crushed stone base layer.



A.1.2 Crushed Stone Base

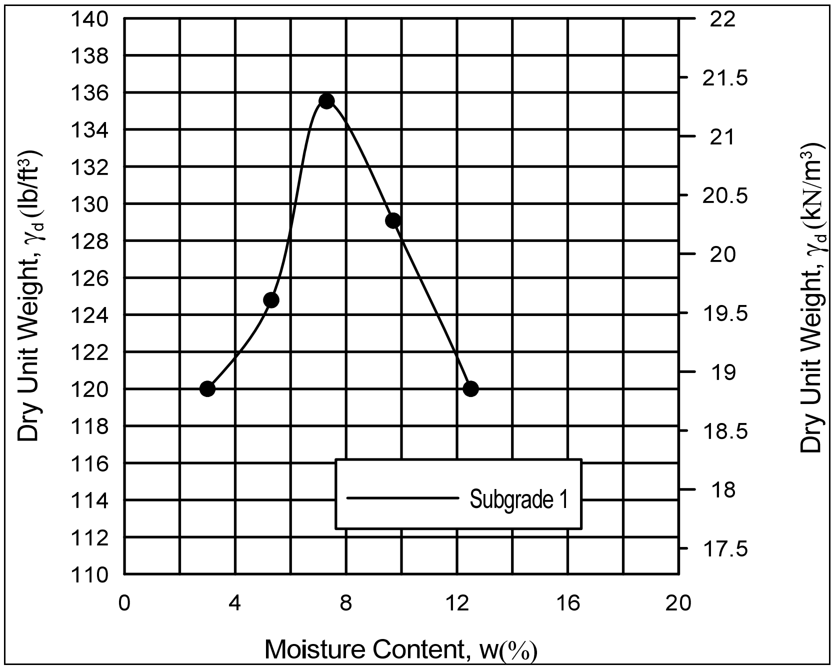
The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the crushed stone base layer from the Highland project.



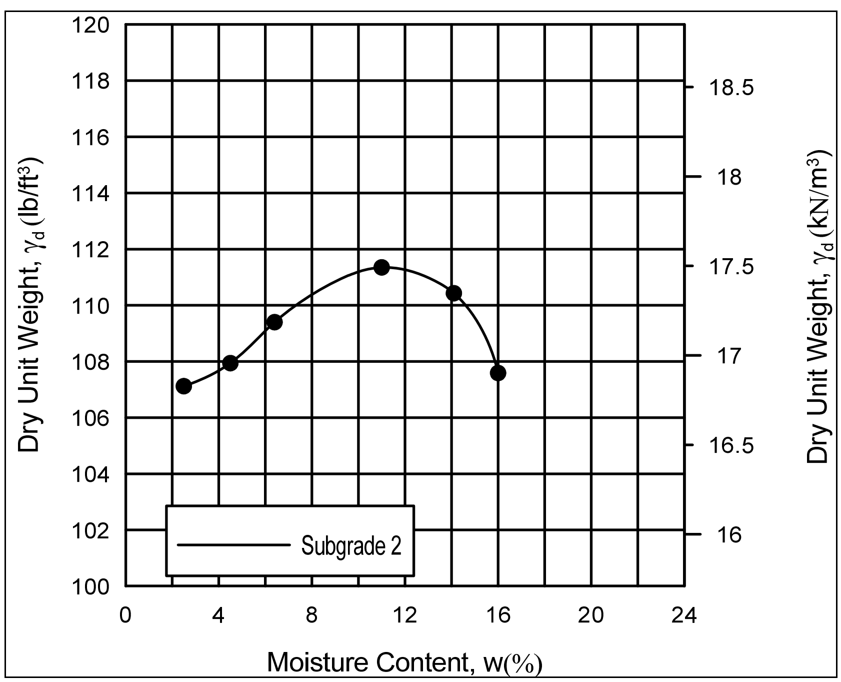
A.2 SH-18 Project Materials

A.2.1 Low Plasticity Soil Embankment

The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the A-4 low plasticity soil embankment, lift #1.

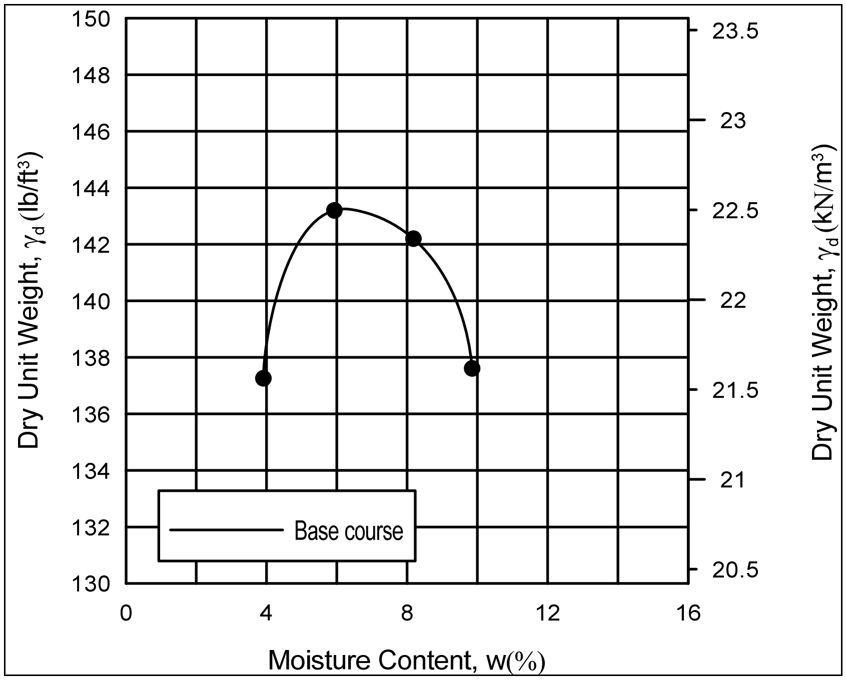


The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the A-3 low plasticity, silty sand soil embankment, lift #2.



A.2.2 Crushed Aggregate Base Layer

The following is a graphical summary of the compaction characteristics (moisture-unit weight curve) for the crushed aggregate base layer from the Jefferson project.

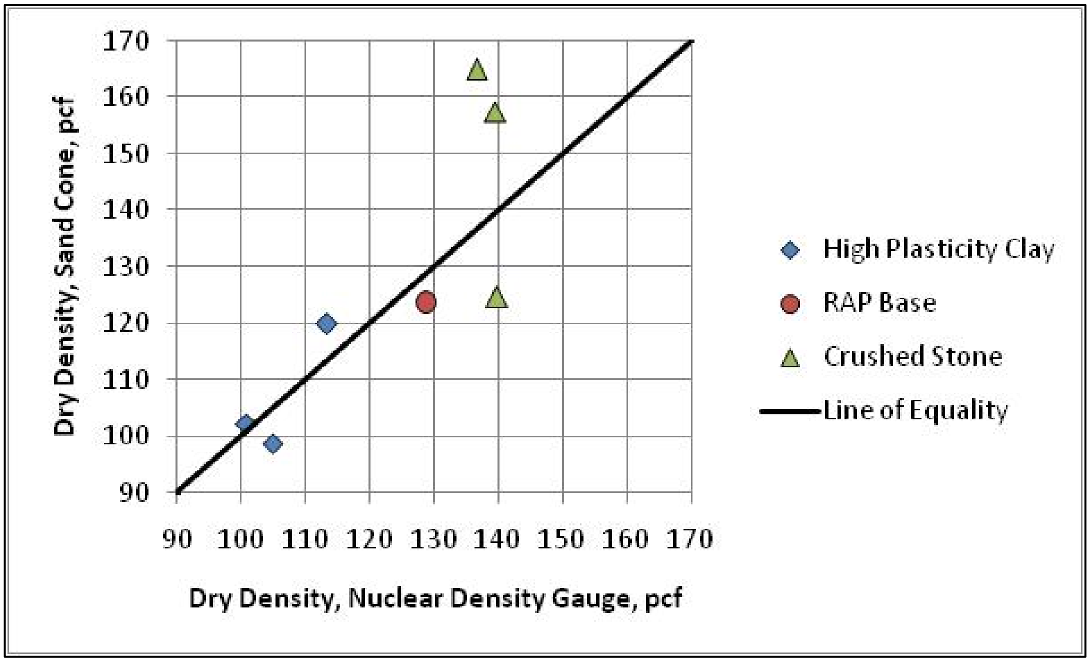


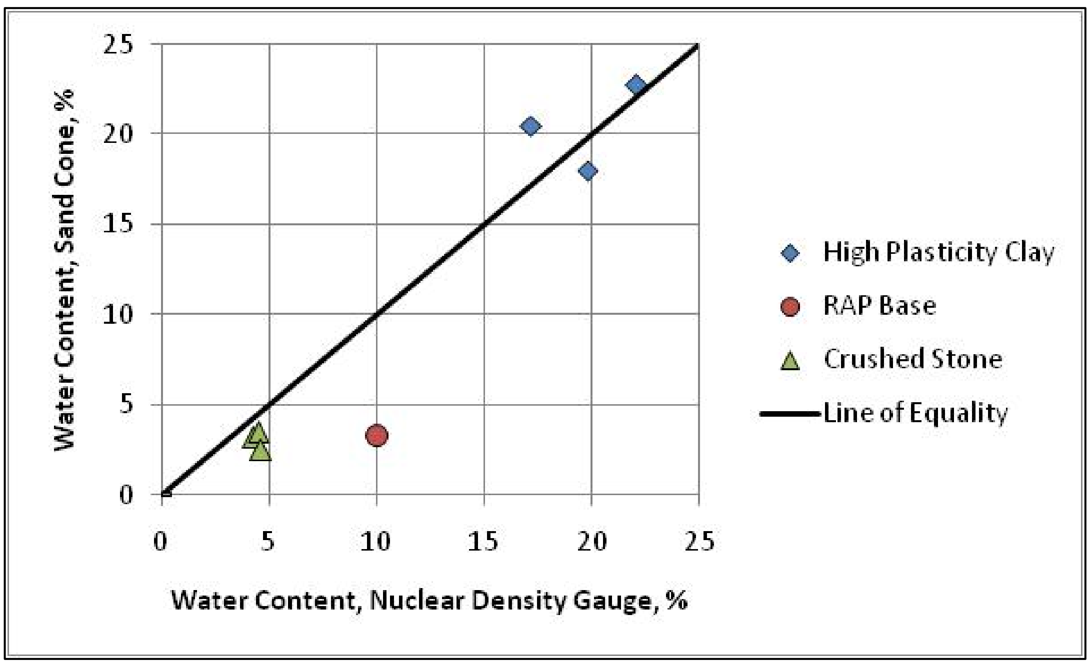
A.3 Sand Cone Test Results

The following is a list of the sand cone tests that were performed on the unbound materials during the IC rolling of the demonstration projects. A graphical comparison of the results measured with the nuclear density gauge and sand cone is included after the tabular summary of test results.

Highland SH 80 Reconstruction Project

	High Plasticity Clay Embankment		
Date	6/17/2009	6/17/2009	6/17/2009
Location ID	Row #2; 25 ft.	Row #2; 25 ft.	Row #2; 25 ft.
Sand Cone No.	4	1	2
Lift Number	#1; Existing	#2	#3
Number of Passes	None	4	After Initial
Wet Unit Weight, pcf	116.56	125.47	144.44
Moisture Content, %	18.01	22.7	20.5
Dry Unit Weight, pcf	98.77	102.26	119.87
	RAP		
Date	6/18/2009		
Location ID	Sta 99+00		
Sand Cone No.	1		
Lift Number	Top of RAP Base		
Number of Passes	Final		
Wet Unit Weight, pcf	127.76		
Moisture Content, %	3.3		
Dry Unit Weight, pcf	123.68		
	Crushed Stone Base		
Date	6/16/2009	6/16/2009	6/16/2009
Location ID	Sta 108+00	Sta 108+00	Sta 108+00
Sand Cone No.	1	2	3
Lift Number	Top of Base	Top of Base	Top of Base
Number of Passes			
Wet Unit Weight, pcf	128.57	163.03	169.01
Moisture Content, %	3.2	3.5	2.5
Dry Unit Weight, pcf	124.58	157.52	164.89


Dry Density, Sand Cone, pcf
170
160
150
140
130
120
110
100
90
90 100 110 120 130 140 150 160 170
Dry Density, Nuclear Density Gauge, pcf
High Plasticity Clay
RAP Base
Crushed Stone
Line of Equality


Water Content, Sand Cone, %
25
20
15
10
5
0
0 5 10 15 20 25
Water Content, Nuclear Density Gauge, %
High Plasticity Clay
RAP Base
Crushed Stone
Line of Equality

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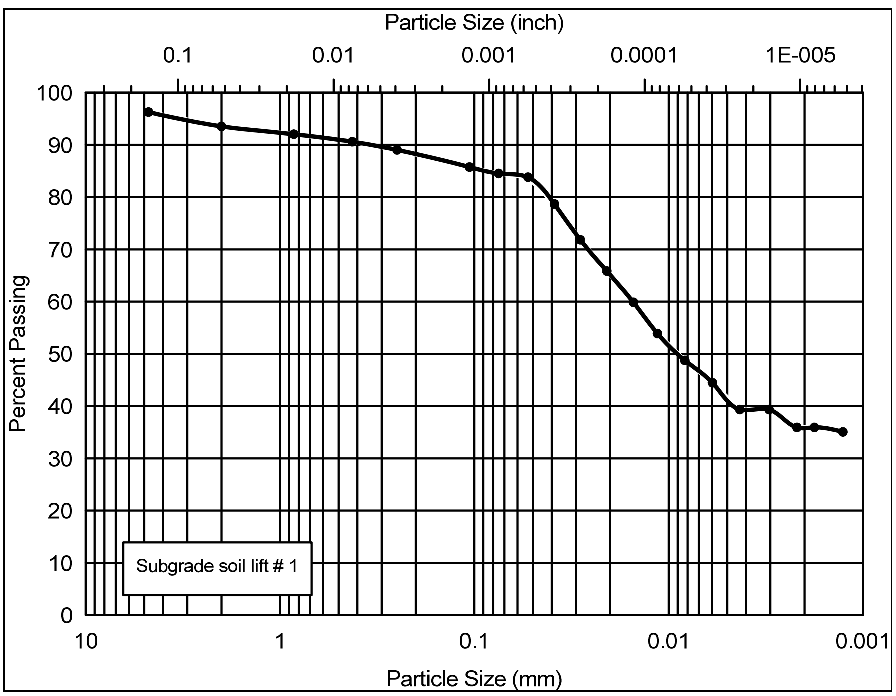
APPENDIX B
GRAIN SIZE DISTRIBUTION RELATIONSHIPS, GRADATION FOR UNBOUND MATERIALS

This appendix provides a summary of the grain size distributions for the unbound embankment soils and materials that were placed on the demonstration projects.

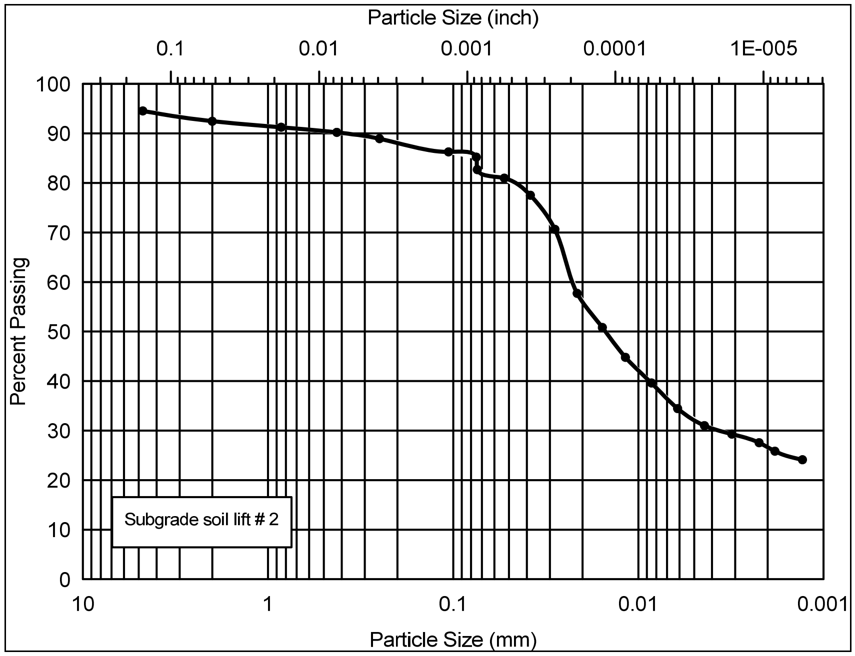
B.1 SH-80 Project Materials

B.1.1 High Plasticity Soil Embankment

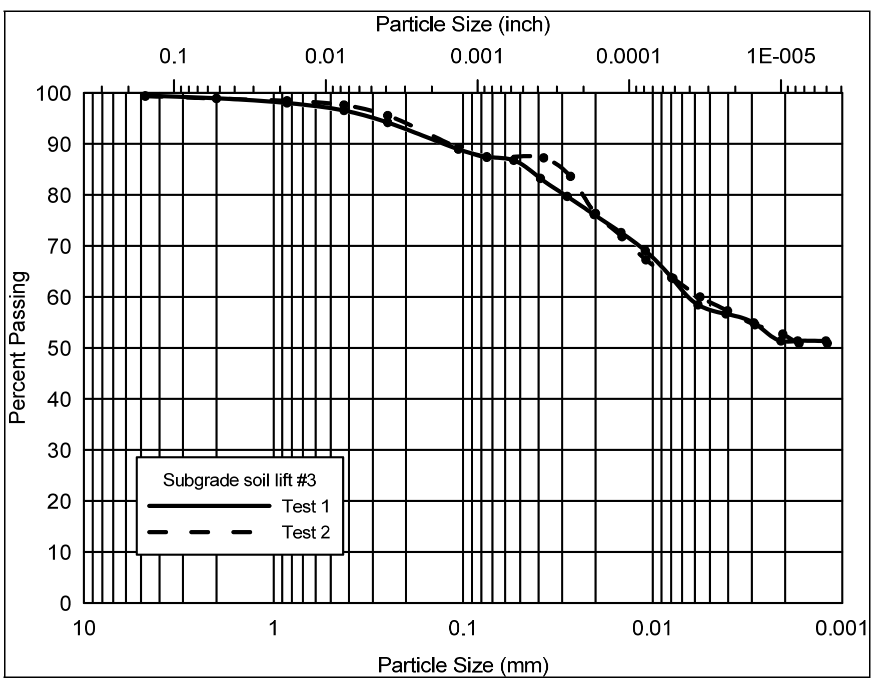
The following is a graphical summary of the particle size distribution for the A-6 high plasticity foundation soil, lift #1, for the existing soil.



The following is a graphical summary of the particle size distribution for the A-6 high plasticity embankment soil, lift #2.



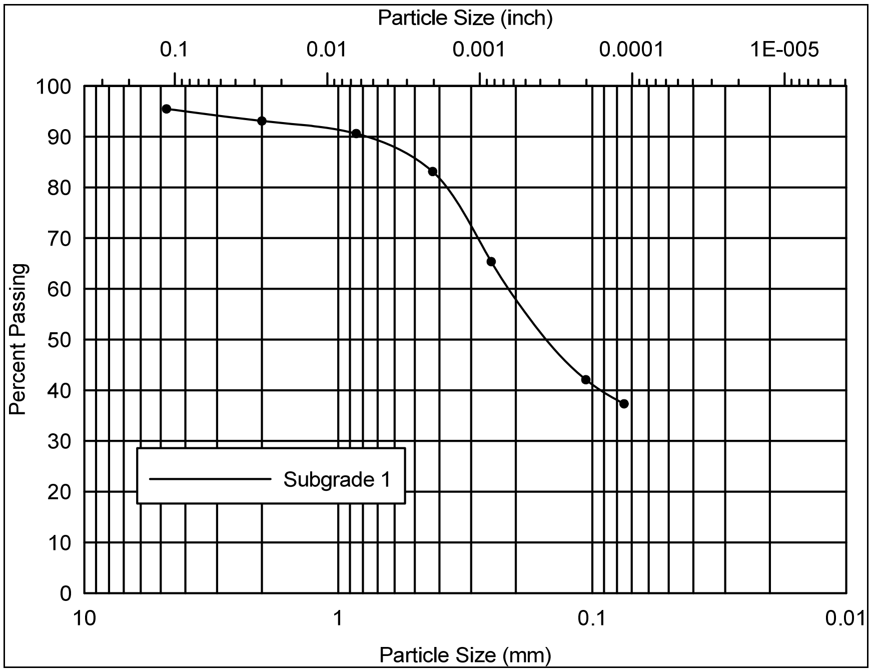
The following is a graphical summary of the particle size distribution for the A-7-6 high plasticity embankment soil, lift #3.



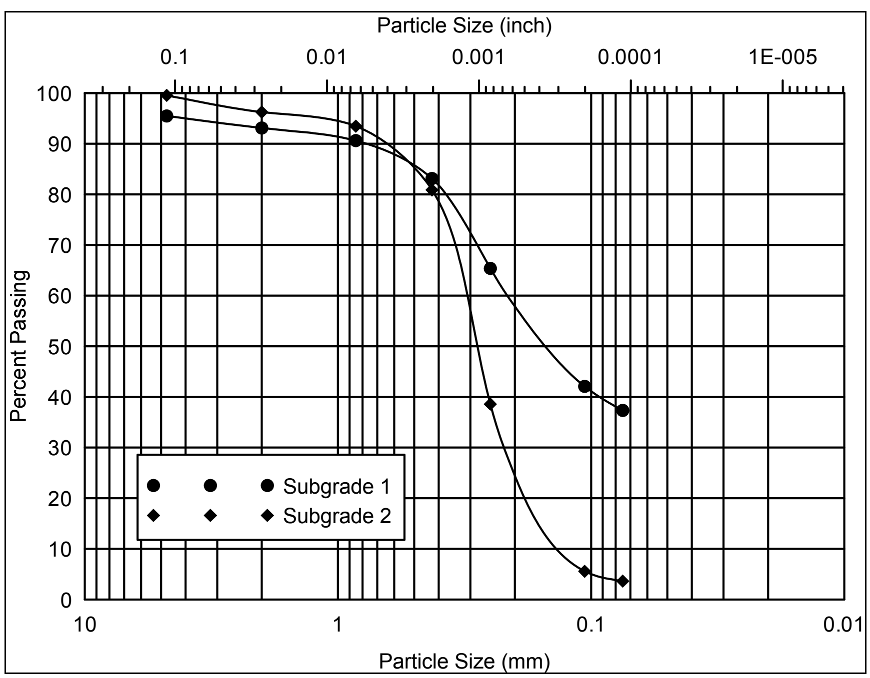
B.2 SH 18 Project Materials

B.2.1 Low Plasticity Soil Embankment

The following is a graphical summary of the particle size distribution for the A-4 low plasticity embankment soil, lift #1.



The following is a graphical summary of the particle size distribution for the A-3 low plasticity, silty sand embankment soil; lift #2.



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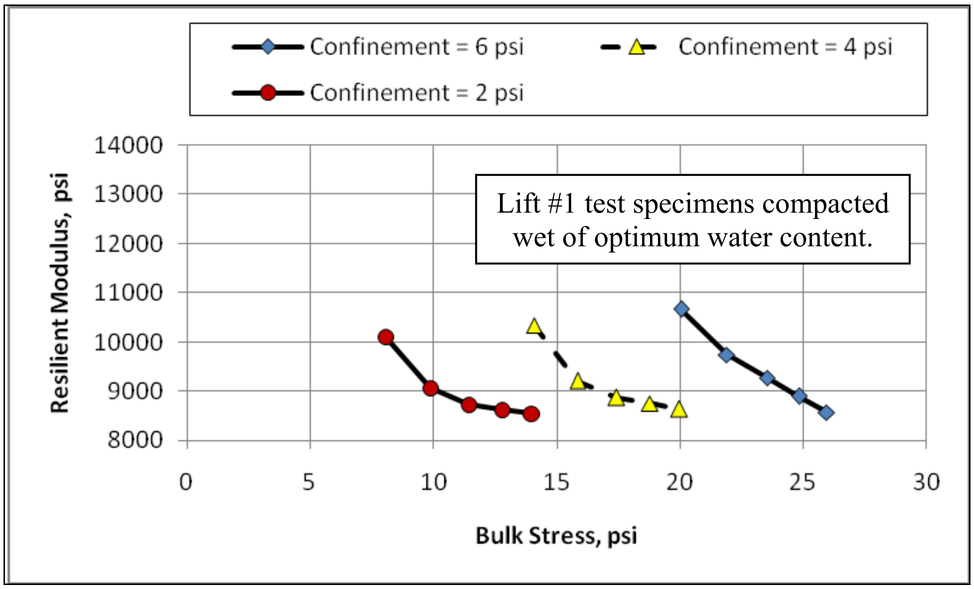
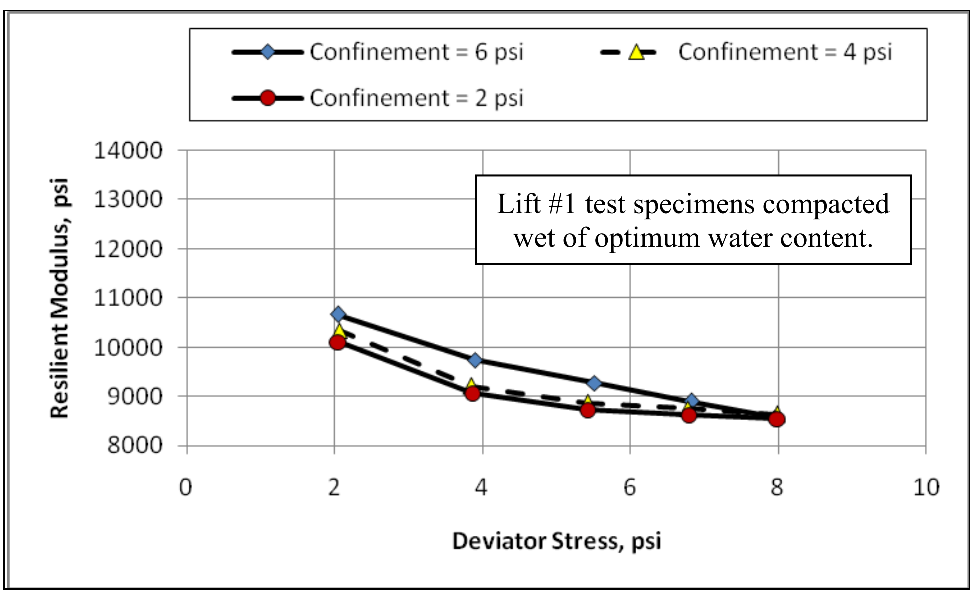
APPENDIX C
REPEATED LOAD RESILIENT MODULUS TESTS FOR UNBOUND MATERIALS

C.1 SH 80 Project Materials

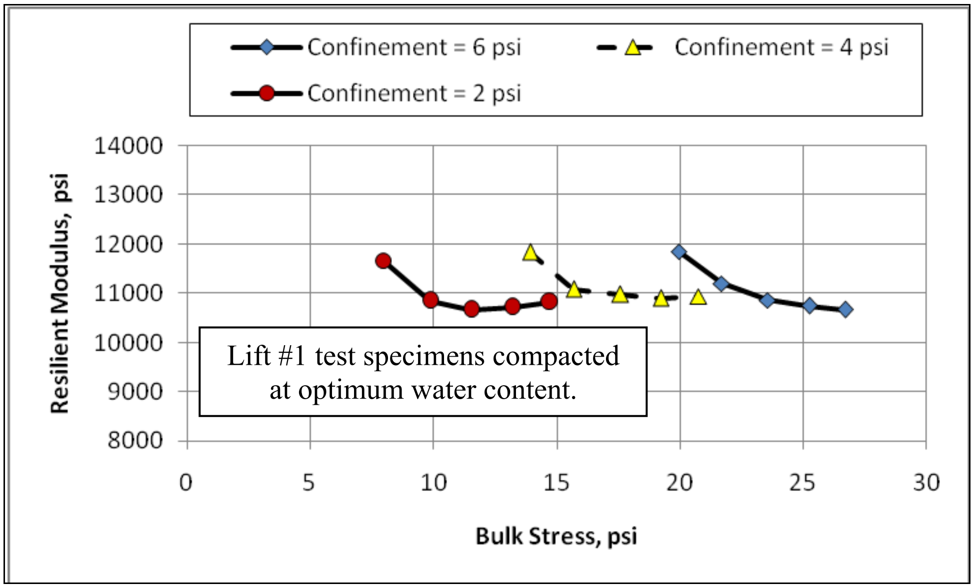
C.1.1 High Plasticity Soil Foundation – Existing Layer, Lift #1

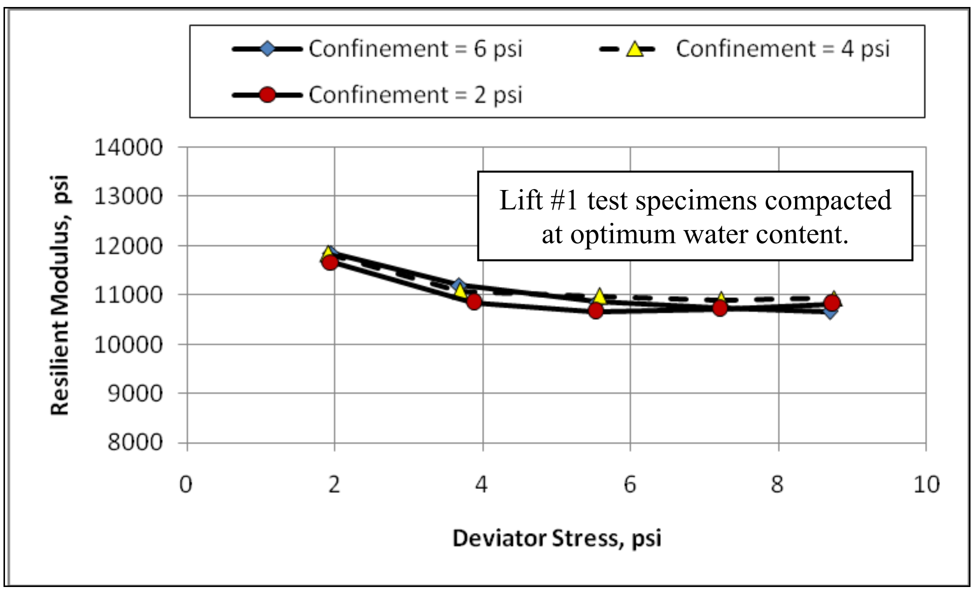
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay foundation soil test specimens that were compacted wet of optimum water content.



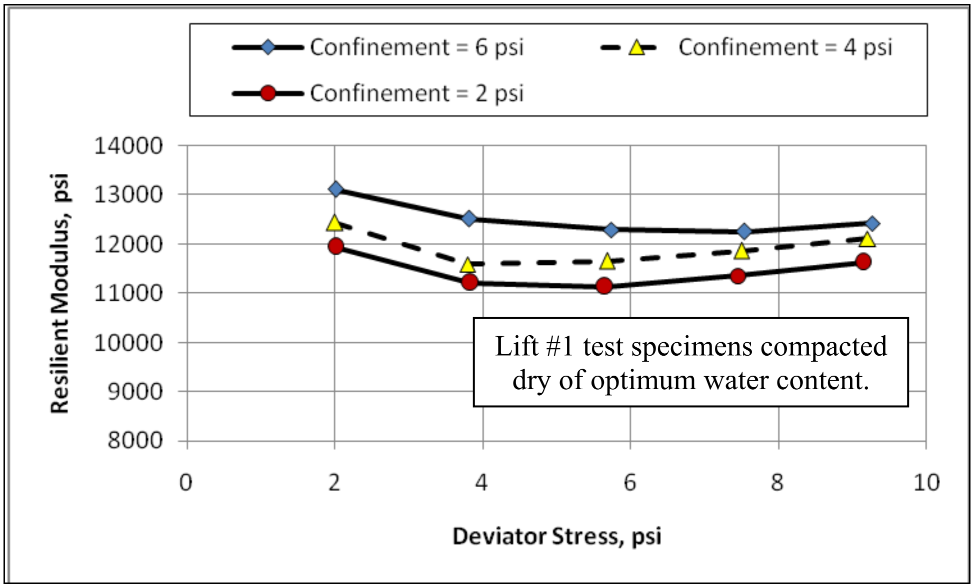


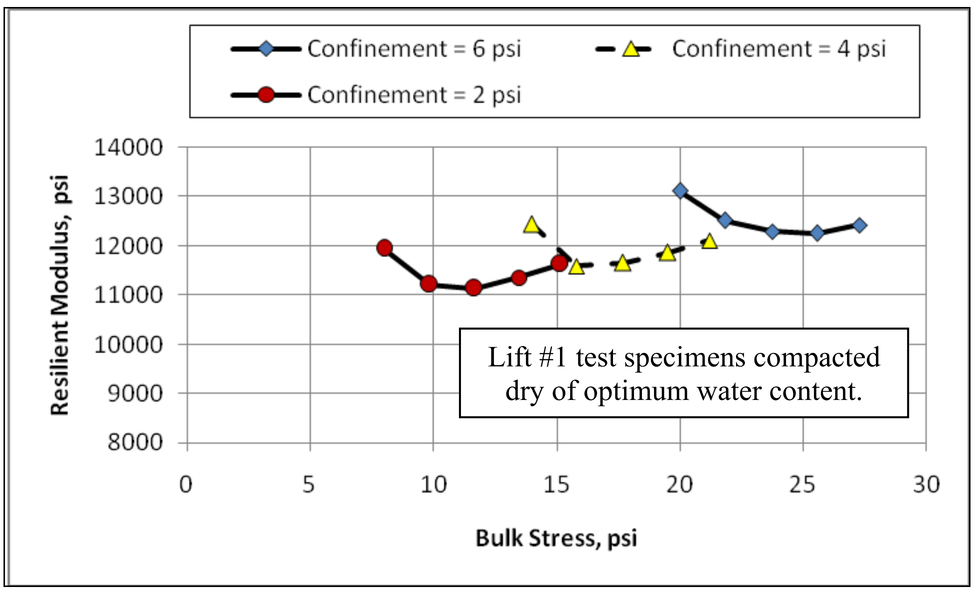
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay foundation soil test specimens that were compacted at optimum water content.





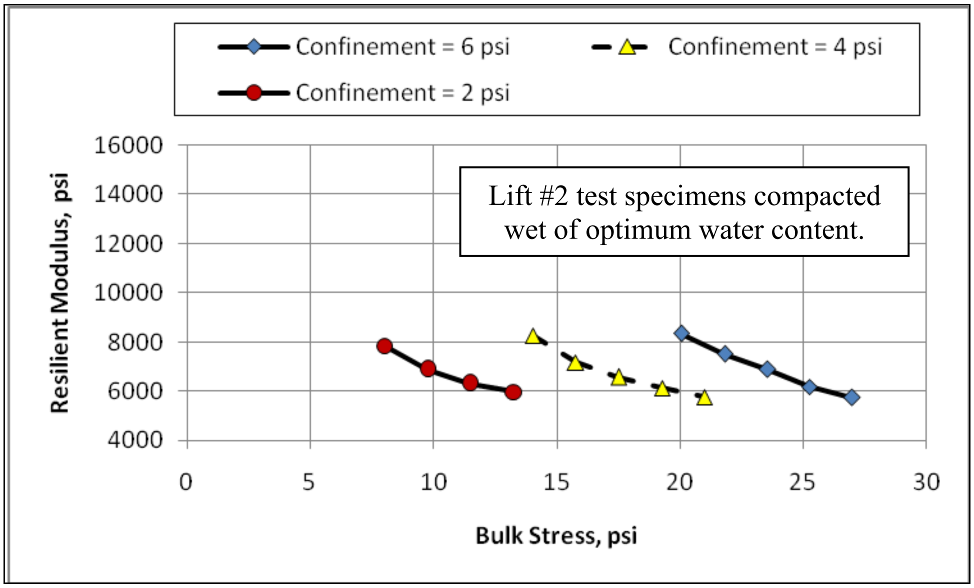
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay foundation soil test specimens that were compacted dry of optimum water content.

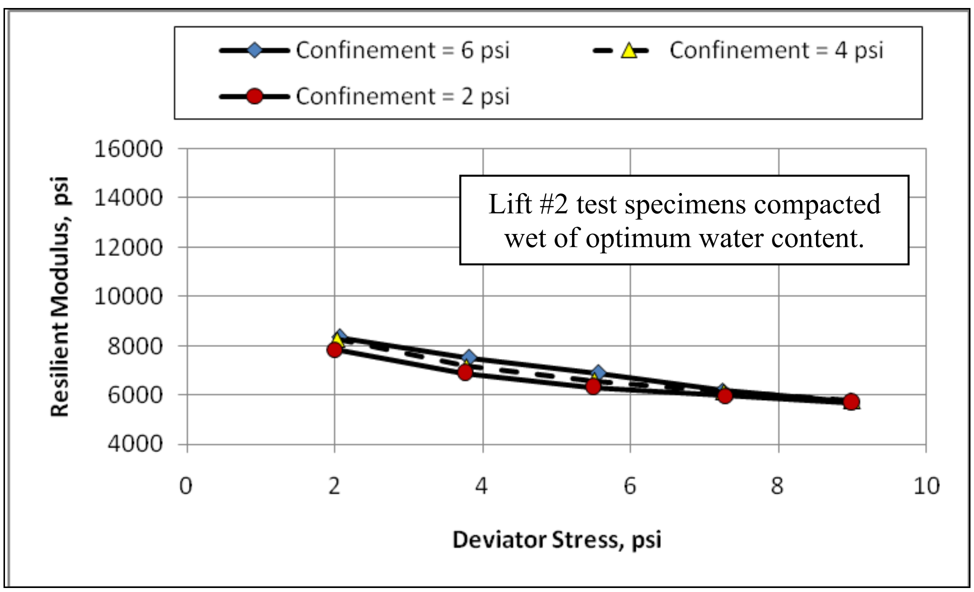




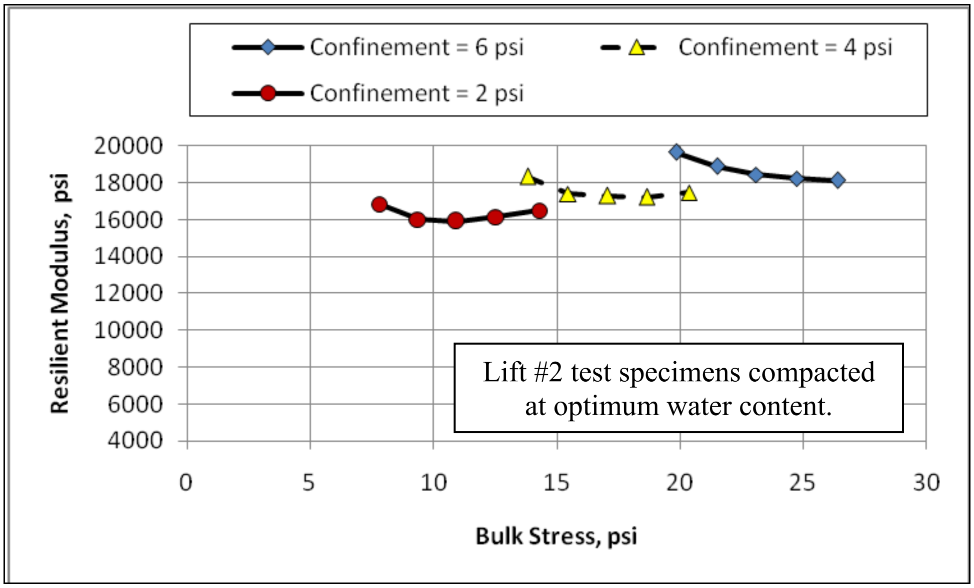
C.1.2 High Plasticity Soil Embankment – Lift #2

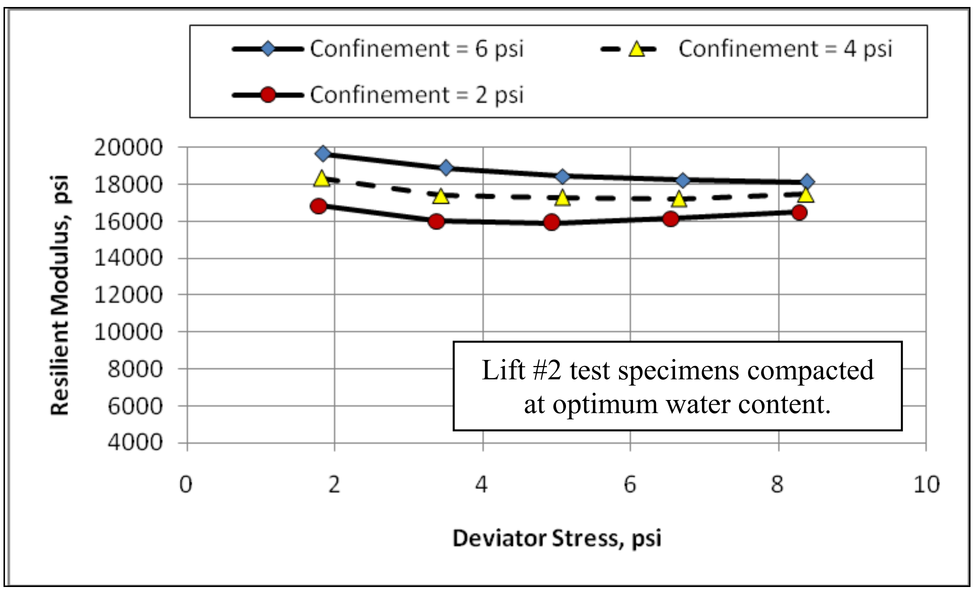
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay embankment soil test specimens that were compacted wet of optimum water content.



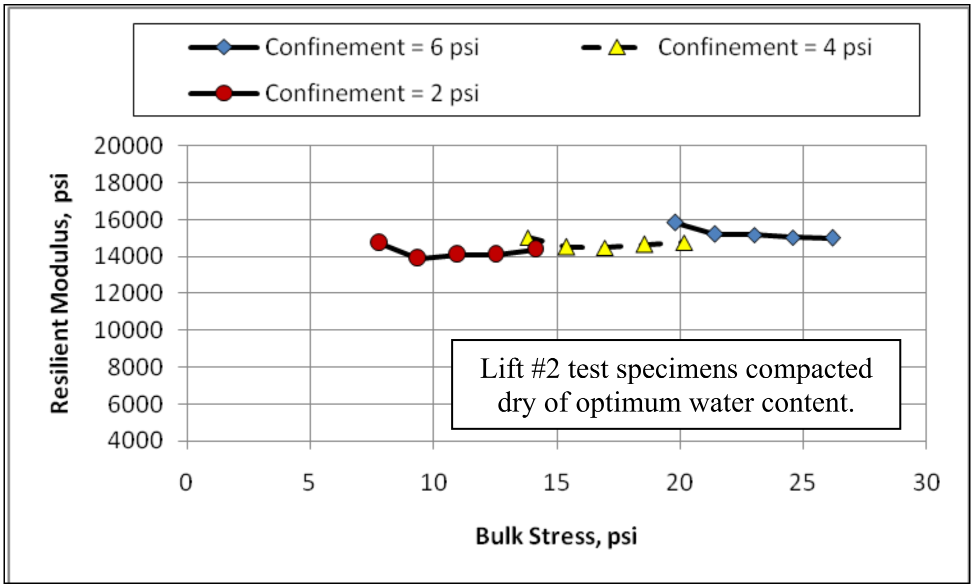


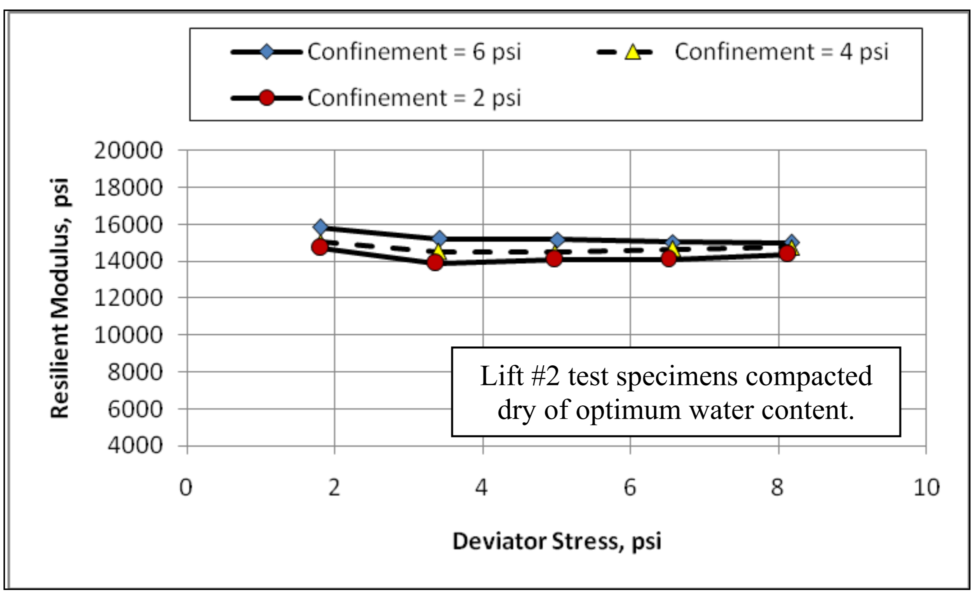
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay embankment soil test specimens that were compacted at optimum water content.





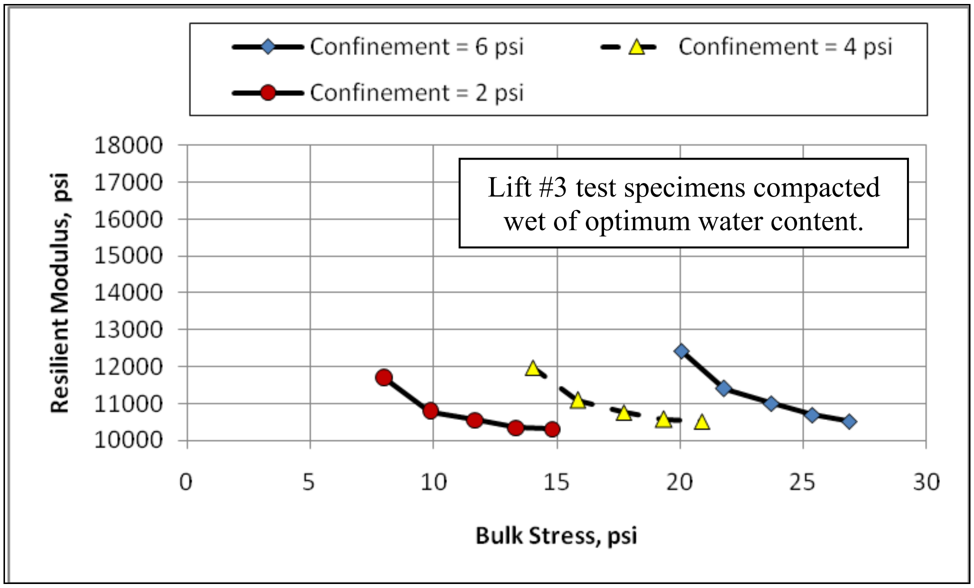
The following is a graphical summary of the resilient modulus versus stress state for the A-6 high plasticity clay embankment soil test specimens that were compacted dry of optimum water content.

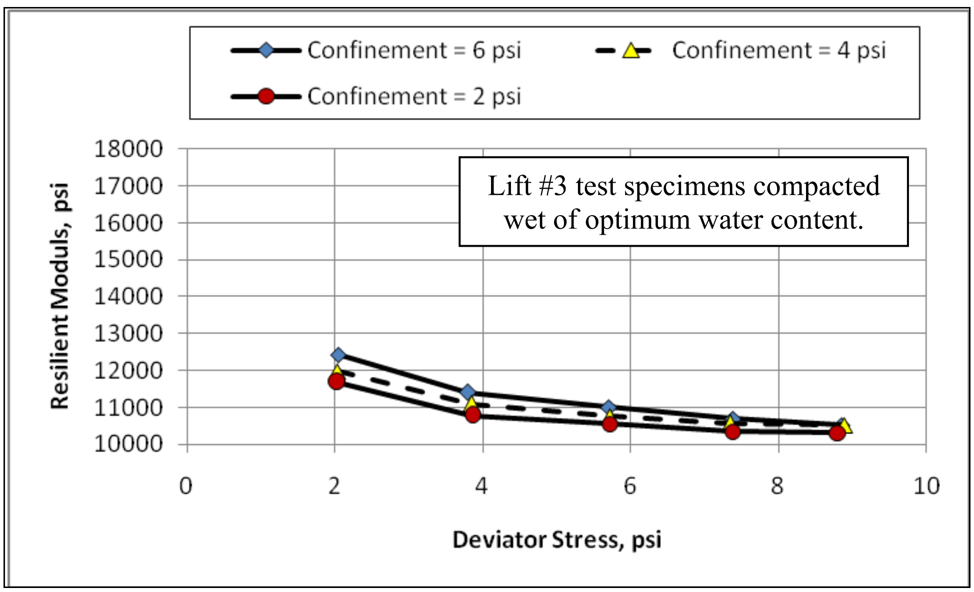




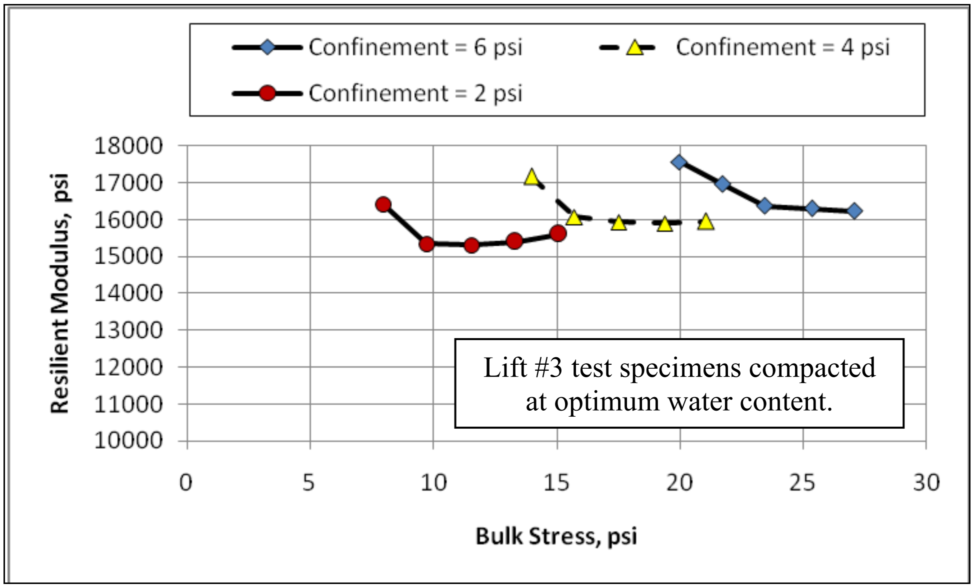
C.1.3 High Plasticity Soil Embankment – Lift #3

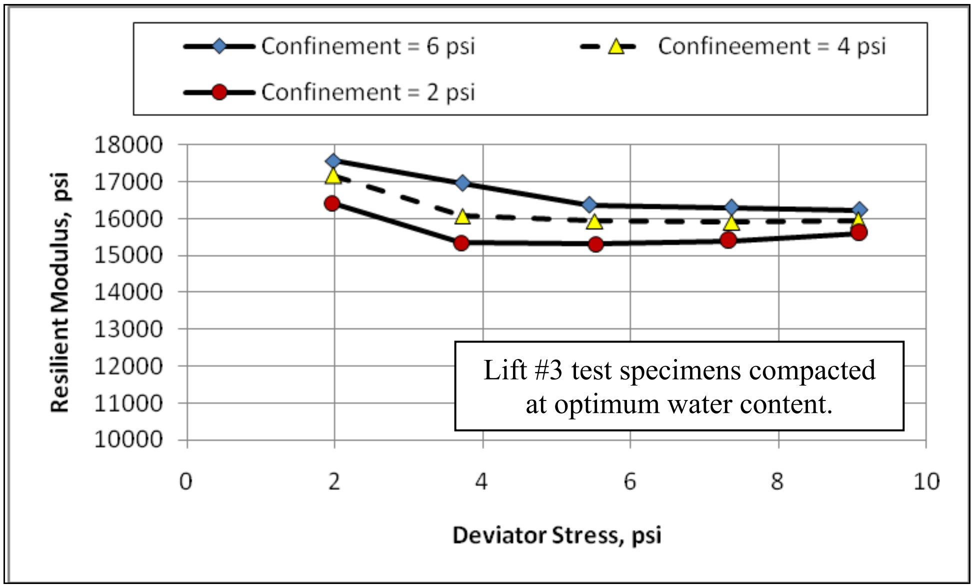
The following is a graphical summary of the resilient modulus versus stress state for the A-7-6 high plasticity clay embankment soil test specimens that were compacted wet of optimum water content.



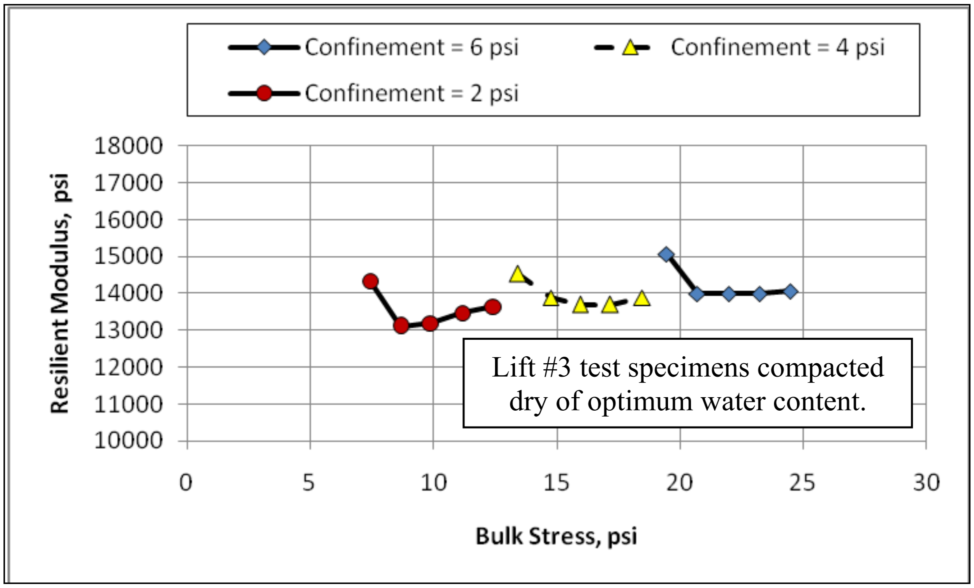


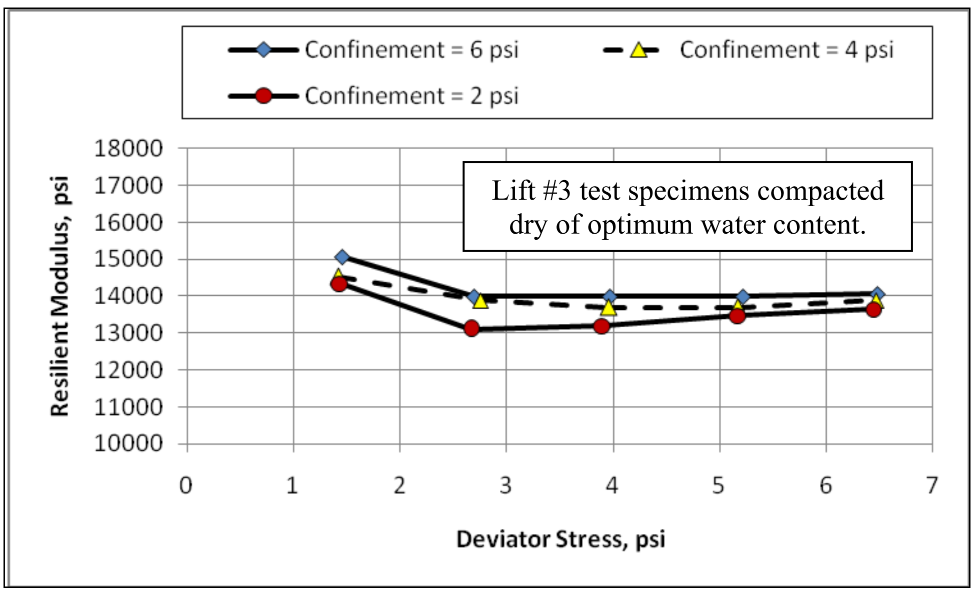
The following is a graphical summary of the resilient modulus versus stress state for the A-7-6 high plasticity clay embankment soil test specimens that were compacted at optimum water content.





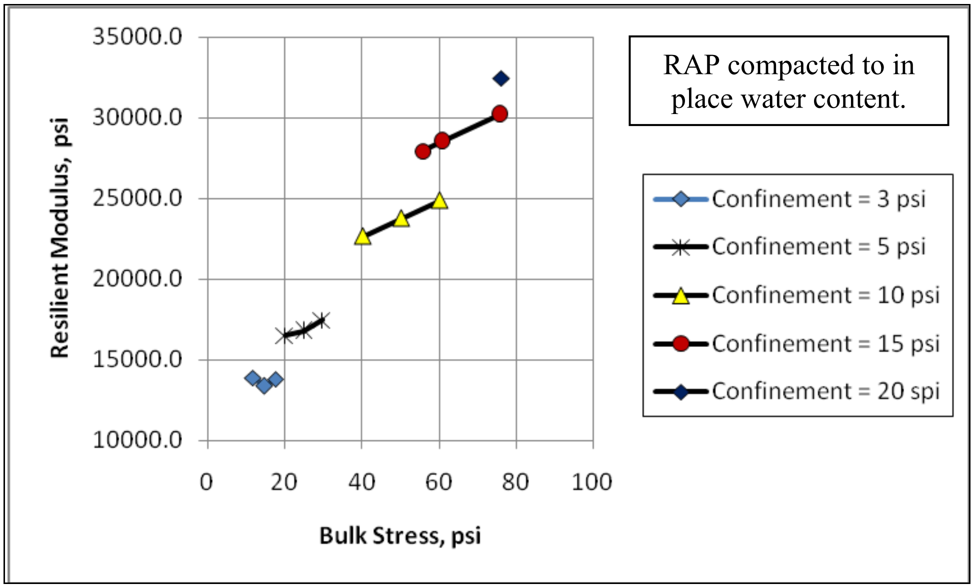
The following is a graphical summary of the resilient modulus versus stress state for the A-7-6 high plasticity clay embankment soil test specimens that were compacted dry of optimum water content.





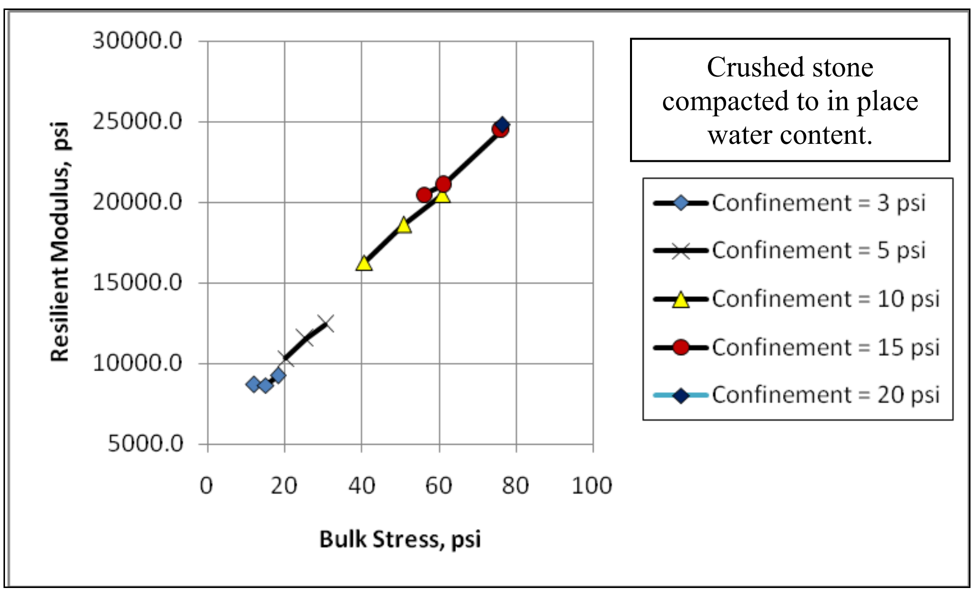
C.1.4 RAP Base Layer

The following is a graphical summary of the resilient modulus versus stress state for the RAP base test specimens that were compacted at the in-place water content measured during construction.



C.1.5 Crushed Stone Base

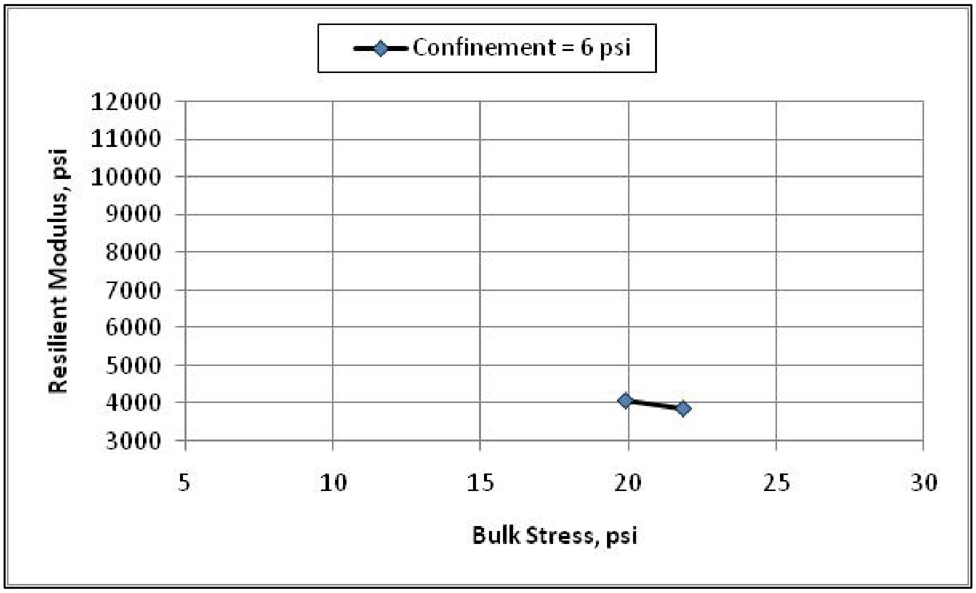
The following is a graphical summary of the resilient modulus versus stress state for the crushed stone base test specimens that were compacted at the in-place water content measured during construction.

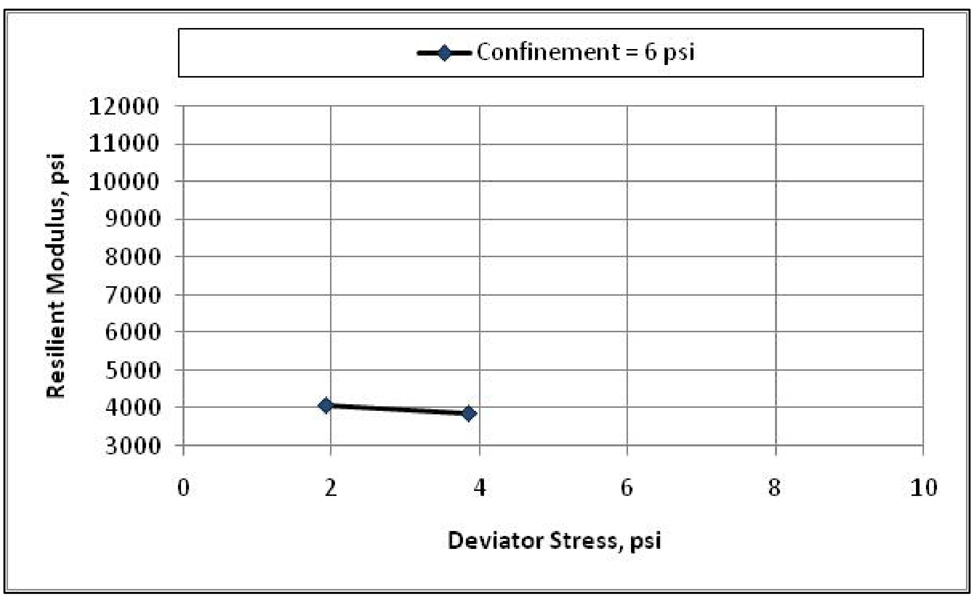


C.2 SH-18 Project Materials

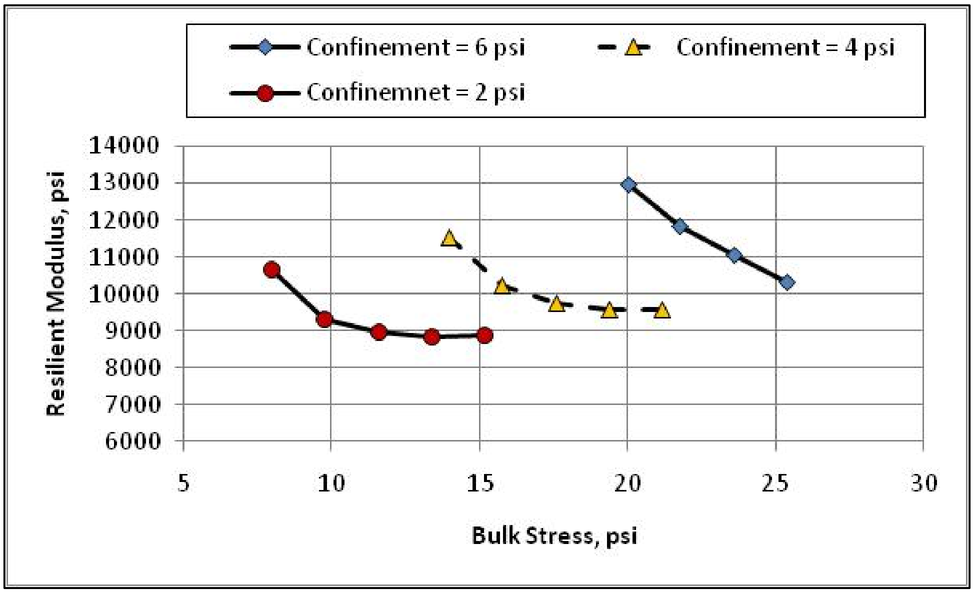
C.2.1 A-4 Low Plasticity Soil Embankment

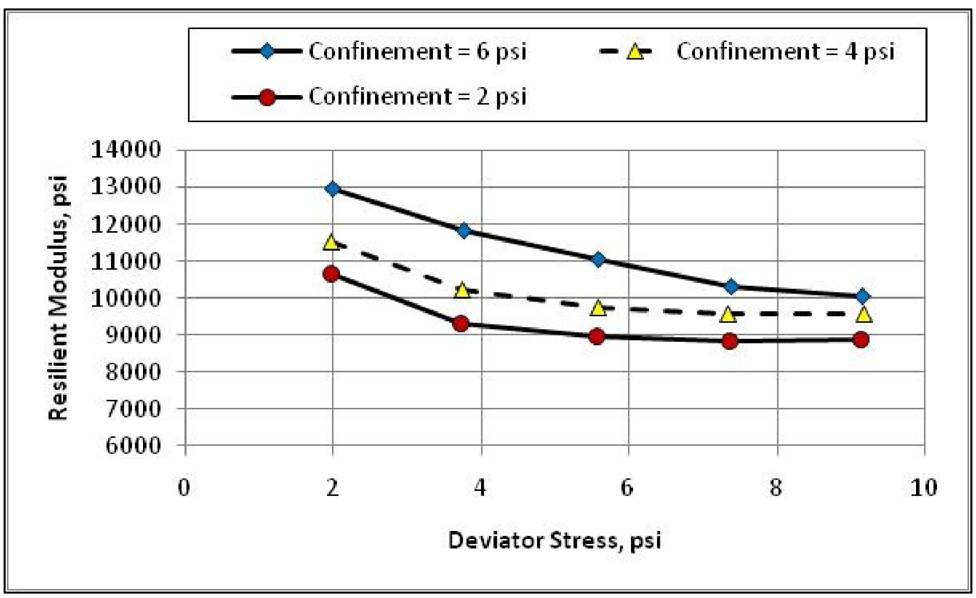
The following is a graphical summary of the resilient modulus versus stress state for the A-4 embankment test specimens that were compacted wet of optimum.



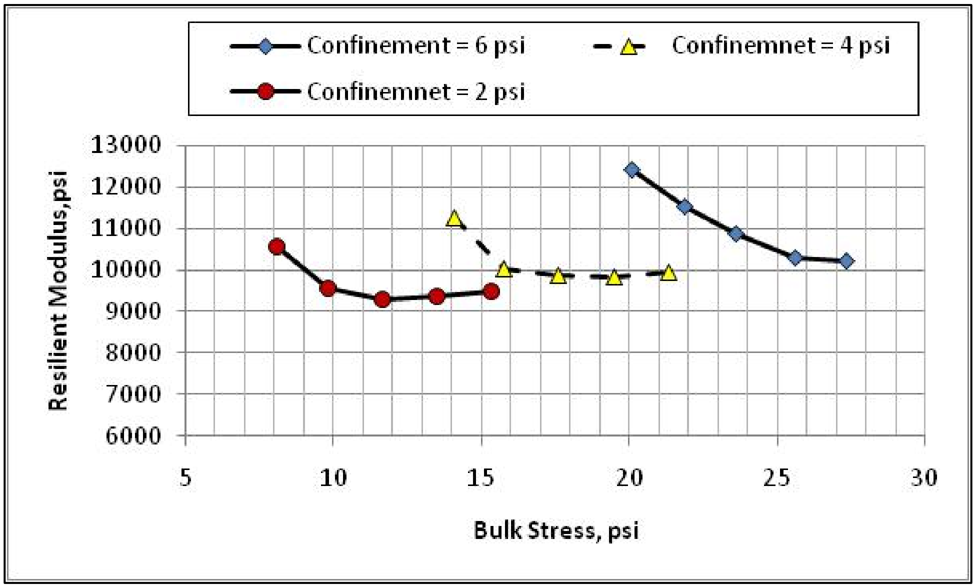


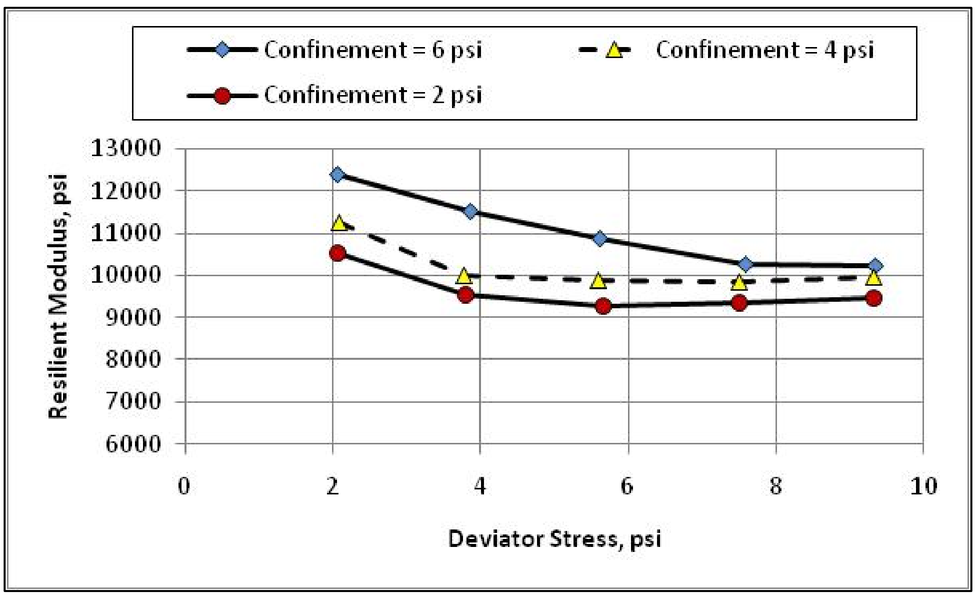
The following is a graphical summary of the resilient modulus versus stress state for the A-4 embankment test specimens that were compacted at the optimum water content and maximum dry density.





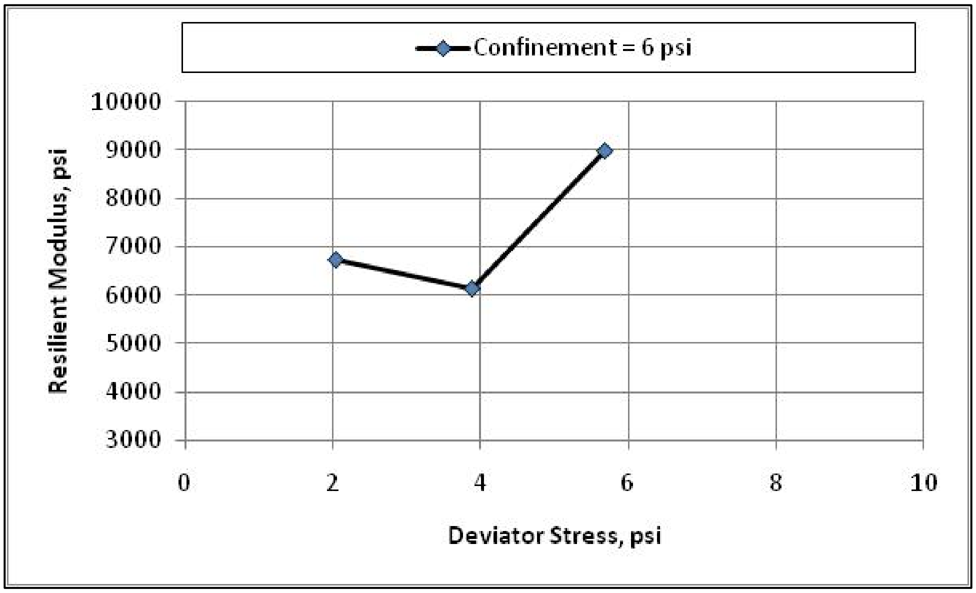
The following is a graphical summary of the resilient modulus versus stress state for the A-4 embankment test specimens that were compacted dry of optimum.





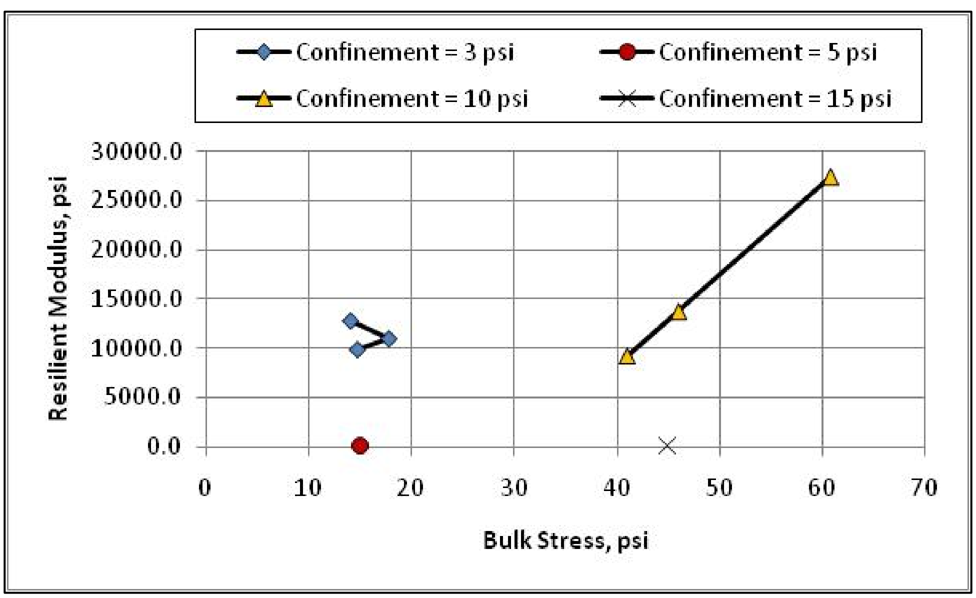
C.2.2 A-3 Silty Sand Soil Embankment

The following is a graphical summary of the resilient modulus versus stress state for the A-3, silty sand, embankment test specimens that were compacted at the in-place water content and dry density measured during construction.

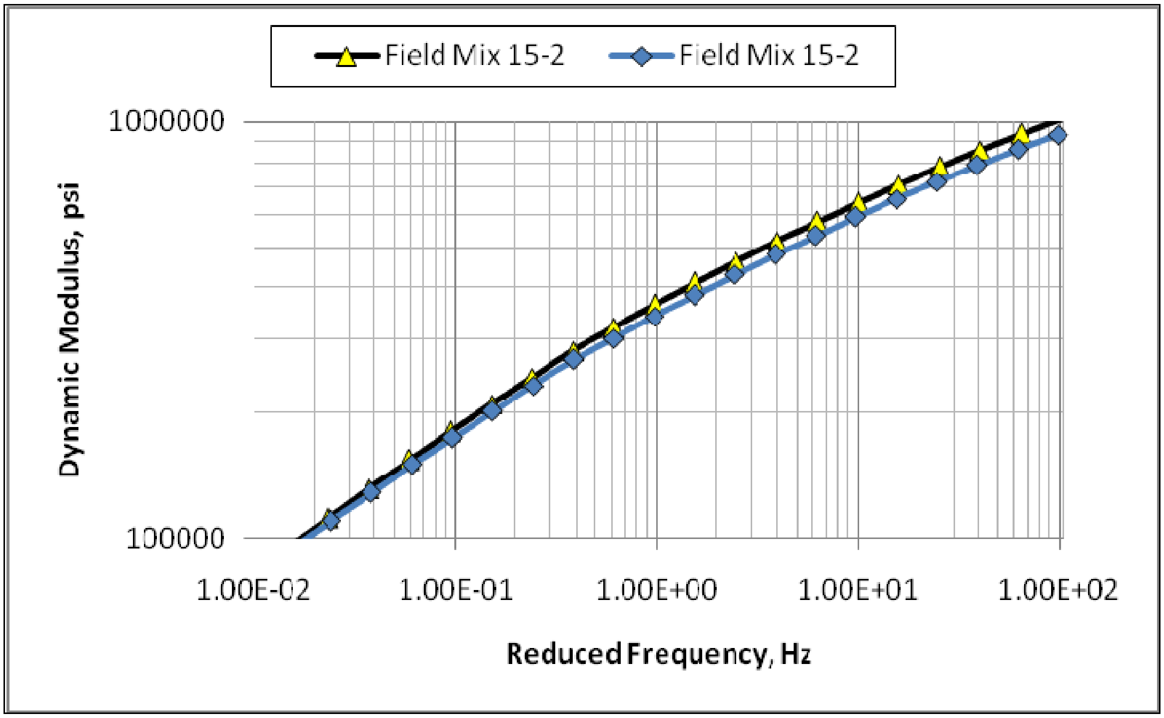


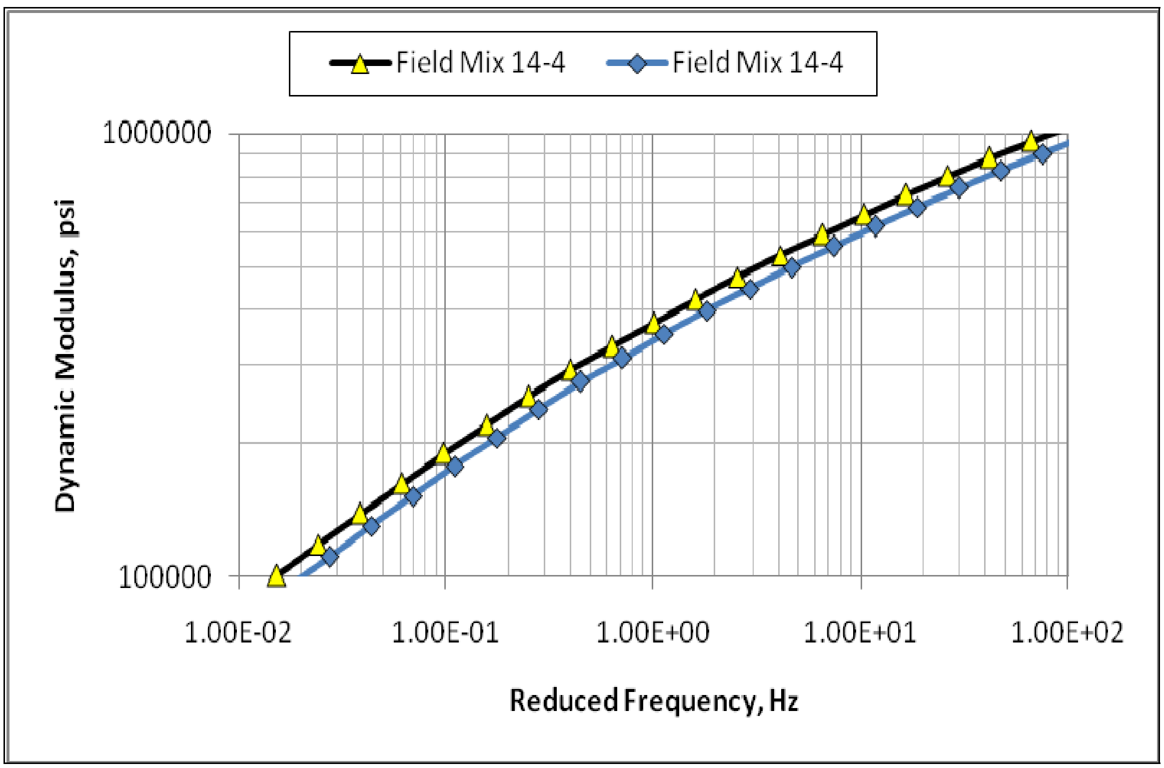
C.2.2 Crushed Aggregate Base Layer

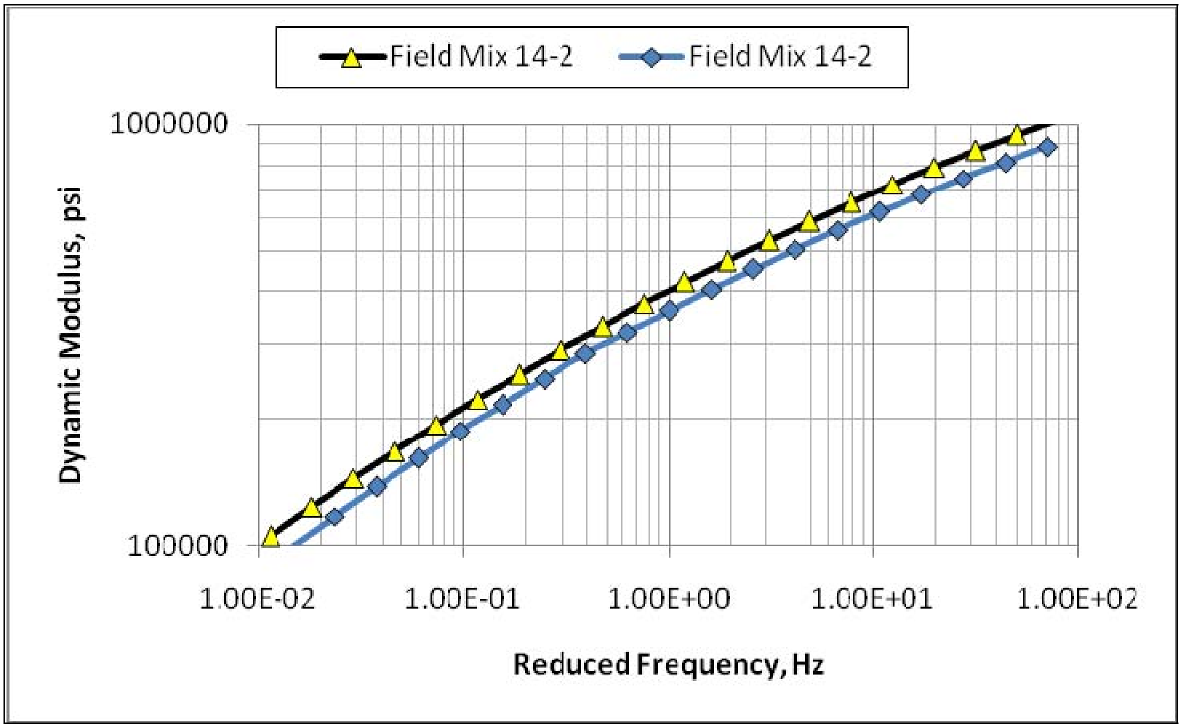
The following is a graphical summary of the resilient modulus versus stress state for the aggregate base test specimens that were compacted at the in-place water content and dry density measured during construction.



APPENDIX D
DYNAMIC MODULUS TEST RESULTS FOR THE HOT MIX ASPHALT MIXTURE






Field Mix 14-2
Field Mix 14-2
1000000
100000
Dynamic Modulus, psi
1.00E-02
1.00E-01
1.00E+00
1.00E+01
1.00E+02
Reduced Frequency, Hz