SOUTHERN PLAINS
TRANSPORTATION CENTER

Special Provisions for Intelligent Compaction of Stabilized Soil Subgrades

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16. ABSTRACT

Intelligent Compaction (IC) of soil and asphalt mixes is an innovative approach that has been utilized to achieve uniform, adequate compaction of pavement layers during construction. Commercially available IC products provide machine specific compaction values that are indirectly related to the compaction quality (stiffness) of the pavement layers. Additional methods have to be developed in order to relate these compaction values to standardized tests used to verify pavement quality during construction. The Federal Highway Administration (FHWA) has drafted *Generic IC specifications* for soils and asphalt pavements to facilitate the early adoption of this technology. These generic specifications are expected to serve as guidance to individual state Departments of Transportation (DOTs) in the development of specifications relevant to the respective states.

In this study, the researchers seek to help ODOT develop and validate 'Special Provisions' for the use of IC rollers during compaction of stabilized subgrades.

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Intelligent Compaction, Soil Subgrade, Stablization, Pavement, Roller, Resilient Modulus, Density

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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Special Provisions for Intelligent Compaction of Stabilized Soil Subgrades

Final Report

December 30, 2017

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EXECUTIVE SUMMARY

Asphalt pavements comprise almost 55 percent of more than 4 million miles of paved roads in the country (FHWA, 2006) and constitute a critical component of the transportation infrastructure. Increased vehicular and truck traffic, insufficient investment in construction and maintenance of roads, and deterioration of roads and bridges have left our transportation infrastructure in a state of disrepair (DOT, 2008). In addition to these problems, Region 6 is also subject to extensive variations arising from seasonal and extreme weather conditions. Our roads and bridges experience tornados and earthquakes, as well as flash floods due to intense localized rainfall. Thus, transportation infrastructure in Region 6 is in far worse shape compared to the rest of the nation.

Improper compaction during construction is one of the leading causes for the early deterioration of asphalt pavements. Current quality control techniques used during construction are time consuming, test the completed pavement at discrete locations, and typically cover less than 1% of the constructed pavement. In recent years, Intelligent Compaction (IC) (IC, 2009; Chang, et al., 2011) has been proposed as a means of constructing high quality and longer lasting roads. Intelligent Compaction techniques rely on analyzing roller vibrations to determine the density or stiffness achieved during the compaction of pavements. Real time knowledge of compaction achieved can be used to identify and remedy under-compaction as well as avoid over compaction of pavement layers, including asphalt mix layer or soil subgrade layer.

Commercially available IC products provide machine specific compaction values that are indirectly related to the compaction quality (stiffness) of the pavement layers. Additional methods must be developed to relate these compaction values to standardized tests used to verify pavement quality during construction. The Federal Highway Administration (FHWA) has drafted Generic IC specifications (Chang, et al., 2011) for soils and asphalt pavements to facilitate the early adoption of this technology. These generic specifications are expected to serve as guidance to individual state Departments of Transportation (DOTs) in the development of specifications relevant to the respective states. At this time, six Departments of Transportations (DOTs) (GA, IN, IA, MI, MN, TX) have used these generic specifications to develop special provisions for IC that take into account the unique requirements of their respective states.

In this study, the researchers helped ODOT develop and validate 'Special Provisions' for the use of IC rollers during compaction of stabilized subgrades. The specif objectives of this study were:

1. Survey existing 'Special Provisions for IC' developed by other states and identify focus areas for ODOT specifications. We shall also develop IC implementation plan that addresses requirements that are specific to Oklahoma;
2. Develop specifications for proof rolling of soil embankments to verify stiffness before construction of pavement layers;
3. Install ICA on contractor roller and assist contractor in the developing a Quality Control Plan. Demonstrate quality control using IC on selected projects and provide a comprehensive report to ODOT on the implementation of IC;
4. Refine IC specifications based on data from field validation, and ODOT and contractor inputs;
5. Train ODOT engineers and contractors in the processing of IC data and in evaluating construction quality both for quality control and quality assurance purposes; and
6. Assist ODOT in the verification of draft specifications on IC for Hot Mix Asphalt pavements.

INTRODUCTION

Intelligent Compaction (IC) is an innovative approach that has been recently utilized to achieve uniform and adequate compaction of subgrade during pavement construction. Several Original Equipment Manufacturers (OEMs) are currently offering IC equipment in the market. Notable among these are, Compaction Information System (Sakai, 2013), Bomag Variocontrol (BOMAG, 2014), Ammann Compaction Expert (AMMANN, 2013), AccuGrade (Young, et al., 2013), and Dynapac Compaction Analyzer (Dynapac, 2013). Several research studies have been carried out to study the construction quality achieved using intelligent compaction. In order to facilitate the implementation of the IC technology, the Federal Highway Administration (FHWA) and some state Departments of Transportation (DOTs) have developed special provision/ specification for intelligent compaction of pavement subgrade or soil in general.

The goal of the current research is to develop a special provision for the Intelligent Compaction of pavement subgrade for the state of Oklahoma. As a first step in this process, the research team studied existing literature to address the state of the art in (i) commercially available IC equipment, (ii) field demonstrations of existing IC products, and (iii) available special provisions/ specifications for Intelligent Compaction of pavement subgrade or soils in general. The following sections present the state of the art in the Intelligent Compaction technology.

IC Equipment

Several IC rollers are commercially available for continuous assessment of the quality of pavement subgrade during its compaction. While there are advantages and disadvantages associated with the IC equipment, each of these devices differ in the manner in which the stiffness computations are carried out and reported. However, all these devices share some common elements such as:

(i) an accelerometer to measure the vibrations of the drum during compaction,
(ii) a measurement system to determine the level of compaction of the pavement in real-time,

(iii) a GPS-based documentation system for continuous recording of roller position, and

(iv) an on-board device to display the real-time operation parameters such as roller pass, direction, GPS coordinates of the roller, and a color coded mapping of compaction level at each location.

Table 1 presents a comparison of five IC rollers that are currently available. Commercially available IC equipment for subgrade compaction is shown in Figure 1. The IC equipment developed at the University of Oklahoma is also discussed in this section.

Table 1. Comparison between five different commercial IC equipment

Vendor	Ammann/ Case	Bomag	Caterpillar	Dynapac	Sakai
Compaction measurements	K_b	E_{VIB}	MDP	CMV	CCV
GPS capability	Yes	Yes	Yes	Yes	Yes
Documentation system	ACE-Plus®	BCM 05® Office and Mobile	AccuGrade®	DCA®	Aithon MT®
Automatic feedback control	Yes	Yes	No	Yes	No
Roller configuration	Pad-foot and Smooth Drum	Smooth Drum	Pad-foot and Smooth Drum	Pad-foot and Smooth Drum	Smooth Drum
Output export file	*.txt	*.csv	*.csv	*.txt	*.csv

Note: Compaction measurement parameters are described in the following pages.

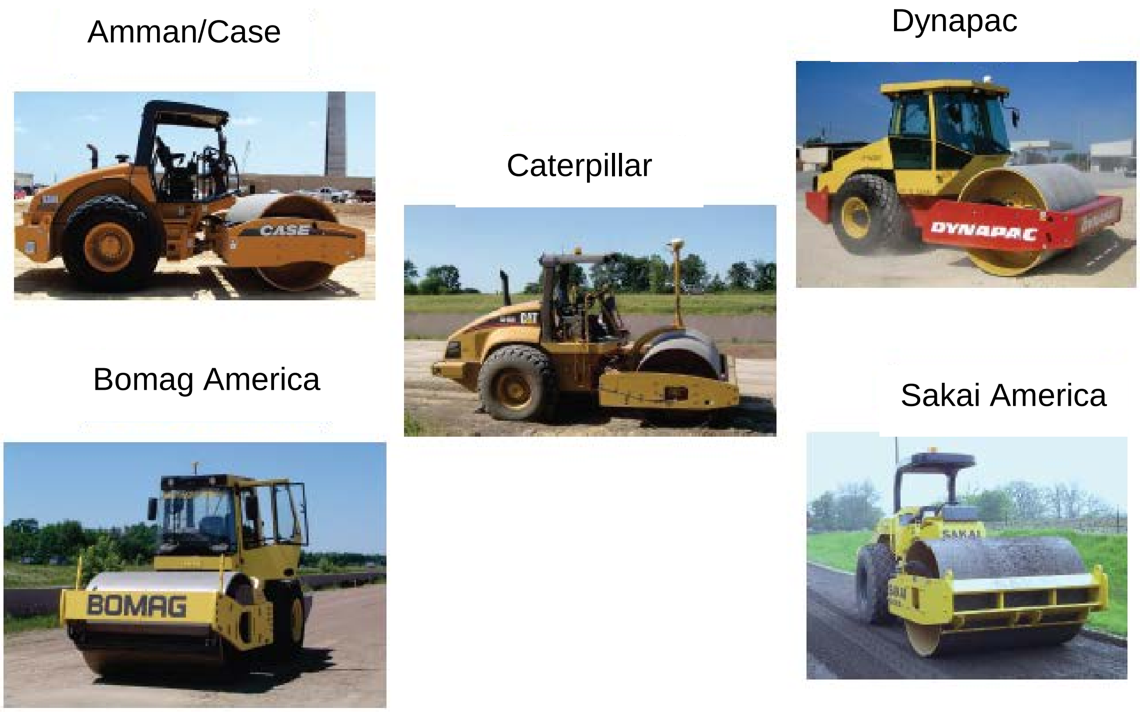

Figure 1. Pictures of different rollers used for Intelligent Compaction of pavement subgrade (Chang, et al., 2011)

Since a standard measure for reporting the compaction results of IC rollers has not yet been established, IC manufacturers have developed individual methods for representing the quality of compacted subgrade. A numerical value indicates the compaction quality, generally regarded as Intelligent Compaction Measurement Value (ICMV). A brief discussion of ICMVs currently used by IC manufacturers is given below.

Roller- Integrated Stiffness (k_b)

The roller-Integrated Stiffness (k_b) is used by the Ammann/Case. The soil is considered as a linear elastic material for estimation of k_b. Stiffness, k_b, is calculated as a ratio of the roller-soil interaction force and the amplitude of measured vibration, and can be expressed as follows.

$$k_b = 4\pi^2 f^2 \left[\frac{m_d + m_e r_e \cos\varphi}{a}\right] \quad \text{(i)}$$

Where, f is the excitation frequency, m_d is the drum mass, $m_e r_e$ is the eccentric moment of the unbalanced mass, φ is the phase angle, and a is vibration amplitude.

Vibratory Modulus(E_{vib})

The IC system manufactured by BOMAG is designed to measure the dynamic stiffness (E_{VIB} in MN/m^2) of the compacted pavement. The relationship of drum force and displacement with the E_{VIB} value is expressed by the following equation.

$$z_d = \frac{1-\eta^2}{E_{VIB}}\frac{F_S}{L}\frac{2}{\pi}\left(1.8864 + ln\frac{L}{B}\right), \quad \text{(ii)}$$

where

$$B = \sqrt{\frac{16}{\pi}\frac{R'(1-\eta^2)}{E_{VIB}}\frac{F_S}{L}}; \qquad \text{(iii)}$$

η is the Poisson's ratio of the material, L is the length of the drum, B is the contact width of the drum, and R' is the radius of the drum.

Machine Drive Power (MDP)

Machine Drive Power (MDP) is a parameter developed by Caterpillar that evaluates the rolling resistance during compaction as an indicator of soil stiffness. Machine Drive Power is defined as the amount of additional power required (in kJ/s) by the roller to compact a given soil (or subbase) layer over the power level required to compact the calibration layer. A positive value of MDP means that the layer being compacted has not yet reached the level of compaction associated with the calibration layer. Similarly, a negative value of MDP indicates that the layer is more compacted than the calibration layer because it requires less power to propel the roller. MDP is calculated using the following equation.

$$MDP = P_g - Wv\left(\sin\alpha + \frac{A'}{g}\right) - (mv + b) \quad \text{(iv)}$$

Where P_g is the gross power needed to move the machine (kJ/s), W is the roller weight (kN), A' is the machine acceleration (m/s^2), g is the acceleration of gravity (m/s^2), α is the slope angle (roller pitch from a sensor), v is the roller velocity (m/s), and, m (kJ/m) and b (kJ/s) are machine internal loss coefficients specific to a particular machine (White, et al., 2005).

Compaction Meter Value (CMV)

Compaction Meter Value is a dimensionless indicator of compaction quality developed by Geodynamic in cooperation with the Dynapac Research Department. It is based on the idea that the ratio of the amplitude of first harmonic of the roller vibration and the amplitude of its fundamental frequency is significantly influenced by the compaction level achieved in the underlying pavement (Sandström, et al., 2004). The CMV also depends on the roller dimension and operational parameters such as frequency, amplitude, and speed of the roller. It can be expressed as

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

where C is a constant, $A_{2\Omega}$ is the amplitude of the first harmonic component of the drum vibration and A_{Ω} is the amplitude of the fundamental component of vibration.

Compaction Control Value (CCV)

Sakai developed an IC system named Compaction Information System (CIS), in which a Compaction Control Value (CCV) is used as an indicator of the stiffness of the pavement. The main concept behind the CCV is that with an increase in ground stiffness, the roller drum starts entering into a 'jumping' motion (Chang, et al., 2011). An irregularity in the drum acceleration is created as a result. The CCV is a unit-less quantity and is computed using the following equation:

$$CCV = \left[\frac{A_{0.5\Omega}+ A_{1.5\Omega}+ A_{2\Omega}+ A_{2.5\Omega}+ A_{3\Omega}}{A_{0.5\Omega}+ A_{\Omega}}\right] * 100 \quad \text{(vi)}$$

where A_{Ω} is the value of amplitude spectrum of the fundamental frequency of vibration; and $A_{N\Omega}$ is the value of amplitude spectrum of the N^{th} harmonic/sub harmonic of vibration.

Intelligent Compaction Analyzer Modulus ($M_{R\text{-}ICA}$)

The University of Oklahoma (OU) has developed IC equipment known as the Intelligent Compaction Analyzer (ICA). The ICA was developed based on the hypothesis that the vibratory roller and underlying layer form a coupled system, and it produces characteristic vibrations during compaction (Commuri, et al., 2012; Commuri, et al., 2010; Commuri, et al., 2009; Commuri, et al., 2008). Different components of the ICA integrated vibratory roller during the compaction of a stabilized subgrade are shown in Figure 2. In the ICA system, an accelerometer is mounted on the frame of the roller to record the vibrations of the roller during compaction. These vibrations are processed in real-time using signal processing techniques to estimate the density or modulus of the material being compacted. Global positioning system (GPS) receivers are used to record the spatial location of the roller at each instant. These readings are used to provide as-built maps showing process information such as number of roller passes, roller path, and density or modulus to the operator, in real-time (Figure 3).

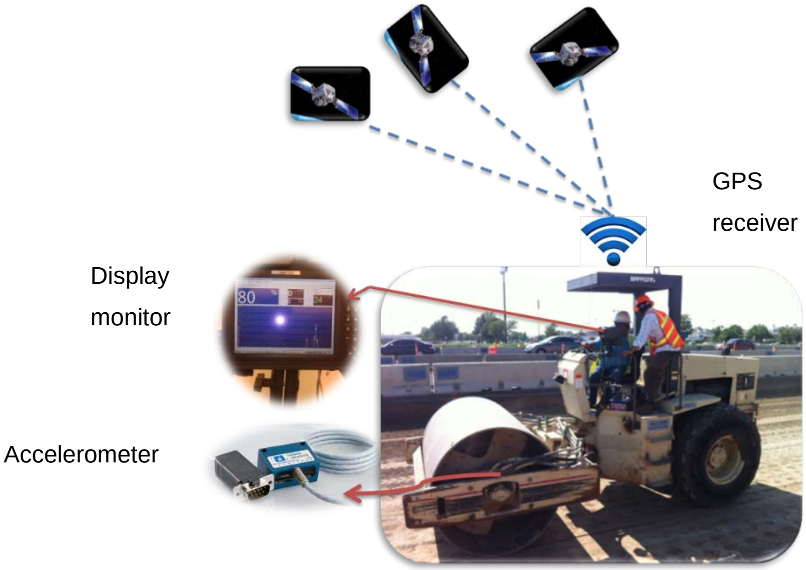

Figure 2. Different components of ICA

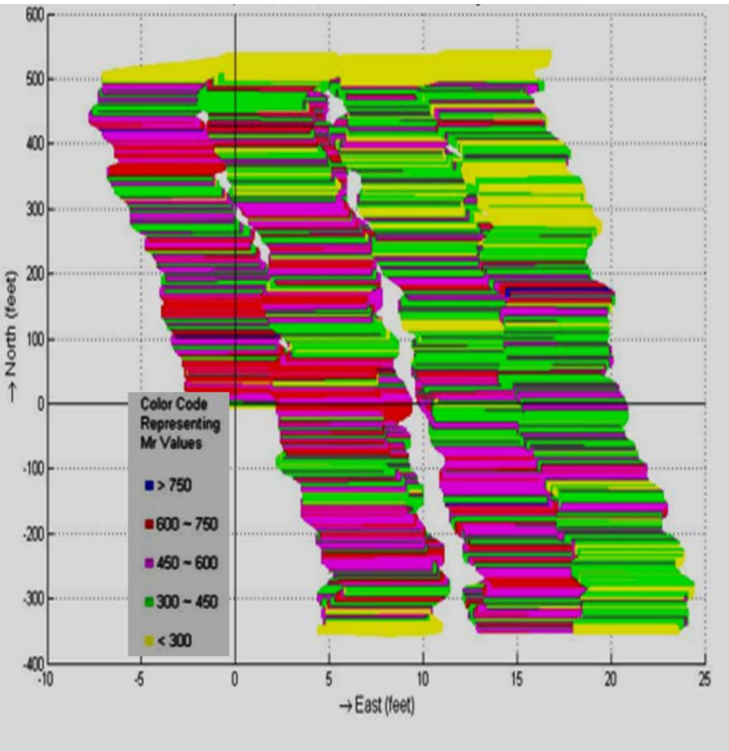

Figure 3. An example of an 'as-built' map for ICA modulus

Relevant Studies on Intelligent Compaction

This section presents a few relevant studies conducted in the area of Intelligent compaction. Only a short description of each of these studies is provided. For more information please refer to the cited studies.

Kansas DOT study, 2008

Kansas State University researchers (Rahman, et al., 2008) conducted a study to evaluate the applicability of IC rollers in real-time estimation of compaction quality of highway embankment soil during construction of two sections of US-56 and I-70 in Kansas. The IC results were compared with those of traditional quality control tests such as Light Weight Deflectometer (LWD), Falling Weight Deflectometer (FWD), and Dynamic Cone Penetrometer (DCP). Significant correlations were not found between the IC roller stiffness and backcalculated subgrade moduli from the LWD and FWD deflection data, the California Bearing Ratio (CBR) obtained from DCP tests. However, the spatial analysis of IC data showed that the IC roller was able to identify the locations of lower soil stiffness in the spatial direction. This indicates that the IC roller can be used in proof rolling. The IC roller stiffness was also found to be sensitive to the field moisture content suggesting that moisture control during compaction is critical.

NCHRP - 676, 2010

Research was conducted under NCHRP Project 21-09 (Mooney, et al., 2011) to investigate the reliability of intelligent compaction systems and to develop generic construction specifications for the application of intelligent compaction systems for quality assurance of soils and aggregate base material during compaction. Field investigations were carried out on numerous earthwork construction projects across five states of the United States. Several roller integrated IC measurement systems were used in those projects in order to improve fundamental understanding of IC measurement systems and to perform comparison and validation of different ICMVs. The effect of roller operational parameters such as eccentric force amplitude, vibration frequency, roller speed, and, forward versus reverse driving mode on ICMVs were studied. The possibility of extracting mechanistic properties such as stress-strain modulus from roller MVs was investigated. The correlation between the roller MVs with the conventional in-situ measurements such as dry unit weight, CBR, LWD modulus and laboratory M_r test measurements were also studied.

Wisconsin DOT study, 2010

The Wisconsin DOT funded a study on the intelligent compaction (Von Quintus, et al., 2010). The objectives of this study were to (i) review the advantages and disadvantages of the IC technologies, (ii) determine the material type and conditions that might cause inaccurate interpretation of the IC results, and (iii) provide recommendations to the Wisconsin DOT on the implementation of the IC technology for the pavement construction. The study recommended the Wisconsin DOT to move forward with the IC technology especially in two areas: (i) to continuously monitor the compaction level of the subgrade and remediate the under-compacted area(s) if necessary, and (ii) to develop correlations between the IN measured stiffness and number of roller passes to determine the appropriate rolling pattern. This study also recommended the Wisconsin DOT to plan on reimbursing to the contractors/ construction agencies for their effort to have a successful implementation of the IC.

FHWA Pooled Fund study, 2011

A strategic plan for the Intelligent Compaction was developed under this study (Chang, et al., 2011). This study was conducted as a Transportation Pooled Fund project, TPF-5(128), which includes 12 participating State Department of Transportations: Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, New York, North Dakota, Pennsylvania, Texas, Virginia, Wisconsin. The FHWA specification for the Intelligent Compaction of both soils and asphalt layers were developed in this study. A comprehensive review was conducted on the different IC practices and reported in the Final Project report. The correlation between different IC parameters and the conventional quality control parameters were studied in this project. Table 2 provides a summary of such correlations developed based on the data collected from different states. It can be seen that the correlation between the ICMVs and other in-situ compaction measuring parameters significantly varies between states and IC vendors, from R^2 equal to 0 to 0.94. Even though a consistent trend was not found, it appears that the ICMV values somewhat agrees with the FWD back-calculated modulus when compared to other in-situ devices. The reason may be the slightly similar loading natures of the IC roller and FWD.

Table 2. Correlation of IC compaction parameters with the conventional compaction parameters

In-Situ Test	**Co-efficient of determination (R^2)**													
	SAKAI (CCV)		**BOMAG (Evib)**		**CATERPILLAR (MDP)**				**DYNAPAC (CMV)**			**AMMAN (Ks)**		
	KS	**MS**	**MN**	**NY**	**IN**	**KS**	**MS**	**NY**	**MS**	**NY**	**TX**	**MS**	**NY**	**TX**
FWD	0.82 (28)	0.5 (24)		0.68 (NA)		0.66 (6)		0.72 (82)			0.15 (11) - 0.94 (26)	0.74 (77)		0.64 (18)
LWD	NA	0.31 (56)			0.75 (79)	0.6 (62)	0.75 (42)		0.24 (42)	0.39 (15)	0.6 (15)	0.49 (88)	0.62 (49)	0.3 (120)
CBR	0.84 (15)	0.26 (60)												
Ev1	NA	0.4 (NA)					0.49		0.64		0.16 (8)	0.68		
Ev2	0.56 (15)	0.18 (NA)					0.78		0.24			0.52		
Dry Density	0.72 (NA)	0(62)			0(7)		0.49		0.21			0.3		
GeoGauge	NA	NA	0.15 (NA)											
DCP	NA	NA	0.74 (NA)											
CBR					0(7)	0.68 (NA)	0.76	0.76 (44)	0.65	0.37 (15)				

Note: NA- data not available; Numbers within the bracket refer to the number of data points that were analyzed during the tests

Highway IDEA Project 145, 2013

Researchers at Colorado School of Mines (Mooney, et al., 2013) studied the impact of vibration on the subgrade and developed a methodology to estimate the layer elastic modulus from composite soil stiffness. According to this study, the estimate of soil stiffness provided by current vibratory smooth drum IC rollers (12-15 ton) is a composite measure of ground stiffness to a depth of 1.0 -1.2 m. This is significantly greater than a 15-30 cm thick layer or lift of subgrade, subbase or base material. This study addresses this limitation of current IC technologies and proposed a procedure to account for the effect of subbbase materials during the estimation of modulus of the base layer using the available IC roller data. The methodology includes development of a compaction model using finite element (FE) and boundary element method (BE) techniques. The model is used to predict roller-measured composite stiffness values for a wide range of layer elastic moduli and layer thickness expected in practice. An Inverse analysis was performed to provide an estimate of individual layer elastic modulus using IC data and

FE and BE model. Statistical regression models were developed from the FE and BE models in order to accommodate the real-time estimation of modulus using inverse analysis.

TxDOT Project Number 0-6740, 2014

TxDOT evaluated the guidelines and test protocols for the use of intelligent compaction as a fast-developing technology for base and soil compaction. Two different proprietary technologies namely Compaction Meter Value (CMV) and the machine Drive Power (MDP) were compared in this study. The results indicated that CMV is more sensitive to compaction process as compared to the MDP. The study showed that the ICMVs and NDT measurements are significantly influenced by the moisture content of the lift.

IC Specifications

The FHWA developed a comprehensive specification for intelligent compaction of soil which was later on referred by DOTs to develop their own specifications/ special provisions. The DOTs of the Iowa (IADOT), Indiana (INDOT), Georgia (GADOT), North Carolina (NCDOT), and Minnesotta (MDOT) have developed the specifications/ special provisions for intelligent compaction of subgrades or soils in general. These specifications/ special provisions provide guidelines about roller configuration, compaction measuring parameters, documentation, data collection/ management system, GPS configuration, target compaction, operation criteria, post processing software, mandatory training and IC work plan. A brief comparison of the above-mentioned six specifications is provided in Table 3 to Table 12.

Table 3. Roller configuration in different IC specifications

Agency	**Roller configuration**
FHWA	Self-propelled single-drum vibratory rollers equipped with accelerometers mounted on the roller drum.
IADOT	Self-propelled roller with a pad-foot configuration weighing at least 10,800 kg with an IC system and as approved by the Engineer.
INDOT	Self-propelled static or vibratory rollers equipped with IC machine drive power and/or with accelerometers. The roller can be smooth or pad foot drums.
GADOT	Self-propelled vibratory rollers equipped with accelerometers. The roller can be smooth or pad foot drums.
NCDOT	Self-propelled vibratory rollers equipped with accelerometers. The roller can be smooth drum.
MnDOT	Self-propelled roller integrated with GPS. It shall be able to automatically adjust roller Operating Settings, such as vibration frequency and amplitude, based upon real-time feedback from the drum vibration measurement system.

Table 4. Compaction measuring value in different IC specifications

Agency	**Compaction Measuring Parameter**
FHWA	Intelligent Compaction Measurement Value (ICMV)
IADOT	Measurement Value (MV)
INDOT	Intelligent Compaction Measurement Value (ICMV)
GADOT	Intelligent Compaction Measurement Value (ICMV)
NCDOT	Intelligent Compaction Measurement Value (ICMV)
MnDOT	Intelligent Compaction Measurement Value (ICMV)

Table 5. Documentation requirements in different IC specifications

Agency	**Documentation**
FHWA	Real-time color-coded maps, location of roller, number of passes, roller speed, vibration frequency, amplitude of roller drums.
IADOT	Real-time color-coded spatial maps of compaction measurement value (MV), roller position, date/time, speed, pass count, travel direction.
INDOT	Real-time color-coded maps of ICMV, roller position, date/time, speed, pass count, travel direction, frequency and amplitude of roller vibration.
GADOT	Real-time color-coded maps of ICMV, roller position, date/time, speed, pass count, travel direction, frequency and amplitude of roller vibration.
NCDOT	Date and time stamps, machine manufacture, model, type and identification number, drum width and diameter, roller and drum weights, roller RTK-GPS positions, roller speed, pass count and travel direction (e.g., forward or backward), drum frequency and amplitude, IC-MV, reporting resolution for independent IC-MVs in the roller moving direction and 90 degrees to the roller moving direction (mm), UTM Zone, offset to UTC (hrs) and Number of IC data points.
MnDOT	Real-time color-coded maps of roller location, number of passes, roller speeds, and amplitude and vibration frequencies of the roller drum.

Table 6. Data collection/management in different IC specifications

Agency	**Data collection/management**
FHWA	On-board display, USB port, on-board printer.
IADOT	On-board display, provide displayed results to the Engineer for review upon request. As a minimum, the file transfer shall occur following the final compaction operations on each working day. The Engineer may request data any time during compaction operations.
INDOT	Wirelessly uploading facility at 10 min. interval.
GADOT	On-board display, USB port, on-board printer.
NCDOT	On-board display, USB port.
MnDOT	Provide the department immediate viewing of the measurement pass data on the IC Roller.

Table 7. GPS configurations in different IC specifications

Agency	**GPS Configuration**
FHWA	IC GPS unit (RTK network, UTM coordinates); hand-held GPS rovers (RTK network, UTM coordinates)
IADOT	Local GPS base station used for broadcasting differential correction data to the rollers with a tolerance less than 30 mm in the verticaland horizontal.
INDOT	Real Time Kinematic (RTK) based GPS with base station corrections shall be used for determining the position of the roller. IC GPS unit (RTK network, UTM coordinates); hand-held GPS rovers (RTK network, UTM coordinates); Data format provided.
GADOT	IC GPS unit (RTK network, UTM coordinates); hand-held GPS rovers (RTK network, UTM coordinates)
NCDOT	IC GPS unit (RTK network, UTM coordinates); hand-held GPS rovers (RTK network, UTM coordinates); Local Base station.
MnDOT	IC GPS unit (RTK network, UTM coordinates); hand-held GPS rovers (RTK network, UTM coordinates); Local Base station.

Table 8. Guidelines on the Target compaction value in different IC specifications

Agency	Target Compaction
FHWA	Test section: 225 ft (75 m) x 24 ft (8 m); 5% of the max. ICMV
IADOT	Test section: 225 ft (75 m) x 16.4 ft (5 m); test strips shall be compacted with 12 roller passes. Three test sections to be selected representing different materials/ conditions.
INDOT	Test section: 225 ft (75 m) x 24 ft (8 m); ICMV to be correlated with DCP test results;
GADOT	Test section: 225 ft (75 m) x 24 ft (8 m); 5% of the max. ICMV
NCDOT	Construct the first test section within 14 days of beginning earthwork operations. Perform the soil classification and Proctor test; Test section: 500 ft x 30 ft wide, not more than 24 inches thick
MnDOT	Test section: 225 ft (75 m) x 24 ft (8 m); 5% of the max. ICMV

Table 9. IC Operation criteria in different IC specifications

Agency	Operation Criteria
FHWA	Coverage: 90% area with 70% of the target ICMV
IADOT	Coverage: Entire area, at least 80% in case of breakdown; measure compaction values at surface and at 0.6 m vertical interval
INDOT	Minimum construction area - 5,000 sq. ft., maximum construction area -75,000 sq. ft. Minimum coverage: 70% of the mapped area with equal or greater than the target IC-MV
GADOT	Coverage: 90% area with 70% of the target ICMV
NCDOT	The Target IC-MV must have a corresponding soil modulus of at least 6,000 psi at a vertical stress of 15 psi, or a corresponding percent compaction of 95% of AASHTO T-99 density, whichever is greater. Coverage: Minimum coverage: 70% of the mapped area with equal or greater than the target IC-MV.
MnDOT	Coverage: Minimum 70%.

Table 10. IC Operation criteria in different IC specifications

Agency	**Post Processing Software**
FHWA	VEDA
IA DOT	ASCII FILE FORMAT
INDOT	VEDA; if others, then shall be included in the QCP.
GADOT	VEDA
NCDOT	VEDA, ASCII
MnDOT	VEDA

Table 11. Mandatory training requirements in different IC specifications

Agency	**Mandatory training**
FHWA	NA
IA DOT	Training shall be provided by the IC equipment manufacturer and Contractor and scheduled in coordination with the Engineer. Ensure the IC roller manufacturer provides onsite technical assistance the first two working days of IC roller use.
INDOT	On-site training
GADOT	NA
NCDOT	Provide 2 consecutive days of IC training, one day of classroom training and another day of field training, for up to 40 personnel.
MnDOT	Provide the proposed demonstration locations and proposed date of roller certification(s) to the Department at least 14-calendar days in advance. The Engineer will approve Project Site demonstration locations at least 7-calendar days prior to roller demonstration.

Table 12. IC work plan in different IC specifications

Agency	Other Requirements
FHWA	NA
IA DOT	Submit a work plan at least 2-weeks prior to the pre-construction conference;
INDOT	Submit a QCP 15 days prior to commencement of compaction
GADOT	Submit a QCP 15 days prior to commencement of compaction;
NCDOT	Submit a QCP 30 days prior to commencement of compaction, Four hard and electronic copies of the IC data, per the IC Plan, and plate load test data/results for each section within 48 hours of proof rolling with IC rollers and/or performing plate load tests. Use an IC Vendor approved by the Department Engineer that has successfully completed 3 IC projects within the last 5 years
MnDOT	NA

QUALITY CONTROL PLAN FOR INTELLIGENT COMPACTION

The research team worked closely with ODOT engineers to identify the acceptance tests to be conducted by the agency for ensuring uniformity and quality of compaction. The team also sought input from contractors in the state of Oklahoma to shortlist implementable quality control plan (QCP) and laboratory test procedures.

Subgrade Quality Improvement using OU-ICA

Prior to the development of QCP, an investigation was carried to study the scope of subgrade quality improvement using intelligent compaction. This investigation was carried by analyzing data collected in six previous studies that dealt with the demonstrations of the OU developed ICA. In general, the following are the different activities involved in the intelligent compaction procedure of the stabilized subgrade when using OU-ICA.

Characterization of Natural and Stabilized Soils

Bulk soil samples are collected from the project site whenever the site is accesible and the grading of the existing soil layer is completed. The additive(s) used in stabilizing the subgrade are collected from the plant of the construction contractor. Soil lumps are grounded in the laboratory and then mixed with the additive in specified amount to replicate the composition of the stabilized subgrade in the field. The particle size distribution (ASTM D6913) and Atterberg’s limits (ASTM D4318) of the natural soils and the moisture-density relationship (ASTM D698) of stabilized soils (soil-additive mixes) are determined.

Resilient Modulus Test of the Stabilized Soil

Druing the field compaction, the ICA is be calibrated using in-situ resilient modulus ($M_{r\text{-}ICA}$) of the compacted subgrade. In order to estimate these $M_{r\text{-}ICA}$ values, resilient modulus tests need to be conducted on the soil-additive mixes collected for the project prior to compaction in the field. Resilient modulus tests are conducted on the soil-additive mix as per AASHTO T307-99. Tests are conducted at different moisture contents and dry densities so that the variations of these two parameters in the field could be captured. Information on the range of moisture content and dry density to be targeted during compaction in the field are collected from the construction agency for selecting these two parameters for M_r tests. Resilient modulus tests are conducted at 15 different combinations of deviatoric stress (σ_d) (14, 28, 41, 55 and 70 kPa) and confining pressure (σ_3) (14, 28 and 41 kPa). Using these resilient modulus test results, a relationship is developed between M_c, γ_d, stress state and M_r to determine the in-situ M_r values for the calibration of the ICA. A number of models are available in the literature for predicting M_r (AASHTO 1993). Using these models, M_r can be predicted as a function of stress state and soil properties. In the present study, the following model (AASHTO 1993) was used.

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \qquad \text{(vii)}$$

where k_1, k_2 and k_3 are the regression coefficients, $p_a$is the atmospheric pressure, θ is the bulk stress (sum of the principal stresses), and σ_d is the deviatoric stress.

Since the coefficients (k_1, k_2 and k_3) are functions of M_c and γ_d, and are different for different specimens, one regression model is developed for each of these coefficients so that these can be derived for any appropriate combinations of moisture contents (M_c) and dry density (γ_d). In order to obtain these regression models, initially, k_1, k_2 and k_3 coefficients are determined for each specimen separately, using the statistical software Minitab®. The M_r and the applied stress state are utilized to backcalculate these coefficients. From the total data set, 80% of the data are generally used for determining these coefficients. The remaining 20% data are used to validate the developed models. Equations (viii) to (x) present the general form of the regression models for k_1, k_2 and k_3.

$$k_1 = a_1 + b_1(M_c) + c_1(\gamma_d) \qquad \text{(viii)}$$

$$\mathrm{k}_2 = a_2 + b_2(\mathrm{M}_c) + c_2(\gamma_\mathrm{d}) \qquad \text{(ix)}$$

$$\mathrm{k}_3 = a_3 + b_3(\mathrm{M}_c) + c_3(\gamma_\mathrm{d}) \qquad \text{(x)}$$

Installation and Calibration of the ICA

Regarding field application, the first step is the installation of the ICA hardware on the roller, and then functional verification of the GPS sensor, accelerometer and the Tablet Computer (Commuri, et al., 2010). Once installed and verified, the ICA calibration is performed for the specific roller and field conditions before it can be used for monitoring the subgrade compaction quality in the actual test stretch. A minimum of 10-meter long and 1.33-m wide calibration stretch is selected. The roller vibrations and GPS measurements are recorded during compaction of this stretch. After each roller pass, the dry densities and moisture contents are measured at selected locations using an NDG. The compaction process is stopped when no appreciable increase in NDG-measured density is observed between subsequent passes. The extracted patterns from the vibration data are then used to train the ANN to classify the vibrations into different compaction levels (Commuri, et al., 2012; Commuri, et al., 2010; Commuri, et al., 2009). The density and moisture contents measured after the last roller pass on at least three selected locations are used to estimate the $M_{r\text{-}ICA}$ for calibration purpose. Previously developed regression models (Equations (viii) to (x)) are used for computing these $M_{r\text{-}ICA}$ values.

In order to use the regression models (Equations (viii) to (x)) to predict modulus during compaction, it is also necessary to determine the stress state that is representative of the field condition. To this end, Mooney and Rinehart (2009) conducted a study where the in-situ stress state (at 140 mm depth) was measured during compaction of a subgrade consisting of clayey sand using a vibratory roller. The static mass (11,500 Kg) and the operating frequency (~34 Hz) of the roller used in that study were similar to the vibratory roller used in the present study. The magnitude of the vertical normal stress was measured as approximately 100 kPa, while the stresses in the transverse and longitudinal directions were approximately 25 to 40 kPa. These values lead to deviatoric stresses between 60 and 75 kPa. Hence, for the estimation of $M_{r\text{-}ICA}$ in the present study, the deviatoric stress, confining pressure and bulk stress were assumed as 69, 41 and 192 kPa, respectively. This stress state is also similar to that used in the last sequence of the resilient modulus test conducted in the laboratory, as per AASHTO T307. Once the $M_{r\text{-}ICA}$ values are established for the selected locations, the ICA can report the classified vibration patterns in terms of estimated modulus values. After the calibration process is complete, the ICA can estimate the modulus of the subgrade continuously during the compaction of the subgrade.

It may be noted that if the soil and additive(s) could not be collected and/or the resilient modulus tests could not be performed and/or regression models could not be developed prior to compaction, the ICA can be calibrated using the NDG-measured density values at selected locations on the calibration stretch. In such case, the ICA compaction will be performed in terms of subgrade density instead of $M_{r\text{-}ICA}$. However, relaxing the calibration requirement results in a tradeoff in accuracy. This is because the roller response is influenced by the stiffness of the pavement layer. In this case, the stiffness is a function of both the density and moisture content of the subgrade. Relying on the density alone will lower the accuracy of the ICA estimated values.

Compaction of the Actual Stretch

The calibrated ICA is used to record compaction data such as spatial locations and vibrations of the roller, the speed and operational frequency of the roller, and the M_i during the compaction of the subgrade. The roller operator initially follows the rolling pattern that is normally used in traditional compaction. During the initial compaction process, the compaction level (in terms of $M_{r\text{-}IAC}$ or density) is monitored by the ICA in real-time, and the under-compacted areas are identified. The under-compacted areas are the areas where the $M_{r\text{-}IAC}$ or ICA measured density values are significantly lower than their average values observed on the entire stretch. After the completion of the initial compaction process, as-built maps are studied to find out the location of the under-compacted areas. The GPS coordinates of these locations are used to plan additional roller passes to improve the level of compaction. Remedial rolling is performed at these locations until target M_i or density is achieved and become uniform across the entire compacted subgrade.

ICA Demonstration Projects

As previously mentioned, the results from six different pavement construction sites, where the ICA was demonstrated, were used for the analysis. Different sites were selected for including the variability in terms of subgrade soil types, stabilizer types and compacted layer thicknesses. Table 13 presents the locations of the six project sites along with the information on the soil classification, stabilizer type, compacted thickness and compaction parameters. All these six sites were located in Oklahoma. The subgrades of these six projects consisted of three different types of soils, namely AASHTO A-6, A-4, A-2-4. The subgrades in two of these sites were stabilized with 15% fly-ash (by weight of soil) and the other four were stabilized with 10 to 12% Cement Kiln Dust (CKD) (by weight of soil). Amongst the four sites stabilized with CKD, the subgrade of one site (Project 6, I-35 Service Road, Norman) was pre-treated by adding 3% lime two weeks before the compaction. This pre-treatment was performed for two reasons: (i) to improve the strength of the existing weak soil, and (ii) to bring down the extra moisture content that existed with the natural soil following a heavy rain event to the proximity of the optimum moisture content.

Table 13. Descriptions of the demonstration sites

Project No.	Project location	Soil type USCS/ AASHTO	Stabilizer	Optimum moisture content (%)	Maximum dry density (kN/m^3)	Stabilized subgrade layer thickness mm (in)	Evaluating parameters
1	Rock Creek Road, Norman, OK	CL/A-6	Fly-ash (15%)	18	16.7	203 (8)	Density
2	Heffner Road, Edmond, OK	CL/A-6	Fly-ash (15%)	19.1	16.5	305 (12)	Density
3	60th Street, Norman, OK	CL-ML/A-4	CKD (10%)	14.6	17.3	203 (8)	Modulus
4	Apple Valley, Oklahoma City, OK	SM/A-2-4	CKD (10%)	12.7	18.3	305 (12)	Modulus
5	I-35, Norman, OK	CL/A-4	CKD (12%)	14.8	17.3	203 (8)	Modulus
6	I-35 Service Road, Norman, OK	CL/A-6	Lime 3%; CKD (12%)	21.4	15.4	203 (8)	Modulus

The objective of the demonstration in the first two studies, conducted at Project 1 (Rock Creek Road and Heffner Road), was to recognize the set of activities that are required for using the ICA in subgrade compaction. Possible issues that arise during the field compaction, laboratory testing and analytical works were identified and addressed using the experience gained in these two studies. The subgrade compaction quality was quantified in terms of ICA-estimated density in these two projects. The ICA was calibrated using NDG-measured densities. It was found that the ICA successfully captured the variations in the compaction quality at different test points (Barman, et al., 2015). The variations in the compaction qualities at different test locations measured by the ICA and NDG were comparable. However, the statistical correlation obtained between the ICA-estimated and NDG-measured densities was not encouraging, probably because the NDG-measured density alone was not an appropriate parameter for calibrating ICA in subgrade compaction. The subgrade density actually does not completely represent the compaction quality of the subgrade. A parameter such as 'subgrade modulus' which characterizes the stiffness of the compacted subgrade is a more appropriate parameter. The subgrade modulus is a function of dry density, moisture content and stress state, and is related to the stiffness of the compacted layer.

In the next four projects reported in this paper, the QC of subgrade compaction was performed in terms of subgrade modulus, referred to as the ICA modulus ($M_{r\text{-}IAC}$) as mentioned previously. The calibration procedure of the ICA in terms of subgrade modulus and the validation procedure of the $M_{r\text{-}IAC}$ were established and refined in Projects 3 and 4. In the last two projects, detailed investigations were carried out to study the applicability of ICA in remediating the under-compacted areas during the construction itself. In those two projects, under-compacted areas were identified in real-time during the compaction, and then additional rolling was provided to improve the quality of compaction.

Validation of ICA-estimated Modulus

The ICA-estimated modulus values were validated by comparing them with the FWD back-calculated subgrade modulus (M_f), DCP index (D_i) and laboratory resilient modulus (M_r), whenever possible. In general, performing FWD tests on the prepared subgrade is a challenging task and may not be feasible at all sites due to cost and time considerations. DCP test is easy to conduct but the test result is highly empirical, and also this test method characterizes the localized strength of the subgrade. Comparing the $M_{r\text{-}ICA}$ values with the M_r values is a logical and mechanistically appropriate approach.

Comparison between M_i and M_f

In Project 3 (60th Street, Norman, OK), the M_i values were compared with the corresponding FWD back-calculated subgrade modulus values. FWD tests were conducted at nine different locations. Because of construction-related issues, the FWD tests could be conducted only on the top of the asphalt surface constructed on the compacted subgrade. FWD tests were conducted 28 days after the compaction of the subgrade. The M_f values were computed by using a back-calculation software (BAKFAA 2013). The required information for back-calculation of subgrade modulus such as the thickness of the asphalt layer was obtained by extracting cores from all the nine locations. The modulus of the asphalt layer was determined by conducting dynamic modulus tests (AASHTO TP79 2009) on the asphalt mixes collected from the project site. Figure 4(a) shows a comparison between the M_i and M_f values. It can be seen that the M_i and M_f values are comparable and exhibit a good correlation ($R^2 = 0.63$), which is comparable to the correlations seen in FWD test data reported in the literature (Nazzal, et al., 2010).

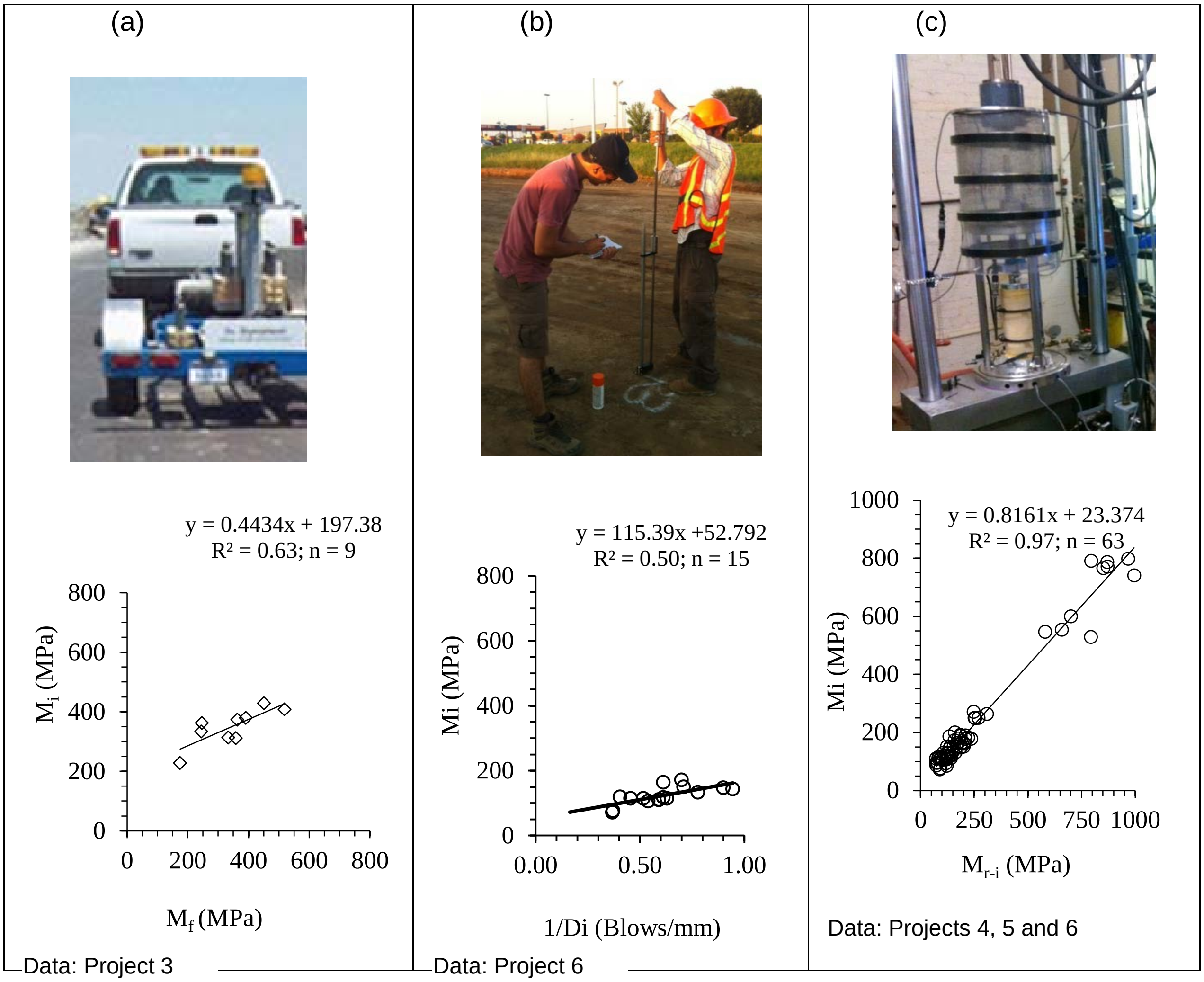

Figure 4. Validation of M_i: (a) comparison of M_i and M_f; (b) comparison of M_i and $1/D_i$; (c) comparison of M_i and $M_{r\text{-}ICA}$

Comparison between Mi and Di

The ICA-estimated moduli were compared with DCP indices in Project 6 (I-35 Service Road, Norman). DCP tests were conducted at 15 different locations on the compacted subgrade. DCP indices were calculated using the 'penetration vs number of blows' relationships obtained at each point as per ASTM 6951. Figure 4(b) presents the correlation between the ($1/D_i$) and the M_i. A fair correlation ($R^2 = 0.50$) was observed between the M_i and D_i. This is in agreement with the correlation between DCP and insitu modulus values that are reported in the literature (Chang, et al., 2011).

Comparison between Mi and Mr-i

The M_i values were compared with $M_{r\text{-}ICA}$ values in Projects 4, 5 and 6. Existing subgrade soil and additives were collected from all three project sites. Resilient modulus tests were conducted on samples prepared with the soil-additive mixture that were mixed as per their corresponding proportions followed in the field. M_r tests were conducted at different combinations of moisture contents, dry densities and stress states in order to develop regression models for predicting M_r. Separate set of regression models were developed for each of these three demonstration site. In order to determine the $M_{r\text{-}ICA}$ values, moisture contents and dry densities were measured on the compacted subgrade by an NDG at least on 10 different test locations in each of the three projects. Then employing these NDG-measured field moisture contents, dry densities and an assumed stress states, in-situ M_r values were determined for all the test locations. It can be seen in Figure 4(c) that the M_i and M_r values correlate well with an R^2 equal to 0.97. A total of 63 numbers of data points from all the three projects were used for this correlation.

Further, a ‘paired two tailed unequal variance t-test’ was performed at a 95% confidence level to determine the statistical significance of the difference between the Mi and Mr-i. When the significant factor, p-value, is greater than 0.05, it indicates that the data sets are not significantly different. Also, the data set is considered significantly not different when the ‘t-stat’ is lower than the t-critical. Results of the ‘t-test’ are provided in Table 14. It can be seen that the p-value (0.587) is larger than the critical value (0.05). Also, the t-stat (0.544) is lower than the t-critical (1.979). These indicate that the difference between the M_i and $M_{r\text{-}ICA}$ are statistically not significant at a 95% confidence level.

Table 14. Comparing Mi and Mr through at t-Test

Mean	M_i = 229 MPa	$M_{r\text{-}ICA}$ =251 MPa
Observations	63	
Hypothesized mean difference	0	
t-stat	0.544	
p-value	0.587	
t-critical	1.979	

Error Range in Estimation of M_i

In order to study the range of errors that occur in the estimation of M_i, the percentage difference (error) between the M_i and the corresponding $M_{r\text{-}i}$ has been plotted against the cumulative frequency of the data. It can be seen in Figure 5(a) that 50% of the total M_i values were estimated with an error less than 20% and 80% of them were estimated with an error less than 30%.

Further, in order to investigate the 75- and 25-percentile errors, the median of the errors, and the influences of soil type, compacted layer thickness and stabilizer type on the error ranges, Whisker plots were constructed categorizing the errors with respect these parameters. Figure 5(b) presents the Whisker plots for the errors with respect to the soil type. It can be seen that the error range for the A-4 soil type was greater than that for the two other soil types. The 75-percentile errors for the A-4, A-2-4 and A-6 soil types were 29, 16 and 21%, respectively. The medians of errors for the A-4, A-2-4 and A-6 soil types were 15, 12 and 15%, respectively. The Figure 5(c) presents the Whisker plots for the errors with respect to the compacted layer thickness. It appears that the error range is low for thicker compacted layer; probably because the variations in the soil composition, additive distribution and moisture contents distribution are slightly compensated when a thicker layer is compacted. The 75-percentile errors (%) for the 203 and 305-mm thick compacted layers were 23 and 17, respectively. The medians of errors for the 203 and 305-mm thick compacted layers were 15 and 13, respectively. Figure 5(d) presents the Whiskers plot for the errors with respect to the additive types. The error range was lower for the 10% CKD, however a consistent trend was not observed. The 75-percentile errors (%) for the 12% CKD, 12% CKD and 3% lime +12%

CKD were 40, 20 and 21, respectively. The medians of errors for the 12% CKD, 12% CKD and 3% lime +12% CKD were 20, 10 and 16, respectively.

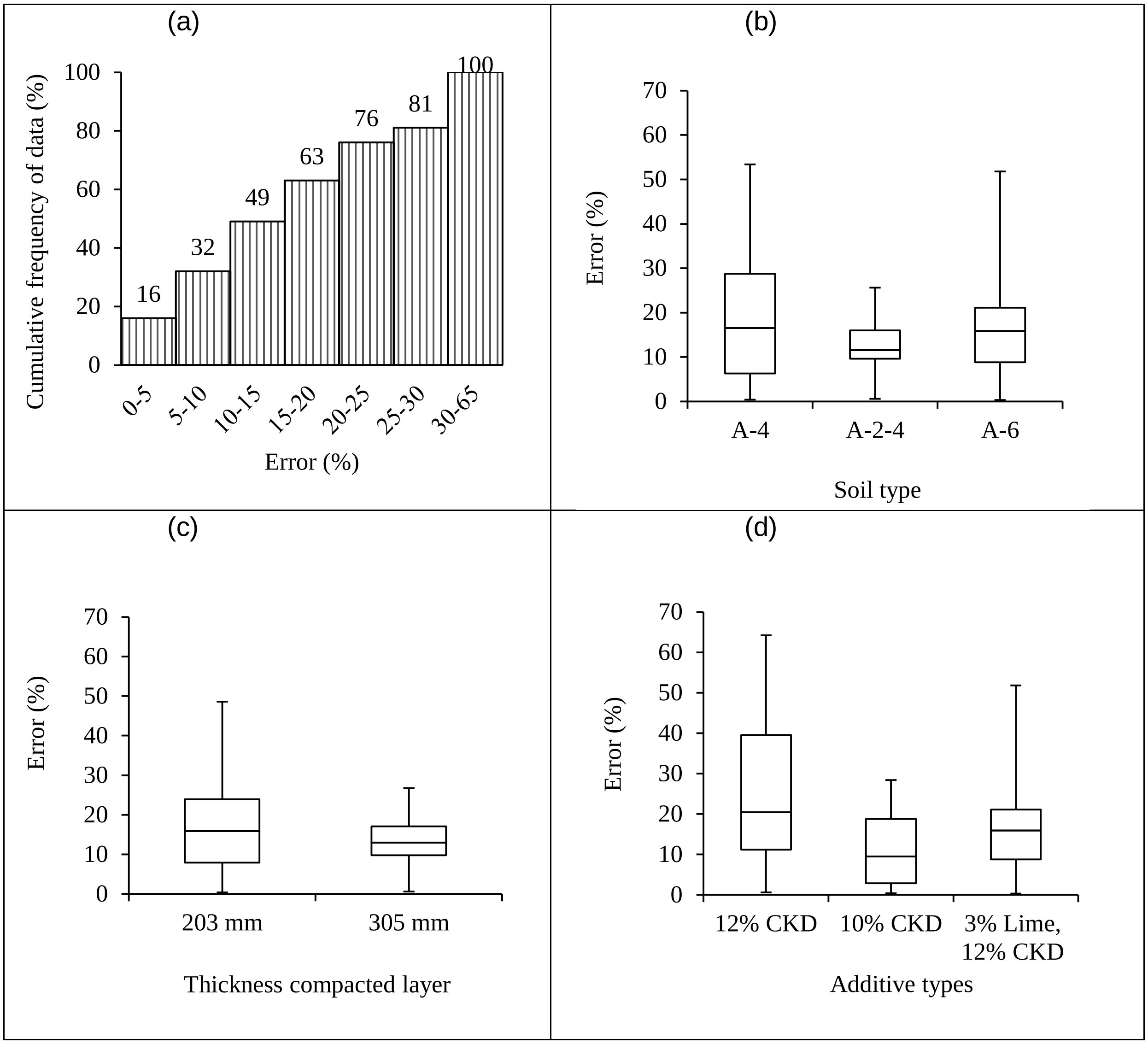

Figure 5. Error range in estimation of Mi: (a) error (%) vs cumulative frequency (%) of data; (b) Whisker plots for error (%) with respect to soil type; (c) Whisker plots for error (%) with respect to compacted layer thickness; (d) Whisker plots for error (%) wi

This type of error, where 75 percentile error is between 25 to 40% and medians of errors is between 10 to 20%, can be assumed reasonable in subgrade modulus estimation considering the large variations involves in the soil composition, additive distribution, moisture contents distribution and thickness of compacted layer throughout the length of the project stretch. So, it can be concluded that the ICA can be used in the quality control of the asphalt pavement subgrade irrespective of the soil type, additive type and compacted layer thickness. However, more research works is suggested in order to expand the database.

Quality Improvement of Subgrade

As previously mentioned, the ICA was used in quality improvement of the subgrade in the last two projects. This section includes results from Project 6 (I-35 Service Road project). The 300-m long I-35 Service Road stretch was divided into four different sections (A, B, C, and D), as shown in Figure 6. The ICA was calibrated at a 15-meter stretch in Section A using $M_{r\text{-}ICA}$ values estimated at locations C1, C2 and C3. The calibrated ICA was then used for intelligent compaction all the four sections. In Sections A and C, the roller operator was not informed about the quality of compaction, and was also not instructed to alter the rolling pattern. However, the quality of compaction was monitored in real-time. The M_i values estimated at randomly selected ten locations (R1 to R10) in Sections A and C were compared with their corresponding $M_{r\text{-}ICA}$ to validate the accuracy of the M_i values in this project. In order to obtain the $M_{r\text{-}ICA}$ values, moisture contents and dry densities were measured at these locations using an NDG right after the completion of compaction. These NDG-measured values were used in the regression models that were developed for this particular project (Commure et al. 2014). It can be seen from Figure 7(a) that the M_i and $M_{r\text{-}ICA}$ values correlates well with an $R^2 = 0.72$. The magnitudes of the M_i values in Sections A and C are plotted in the form of a bar chart as is shown in Figure 7 (b). The average M_i of the Sections A and C was 125 MPa with a standard deviation of 30 MPa and a coefficient of variation (COV) of 24%. The maximum observed M_i is 179 MPa, observed at R3, and the minimum is 72 MPa, observed at R5. This considerably high standard deviation and the significantly low value M_i at R5 certainly indicates that a better and unifirm quality of compaction was required and acheiveable with additional roller pass at the under-compacted locations such as R5.

In Section B, the roller operator was first allowed to perform compaction following the traditional method; the M_i values were monitored in real-time to identify under-compacted areas. It was found that M_i values at two different locations namely, S1 and S2 were very low, 76 and 75 MPa, respectively, as compared to M_i values estimated at four (S3 to S6) other randomly selected test locations (110 to 150 MPa). In order to improve the magnitude of M_i, additional two roller passes were provided on S1 and S2. It can be seen in Figure 6 (b), that the M_i value at S1 could be increased from 76 MPa to 118 MPa (55% increase) and from 75 MPa to 120 MPa (59% increase) at S2.

Also, in Section D, the roller operator was first instructed to perform compaction following the traditional method. During this traditional compaction the M_i values were monitored in real-time. After the completion of the traditional compaction, it was found that almost the entire section had low values of M_i. Even though M_i was computed at the entire section, seven locations (S7 to S13) were selected to observe the improvement of the compaction level with remedial rolling. It can be seen in Figure 7 (b) that M_i values after the traditional compaction in those seven locations vary between 86 to 130 MPa. So it was decided to provide additional roller passes on the entire section instead of at some selected locations. The M_i values were again monitored pass by pass during additional compaction on the entire section. As the section was initially relatively weak, as much as four additional passes were required to bring up the average M_i on the entire section. The average M_i in this section could be increased from 104 MPa to 152 MPa (46% increase) and the M_i has increased in all the seven locations. Therefore, it can be concluded that the ICA (i) is able to identify under-compacted areas, (ii) is helpful in developing the remedial compaction plan and (ii) can help in improving the quality of the subgrade with the remedial compaction.

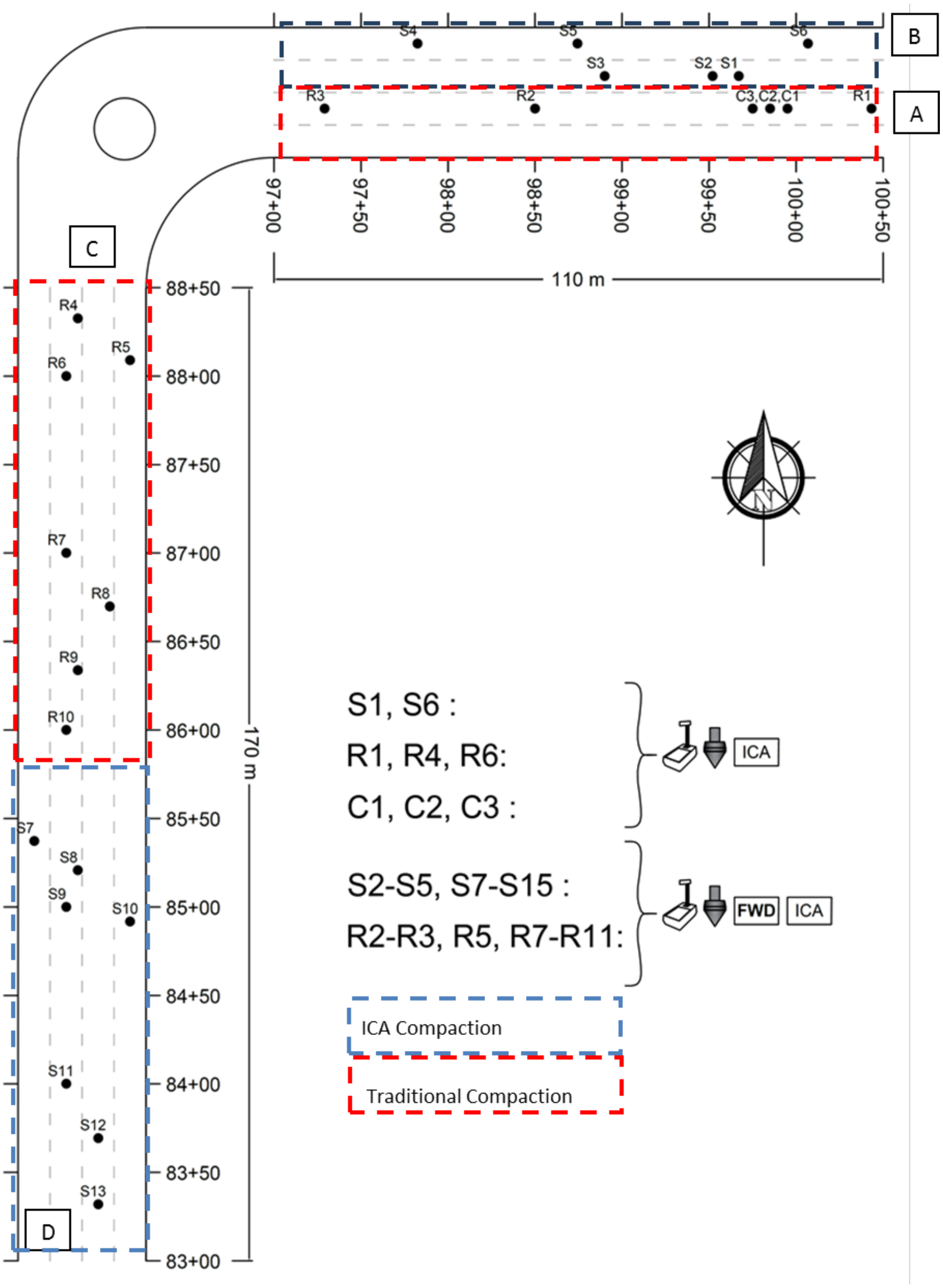

Figure 6. Location of test points at the I-35 Service Road project

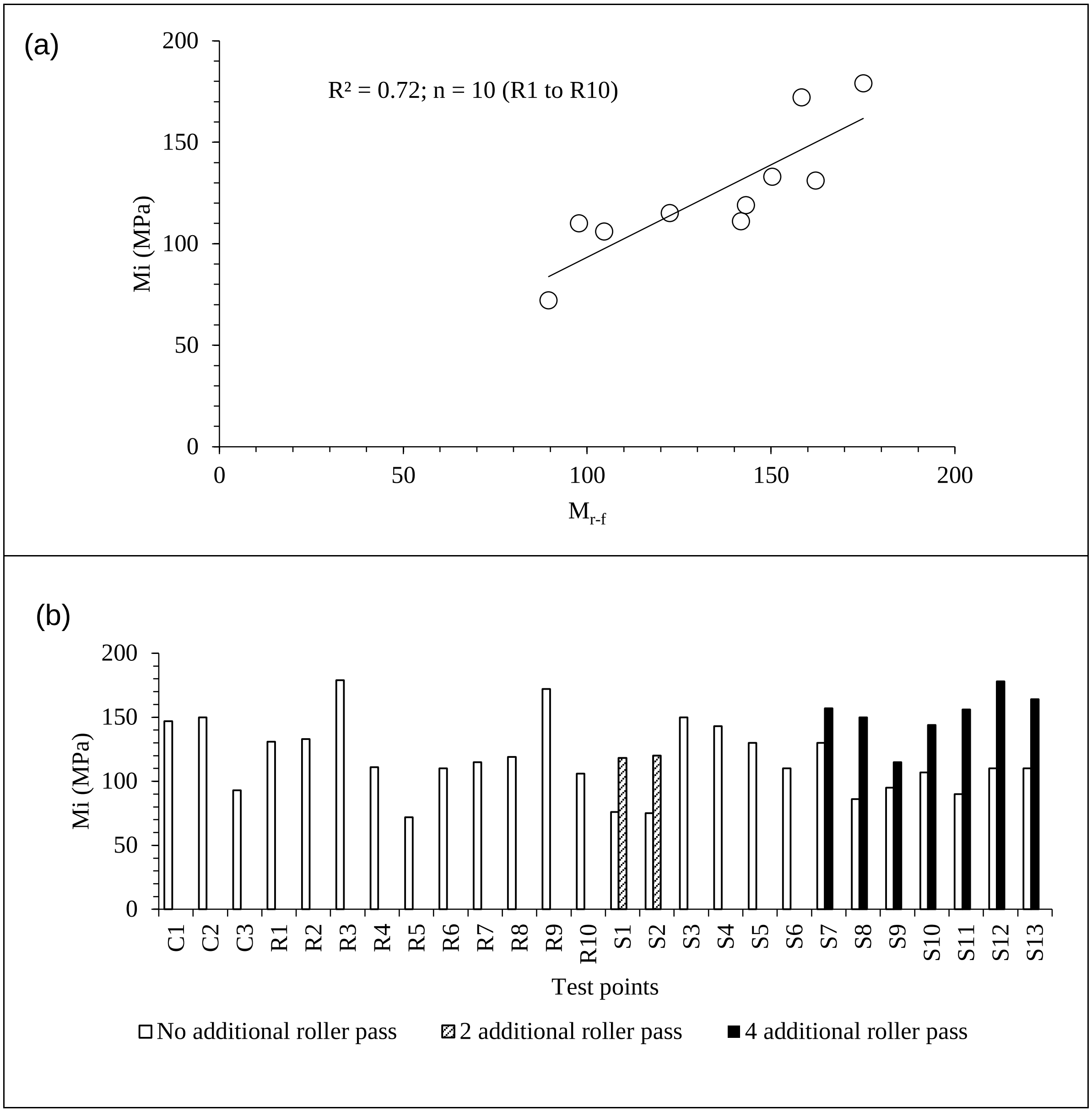

Figure 7. (a) Validation of Mi values in Project 6; (b) Magnitudes of Mi values at different test locations in Project 6

The analysis of the data from the above mentioned six demonstrations confirms that the intelligent compaction can be used in quality control and quality improvement of the stabilized subgrade. In the first two demonstrations, the applicability of the intelligent compaction in real-time monitoring of the subgrade density was studied. It was found that the variation in the compacted densities among various locations on the compacted subgrade captured by the ICA were similar to that measured by nuclear density gauge. However, the statistical correlation between the ICA-estimated density and NDG-measured density was not satisfactory. Then in the next four demonstrations, the quality of compaction of the stabilized subgrade was quantified and monitored in terms of subgrade modulus, known as ICA modulus. The calibration procedure for the ICA was established and refined using the data from the third and fourth projects. The ICA modulus values were validated by comparing them with the FWD back-calculated subgrade modulus, DCP index and in-situ subgrade resilient modulus, wherever possible. It was found that ICA modulus correlates well with FWD back-calculated subgrade modulus with a $R^2 = 0.63$. A fair correlation was obtained between ICA modulus and DCP test result with an $R^2 = 0.50$. The best correlation was obtained between ICA modulus and in-situ resilient modulus. The R^2 for the correlation was obtained as much as 0.97 when data from the last three projects were used and it was 0.72 when data from only the sixth project was used. It was found that the ICA can identify under-compacted areas. The under-compacted areas can be improved by providing remedial roller passes. In the sixth project, the subgrade modulus could be increased at some under-compacted areas by as much as 59%. The average subgrade modulus could be increased by more than 40% in this project.

Based on the findings from the literature review about the different intelligent compaction tools, different specifications developed by FHWA and state DOTs and analysis conducted for verifying the application of Intelligent compaction (e.g., ICA) for quality control and quality improvement of the stabilized subgrade, the draft of the QCP was developed and provided below.

QUALITY CONTROL PLAN FOR THE IC OF SUBGRADE

The contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. The QCP shall be contract specific and submitted 15 days prior to commencement of the field work. The QCP shall identify the field operations including calibration and functional verification of equipment, field and laboratory testing, material testing and handling, and data collection and documentation procedures. Activities to be performed before-, during- and after- the construction shall be specified. The QCP shall also identify the contractor staff responsible for ensuring quality during the compaction process.

PRE-CONSTRUCTION REQUIREMENTS

QCP Field Manager

The QCP Field manager shall be a full-time employee of the contractor or an independent consultant, and must not be involved with the quality assurance (QA) activities. He or she shall have the authority to institute actions necessary for successful implementation of the QCP.

QCP Technician(s)

The QCP Technician(s) will be responsible the following minimum functions:

- Testing the GPS associated in the IC roller(s) and rover(s);
- Constructing the test/calibration section;
- Establishing target values for the maximum dry density (MDD), optimum moisture content (OMC), production moisture content, strength of the materials using the dynamic cone penetrometer (DCP), light weight deflectometer (LWD), nuclear gauge, and the IC-roller(s);
- Monitoring the IC roller(s) throughout the operation;
- Conducting Quality Control (QC) test for the maximum dry density and moisture content;
- Downloading and analysis of the IC-data from the roller(s).

- Daily set-up, take down and secure storage of GPS, IC roller components and other testing devices used in the QC test.

In-field Laboratory Testing Facility

The in-field laboratory testing facility shall be of sufficient size to conduct the QC tests. A list of the testing equipment proposed for QC tests, the test methods, and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility.

Roller Information

Information such as the manufacturer, model, and type of rollers or IC rollers to be used each day of soil compaction shall be provided in the QCP.

Materials Sampling and Testing

The procedures for sampling and testing of the subgrade soil, and the frequency of tests shall be identified and include as a minimum of the following:

- The procedure for measuring the field moisture content of the soil during compaction. The minimum frequency of tests shall be 3 tests per lane mile (one test for every 500 m of the lane).
- The procedure for conducting the QC test for measuring the in-place strength of the soil.
- The procedure for obtaining the IC roller data. The frequency of obtaining the data shall be a minimum of two times each day of soil compaction. The data shall be date/time stamped which permits for external evaluation at a later time.

Calibration Section

A comprehensive plan for the construction of the calibration section to establish target compaction pass counts and target values for the strength of the materials (using the standard testing devices, e.g. Non-Destructive density gauges and IC rollers) is required. The requirement related to the calibration section is given below.

- Test sections shall be approximately 225 ft (75 m) long and 24 ft (8 m) wide.

Construction Areas

The procedure for determining the minimum and maximum construction areas shall be included in the QCP. The minimum construction area evaluated shall be 5000 ft^2 (500 m^2).

Pre- Construction Mapping

- Pre-construction mapping/proofing of the initial layer of the fill is recommended to identify weak areas that may need to be addressed in advance of the production fill operations.
- The procedure for mapping and recording the construction area and stiffness with the IC roller upon completion of the compaction operations for each mapped lift shall be included in the QCP.

Soil Management

- The procedures for management of the borrow pit and soil cut sections to assure uniform soil material shall be included in the QCP.
- The procedures for the necessary adjustments in compaction because of a change in soil type shall be stated.

AT-CONSTRUCTION REQUIREMENTS

GPS Testing

A proper referencing of the test location or the entire project is very important in order to generate compaction strip chart or other QC related data. The QC technician(s) shall perform the following activities during the construction.

- Establishment of a GPS base station (if required by the GPS);
- Verification of the roller and rover devices; Compaction shall not begin until proper GPS verification has been obtained. IC vendors’ recommended verification process can be used to augment the verification procedure.
- GPS check testing shall be conducted daily during compaction operations.

IC Calibration

The calibration shall be performed separately for every lift or when the soil property changes. The IC rollers shall use the same settings (speed, frequency) throughout the section. After each roller pass, a nondestructive density device shall be used to estimate the density or stiffness of the material and a hand-held GPS rover to measure the positions at least 10 locations uniformly spaced throughout the test section.

The estimated target density will be the peak of the nondestructive readings within the desired moisture range. The IC roller data using software will create an IC compaction curve for the mixture. The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. Linear regression relationships between the point test results and the IC-MV results will be used to establish the production target IC-MV as the target density meets the ODOT in-place compaction requirements. The target ICMV is recommended only for QC.

Construction Coverage

A minimum coverage of 90% of the individual construction area shall meet the optimal number of roller passes determined from the test sections. A minimum of 70% of the individual construction area shall meet the target IC-MV values determined from the test sections.

Compaction Strip Chart/Mapping

The mapping shall be conducted at least once for intervals not to exceed 24 in. (600mm) and on the surface of the completed construction.

Interruption during Construction

Separate calibration shall be performed if the compaction process is interrupted due to natural events such as rain or any equipment breakdown. The calibration parameter shall be established for each roller separately, if multiple rollers are used.

Response to Test Results

The response to QC tests for the test sections and during compaction shall include as a minimum the following:

- The procedure for corrective action when the QC moisture tests are not within -3 and +2 percentage points of the optimum moisture content.
- The procedure for corrective action when tests do not meet the ODOT requirements strength for each soil type.
- The procedure for corrective action when the maximum dry density and optimum moisture content test results indicate that there is a change in the soil type.

The procedures for re-working the construction area when IC criteria for coverage area or the minimum IC-MV are not met.

POST-CONSTRUCTION REQUIREMENTS

Documentation

The documentation shall include the following:

- The results from the moisture, strength, and maximum dry density and optimum moisture content tests. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 hours of testing.
- Documentation of the manufacturer, model, and type of rollers used each day of soil compaction and the IC roller used for mapping the compaction of the soil. The positioning of the IC roller(s) in the paving operations shall be noted.
- At a minimum, the electronic data from IC roller(s) and the data analysis software shall be provided to the Engineer upon the completion of the Test Section, Mapping and individual IC Construction Area operations.
- The Contractor(s) will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.

IC data shall be exported from the vendor’s software in both all passes and final coverage data files. All passes data includes the data from all of the passes and final coverage data is the data from just the last pass within a given area.

SPECIAL PROVISION FOR PAVEMENT SUBGRADE COMPACTION UTILIZING IC ROLLERS

The specifications were developed for the intelligent compaction of stabilized subgrades that addresses IC rollers, GPS and data recording, Quality Control Plan, IC calibration and verification procedures, establishment of target IC-MV, and statistical acceptance testing and verification of IC-MV values reported at test locations. The specifications also cover the verification of adequate site preparation prior to the construction. The developed specifications were validated, reviewed, and modified through two different field projects. The details of those projects are presented on following chapters. The developed ODOT specifications for intelligent compaction stabilized subgrades are presented below.

DESCRIPTION

This work shall consist of the construction of the pavement subgrade utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records compaction parameters in real-time during the compaction process. IC uses roller vibration measurements to assess the mechanistic subgrade soils properties and to ensure optimum compaction is achieved through continuous monitoring of the operations.

EQUIPMENT

1. IC rollers shall be self-propelled single-drum vibratory rollers equipped with accelerometers mounted on the axle of the roller drum to collect the feedback vibration of the roller in order to evaluate the applied compaction effort. The accelerometer should be installed on a roller rod directly contacted to the roller

axle to make sure minimum damping of vibration occurs before recording the vibration data. IC rollers may be smooth drums.

2. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.
3. GPS receiver units shall be mounted on each IC roller to monitor the drum locations and track the number of passes of the rollers. It is best to install the GPS receiver on the roof of the roller. GPS receivers shall utilize the Universal Transverse Mercator (UTM), or the Oklahoma State Plane coordinate system, and have a survey tolerance of not greater than 3.0 in [76.2 mm] in both the horizontal (x and y) directions. Once declared, utilize the same coordinate system for all rollers for the entire project.
4. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the IC-MV values, location of the roller, number of roller passes, roller speeds, together with the vibration frequency and amplitude of roller drums.
5. The display unit shall be capable of transferring the data by means of a USB port.

QUALITY CONTROL PLAN

The contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. The QCP shall be contract specific and submitted 15 days prior to commencement of the field work. The QCP shall identify the field operations including calibration and functional verification of equipment, field and laboratory testing, material testing and handling, and data collection and documentation procedures. Activities to be performed before-, during- and after- the construction shall be specified. The QCP shall also identify the contractor staff responsible for ensuring quality during the compaction process.

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The QCP Field manager shall be a full-time employee of the contractor or an independent consultant, and must not be involved with the quality assurance (QA) activities. He or she shall have the authority to institute actions necessary for successful implementation of the QCP.

QCP Technician(s)

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- Monitoring the IC roller(s) throughout the operation;
- Conducting Quality Control (QC) test for the maximum dry density and moisture content;
- Downloading and analysis of the IC-data from the roller(s).
- Daily set-up, take down and secure storage of GPS, IC roller components and other testing devices used in the QC test.

In-field Laboratory Testing Facility

The in-field laboratory testing facility shall be of sufficient size to conduct the QC tests. A list of the testing equipment proposed for QC tests, the test methods, and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility.

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Information such as the manufacturer, model, and type of rollers or IC rollers to be used each day of soil compaction shall be provided in the QCP.

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The procedures for sampling and testing of the subgrade soil, and the frequency of tests shall be identified and include as a minimum of the following:

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A comprehensive plan for the construction of the calibration section to establish target compaction pass counts and target values for the strength of the materials (using the standard testing devices, e.g. Non-Destructive density gauges and IC rollers) is required. The requirement related to the calibration section is given below.

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- The procedures for management of the borrow pit and soil cut sections to assure uniform soil material shall be included in the QCP.
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A proper referencing of the test location or the entire project is very important in order to generate compaction strip chart or other QC related data. The QC technician(s) shall perform the following activities during the construction.

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The calibration shall be performed separately for every lift or when the soil property changes. The IC rollers shall use the same settings (speed, frequency) throughout the section. After each roller pass, a nondestructive density device shall be used to estimate the density or stiffness of the material and a hand-held GPS rover to measure the positions at least 10 locations uniformly spaced throughout the test section.

The estimated target density will be the peak of the nondestructive readings within the desired moisture range. The IC roller data using software will create an IC compaction curve for the mixture. The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. Linear regression relationships between the point test results and the IC-MV results will be used to establish the production target IC-MV as the target density meets the ODOT in-place compaction requirements. The target ICMV is recommended only for QC.

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- The procedure for corrective action when the maximum dry density and optimum moisture content test results indicate that there is a change in the soil type.

The procedures for re-working the construction area when IC criteria for coverage area or the minimum IC-MV are not met.

POST-CONSTRUCTION REQUIREMENTS

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- Documentation of the manufacturer, model, and type of rollers used each day of soil compaction and the IC roller used for mapping the compaction of the soil. The positioning of the IC roller(s) in the paving operations shall be noted.
- At a minimum, the electronic data from IC roller(s) and the data analysis software shall be provided to the Engineer upon the completion of the Test Section, Mapping and individual IC Construction Area operations.
- The Contractor(s) will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.

IC data shall be exported from the vendor’s software in both all passes and final coverage data files. All passes data includes the data from all of the passes and final coverage data is the data from just the last pass within a given area.

METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for Soils on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for Soils**.** Payment will be made under pay item unit, intelligent compaction for soils (LS).

This item includes all costs related to providing the IC roller including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support, on-site training and testing facility shall be included in the contract lump sum price.

VERIFICATION OF THE DEVELOPED SPECIFICATION THROUGH FIELD COMPACTION

The research team worked with ODOT engineers to identify two field compaction projects for IC demonstration in order to validate the developed specifications. The site was surveyed and raw soil and modifier was collected for analysis in Broce Lab. The soil characterization tests were used to determine optimum moisture content (OMC) and maximum dry density (MDD) for the specimen soil. Resilient modulus tests were also conducted in the laboratory per procedures identified in the draft specifications.

The research team in collaboration with ODOT identified two suitable field compaction projects in Hwy 9 and US-77 to verify the developed IC Specifications. The specifications developed for the IC of subgrade were tested in these field projects. The details regarding the projects are summarized below.

Highway-9 Project

This field compaction project is located in Norman, Cleveland County, Oklahoma. The location of the project stretch is shown in Figure 8. This 3-mile long project stretch on the Highway-9 is located between East 36th Avenue and East 72nd Avenue in southeast Norman. The subgrade compaction work was performed during the last two weeks of January 2016 (Figure 9). The construction was performed by the Silverstar Construction Company, Moore, OK.

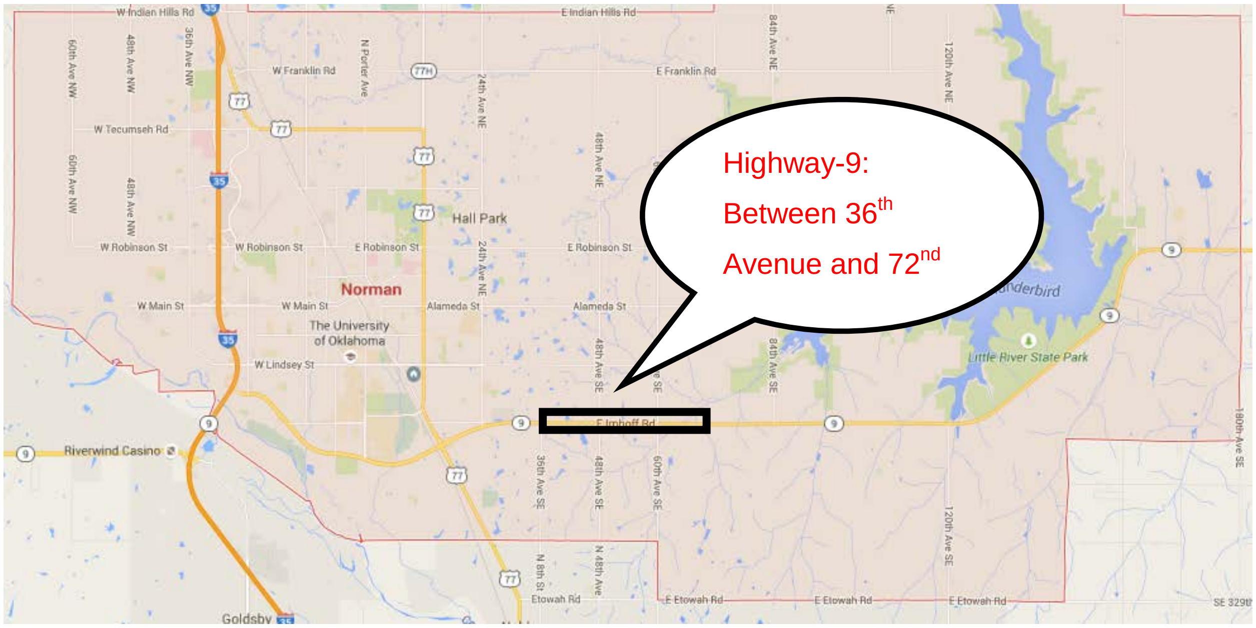

Figure 8. Project stretch of the Hwy-9 Field Project, Cleveland County, Oklahoma

Figure 9. Subgrade compaction on Westbound Hwy-9, Cleveland County, Oklahoma

On the subgrade compaction day, the team installed Intelligent Compaction Analyzer on the contractor equipment. Measuring the acceleration of the roller drum would allow the analysis of its vibration characteristics. Figure 10 shows an IACA instrumented vibratory compactor which includes an accelerometer, a GPS receiver and a real time data acquisition, analysis and display system. Vibration of roller is measured by an accelerometer mounted to the axle of the drum. A GPS receiver is set on top of the roller and is used in determining the location of the drum with sub meter accuracy. All of them are connected to a data acquisition system which collects the data in real time and store them for analysis. IACA displays various process parameters like the density/stiffness of the compacted layer, frequency of the eccentric rotation, and speed, direction, and location of the roller in real time.

Figure 10. OU developed IACA in operation

The research team coordinated with the construction agency for ascertaining the construction schedule and plan the IC demonstrantion. The virgin soil samples were collected from the job site and brought to the Broce laboratory in the University of Oklahoma. The stabilizers used in the project (CKD and Lime) were collected from the site. The properties of the virgin soil and stabilized soil samples were studied in the laboratory. The stabilized soil mixture was prepared replicating the design that was followed in the field. Required tests as indicated in the IC specifications were conducted for characterizing the modified soil mixture prior to the compaction .

The subgrade soil was stabilized by mixing 12% CKD and 2.75% Lime to a depth of 200 mm (8 inches) in the field. The optimum moisture content (OMC) and maximum dry density (MDD) of the stablized soil were found as 13.1% and 17.6 kN/m^3, respectively (Figure 11).

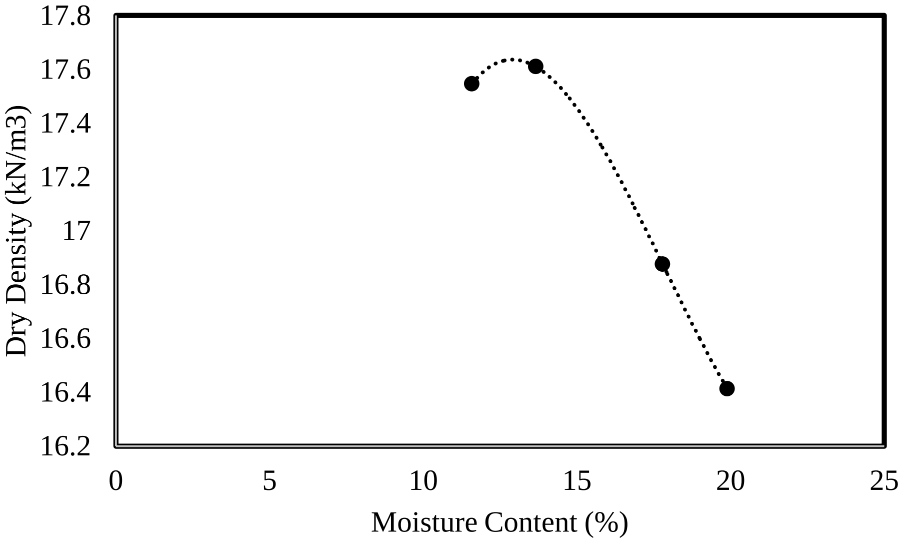

Figure 11. Moisture content and dry density relationship for the stabilized soil

In this study, the resilient modulus test was performed on five different soil specimens. Sample specimens were prepared by mixing virgin soil with 12% CKD and 2.75% lime, by weight of the soil in order to replicate the field conditions. Table 15 lists the moisture content and degree of compaction for each of the four compacted specimens at 0-day curing period. Each specimen was tested with 15 different combinations of deviatoric

(σ_d) (13.78, 27.56, 41.34, 55.12 and 68.9 kPa) and confined (σ_3) stresses (13.78. 27.56 and 41.34 kPa), according to AASHTO T307-99.

Table 15. Moisture content, dry density and degree of compaction values for the five resilient modulus specimens at 0-day curing period

Specimen No.	moisture content w (%)	dry density W (kN/m3)	Degree of compaction (% of γ_{dmax})	k_1	k_2	k_3
1	11.5810675	17.54583	99	546.5	0.08	-0.35
2	13.66171	17.61009	100	936.246	0.27	-0.36
3	17.7879133	16.87649	96	440.2698	0.23	-0.4
4	19.8900092	16.41357	93	251.013	0.1	-0.42
5	23.1	15.35393	87	160	0.1	-0.35

As it was not possible to conduct resilient modulus test for every single variation of moisture contents and dry densities, separate regression relationship was developed for the resilient modulus as explained in the developed specifications. Regression model was helpful in predicting the equivalent resilient moduli at different points in field as a function of moisture content and dry density (within a specified margin of error). The state of stress in the subgrade under the roller was not measured *as* it was beyond the scope of the current project. Also measuring the state of stress during the subgrade compaction is itself an extensive study which requires a considerable amount of resources. The state of stress was assumed based on the literature data (Mooney, et al., 2011).

Regression models were developed based on the laboratory resilient modulus test results as a function of moisture content (M_c), dry density (γ_d) and stress state (σ_d and σ_3). A comprehensive detail of the regression model development procedure can be found in Commuri et al. (2013). Regression models were developed based on the 80% percent of the test results and were validated by the remaining 20% test results.

A number of models are available in literature for predicting M_r (AASHTO 1993). Using these models, M_r can be predicted as a function of stress state and soil properties. In the current work, the following model (AASHTO 1993) was referred as presented in the developed IC specifications.

$$\mathrm{M_r} = \mathrm{k_1 p_a} \left(\frac{\theta}{\mathrm{p_a}}\right)^{\mathrm{k_2}} \left(\frac{\sigma_\mathrm{d}}{\mathrm{p_a}}\right)^{\mathrm{k_3}} \quad \text{(xi)}$$

where $\mathrm{k_1}$, $\mathrm{k_2}$ and $\mathrm{k_3}$ are the regression coefficients; $\mathrm{p_a}$is the atmospheric pressure; θ is the bulk stress (sum of the principal stresses) and σ_d is the deviatoric stress.

Since, the coefficients ($\mathrm{k_1}$, $\mathrm{k_2}$ and $\mathrm{k_3}$) are function of M_c and γ_d, and are different for different specimens, one regression model was developed for each of these coefficients so that these can be derived for any appropriate combinations of M_c and γ_d. For each specimen, $\mathrm{k_1}$, $\mathrm{k_2}$ and $\mathrm{k_3}$ coefficients (Table 15) were backcalculated using MATLAB. The $M_{r\text{-}0}$, M_c, γ_d. and the applied stress state were utilized to backcalculate these coefficients. From the total data set, 80% of the data were used for determining these coefficients. The remaining 20% data were used to validate the developed model. The regression models are given in Equations xii.

$$\begin{cases} k_1 = -59658.9 + 17.8M_c + 365.1\gamma_d \\ k_2 = -4.5391 + 0.0409M_c + 30.2382\gamma_d \\ k_3 = 1.5042 - 0.0197M_c + 0.0919\gamma_d \end{cases} \quad \text{(xii)}$$

The vibration data were collected over several roller passes on the calibration section as indicated in the IC specifications. These data were then used to train the IACA in order to recognize the features of the vibratory signal corresponding to the different levels of compaction. The target compaction values determined in the laboratory were used to perform raw calibration of the IACA. The calibration parameters were then adjusted to minimize the error between the IACA estimated density and density at selected stations on the compacted subgrade.

After completion of the compaction, a Nuclear Density Gauge (NDG) was used to collect the field moisture content and dry density at predetermined number of test locations. A total of twenty points were marked on the compacted soil and the density and the in-situ moisture content were recorded at each station using an NDG (Figure 12). Eight stations named, T1 to T8 and twelve stations named S1 to S12. The in-situ density and moisture content were measured on these twenty different stations by a Nuclear Density Guage. The degree of compaction in each station was determined using the laboratory determined MDD for stabilized soil (i.e., 17.6 kN/m3) and the measured dry density by NDG. The degree of compactions and the measured field moisture contents for the twenty stations are presented in Table 16 and Table 17. It can be seen that the degree of compaction ranged from 86 to 96%, while the moisture content ranged from 14.2 to 21.7%. It should be noted here that the OMC of stabilized soil was determined as 13.1%, but the mesured field moisture contents were above the OMC.

Figure 12. Recording density and moisture content on compacted subgrade using a Nuclear Density Gauge

Table 16. Field moisture contents and degree of compactions of locations compacted on January 20, 2016

Point	Dry density (kN/m3)	Degree of compaction	Moisture Content (%)
T1	15.9616648	90.69127727	20.8
	15.8202721	89.88790966	21.2
T2	15.8831133	90.24496193	21.2
	16.024506	91.04832955	20.6
T3	15.6317485	88.81675284	20.5
	15.4275146	87.65633295	21.7
T4	15.65	86.31738693	15.6
	15.74	87.21001761	14.2
T5	16.2601605	92.38727557	20
	16.1973193	92.0302233	19.8
T6	16.5743665	94.17253693	19.4
	16.4172635	93.27990625	20.3
T7	15.9302442	90.51275114	21
	15.9145339	90.42348807	21.3
T8	16.024506	91.04832955	19.4
	16.1501884	91.76243409	19

Table 17. Field moisture contents and degree of compactions of locations compacted on January 21, 2016

Point	Dry density (kN/m3)	Degree of compaction	Moisture Content (%)
S1	16.7471798	95.15443068	19.4
	16.9199931	96.13632443	18.8
S2	15.7417206	89.44159432	19.1
	15.8831133	90.24496193	18.3
S3	16.4172635	93.27990625	17.2
	16.4329738	93.36916932	17
S4	15.7888515	89.70938352	19.2
	15.8988236	90.334225	18.5
S5	15.9145339	90.42348807	18.5
	15.9302442	90.51275114	18.3
S6	15.95	89.26306818	18.1
	15.91	89.17380511	18.4
S7	15.8831133	90.24496193	18.5
	15.9302442	90.51275114	18.4
S8	15.8831133	90.24496193	18.5
	15.9	89.17380511	18.4
S9	16.338712	92.83359091	18.8
	16.3230017	92.74432784	18.9
S10	15.4285615	87.66228124	16.2
	15.9	87.65781809	18.2
S11	15.6	87.83485909	16.3
	15.7	88.19191136	16
S12	15.553197	88.3704375	17.7
	15.6	87.83485909	18.2

In order to validate the developed subgrade pavement IC specifications, the comparison is made between the resileint modulus obtained based on the regression model and NDG readings and ICA calibrated resilient modulus. As demonstrated in Figure 13, there is a good correlation between laboratory masured resilient modulus and IC calibrated modulus. As shown, the R^2 value is highr that 0.65.

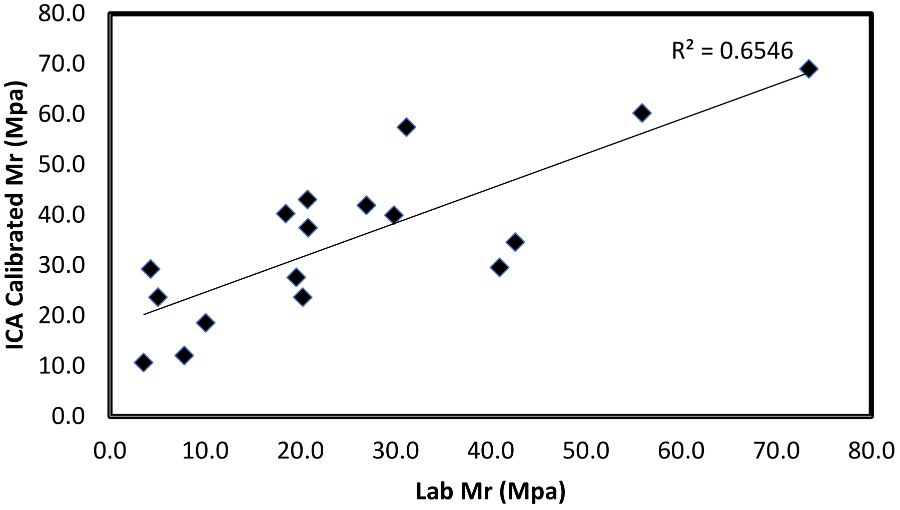

Figure 13. Comparison between the laboratory obtained resilient modulus and ICA calibrated Mr

Figure 14 shows the comparison between the NDG measurments and ICA estimated density. As shown both values follow a similar trend specially for “S” stations.

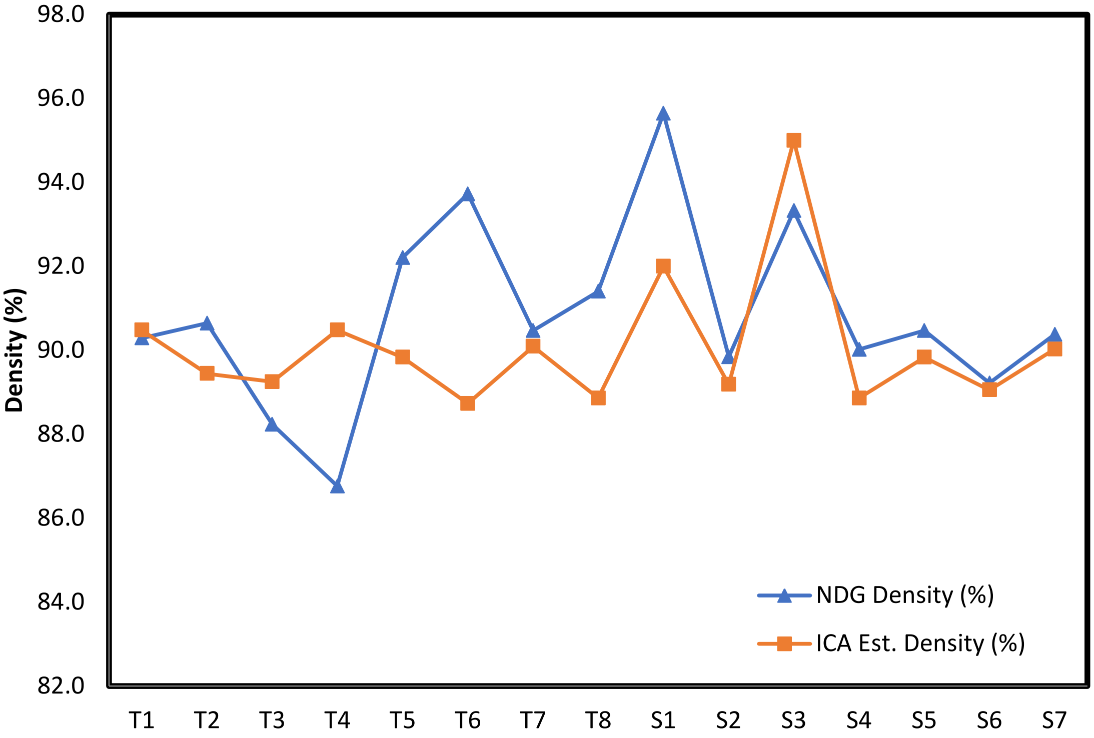

Figure 14. Comparison between the NDG measurements and ICA estimated density

Application of the OU developed IC technology by following the subgrade IC specifications, indicated the effectiveness of the developed specifications in compaction of soil subgrade pavement layer in Hwy-9 project.

US-77 Project

The second project was selected with help of ODOT engineers. This project was a Bridge and Approaches project on US-77 that has embankment construction ODOT specified soil subgrade compaction for a quarter of a mile (Figure 15 and Figure 16).

Figure 15. Project stretch of US-77 Field Project, Cleveland County, Oklahoma

Figure 16. Us-77 Construction Project

In order to verify the developed IC specifications, the research team followed the specifications in this field project. The research team collected virgin soil and cement samples from the construction site. The subgrade soil was stabilized by mixing 4% cement to a depth of 200 mm (8 inches). The optimum moisture content (OMC) and maximum dry density (MDD) of the stablized soil were found as 9.3% and 19.1 kN/m^3, respectively (Figure 17).

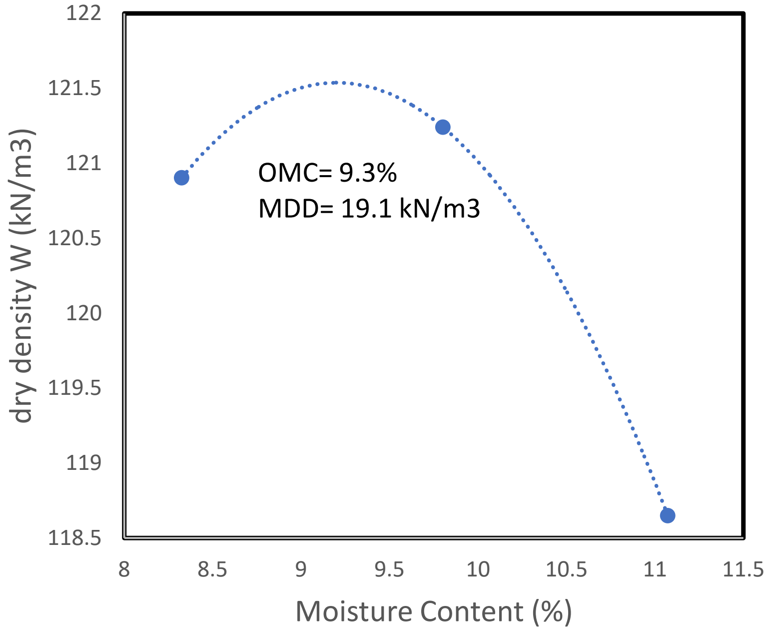

Figure 17. Moisture content and dry density relationship for the stabilized soil

The resilient modulus tests were performed on five different soil specimens. Soil specimens were prepared by mixing virgin soil with 4% cement, by weight of the soil in order to replicate the field conditions. Each specimen was tested with 15 different combinations of deviatoric (σ_d) (13.78, 27.56, 41.34, 55.12 and 68.9 kPa) and confined (σ_3) stresses (13.78. 27.56 and 41.34 kPa), according to AASHTO T307-99 and as specified in the developed Subgrade IC specifications.

Regression models were developed based on the laboratory resilient modulus test results as a function of moisture content (M_c), dry density (γ_d) and stress state (σ_d and σ_3). A comprehensive detail of the regression model development procedure can be found in Commuri et al. (2013). In the current work, the AASHTO 1993 was referred as presented in the developed IC specifications. Since, the coefficients (k_1, k_2 and k_3) are function of M_c and γ_d, and are different for different specimens, one regression model was developed for each of these coefficients so that these can be derived for any appropriate combinations of M_c and γ_d. The regression models are given in Equations xiii.

$$\begin{cases} k_1 = -24000.3 - 375.3M_c + 1716.4\gamma_d \\ k_2 = -0.466 + 0.053M_c + 0.008\gamma_d \\ k_3 = -2.549 - 0.082M_c + 0.174\gamma_d \end{cases} \quad \text{(xiii)}$$

The vibration data were collected over several roller passes on the calibration section as indicated in the IC specifications. These data were then used to train the IACA in order to recognize the features of the vibratory signal corresponding to the different levels of compaction. The target compaction values determined in the laboratory were used to perform raw calibration of the IACA. The calibration parameters were then adjusted to minimize the error between the IACA estimated density and density at selected stations on the compacted subgrade.

After completion of the compaction, a Nuclear Density Gauge (NDG) was used to collect the field moisture content and dry density at predetermined number of test locations. A total of twenty points were marked on the compacted soil and the density and the in-situ moisture content were recorded at each station using an NDG. The in-situ density and moisture content were measured on a number of stations by a Nuclear Density Guage in order to evaluate the accuracy of the IC analyzer. The degree of compactions and the measured field moisture contents for the twenty stations are presented in Table 18.

Table 18. Field moisture contents and degree of compactions of the marked stations

Point	***Dry density (kN/m3)***	***Degree of Compaction (%)***	***Moisture Content (%)***
T1	17.04065844	89.218107	13.2
	16.94633745	88.72427984	13.5
T2	16.8362963	88.14814815	8.6
	16.74197531	87.65432099	8.8
T3	16.94633745	88.72427984	7.5
	16.94633745	88.72427984	7.3
T4	17.40222222	91.11111111	9.7
	17.40222222	91.11111111	9.9
T5	17.38650206	91.02880658	6.9
	17.33934156	90.781893	7
T6	17.46510288	91.44032922	12.3
	17.48082305	91.52263374	12
T7	17.57514403	92.01646091	13.2
	17.71662551	92.75720165	12.6

T8	18.48691358	96.79012346	11.1
	18.40831276	96.37860082	11.7
T9	17.26074074	90.37037037	10
	17.15069959	89.79423868	10.4
T10	17.11925926	89.62962963	11.7
	17.24502058	90.28806584	11.3
T11	17.70090535	92.67489712	11.1
	17.60658436	92.18106996	11.3
T12	17.00921811	89.05349794	8.2
	17.10353909	89.5473251	7.8
T13	18.10962963	94.81481481	8.8
	18.04674897	94.48559671	9.4
T14	17.46510288	91.44032922	13.5
	17.43366255	91.27572016	13.8
T15	17.63802469	92.34567901	11
	17.38650206	91.02880658	11.5
T16	18.18823045	95.22633745	10.4
	18.18823045	95.22633745	10.3
T17	17.19786008	90.04115226	8.2
	17.26074074	90.37037037	7.9
T18	17.27646091	90.4526749	10.9
	17.19786008	90.04115226	11.1
T19	16.94633745	88.72427984	11.6
	16.94633745	88.72427984	11.5
T20	17.52798354	91.76954733	8
	17.55942387	91.93415638	7.9

In order to validate the developed subgrade pavement IC specifications, the comparison is made between the resileint modulus obtained based on the regression model and NDG readings and ICA calibrated resilient modulus. As demonstrated in Figure 18, there is a good correlation between laboratory masured resilient modulus and IC calibrated modulus. As shown, the R^2 value is highr that 0.62.

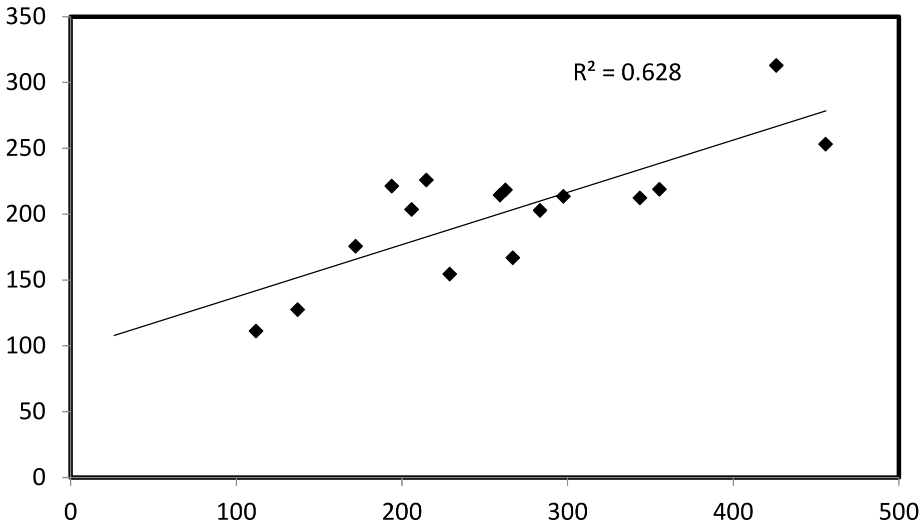

Figure 18. Comparison between the laboratory obtained resilient modulus and ICA calibrated Mr

Application of the OU developed IC technology by following the subgrade IC specifications, indicated the effectiveness of the developed specifications in compaction of soil subgrade pavement layer in US-77 project.

VERIFICATION OF THE ODOT DEVELOPED IC SPECIFICATIONS FOR HMA PAVEMENTS

Oklahoma Department of Transportation has developed special provisions for implementation of Intelligent Compaction of HMA pavements. The team leveraged its expertise in IC evaluations to validate the provisions and identify any revisions that may be necessary for its complete implementation. The draft specifications for compaction of HMA layer prepared by ODOT is given in the Appendix.

The research team in collaboration with SilverStar Co. used the ODOT specifications for compaction of the asphalt overlay in construction of Hwy-9 project. Similar to the subgrade soil layer, for the asphalt overlay, the research team conducted NDG measurement on 33 marked points right after completion of the intelligent compaction. In addition, 3 out of those 33 points got selected and the field cores were extracted and transferred to the Broce laboratory to measure the compaction level.

In the case of asphalt compaction, an infrared temperature sensor is also used to measure the surface temperature of the pavement. A data acquisition system is used to collect the GPS readings, accelerometer and temperature sensor data in real time. This data is processed by the ICA to estimate the density/stiffness of the pavement layer. During compaction, the ICA displays various process parameters like the density/stiffness and temperature of pavement, frequency of the eccentric rotation, and speed, direction, and location of the roller in real time. IACA compaction was implemented on a 50-mm (2-inch) lift of the asphalt overlay constructed at Hwy 9 Project. The particular lift was constructed using a S4 asphalt mix that had PG 76-28 OK asphalt binder.

A Dynapac drum vibratory compactor was used for compaction of the asphalt layer. The IACA was installed on this vibrator. At first, a 10-m (30 ft) long stretch was marked as a control or calibration stretch to perform the calibration procedure. The roller was directed to perform compaction on that stretch. Vibration data was collected over several roller passes. This data were then used to train the IACA to recognize the power features in the vibratory signal. The IACA was calibrated considering an approximate laydown density and a maximum final density based on the experience gained in the previous field studies. Three cores were marked and cut from this control stretch for determing the laboratory density. Their densities were determined according to the AASHTO T-166 (Table 19). The calibration parameters were adjusted later to minimize the error between IACA estimated density and the laboratory core density at those three selected locations on the calibration stretch. Table 20 presents a comparison of the core densities with the IACA estimated densities. The density is presented as the percentage of the maximum theoretical density (MTD). The value of MTD was collected from the Mix design sheet prepared by the contractor, and it was 2.488.

Table 19. AASHTO T-166 test method to measure core densities

Core ID	A (gr)	B (gr)	C (gr)	Gmb	% of water absorbed by volume	***Gmm (Mix Design Report)***	***Air Void Content (%)***
Core 1	1772.3	1786.4	1003.5	2.263763	1.800996	2.488	9.012744
Core 2	1697.5	1708.3	963.1	2.277912	1.449275	2.488	8.444053
Core 3	1612.5	1619.3	916	2.292763	0.96687	2.488	7.847159

A = mass of the specimen in air, g;
B = mass of the surface-dry specimen in air, g; and
C = mass of the specimen in water, g.

Table 20. Comparison between IACA, NDG, and lab measured core densities

Core ID	IACA (%)	NDG (%)	Lab (%)
C1	91.8	90.3	91
C2	91.7	90.5	91.6
C3	92.5	91.4	92.1

The performance of the IACA was tested during the construction of the asphalt layer following the draft specifications for HMA compaction. As shown in Figure 19 there is a good correlation between IACA measured densities and adjusted NDG readings.

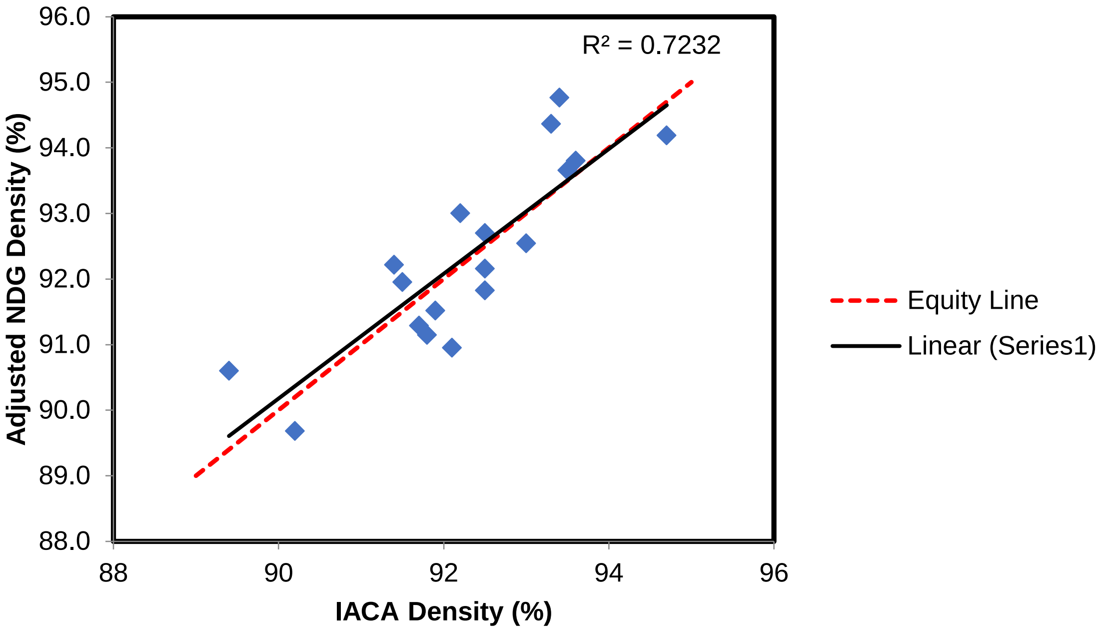

Figure 19. IACA measured asphalt layer density vs. adjusted NDG readings

Application of the OU developed IC technology by following the HMA IC specifications, indicated the effectiveness of the developed specifications in compaction of soil subgrade pavement layer in Hwy-9 project.

TECHNOLOGY TRANSFER

The research team is planing to hold a comprehensive technology transfer seminar on March 6, 2017. In this seminar engineers from industary, ODOT, and FHWA will be invited and trained on the implementation of intelligent compaction technology on stablized soil subgrade layers.

CONCLUSIONS

The Federal Highway Administration (FHWA) has drafted Generic IC specifications for soils and asphalt pavements to facilitate the early adoption of this technology. These generic specifications are expected to serve as guidance to individual state Departments of Transportation (DOTs) in the development of specifications relevant to the respective states. In this study, the researchers developed and validated 'Special Provisions' for the use of IC rollers during compaction of stabilized subgrades. Use of the Intelligent Compaction Analyzer (ICA) to estimate the resilient modulus of stabilized subgrade and the relative density of asphalt layers during compaction was evaluated in this study following the developed soil subgrade IC specifications. Moreover, the ODOT developed IC specifications for HMA pavements were evaluated in this study.

The research team in collaboration with ODOT identified two suitable field compaction projects in Hwy 9 and US-77 to verify the developed IC Specifications. The specifications developed for the IC of subgrade were tested in these field projects. Application of the OU developed IC technology by following the subgrade IC specifications, indicated the effectiveness of the developed specifications in compaction of soil subgrade pavement layer in Hwy-9 project and US-77 project. t was found that the ICA modulus and laboratory resilient modulus correlate well when the comparison was performed separately for each site, with limited data points. The coefficient of determination (R2) was found to be between 0.60 and 0.65 at each test site.

The research team in collaboration with SilverStar Co. used the ODOT specifications for compaction of the asphalt overlay in construction of Hwy-9 project. Application of the OU developed IC technology by following the HMA IC specifications, indicated the effectiveness of the ODOT developed specifications in compaction of asphalt layers.

In the asphalt layer compaction projects, the ICA was used in real-time monitoring of level of compaction in terms of relative density. The relative density is the ratio of the density at any location to the maximum theoretical density. The relative density was monitored throughout the compaction process. Under-compacted regions were identified during this process. Additional remedial passes were applied to improve the level of compaction on the identified under-compacted regions.

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APPENDIX- ODOT SPECIAL PROVISION FOR ASPHALT IC

OKLAHOMA DEPARTMENT OF TRANSPORTATION SPECIAL PROVISION FOR INTELLIGENT COMPACTION OF ASPHALT

These Special Provisions revise, amend, and where in conflict, supersede applicable sections of the 2009 Standard Specifications for Highway Construction, English and Metric.

411.01 DESCRIPTION

This work consists of the compaction of the asphalt mixtures utilizing intelligent compaction (IC) rollers within the limits of the work as described in the plans. Intelligent compaction is defined as a process that uses vibratory rollers equipped with a measurement and documentation system that automatically records various critical compaction parameters in real time during the compaction process. Intelligent compaction uses roller vibration measurements to assess the mechanistic properties of the compacted materials to ensure optimum compaction is achieved through continuous monitoring of the operations.

Intelligent compaction applies to all asphalt on the project with the exception of drives, tapered transitions associated with shoulders, ramps, acceleration, deceleration, climbing and turn lanes, and short isolated pavement areas requiring handwork.

411.03 EQUIPMENT

Compactor

Supply sufficient numbers of rollers and other associated equipment necessary to complete the compaction requirements for the specific materials. Ensure that at least one IC roller is used. The required position for an IC roller is in the initial phase (breakdown) in the paving sequence. Use any additional IC rollers in the intermediate phase.

Provide the supplier, make, model, and unique identifier of the GPS system to be utilized. Sufficient training for the operator(s) shall be supplied by a representative of the manufacturer of the equipment.

Breakdown Roller Global Positioning System (GPS) Requirements

Provide IC breakdown rollers equipped with GPS radio and receiver units to monitor the equipment locations and track the number of roller passes. GPS receivers shall utilize the Universal Transverse Mercator (UTM), or the Oklahoma State Plane coordinate system, and have a survey tolerance of not greater than 3.0 in [76.2 mm] in both the horizontal (x and y) directions. Once declared, utilize the same coordinate system for all rollers for the entire project.

Utilize GPS data in the following format:

Table GPS Data Format

Data	Format	Example
Time	Military local time zone	hhmmss.ss
GPS	Latitude/Longitude degrees/minutes, or decimal degrees	 ddmm.mmmmmmmm dd.dddddddd
Grid	Feet	0.25 ft

Intelligent Compaction Measured Values (IC-MV)

Provide vibratory type IC breakdown rollers equipped with accelerometers to measure the interaction between rollers and compacted asphalt in order to evaluate the applied compaction effort. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV), which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.

Temperature Measurement

Provide IC breakdown rollers equipped with non-contact temperature sensors for measuring pavement surface temperatures.

Integrated On-Board Documentation System

Provide IC breakdown rollers equipped with an on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values, including the stiffness response values, location of the roller, number of roller passes, pavement surface temperatures, roller speeds, vibration frequencies, and amplitudes of roller drums. Ensure that the display unit is capable of transferring the data by means of a USB port. Ensure the produced data files are compatible with the latest version of Veda IC data analysis software, available at www.intelligentcompaction.com.

Hand-Held Rovers

Provide a GPS system (including GPS receivers on equipment and handheld GPS receivers (i.e. Rovers)) that makes use of the same reference system that can be a ground-based base station or network-RTK (network-Real-Time Kinematic), to achieve RTK-GPS accuracy. Examples of combinations are:

- GPS receivers on equipment and hand-held GPS rovers referenced to the same on-ground base station.
- GPS receivers on equipment and hand-held GPS receivers referenced to the same network-RTK.

411.04 CONSTRUCTION METHODS

Compaction

Intelligent Compaction

a. GPS Setup

Prior to the start of production, the Contractor and representatives of the GPS and equipment manufacturer shall ensure that the equipment is set up and operating properly.

Conduct GPS setup daily during production operations to ensure consistency and accuracy of GPS measurements for all GPS devices prior to the compaction operation.

b. Quality Control During Rolling

In addition to any other QC responsibilities, the Contractor is responsible for the following:

- Daily GPS check testing for the equipment and rover(s).
- Establishing target number of passes using data from standard testing devices (i.e. nondestructive density gauges, roadway density cores, and roller(s)).
- Using hand-held GPS rovers to determine the GPS coordinates of the selected roadway density core locations.
- Monitoring the equipment location during paving operations, and the operation of the entire GPS system on the project site.
- Quality control testing to monitor the pavement temperature.
- Downloading and analysis of the data from the roller(s) daily.
- Daily Setting-up, taking down, and securing storage of GPS and equipment components daily.

c. Materials Sampling and Testing

Construct a test strip in accordance with Subsection 411.04.D of the Standard Specifications. Roll the test section at 100% coverage with optimal number of roller passes to achieve acceptable roadway density.

Ensure a minimum coverage of 90% of the mat for the total project meets or exceeds the optimal number of roller passes when analyzed using Veda software.

As a minimum, obtain the data from the equipment two times per day of asphalt compaction operations. Ensure the data is date and time stamped permitting external evaluation at a later time. The data may be requested at any time by the Engineer.

Provide access to the raw data and results from the analysis software to the Engineer within 24 hours of obtaining the data.

d. Documentation

Provide documentation of the manufacturer and model of the IC rollers used each day of paving. Note the relative positioning of the equipment in the paving operations.

Upon the completion of the first day's paving, at a minimum, provide the Engineer with the electronic data, including IC-MV, from the equipment and the data analysis software.

Export all data from the vendor's software on a daily basis. Following each work day or shift, operators shall make daily data files available to ODOT Materials & Research Division, and Residency personnel for review.

At the complection of the Contract, provide a summary of all equipment data, coverage area and uniformity, and color prints of all compaction data to the Department.

e. Assistance and Training

1) Technical Assistance

Coordinate for on-site technical assistance from the equipment representatives during the initial three days of production, and then as needed during the remaining operations. As a minimum, the equipment representative shall be present during the initial setup and verification testing of the equipment. The equipment representative shall also assist the Contractor with data management using the data analysis software including data input and processing.

2) On-Site Training

- Coordinate for on-site training for Contractor and Department project personnel related to operation of the technology. Contractor’s personnel shall include the paving superintendent, QC technicians (if applicable), and equipment operators. At a minimum, training topics are to include:
- Background information for the specific system(s) to be used
- Setup and checks for system(s), GPS receiver, base-station and hand held rovers
- Operation of the system(s) on the equipment (e.g. setup data collection, start/stop of data recording, and on-board display options)
- Transferring raw data from the equipment (e.g. via USB connections)
- Operation of vendor’s software in order to open and view raw data files and export all-passes and proof data files in Veda-compatible format.
- Operation of Veda software in order to import the above exported all-passes and proof data files, inspect maps, input point test data, perform statistical analysis, and produce reports for project requirements.

411.05 METHOD OF MEASUREMENT

Intelligent Compaction of Asphalt will be measured for payment on a Lump Sum basis.

411.06 BASIS OF PAYMENT

The Department will pay for each pay item at the contract unit price per the specified pay unit as follows:

Table Unit price of IC items

Pay Item:	**Pay Unit:**
INTELLIGENT COMPACTION OF ASPHALT	Lump Sum

The Lump Sum bid price constitutes full and complete compensation for all labor, materials, equipment, and incidentals required to complete the work in a manner accepted by the Engineer.