

Quality control of subgrade soil using intelligent compaction

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Abstract Intelligent Compaction (IC) of subgrade soil has been proposed to continuously monitor the stiffness of subgrade during its compaction. Modern IC rollers are vibratory compactors equipped with (1) an onboard measuring system capable of estimating the stiffness of the pavement material being compacted, (2) Global Positioning System (GPS) sensor to precisely locate the roller, and (3) an integrated mapping and reporting system. Using IC, the roller operator is able to evaluate the entire subgrade and address deficiencies encountered during compaction. Continuous monitoring of quality during construction can help build better quality and long-lasting pavements. However, most of the commercially available IC rollers report stiffness in terms of Original Equipment Manufacturer (OEM) specified indicator, known as Intelligent Compaction Measurement Value

(ICMV). Although useful, additional tests are required to establish the correlation between these ICMV values and the resilient modulus of subgrade (M_r). Since the mechanistic design of the pavement is performed using M_r , it is important to know if the design M_r is achieved on the entire subgrade during compaction. This paper presents a systematic procedure for monitoring the level of compaction of subgrade in real time using intelligent compaction (IC). Specifically, the Intelligent Compaction Analyzer (ICA) developed at the University of Oklahoma was used for estimating the modulus of the subgrade. Results from two demonstration studies show that the ICA is able to estimate subgrade modulus with an accuracy that is acceptable for quality control activities during the construction of pavements.

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Introduction

In the mechanistic-empirical design of asphalt pavements, the strength of the subgrade is represented in terms of resilient modulus (M_r). During the construction, it is important to perform sufficient compaction, so that the compacted subgrade modulus matches with design M_r to avoid pavement distresses, such as rutting, fatigue, and potholes during the early service life. Traditionally, quality control (QC) measures undertaken during the construction of the subgrade often check only the moisture content (M_c) and dry density (γ_d) of the subgrade. Although the resilient modulus is the function of M_c and γ_d , it also depends on the type of soil, type, and amount of additive (soil stabilizer) used and stress state of the soil [1, 2]. Therefore, M_c and γ_d are not the appropriate indicators of level of compaction, neither are they adequate to determine M_r of the subgrade at the time of construction. In some cases, Dynamic Cone Penetration (DCP) [3–5], Falling Weight Deflectometer (FWD) [6, 7], or Light Weight Deflectometer (LWD) [3] tests are performed to assess the stiffness (function of modulus, compacted layer thickness, and Poisson's ratio) of the subgrade during construction. However, these tests do not provide a direct measurement of the resilient modulus and are not commonly performed due to cost and time constraints. Another disadvantage of the traditional QC test methods is the inability of evaluating the entire compacted area. Tests at discrete locations may leave undetected soft spots on the finished subgrade. Poor quality can also have an adverse effect on pavement layers constructed on top of the prepared subgrade.

Intelligent Compaction (IC) of subgrade has been proposed in recent years to address the shortcomings of traditional QC test methods [8–12]. Modern IC rollers are vibratory compactors equipped with (1) an onboard measuring system capable of estimating the stiffness of the pavement material being compacted, (2) Global Positioning System (GPS) sensor to precisely locate the roller, and (3) an integrated mapping and reporting system. Using IC, the roller operator is able to evaluate the entire subgrade and address deficiencies encountered during compaction. There are several Original Equipment Manufacturers (OEMs) currently offering the IC equipment in the market. Notable of these are Compaction Information System [13], Bomag Variocontrol [14], Ammann Compaction Expert [15], AccuGrade ([16], and Dynapac Compaction Analyzer

[17]. In Intelligent Compaction, roller vibrations are collected and analyzed to estimate the level of compaction of subgrade in real time. The stiffness is then reported in terms of Original Equipment Manufacturer (OEM) specified indicator, such as Intelligent Compaction Measurement Value (ICMV) or Roller Measurement Value (RMV). Although useful, additional tests are required to establish the correlation between these ICMV or RMV values and the resilient modulus of subgrade (M_r). The use of these devices in assessing the quality of subgrade during compaction is still under investigation, and a standard measure for reporting the quality of compaction has not yet been established [8]. Research is still underway to study the correlation between ICMV and the insitu density, stiffness or resilient modulus estimated by the conventionally available QC test methods, such as Nuclear Density Gauge (NDG), FWD, DCP, and LWD.

The Intelligent Compaction Analyzer (ICA) was initially developed at the University of Oklahoma (OU) [18–20] to provide a real time estimation of compaction level (density and dynamic modulus) of asphalt pavement during construction. The use of ICA in quality control operations was demonstrated during the construction of asphalt overlays and full-depth pavements at different sites [18, 19, 21–24]. The extension of ICA for estimating the stiffness of subgrades during compaction is presented in this paper. The stiffness of the subgrade is estimated in terms of a modulus, referred to as the ICA modulus (M_{ICA}). A calibration procedure is developed to ensure that M_{ICA} has numerical values comparable to the laboratory measured M_r values for an assumed stress state of the soil. This helps the roller operator to verify if target compaction (in terms of modulus) is reached during the compaction of the subgrade.

The results of two case studies reported in this paper show that the ICA can estimate the modulus of the subgrade in real time during the compaction. Furthermore, the estimated modulus, M_{ICA} , compares favorably with the M_r values for the same dry density, moisture level, and assumed stress state of the soil. Two different techniques are illustrated to validate the accuracy of M_{ICA} through two separate case studies. In the first study, FWD tests were conducted to validate the M_{ICA} values by comparing them with the corresponding FWD back-calculated subgrade moduli (M_{FWD}). Since FWD tests are not always feasible to carry out, in the second study, the accuracy of the estimated M_{ICA} values was validated by comparing M_{ICA} values with the corresponding M_r values estimated from regression models developed based on the laboratory M_r (M_{r-reg}) test results. These two studies demonstrate that the ICA is able to estimate the subgrade modulus in real time with an accuracy suitable for the quality control measures during the construction of subgrades.

Background of ICA

Principle of operation

The ICA is based on the hypothesis that the vibratory roller and the underlying pavement form a coupled system, whose response during compaction is influenced by the stiffness of the pavement layers [19, 20]. The response of the roller is determined by the frequency of the vibratory motors and the natural vibratory modes of the coupled system. The vibration of the roller varies with the stiffness of the underlying pavement layer. The analysis of the vibration spectra can, therefore, be used to estimate the stiffness of the pavement layer(s). To accomplish this, the vibrations of the drum are first analyzed to determine the vibration patterns. An Artificial Neural Network (ANN) that is central to the ICA then classifies the vibration patterns in real time into appropriate stiffness levels. These stiffness levels are then converted to M_{ICA} values in the calibration module. The ICA display then combines the GPS locations and M_{ICA} values to present compaction data in real time to the roller operator. It may be noted as the objective of this paper is only to demonstrate the application of ICA in the QC of subgrade compaction, a detailed description on the theoretical and fundamental mechanism of the ANN model has been kept out of the scope of this paper, which can be found in [19, 20, 23, 24]. The components, functional modules, and operation of the ICA are presented in the following paragraphs.

Hardware

The ICA consists of a roller-mounted rugged tablet computer, a Global Positioning System (GPS) receiver, and a uniaxial accelerometer. A picture of an ICA-integrated roller is shown in Fig. 1a. The tablet computer is mounted close to the roller instrument cluster, and the GPS is mounted on the roof of the roller and referenced with respect to the axle of the roller drum. The accelerometer is mounted on the axle of the roller drum and is used to sense the vibrations of the drum during compaction.

Functional modules

The functional modules of the ICA are shown in the flowchart in Fig. 1b. The accelerometer and the user interface for specifying the amplitude and frequency of the vibration motors are part of the Sensor Module (SM). The Feature Extraction (FE) module computes the Fast Fourier Transform of the drum vibrations and extracts the features corresponding to vibrations at different salient frequencies.

The ANN classifier is a multi-layer neural network that is trained to classify the extracted features, so that each class represents a vibration pattern specific to a pre-specified level of compaction [19, 25]. The Compaction Analyzer (CA) then post-processes the output of the ANN and estimates M_{ICA} in real time.

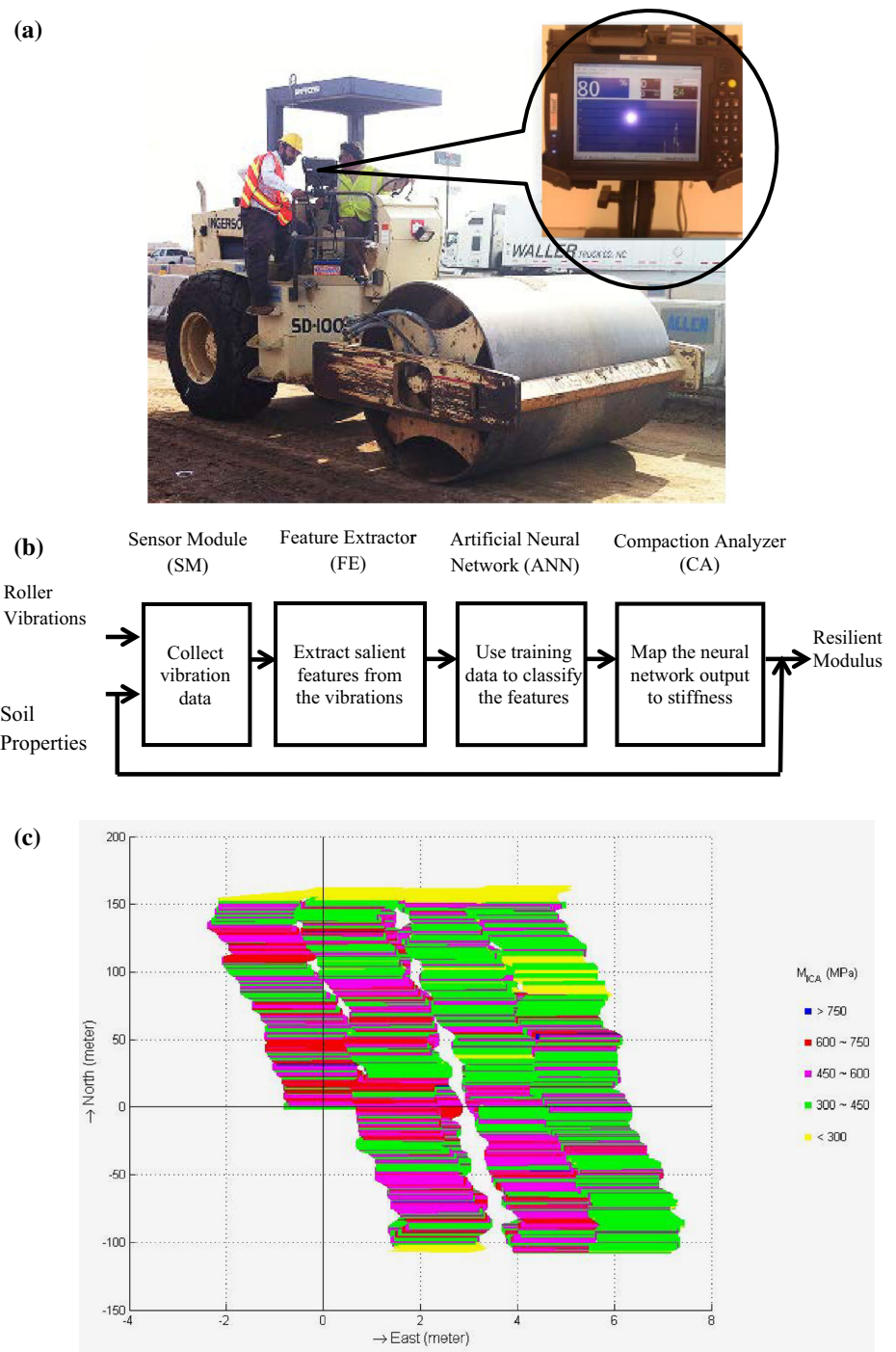
Documentation

During compaction, ICA provides as-built maps showing process information, such as number of roller passes, roller path, and GPS coordinates of the roller, and a color coded as-built map showing the value of M_{ICA} to the operator, in real time. Figure 1c shows a typical as-built map generated during the subgrade compaction using the ICA. Access to compaction quality in real time enables the roller operator to detect and correct any soft spots on the subgrade and thereby improve the quality of compaction.

Installation and use of ICA during compaction

The first step in Intelligent Compaction of subgrade is installation of ICA hardware on the roller and functional verification of the GPS sensor, accelerometer, and the tablet computer [26]. Once installed and verified, the ICA is needed to be calibrated for the specific roller and field conditions before it can be used to estimate the modulus of the subgrade. Prior to the start of the project, a 10-m-long and 1.33-m-wide calibration stretch is selected; the roller vibrations and GPS measurements are recorded during compaction. After each roller pass, in situ tests are conducted using an NDG to measure M_c and γ_d at selected locations. The compaction process is stopped when no appreciable increase in density is observed between the subsequent passes. The extracted patterns from the vibration data collected during the compaction of calibration stretch are then used to train the ANN to classify the vibrations into those corresponding to different compaction levels [19, 21, 25]. In situ tests conducted after the compaction process are used to estimate the subgrade modulus at test locations marked on the compacted subgrade. These in situ subgrade modulus values are compared with the M_{ICA} values at the test locations, and the calibration coefficients are determined to minimize the estimation error [25]. In situ subgrade modulus can be calculated by first conducting FWD tests on the finished subgrade and then back-calculating the modulus using software, namely, Modulus 6.0 [27]. An alternate approach for estimating in situ subgrade modulus is to first perform laboratory M_r tests of the representative soil and then develop regression

Fig. 1 **a** Picture of an ICA-integrated roller during subgrade compaction. **b** Flowchart of the modules involved in the estimation of resilient modulus of subgrade. **c** As-built map generated by ICA during subgrade compaction showing estimated M_{ICA} values



models to correlate dry density and moisture content to the M_r values. NDG reading taken after the compaction of the calibration stretch can then be used to determine the corresponding M_r values at test locations. After the calibration process is complete, the ICA can estimate the modulus of the subgrade continuously during the compaction.

ICA compaction process

The calibrated ICA is used to record compaction data, such as spatial location and vibrations of the roller, the speed and operational frequency of the roller, and the estimated ICA modulus 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_{ICA}) is monitored by the ICA in real time, and the under-compacted regions are identified. The under-compacted regions are the regions, where the M_{ICA} values are significantly lower than the average M_{ICA} 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 regions. 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_{ICA} is achieved and uniform across the entire compacted subgrade.

Case studies

ICA compaction was performed on two separate projects under the current study. The overall ICA-based subgrade compaction procedure involved collection of raw soil and additive, laboratory testing of raw soil and soil-additive mixes, development of regression models for estimation of M_r , calibration of ICA, and real time monitoring of compaction level in the field. Pertinent properties of the soil and soil-additive mix, namely, particle size distribution [28], Atterberg’s limits [29, 30], relationship between moisture content (M_c) and dry density (γ_d) [31], and M_r [32] were determined in the laboratory. Resilient modulus values were determined at different values of M_c , and γ_d and stress levels of the soil-additive mix. Regression models were developed for M_r with respect to M_c , γ_d , and stress states. Validation of the ICA moduli was performed by comparing the M_{ICA} values with the corresponding FWD moduli in one project and with the laboratory M_r values in the other project. A brief description of each project is given below. It may be noted that since γ_d is measured at the mid-depth of the

compacted subgrade, the M_{ICA} value corresponds to mid-depth resilient modulus.

Project 1 (West 60th Street)

ICA compaction was performed during the construction of a full-depth asphalt pavement on a 3.4-kilometer (2.13 miles) stretch at the West 60th street between Tecumseh Road and Franklin road in Norman, Oklahoma. The raw subgrade soil was stabilized by mixing 10 % Cement Kiln Dust (CKD) up to a depth of 152 mm (6.0 in).

Properties of soil and soil-CKD mixes

Figure 2a shows the particle size distribution [28] of the raw soil collected from the project site. The liquid limit [30] and plasticity index [29] were found to be 23 and 4 %, respectively. According to the Unified Soil Classification System (USCS), the soil was classified as CL-ML. The moisture-density relationship for the stabilized soil (with 10 % CKD, by weight) was obtained by conducting standard Proctor tests as per AASHTO T99 [31]. From Fig. 2b, the maximum dry density (γ_{dmax}) and optimum moisture content (OMC) were found as 17.3 kN/m³ and 14.6 %, respectively.

Regression models for M_r

As mentioned earlier, the relationship between M_c , γ_d , and M_r is required to determine the equivalent in situ M_r values for calibrating the ICA. To develop this relationship, five M_r specimens with five different combinations of M_c and γ_d (Table 1) were tested using an MTS[®] actuator-controlled resilient modulus setup. The degree of compaction achieved in these specimens varied between 97 and 99 %. Each specimen was tested with 15 different combinations of deviatoric stress (σ_d) (14, 28, 41, 55 and 70 kPa) and

Fig. 2 a Particle size distribution for soil, and **b** M_c – γ_d relationships for soil-CKD mix for the West 60th Street project

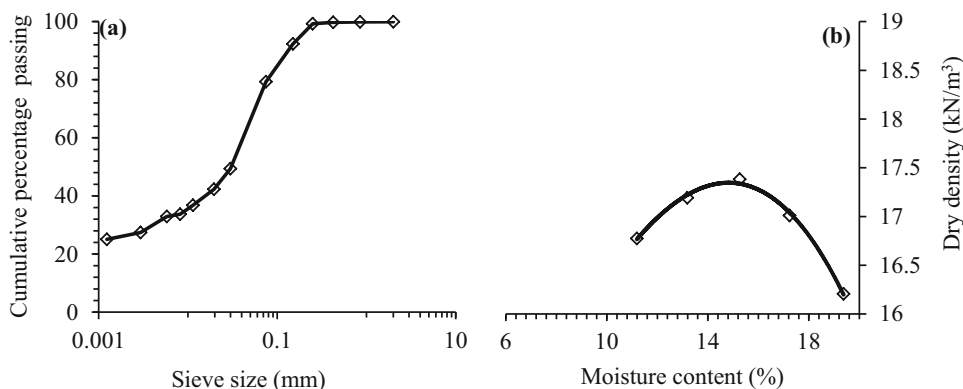


Table 1 Features of M_r test specimens and their regression coefficients for the West 60th Street project

Specimen No.	Moisture content (%)	Dry density (kN/m ³)	Degree of saturation (%)	Degree of compaction (% of γ_{dmax})	k_1, k_2 and k_3 based on M_{r-0}			R^2
					k_1	k_2	k_3	
1	12.1	17.26	60.7	98	6511.07	0.082	-0.154	0.96
2	12.4	17.12	60.8	97	5830.8	0.091	-0.194	0.93
3	12.1	17.2	60.1	97	6310.23	0.082	-0.163	0.9
4	14.7	17.43	75.8	99	5926.52	0.173	-0.257	0.95
5	14.8	17.56	78	99	6346.92	0.177	-0.241	0.96

confining pressure (σ_3) (14, 28 and 41 kPa), according to AASHTO T307 [32]. Specimens were tested following 0- and 28-day curing periods. The M_r values at 0- and 28-day curing periods are referred to as M_{r-0} and M_{r-28} , respectively.

A number of models are available in the literature for predicting M_r [2, 33]. Using these models, M_r can be predicted as a function of stress state and soil properties. In the present study, the following model [34] was used

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \tag{1}$$

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 the functions 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 . It may be mentioned that the use

Table 2 Regression coefficients for determining k_1, k_2 , and k_3

Regression coefficients	k_1	k_2	k_3
a	-53060.478	-0.467	-2.553
b	-482.317	-0.467	-0.052
c	3790.046	0.008	0.175

of gravimetric moisture content (instead of degree of saturation) in resilient modulus regression models [33, 35–37] is quite common. The Mechanistic-Empirical Pavement Design Guide (MEPDG) [1] also uses gravimetric moisture content for determining the subgrade resilient modulus. For each specimen, k_1, k_2 , and k_3 coefficients (Table 1) were determined using the statistical software Minitab®. The laboratory test results for M_{r-0} 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. This type of data splitting is a standard procedure and followed by several researchers [33, 38]. The general regression model for determining the coefficients k_1, k_2 , and k_3 is given in Eq. 2. The total number of data considered for this equation was 75

$$k_i = a + b(M_c) + c(\gamma_d) \tag{2}$$

where $i = 1, 2$, and 3 for k_1, k_2 and k_3 , respectively; a, b , and c are the regression coefficients for determining k_1, k_2 , and k_3 , as given in Table 2.

Figure 3 shows the comparison of actual M_{r-0} and predicted resilient moduli ($M_{r-reg-0}$) on the day of compaction (0-day curing). It can be seen that the coefficient of determination ($R^2 = 0.81$) is very good for the developed model to predict resilient modulus of stabilized soils. Furthermore, $M_{r-reg-0}$ could be predicted with an error of less than $\pm 15\%$ %.

Fig. 3 Comparison between M_{r-0} and $M_{r-reg-0}$ for the West 60th Street project

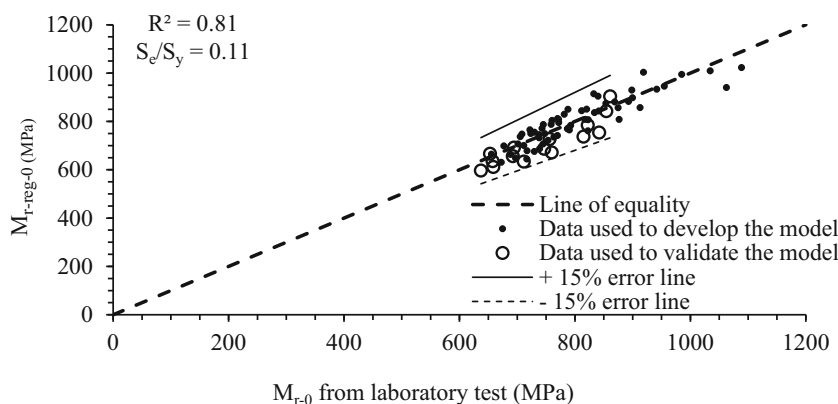
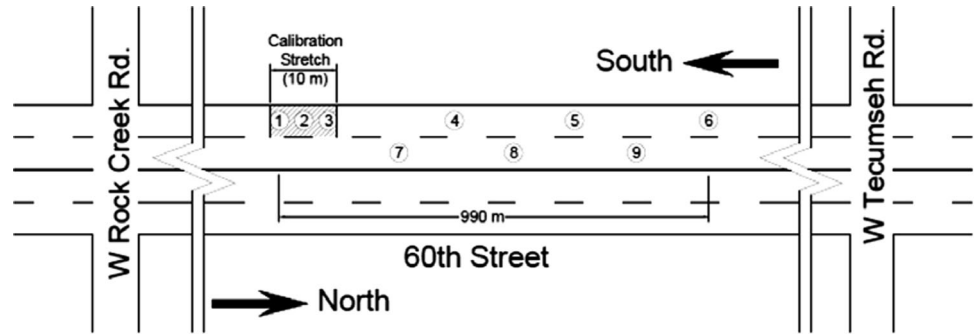


Fig. 4 Schematic of different test stations in the West 60th Street project



Stress state for estimating M_{ICA}

To use the regression models (Eq. 2) to predict modulus during compaction, it is necessary to first determine the stress state that is representative of the field condition. To this end, Mooney and Rinehart [39] conducted a study, where the in situ stress state (at 140 mm depth) was measured during the 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 25–40 kPa. These values lead to deviatoric stresses between 60 and 75 kPa. Hence, for the estimation of field M_r in the present study, the deviatoric, confining and bulk stresses 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 [32]. It may be noted that M_{ICA} is equivalent to the laboratory M_r when the stress state in the M_r test is equivalent to the stress state existing in the field ($\sigma_d = 69$ kPa and $\sigma_3 = 41$ kPa, in the present study).

ICA measurements

In the field, the existing soil was first mixed with CKD and then compacted using a pad-foot roller. This roller consisted of a large number of pads or spikes on the drum that compact and perforate the rolled surface. A smooth steel drum vibratory roller instrumented with the ICA was used for proof-rolling the compacted subgrade. The drum width, drum diameter, operational weight, and vibration frequency of the smooth steel drum vibratory roller used herein were 2.134, 1.499 m, 10,750 kg, and 31–34 Hz, respectively. Calibration of the ICA was performed on a 10-m-long stretch at the beginning of the proof-rolling process. Figure 4 shows a sketch indicating different test stations on the compacted subgrade. During the

compaction of the calibration stretch, the ICA was used to continuously record the location of the roller and the estimated (raw) modulus based on the vibration data collected on the calibration stretch. The compaction process was stopped when no appreciable increase in estimated modulus values was observed between two subsequent passes. After the compaction was complete, three test stations (Stations 1, 2, and 3 in Fig. 4) were marked and the dry density and moisture content were measured at each location using a Humboldt 5000 EZ Nuclear Density Gauge. The estimated M_r values at these three stations were then determined using Eqs. 1 and 2. The ICA data were used to determine the estimated modulus (M_{ICA}) at these three locations, and the calibration constants were calculated to minimize the difference between M_{ICA} and $M_{r-reg-0}$.

For the validation of the ICA, roller vibration data were recorded on the entire compacted subgrade during the proof-rolling process. The vibration data and GPS reading were processed in real time to estimate M_{ICA} . For the validation of M_{ICA} , six random stations (Stations 4–9) were marked and properly referenced on the compacted subgrade. The M_{ICA} values at all the nine stations (three calibrations and six validations) are given in Table 3.

FWD test

In this project, the ability of the ICA to estimate the modulus of the stabilized subgrade was validated by comparing the M_{ICA} values with the M_{FWD} values. FWD tests were conducted at three stations (Stations 1, 2, and 3) on the calibration stretch as well on the other six random stations (Stations 4–9) on the remaining stretch, as shown in Fig. 4. FWD tests were conducted on the asphalt surface 28 days after the compaction of subgrade when the asphalt overlays were already completed. It may be noted that FWD test could not be conducted right after the subgrade compaction because of construction-related issues. The corresponding subgrade modulus at each of the nine stations was backcalculated using a back-calculation software [40]. The required information for backcalculation of subgrade modulus, such as the thickness of the asphalt

Table 3 Summary of Test Results for the West 60th Street project

Stations	Moisture content (%)	Dry density (kN/m ³)	Degree of saturation (%)	M_{ICA} (MPa)	M_{FWD-28} (MPa)	M'_{FWD-0} (MPa)	Difference between M_{ICA} and M'_{FWD-0} (%)
1	16	17.10	78.2	380	1125	391	3
2	16.7	16.89	78.8	374	1012	363	-3
3	17.1	16.59	76.9	334	586	244	-37
4	14.2	16.59	63.8	429	1384	451	5
5	12.3	17.61	65.4	408	1707	519	21
6	13.9	16.89	65.6	312	993	358	13
7	13.8	16.75	63.6	228	380	174	-31
8	15.1	17.31	76.4	314	894	333	6
9	15.1	17.13	74.2	363	593	246	-48

layer, was obtained by extracting a roadway core at each of the nine stations. The modulus of the asphalt layer was determined by conducting dynamic modulus test [41] on the asphalt mixes collected from the project site. Table 3 shows M_{FWD} of the compacted subgrade at nine different stations. Since the FWD tests were conducted at 28 days after the compaction of the subgrade, the calculated FWD modulus at 28 days is denoted as M_{FWD-28} . Since the M_{ICA} values refer to the modulus estimated during the compaction of the subgrade (0-day curing period), it is necessary to compare M_{ICA} with the corresponding FWD modulus (at 0-day curing period). Determination of equivalent FWD modulus for 0-day curing, denoted as M'_{FWD-0} , is addressed next.

Relationship between 0- and 28-day moduli

To determine M'_{FWD-0} from FWD tests conducted 28 days after the compaction of the subgrade, it is assumed that the relationships between the M'_{FWD-0} and M_{FWD-28} values and the M_{r-0} and M_{r-28} values are similar. This assumption is reasonable as the soil-CKD mix was identical to both the laboratory tests as well as the field compaction. The strength of the CKD-stabilized soil increases with the curing period because of the hydration of the CKD. Since soil-CKD mixes were cured for 28 days in both FWD and resilient modulus tests, the gain in strengths in terms of FWD modulus and resilient modulus is expected to be similar. Using 80 % of M_r test results for both curing periods, a relationship between the M_{r-0} and M_{r-28} values was developed. The ratio of M_{r-28} to M_{r-0} , denoted as 'x', is correlated with σ_d , σ_3 , and M_{r-0} , as given in Eq. 3

$$x = -0.0091(\sigma_3) + 0.0289(\sigma_d) + 0.0032(M_{r-0}). \quad (3)$$

It was found that the accuracy of the developed regression model is quite good; M_{r-0} could be estimated with an error less than ± 20 %. M'_{FWD-0} was calculated at

the nine different test stations using this developed regression model, as provided in Table 3.

Comparison between M_{ICA} and M'_{FWD-0}

Figure 5a shows a comparison between M_{ICA} and M'_{FWD-0} . It can be seen that the FWD modulus and ICA-estimated modulus are comparable and have good correlation ($R^2 = 0.63$, which is comparable to correlations seen in FWD test data reported in the literature [6]). Furthermore, the comparison also shows that the M_{ICA} values are indicative of the stiffness of the subgrade and have accuracy suitable for quality control-related tests for stabilized subgrades [6]. Figure 5b shows a stationwise comparison between M_{ICA} and M'_{FWD-0} . It is seen that the M_{ICA} and M'_{FWD-0} values follow a similar trend with the minimum being recorded at Station 6 (Fig. 4). It can be seen from Fig. 2 that the difference between M_{ICA} and M'_{FWD-0} varies between 3 and 48 %. This finding is encouraging, and suggests that the ICA can not only predict the subgrade modulus in real time but can also be used to control compaction quality in the field.

Project 2 (East Hefner Road)

Performing FWD test on the prepared subgrade is a challenging task and may not be feasible at all sites due to cost and time considerations. For example, in the first project, construction schedules led to FWD test after the completion of asphalt overlays 28 days after the subgrade was compacted. Consequently, efforts were made to develop an alternative method for validating the accuracy of ICA. This alternative approach was pursued at the second site involving the construction of a full-depth asphalt pavement on a 1.12-km (0.70 miles) stretch in East Hefner Road in Apple Valley, Edmond, Oklahoma. At this location, the

Fig. 5 a Comparison between M_{ICA} and M'_{FWD-0} and **b** Stationwise comparison between M_{ICA} and M'_{FWD-0}

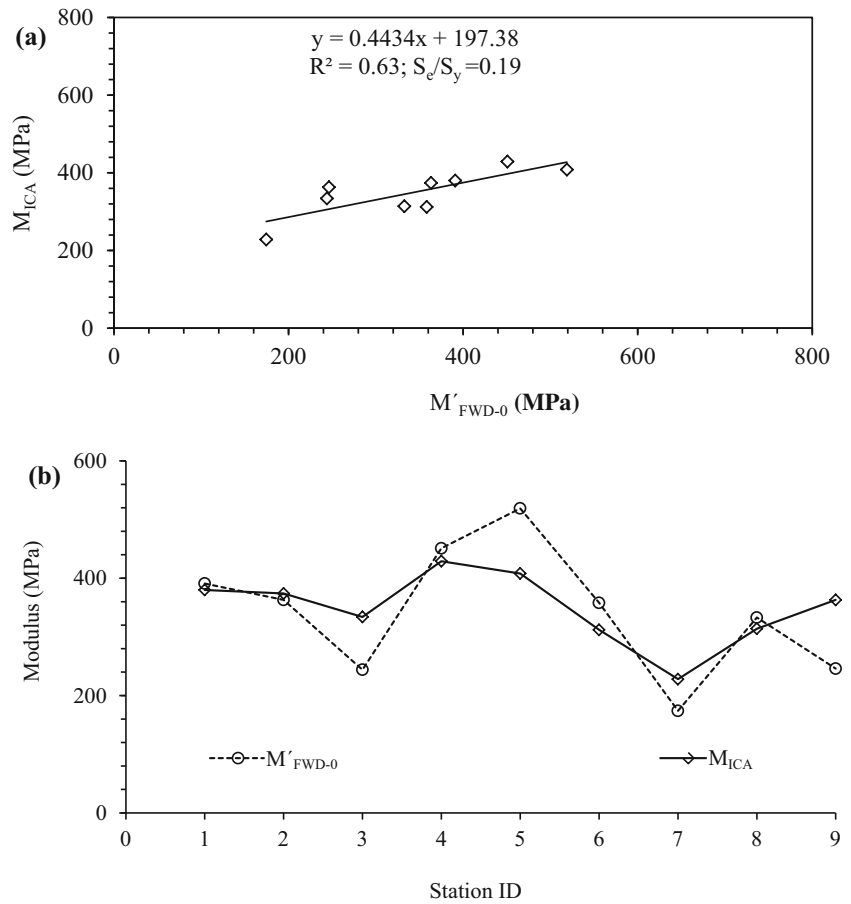
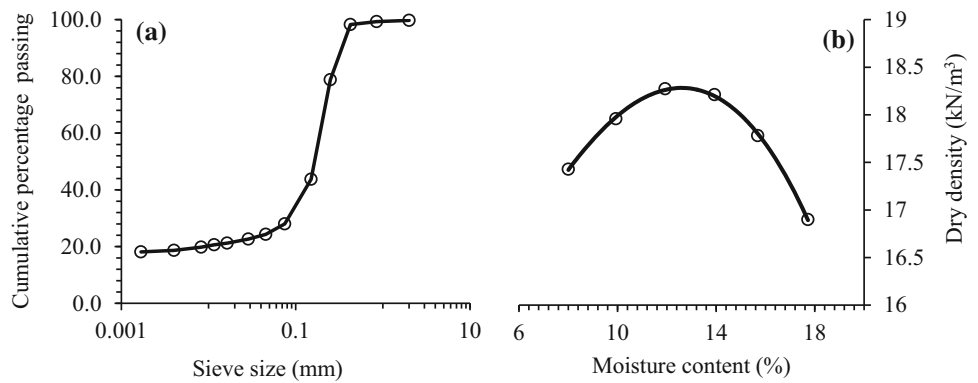


Fig. 6 a Particle size distribution for soil, and **b** M_c – γ_d relationships for soil-CKD mix for the East Helfner Road project



subgrade was stabilized by mixing 10 % CKD with the existing soil up to a depth of 304.8 mm (12 in.).

Properties of soil and soil-CKD mixes

Similar to the previous project, soil and soil-CKD mix samples were tested for determining particle size distribution [28], Atterberg limits [29, 30], M_c – γ_d relationship [31], and

resilient moduli [32] at different combinations of M_c and γ_d . Figure 6a shows the particle size distribution of the soil collected from the project site. The soil could be classified as SM. From the Atterberg limits test results, it was found that the subgrade soil was non-plastic (NP). The M_c – γ_d relationship for the stabilized soil (with 10 % CKD, by weight) is given in Fig. 6b; the γ_{dmax} and OMC values were obtained as $18.3 kN/m^3$ and 12.7 %, respectively.

Table 4 Features of M_r test specimens along with their back-calculated regression coefficients for the East Helfner Road project

Specimen No.	Moisture content (%)	Dry density (kN/m ³)	Degree of saturation (%)	Degree of compaction (% of γ_{dmax})	k_1, k_2 and k_3 based on M_{r-28}			R^2
					k_1	k_2	k_3	
1	10.8	18.1	65	97.3	43,609.1	0	-0.0327	-0.27
2	10.8	18.3	67.4	98.3	43,347.8	0.04376	-0.0737	0.24
3	10.6	18.3	66.2	98.1	39,877.5	0	-0.1692	0.96
4	12.6	18.5	81.6	99.2	37,817.5	0.04545	-0.0566	-0.39
5	12.8	18.3	79.9	98.1	41,754	0.1004	0.01423	0.52
6	11.4	18.6	75.3	99.9	41,798.9	0.05076	-0.1266	0.89

Table 5 Regression coefficients for determining $k_1, k_2,$ and k_3

Regression coefficients	k_1	k_2	k_3
a	0.175	-0.880	3.662
b	-835.980	0.035	0.055
c	-4183.115	0.028	-0.238

Regression models for M_r

In this project, the calibration and validation of the ICA were performed using M_r values obtained from the laboratory test data. Six specimens were prepared for laboratory compaction at different $M_c, \gamma_d,$ and degree of compactions (see Table 4). The degree of compaction achieved in the specimens varied between 97 and 100 %. The combinations of σ_d and σ_3 were kept similar to that of the West 60th street project. M_r test was conducted both at 0- and 28-day curing periods. However, two specimens (Numbers 5 and 6 in Table 4) provided outlying results when tested at 0-day curing period. As a result, M_r regression models were developed using only the M_{r-28} values.

The coefficients $k_1, k_2,$ and k_3 (Table 4) were determined following the procedure as similar to that followed in the

West 60th Street project, but using the M_{r-28} values. The regression coefficients for determining $k_1, k_2,$ and k_3 are given in Table 5. The total number of data for this case was 80.

Figure 7 shows the predictability of the developed regression models. The correlation between the laboratory measured modulus, M_{r-28} , and regression model predicted M_r after curing for 28 days, $M_{r-reg-28}$, is good ($R^2 = 0.65$) and is comparable to the results reported in the literature [6]. It can also be seen that M_r can be predicted with an error less than $\pm 15\%$ of the actual modulus value.

Relationship between M_{r-0} and M_{r-28} values

The relationship between the M_{r-0} and M_{r-28} values was established through a regression model. The ratio of M_{r-28} to M_{r-0} , denoted as ‘y’, was related to M_c, γ_d and stress state at 0-day curing period and M_{r-0} . Equation 4 presents the relationship. It was observed that the developed model can predict M_{r-0} with an error less than $\pm 15\%$

$$y = -0.90497(M_c) + 1.56633(\gamma_d) - 0.00312996(\theta) - 0.0168001(M_{r-0}). \tag{4}$$

Fig. 7 Comparison between laboratory M_{r-28} and $M_{r-reg-28}$ for the East Helfner Road project

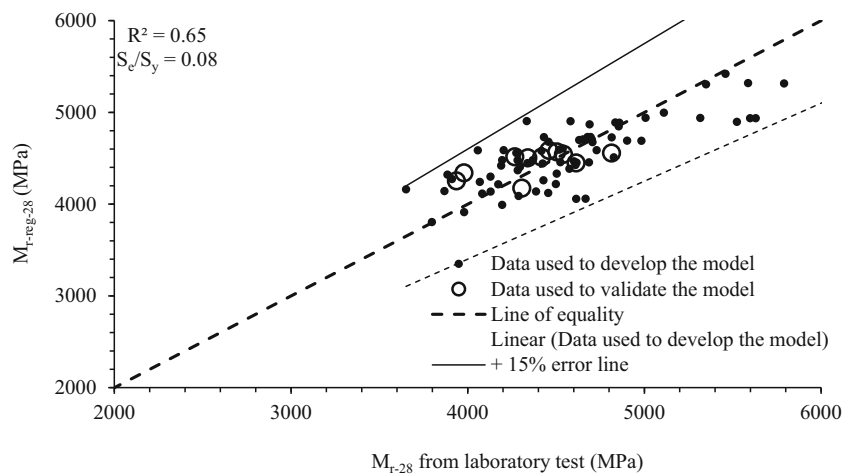


Fig. 8 Schematic for indicating different test stations in the East Hefner Road project

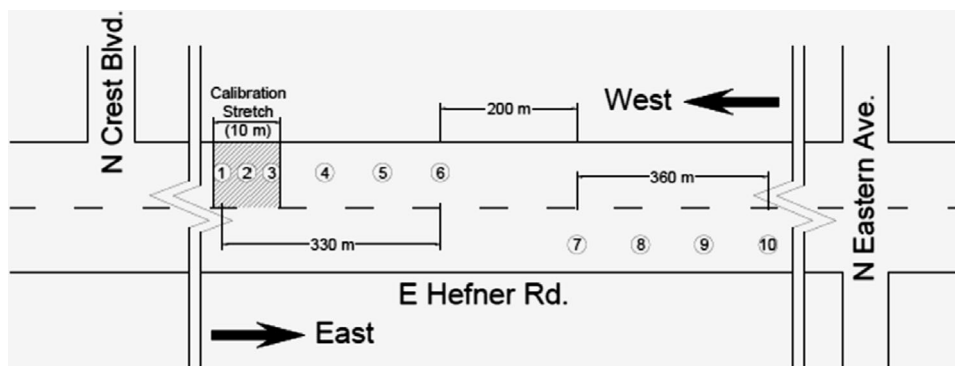


Table 6 Summary of test results for the East Hefner Road project

Stations	Moisture content (%)	Dry density (kN/m ³)	Degree of saturation (%)	Degree of compaction (% of γ_{dmax})	M_{ICA} (MPa)	$M_{r-reg-28}$ (MPa)	$M_{r-reg-0}$ (MPa)	Difference between M_{ICA} and $M_{r-reg-0}$ (%)
1	9.7	19.4	74.8	104	853	4589	967	12
2	10.6	19	75.5	102	942	4503	851	-11
3	10	19.8	83.7	106	922	4558	995	7
4	10.7	19.2	79.3	103	852	4496	871	2
5	9.9	18.3	61.8	98	876	4536	795	-10
6	9.3	18.5	60.3	99	919	4596	869	-6
7	11.7	19.2	86.7	103	801	4405	794	-1
8	12.6	18.6	83.2	100	751	4323	580	-29
9	12.8	19	91.2	102	762	4306	658	-16
10	12.4	19	88.3	102	758	4342	700	-8

Stress state for estimating M_{ICA}

The vibratory roller used for the proof-rolling in this project was similar to the one used in the West 60th Street project. Therefore, a same stress state was considered for both the projects, i.e., $\sigma_d = 69$ kPa and $\sigma_3 = 41$ kPa.

ICA measurements

The construction procedure of the stabilized subgrade and also the ICA test procedure in this project were similar to that of the West 60th Street project. The ICA was calibrated on a 10-m-long calibration stretch following a similar procedure that was used in the West 60th Street project. Figure 8 shows different test stations, including the calibration stations (Stations 1, 2, and 3). ICA measurements were recorded on the entire compacted subgrade during the proof-rolling. The vibration data and GPS reading collected during proof-rolling were processed real time to estimate M_{ICA} . Table 6 presents M_{ICA} values estimated at the three calibration stations.

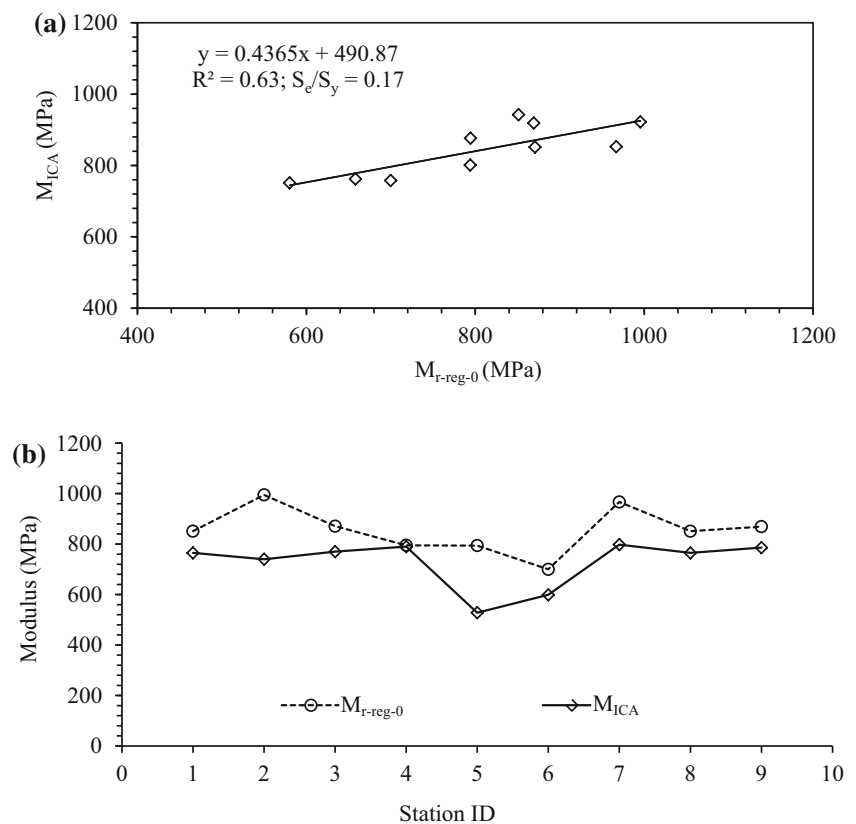
NDG test

Seven equally spaced test stations (Stations 4–10) were marked immediately after the proof-rolling process, as shown in Fig. 8. Tests were conducted at these stations using a Humboldt 5000EZ nuclear density gauge. It can be seen in Table 6 that the degree of compaction varied between 98 and 106 %, while the moisture content varied between 9.3 and 12.8 %. It may be noted here that the degree of compaction values in many stations were considerably higher than that were achieved in the laboratory during the M_r testing. The values of $M_{r-reg-0}$ were determined for all the ten stations using Eqs. 2 and 4 and regression coefficients from Table 5, as provided in Table 6.

Comparison between M_{ICA} and $M_{r-reg-0}$

Table 6 and Fig. 9a show comparisons between M_{ICA} and $M_{r-reg-0}$. The correlation between the M_{ICA} and $M_{r-reg-0}$ is good with R^2 equal to 0.63. Figure 9b shows a stationwise comparison between M_{ICA} and $M_{r-reg-0}$. It can be seen that the variations of M_{ICA} and $M_{r-reg-0}$ at different stations

Fig. 9 a Correlation between M_{ICA} and $M_{r-reg-0}$. **b** Stationwise comparison between M_{ICA} and $M_{r-reg-0}$



obtained by both the methods are in agreement. It can also be seen in Table 6 that the difference between M_{ICA} and $M_{r-reg-0}$ varies between 1 and 29 % indicating that the ICA was able to estimate with accuracy that makes it suitable for quality control operations during the construction of pavement subgrades.

Conclusions and future study

In this paper, the ability of the Intelligent Compaction Analyzer (ICA) developed at the University of Oklahoma (OU) to evaluate the subgrade modulus during the compaction was investigated. The ICA-estimated moduli were validated by comparing them with the FWD back-calculated subgrade moduli and laboratory resilient moduli in two different field studies. In both these projects, it was verified that the ICA could predict subgrade modulus with a reasonable accuracy. The following conclusions are drawn based on the results presented in this paper.

- The ICA can detect changes in stiffness in real time, during the compaction of the subgrade. Furthermore, for an assumed stress state, the calibrated ICA can estimate subgrade modulus with an accuracy that is suitable for field quality control applications.
- In the first demonstration (West 60th Street), the ability of the ICA was verified using the FWD modulus. It was observed that the ICA-estimated subgrade modulus and FWD modulus have a good correlation ($R^2 = 0.63$).
- In instances where FWD testing is not feasible, M_r regression models based on the laboratory results could be used to calibrate and validate ICA. In the second demonstration (East Hefner Road), it was observed that the ICA-estimated subgrade modulus and laboratory model predicted M_r have a good correlation ($R^2 = 0.63$).
- The regression model developed from the laboratory M_r test results can be used to predict M_r in the field as a function of dry density, moisture content, and soil properties.

While the results presented herein are promising, it is necessary to point out that the tests so far have focused on cementitious-stabilized subgrades. Additional tests for different soil types and additives are required to fully validate this technology. Research is currently underway to verify the ability of the ICA to identify and rectify under-compacted regions on the prepared subgrade. Finally, it shall be noted that ICA does not provide a direct measurements of M_r , rather it provides an indirect M_r value.

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