Non-Nuclear Methods for Compaction Control of Unbound Soils and Granular Layers

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report
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Non-Nuclear Methods for Compaction Control of Unbound Soil and Granular Layers

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16. Abstract

In highway construction, the nuclear density gauge (NDG) is the industry standard for measuring soil density and moisture. They are widely used at state transportation agencies, however, because of their reliance on radiation, NDGs are expensive to maintain and have unique storage requirements. Operators must also earn specialized certifications and adhere to rigorous safety protocols. Equipment manufacturers have developed several non-nuclear density gauges which are more user friendly, however, their accuracy has sometimes not equaled NDGs. This comparative study evaluated the performance of the eGauge (a relatively new device) to NDGs. Over 100 soil density and moisture measurements were collected from nine field sites throughout Kentucky. At sites characterized by silt/clay and shale or stabilized clay, NDGs and the soil density eGauge produced statistically similar soil density readings, while significant differences were observed for clays and full depth reclamation (FDR). Across all sites, 82.5% of the NDG and eGauge density readings were within +/- 5% of one another. For soil moisture, readings from NDGs and the eGauge were compared to samples dried in an oven laboratory. At sites characterized by silt/clay and shale, the NDGs, eGauge, and lab samples yielded significantly different measurements, while at sites with clay the eGauge measures differed significantly from those acquired via NDGs and the lab samples. No significant differences were noted for stabilized clays. Based on raw data, 88.2% of NDG and 48.0% of eGauge soil moisture readings were within +/- 5 percentage points of the corresponding lab measurement. For most soil types, the eGauge produces sufficiently accurate readings for field use, although further study of clays and FDR is needed.

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nuclear density gauge, eGauge, soil moisture, soil density, highway construction

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Table of Contents

List of Figures

List of Tables

Executive Summary

Achieving the proper density in unbound soil layers is essential for building durable, high-performance roadways. Many instruments have been developed to measure in-situ soil density and therefore ensure that the correct soil density is attained before construction activities begin. Many state departments of transportation rely on the nuclear density gauge (NDG), a device which executes soil compaction tests that measure soil density and water content. NDGs produce highly accurate readings. But they emit radiation, are expensive to maintain, and require special storage. Operators must earn certifications and adhere to rigorous safety protocols. Over the past 20 years, manufacturers have introduced several non-nuclear density gauges designed to equal the accuracy of NDGs. Because they lack a radiation source or emit minimal radiation, these instruments eliminate the certification and training requirements, as well as the costs and logistical hassles, associated with NDGs. Examples of non-nuclear density gauges include the Light Falling Weight Deflectometer (LFWD) or Light Weight Deflectometer (LWD), Soil Density Gauge (SDG), Electrical Density Gauge (EDG), Moisture Density Indicator (MDI), and the soil density eGauge. Previous studies have compared the performance of many of these devices to NDGs, however, no formal studies have compared the eGauge to NDGs. Wanting to determine if the eGauge is a viable replacement for NDGs, the Kentucky Transportation Cabinet (KYTC) asked our Kentucky Transportation Center (KTC) research team to undertake a comparative field study of the two devices and explore other stiffness/strength devices that can be used as alternatives to conventional NDGs.

After reviewing soil compaction methodologies and the features of five density and moisture gauges (see Table 2.1), we present the results of our comparative analysis. Our team collected over 100 soil density and soil moisture measurements at nine field sites across Kentucky. For analytical purposes, sites were classified into four groups based on soil characteristics: (1) silt/clay and shale, (2) stabilized clay, (3) clay, and (4) full depth reclamation (FDR). Statistical analysis demonstrated that the mean differences in soil density readings obtained with the eGauge and NDGs were not significant at sites characterized by silt/clay and shale or stabilized clay. At sites with clay or FDR, significant differences occurred. The eGauge produced several anomalously low readings at our FDR site. Confidence intervals of the mean differences tended to be narrow, which indicates that even statistically significant findings may not have practical implications. Across all sites, 82.5% of the NDG and eGauge density readings were within +/- 5% of one another. Exclude data from the FDR site and this figure climbs to 88.1%. Importantly, had crews used eGauges to measure soil density, they would have arrived at the correct decisions about whether to go forward with construction. Greater variability characterized the soil moisture data. We compared measurements from NDGs and the eGauge to those obtained from oven-dried samples in a laboratory. The mean differences in data obtained from the NDG, eGauge, and from lab samples were statistically significant at sites with silt/clay and shale soils but not at sites with stabilized clays. In clay soils, the eGauge produced readings significantly different from the NDGs and lab samples. Using raw data, 88.2% of NDG and 48.0% of eGauge soil moisture readings were within +/- 5 percentage points of the corresponding lab measurement. Computing the percentage differences in readings found that 47.5% of the NDG soil moisture readings were within +/- 10% of lab measurements; this drops to 17.8% for the eGauge. While using the eGauge to measure soil density appears warranted at sites with silt/clay and shale or stabilized clay, further study of its performance in clay soils and FDR is necessary. The eGauge appears less adept at measuring soil moisture.

Our review of stiffness/strength devices included the Clegg Impact Hammer, GeoGauge, Light Weight Deflectometer (LWD), Dynamic Cone Penetrometer (DCP) (none of which can measure the moisture content of material). Table 5.1 summarizes key characteristics of each device. Their principal outputs differ — while the Clegg Hammer, GeoGauge, and LWD assess the soil's elastic modulus, the DCP obtains the penetration index. Previous work found that 84% of STAs use NDGs for in-place density-moisture measurements, while 70% do not use any stiffness/strength methods. The GeoGauge and LWD have been evaluated and are used by roughly 50% of state departments of transportation, while the Clegg Hammer (15%) and DCP (32%) are less widely used. Measuring soil stiffness/modulus instead of soil density is a promising alternative to NDGs. Portable soil stiffness gauges and LWD produce accurate measurements while being faster, cheaper, and safer to use than NDGs

Chapter 1 Introduction and Background

Proper density in the unbound soil layers is critical for building a long-lasting road that meets performance expectations. Transportation agencies and contractors must have reliable devices and methods to determine in-situ density. Kentucky Transportation Cabinet (KYTC) inspectors and engineers currently use nuclear gauges to perform soil compaction tests that measure soil density and water content. Nuclear gauges are expensive to maintain, require special storage and adherence to safety protocols, demand repeated training, and must be certified for use. Over the past 20 years, extensive research on and development of non-nuclear density gauges (NNDG) has occurred. NNDGs may offer all the benefits of the nuclear density gauge (NDG) while eliminating the need for licenses, hassles, and the costs of NDG ownership. NNDGs being tested by transportation agencies and contractors. They include Light Falling Weight Deflectometer (LFWD) or Light Weight Deflectometer (LWD), Soil Density Gauge (SDG), Electrical Density Gauge (EDG), Moisture Density Indicator (MDI), and the eGauge. This research investigates non-nuclear test methods for compaction control of unbound soil and granular layers and advances recommendations on which devices are best suited for compaction control.

1.1 Soil Compaction

According to the US Department of Agriculture, "soil compaction occurs when soil particles are pressed together, reducing pore space between the particles and pushing out the air normally located there" (USDA 2012)[1]. Compacting soil increases its bearing capacity, stability, and bulk density. In the context of road construction, the main objective of controlled soil compaction is improving the bearing capacity of the material treated and create a suitable base for construction, one that is firm, stable, dense, resistant, and complies with the project's required load support and specifications (Paez 2018). As gaps between soil particles are reduced in size, instability and the movement of particles becomes less likely. Compaction may be used for a variety of projects requiring greater bearing capacity and stability. Examples include retaining walls, embankments, roads, utility trenches, construction sites, foundations, and landfill stabilization. Additionally, compaction helps mitigate the risk of a structure settling, subsiding, deforming, or collapsing. Because compacted soil particles have better surface contact, they can support higher loads. Soil compaction also lowers the risk of shrinkage and swelling and can prevent soil heave in cold environments by eliminating void spaces in which water can become trapped (Paez 2018)[2].

1.2 Methods of Soil Compaction

When deciding on a method of soil compaction, it is imperative to select equipment compatible with the soil type. Four methods of soil compaction are available (*Soil Compaction Handbook* 2011)[3]:

Pressure or Static Force

This is done using heavyweight equipment. When the machine's mass load applies downward forces, soil particles are compressed, desegregating them without the need of vibration. Smooth soil rollers are used for this method, which is recommended for non-cohesive soils and soils with large particle sizes (e.g., RCA, DGA, coarse aggregate sub-base, or asphalt).

Vibratory

This method commonly uses engine-driven forces that — together with static forces (deadweight load) — produces a vibratory effect where equipment contacts the surface. Thus, the equipment applies its deadweight plus a vibratory force. Equipment able to execute vibratory soil compaction is wide-ranging and includes manually operated vibratory plates, unmanned vibratory rollers, and manned vibratory rollers. This method is recommended for non-cohesive, granular soils and soils with large particle sizes.

Impact

Soil is compacted through repeated, continuous application of blows delivered at high impact force. This action increases the soil's bearing capacity. The equipment most commonly used is the Impact Rammer, which has small dimensions and great versatility. This method is recommended for cohesive and semi-cohesive soils (e.g., clay and clayey sands).

Kneading

Sheep foot equipment is used for this method. It concentrates high pressures applied to the top of the sheep foot. The immersion of the sheep foot decreases as soil density increases. This roller compacts the material from the ground upward and is recommended for cohesive and semi-cohesive soils.

1.3 Soil Field Quality Control

To guarantee that compacted soils will meet project specifications and perform as expected, quality control procedures and measurement techniques appropriate for the soil properties need to be codified. Soils quality control begins in the laboratory with tests such as grain size analysis, Atterberg limits, and modified and standard proctor. These procedures determine the mechanical properties of materials used in the field as well as their classifications, natural moisture contents, maximum dry densities, optimum densities, and grain sizes. Knowledge of these properties enables a better assessments of soil compaction and helps with selection of the right equipment. Data on moisture content is useful for attaining the required level of compaction. To effectively compact soil, it is also critical to identify the characteristics needed for the soil type (e.g., mass and frequency of equipment, travel speed, number of passes). These factors significantly affect the level of energy applied and depth of influence on the compacted material (Kim et al. 2010b)[4]. Several methods are available for in-situ quality control of soils. However, a better approach is to classify them into major groups.

Density-Moisture Control

This is the most common and widely used quality control practice for soil compaction. Relative compaction is measured as the ratio between the dry density obtained in the field and the maximum dry density obtained through the proctor test at an optimum moisture content. Even after more than eight decades, the proctor test remains the principal method for quality control of soils. State DOTs have different requirements for relative compaction and moisture control, depending on structure type and their structure range.

Stiffness-Strength Control

This measures the soil's stiffness modulus and bearing capacity. Recently, considerable research has focused on this method, positioning it as a viable complement to or replacement for soil density-moisture testing. From an engineering perspective, these properties yield better evaluations of soil functionality, stability, and resistance to deformation.

Chapter 2 Review of Compaction Technologies and Methodology

Volume replacement devices have been available for years, however, they may not be the most practical replacement for the NDG given the amount of time it takes to run a test and the lack of a moisture content reading. As such we do not evaluate volume replacement devices. Our goal is to determine whether density testing devices for unbounded soils that have become available since Graves et al. published their study of NNDGs in 2011 perform better than their predecessors. The 2011 report, for seven different Kentucky soils, compared MDI, EDG, NDG, and SDG devices to that of a sand cone density and oven moisture content sample[5]. Across the seven sites, the NDG tended to provide the most accurate and consistent evaluations of moisture content and density compared to the sand cone density with oven moisture content. Although the SDG was occasionally more accurate than the NDG in reading wet unit weights, it consistently failed to provide unique solutions for moisture content calculations. As a result, the SDG calculations for dry unit weight were inaccurate as well. Neither the MDI nor the EDG had acceptable results in field testing. Based on these results, Graves et al. (2011) were hesitant to recommend that any of the devices replace the NDG.

Paez's (2018) study of NNDGs found that the SDG is a faster method than the NDG, EDG, and MDI thanks to its non-destructive procedure which does not require penetrating soil with spikes, rods, or probes. The NDG, SDG, and MDI do not require any other device in the field to complete soil testing, while the EDG requires the use of the SC, NDG, or any other method to develop the soil calibration model. Paez reported that state departments of transportation (DOTs) have widely embraced the NDG for in-situ compaction testing. A smaller fraction of agencies uses the EDG (29%) SDG (12%), and MDI (15%) for field quality control[2].

Troxler released a new Low Level Nuclear Density Gauge in 2017 called the eGauge (ASTM D8167), but we could not locate any state DOTs which have evaluated its performance. The device can measure in-situ moisture and density of soils, aggregates, cement, lime-treated materials, and asphalt. Troxler states that the eGauge is a fast and accurate alternative for obtaining in-situ soil moisture and density. It uses low level gamma rays from a radioactive source which penetrate compacted soil; a separate moisture probe records moisture content. Air voids within the soil profile dictate the extent to which gamma rays are reflected back to and registered by the gauge, which measures the soil's moisture content, wet density, and dry density. The latter density is compared with the laboratory-derived maximum dry density to obtain the soil's relative density. One attractive feature of the gauge is that users do not have to acquire a radioactive material license. As such, there are no requirements for TLD badges, special shipping, or reciprocity to operate the eGauge in multiple states. Table 2.1 summarizes information on the NDG and NNDGs commonly used throughout the US, including the eGauge. We discuss the eGauge's performance on Kentucky construction projects in Chapter 4.

Table 2.1 Density and Moisture Gauges

	Nuclear Density Gauge (NDG)	Electrical Density Gauge (EDG)	Soil Density Gauge (SDG)	Moisture-Density Indicator (MDI)	Low Level Nuclear Density Gauge (eGauge)
ASTM Standard	ASTM D6938, D2950, and C1040	ASTM D 7698	ASTM D7830	ASTM D 6780	ASTM D8167
Measurement	MC, DD, %Compaction, %Moisture	MC, DD, %Compaction, %Moisture	MC, DD, %Compaction, %Moisture	Moisture Content and Dry Density	MC, DD, %Compaction, %Moisture
Calibration of Device	- Yearly. Third Party - Daily Standardization	Field Calibration and Lab testing in Proctor mold	- Yearly. Third Party - Daily Standardization with a	Lab testing in Proctor mold	- Yearly. Third Party Daily

	Nuclear Density Gauge (NDG)	Electrical Density Gauge (EDG)	Soil Density Gauge (SDG)	Moisture-Density Indicator (MDI)	Low Level Nuclear Density Gauge (eGauge)
	with standard block		metallic plate		
Operator Skills and Training	Low	Difficult	Extensive	Difficult	Low
Initial Cost	$8,000	$9,300	$10,000	$6,000	$10,000
Influence depth	12 inches	12 inches		8 inches	8 inches
Accuracy	Good	Mixed results	Good	Mixed results	Mixed
GPS	Yes	Yes	Yes	No	Yes
Advantages	- Fast - Easy to redo tests - Reliability - Non- destructive - Moisture measurement - Good portability and durability - Data storage	- Fast - Easy to redo tests - Non- destructive - No licensing fees - No annual regulation fees - Moisture measurement - Good portability and durability - Data storage	- Fast - Easy to redo tests - Non- destructive - No licensing fees - No annual regulation fees - Low calibration and repair cost - No special training - Moisture measurement - Good portability and durability - Data storage	- No licensing fees - No annual regulation fees - Moisture measurement - Good portability and durability - Data storage	- No licensing fees - No annual regulation fees - Moisture measurement - Good portability and durability - Data storage
Disadvantages	- No sample is taken - Radiation exposure - Moisture suspect - Encourages amateurs	- Complex procedure - Time-consuming - NDG, SC, or Large Proctor mold required for calibration - Not acceptable for plastic clay soils	- Extensive Training - Elevate initial price	- Complex procedure - Time-consuming - Not acceptable for plastic clay soils - Several accessories - Max. particle size ¾”	- Separate moisture device has mixed results. Results vary greatly around rocky soils.
Use by DOTs Agencies	Most DOTs	29%	12%	15%	0%

Sources: *Soil Compaction Handbook* (2011); “Construction Materials Testing Equipment” (2018); Nazzal (2014)[6]

Chapter 3 Methods

3.1 In-Situ Soil Q/C Measurements

Three compaction measurement devices are used to measure soil moisture, stiffness, and density in the field: volume replacement devices, density and moisture gauges, stiffness/strength devices (Table 3.1) (Paez 2018)[2].

Table 3.1 Data Generated by Compaction Measurement Devices

Compaction measurement devices	Wet Density	Moisture Content	Modulus
Volume Replacement Devices			
Sand Cone (SC)	X		
Rubber Balloon (RB)	X		
Density Drive-Cylinder (DDC)	X		
Density and Moisture Gauges			
Nuclear Density Gauge (NDG)	X	X	
Electrical Density Gauge (EDG)	X	X	
Soil Density Gauge (SDG)	X	X	
Moisture Density Indicator (MDI)	X	X	
Low Level Nuclear Density Gauge (E Gauge)	X	X	
Stiffness/Strength Devices			
Clegg Impact Hammer (CIH)			X
Soil Stiffness Gauge (GeoGauge)			X
Light Weight Deflectometer (LWD)			X
Dynamic Cone Penetrometer (DCP)			X
Briaud Compaction Device			X

3.2 Evaluation of the eGauge

With KYTC hoping to shift away from the NDG, we evaluated the eGauge against the NDG on multiple Cabinet construction projects. The projects had varying soil types. Our team was careful to select sites where soils would be stabilized with either hydrated lime or cement as well as projects slated for full-depth reclamation (FDR). The latter involves mixing asphalt pavement, aggregate, and oftentimes the underlying soil (depending on depth of reclamation) and then adding cement/lime and water to achieve a stabilized composite layer.

Figure 3.1 eGauge

Testing was conducted on nine projects around the state (Table 3.2). Ultimately, we eliminated two test sites from our composite test data — one due to the small number of tests conducted with the NDG, and the second as a result of the wide variance between gauges based on the material type tested, specifically the amount of rock contained in the sampled area.

In the field, we used the same test holes to obtain a reading with each device. Oven dry moisture samples were taken from areas adjacent to test holes. To avoid unintentionally skewing the data no offsets were used for density or moisture. Wet density values were used for each device; moisture content values were verified with moisture content measured in the laboratory (AASHTO T-265). A few field moisture content tests using the speedy moisture meter were also taken for additional analysis (AASHTO T-217).

Table 3.2 Project Sites for eGauge Testing

County	CID	Route	Soil Type	Number of Tests	Data used for Analysis	Reason for data exclusion	NDG for comparison
Bullitt	**181041**	**I-65**	**Gray shale**	**6**	**Y**		**CPN MC-1DR-P Portaprobe**
Monroe	**191036**	**KY 163**	**Cement-stabilized clay, clay**	**15**	**Y**		**Troxler 3411-B**
Scott	**181239**	**US 460**	**Lime-stabilized clay**	**13**	**Y**		**Troxler 3411-B**
Boone	**191001**	**I-75**	**Cement-stabilized rock**	**1**	**N**	**Mostly rock, few tests**	**Humboldt HS-5001 EZ**
Marion	**191220**	**KY 49**	**Cement-stabilized clay**	**6**	**Y**		**Troxler 3430**
Shelby	192383	KY 1779	Full-depth reclamation	11	N	Differing density test methods	Troxler 3440, 3450
Boone	199001	I-275	Clay	14	Y		Instrotek Xplorer2, Humboldt 5001 EZ
Henderson	191247	US 60	Silty clay	12	Y		Troxler 3411-B, 3440
Taylor	191238	KY 555	Silty clay	38	Y		Troxler 3430

Chapter 4 Analysis of Field Data

This chapter presents our findings from each test site. Individual subsections dedicated to each site provide a brief site description and the results of statistical analyses on soil density and soil moisture content. The next section talks about the statistical methods we used to evaluate data and how to interpret statistical outputs.

4.1 Statistical Analysis

In this chapter we explore the statistical relationships between density data collected using the NDG and eGauge as well as moisture data obtained with the NDG, eGauge, and from oven-dried samples. Three forms of statistical analysis underwrite our efforts — (1) correlation, (2) paired samples t-test, and (3) Analysis of Variance (ANOVA). Correlation and the paired samples t-test were chosen to assess data on wet soil density; for moisture data we opted to use correlation and ANOVA. ANOVA was the best choice for evaluating moisture data because we compared three methods of measurement. Below, we summarize each statistical procedure and describe how to interpret statistical results using case studies from later in the chapter.

Correlation analysis characterizes the strength of association between two variables, or how the measured values of those variables move in relation to one another. A correlation coefficient (termed Pearson's r) takes on a value between -1 and +1. Negative correlation indicates that the values of variables move in opposite directions (e.g., as values of one variable increase, values of the second variable decrease). Positively correlated variables trend in the same direction (e.g., as values of one variable increase, values of the second variable also increase). As Pearson's r approaches -1 or +1, the strength of association increases. That is, values exhibit a more pronounced linear relationship. For example, the Pearson's r listed for the Bullitt County site in Table 1 is 0.95, which reflects a strongly positive association. This is evidenced in Figure 1 as well — it is easy to imagine a straight line being drawn through the data points. Correlation analysis makes no implications about causality. It only evaluates whether two variables are related. Significance testing, captured by the p-value, indicates whether the correlation is statistically significant. We use a p-value of 0.05 as our threshold for statistical significance. The p-value for the Bullitt County data is 0.00372, confirming the correlation between measurements obtained using the NDG and eGauge is significant.

The paired samples t-test evaluates whether the mean difference between pairs of measurements equals zero. How is the mean difference calculated? Let's use data from Figure 1 as an example. At the I-65 Bullitt County site data were collected at six (6) locations using the NDG and eGauge. First, for each pair of observations, the value measured using the eGauge is subtracted from the value measured using the NDG. This provides the differences in values acquired by the devices at each location. Those differences are then averaged (3.82). Much like a one-sample t-test, a paired sample t-test determines whether the averaged differences differ significantly a given value — zero in this case. We use a p-value of 0.05 as our threshold for statistical significance. Tables in the following sections report the t-statistic, mean difference, and p-value. For the Bullitt County example, p = 0.045, so the mean differences in pairs of measurements is significantly different from zero. Underneath each table we include the 95% confidence interval. Continuing with the Bullitt County data, the 95% confidence interval is 0.121 – 7.52, which means we can be 95% certain that the actual mean difference for measurements taken with the NDG and eGauge lies between 0.121 and 7.52. When interpreting statistical analyses, it is important to distinguish statistical significance from practical significance. Although it is true a statistically significant result can have practical (i.e., real world) significance, this is not always the case. As readers pore over the results which appear in the following pages, they need to keep this distinction between statistical and practical significance in mind. The concluding section discusses what our statistical findings mean for how the eGauge performs relative to the NDG.

ANOVA compares the mean values of groups (or treatments) to determine whether they differ significantly from one another. We chose one-way Welch's ANOVA because it is robust to unequal variances. Again, a p-value of 0.05 served as the threshold for statistical significance. For each site, plots are included that compare mean values and 95% confidence intervals for measurement techniques (e.g., Figure 8). While ANOVA indicates whether group means differ from one another, alone it does not indicate which groups differ. We used the Games-Howell Post-Hoc Test to determine where mean values for different techniques were significantly different. Post-hoc comparisons are summarized in matrix tables. For example, Table 5 shows that the mean difference between moisture data acquired with the eGauge differs significantly from measures taken with the NDG and acquired from oven-dried samples.

4.2 Bullitt Co. CID 181041, New Interchange on I-65

The Bullitt County project is new interchange construction near an industrial park (Figure 4.1). Density tests were conducted in two adjacent fill areas in soil consisting mostly of shale. The dataset contains more information on density than moisture.

Figure 4.1 Bullitt Co. CID 181041, New Interchange on I-65

4.1.1 Bullitt Country — Comparison of NDG and eGauge Density Readings

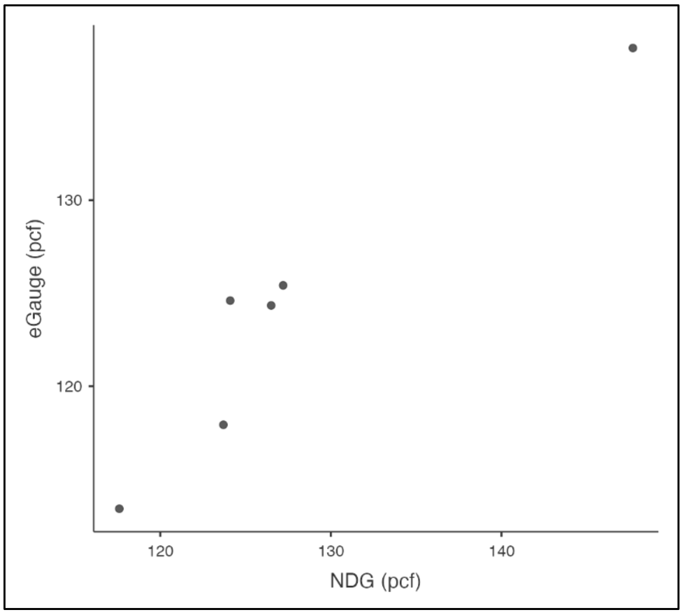

Figure 4.2 Bullitt County Density Readings (NDG v. eGauge)

Table 4.1 Descriptive Statistics for Bullitt County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Pass**
NDG	127.80	10.32	116.97	138.63	107.35
eGauge	123.98	8.39	115.17	132.79	107.35

Table 4.2 Correlation and T-Tests for Bullitt County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.950	0.00372	2.65	3.82*	0.045

* 95% Confidence Interval for Mean Difference: 0.121 – 7.52

4.1.2 Bullitt County — Moisture Data

As moisture data could only be collected at two sites, we have refrained from statistical analysis due to the small the sample size. Data are presented in Table 4.3.

Table 4.3 Bullitt County Soil Moisture Data

	NDG Moisture %	eGauge Moisture %	Oven-Dried Moisture %
Site 1	9.20	9.50	7.12
Site 2	7.40	9.91	6.98

4.3 Monroe Co. CID 191036, KY 163, New Eastern Bypass Around Tompkinsville

Beginning at the northern end of Tompkinsville, this bypass project extends eastward and will connect at both ends at KY 163. The highway is cement stabilized and several tests were taken in stabilized and unmodified areas. Density values have been provided for native soil, cement-stabilized soil, and a composite of both.

Figure 4.3 Monroe Co. CID 191036, KY 163

4.2.1 Monroe Country — Comparison of NDG and eGauge Density Data

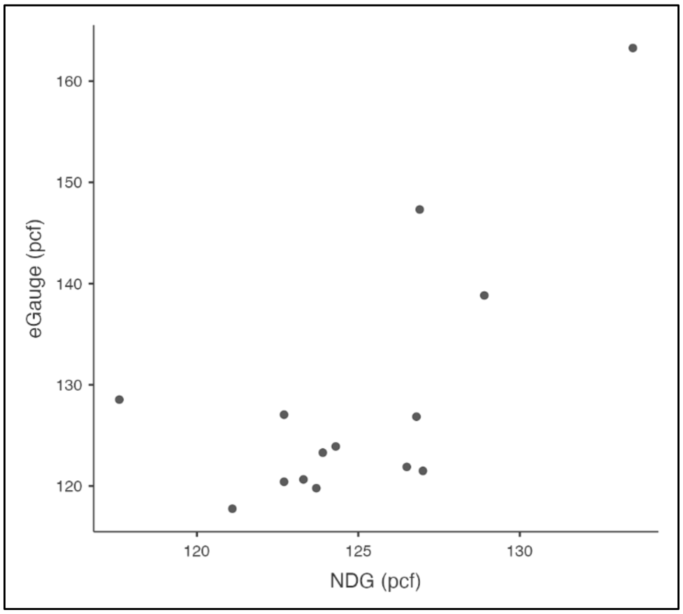

Figure 4.4 Monroe County Density Readings (NDG v. eGauge)

Table 4.4 Descriptive Statistics for Monroe County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Pass**
NDG	124.92	3.80	122.73	127.11	103.55
eGauge	128.01	12.59	121.04	134.98	103.55

Table 4.5 Correlation and T-Tests for Monroe County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.699	0.00539	-1.33	-3.73*	0.207

* 95% Confidence Interval for Mean Difference: -9.80 – 2.34

4.2.2 Monroe County — Comparison NDG, eGauge, and Oven Moisture Data

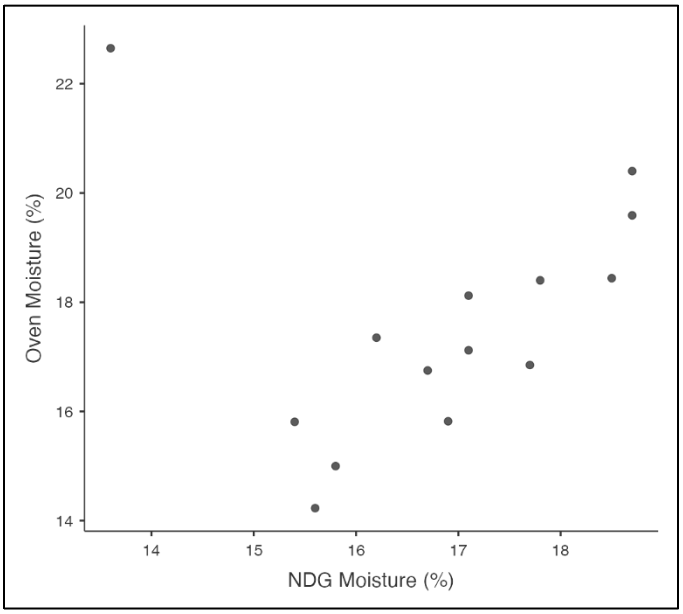

Figure 4.5 Monroe County Moisture Scatterplot I (NDG v. Oven)

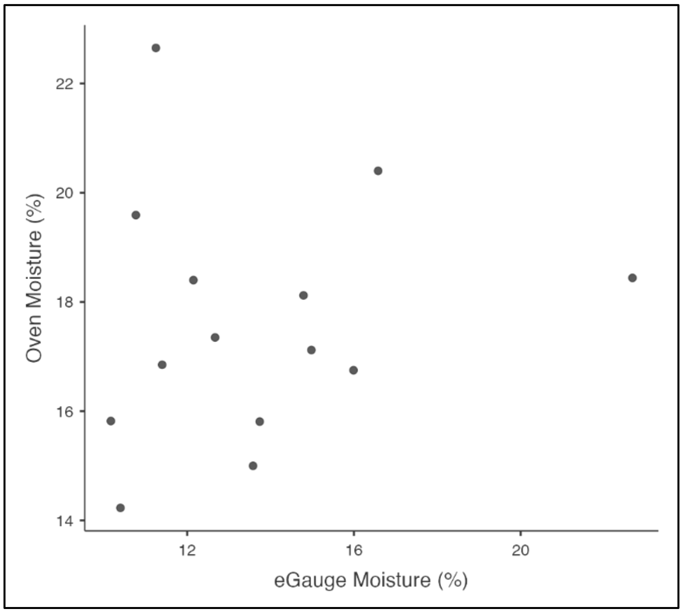

Figure 4.6 Monroe County Moisture Scatterplot II (eGauge v. Oven)

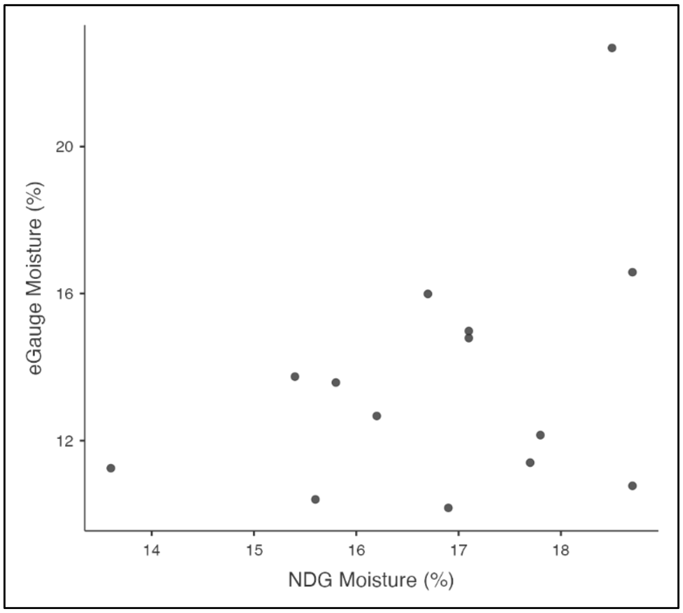

Figure 4.7 Monroe County Moisture Scatterplot III (NDG v. eGauge)

Table 4.6 Descriptive Statistics for Monroe County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	16.84	1.44	16.01	17.68
eGauge	13.65	3.32	11.73	15.57
Oven	17.61	2.24	16.32	18.90

Table 4.7 Correlation Matrix for Monroe County Soil Moisture Data

		NDG Moisture (%)	**eGauge Moisture (%)**	**Oven Moisture (%)**
NDG Moisture (%)	Pearson's r p-value N	— — —		
eGauge Moisture (%)	Pearson's r p-value N	0.388 0.171 14		
Oven Moisture (%)	Pearson's r p-value N	0.088 0.764 14	0.143 0.626 14	

4.2.3 Monroe County — ANOVA for Moisture Data

- ANOVA found a statistically significant difference in mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples (p = 0.004). Post-hoc testing indicated that mean moisture values for the NDG and oven-dried samples differed significantly from those measured with the eGauge (Table 4.8).

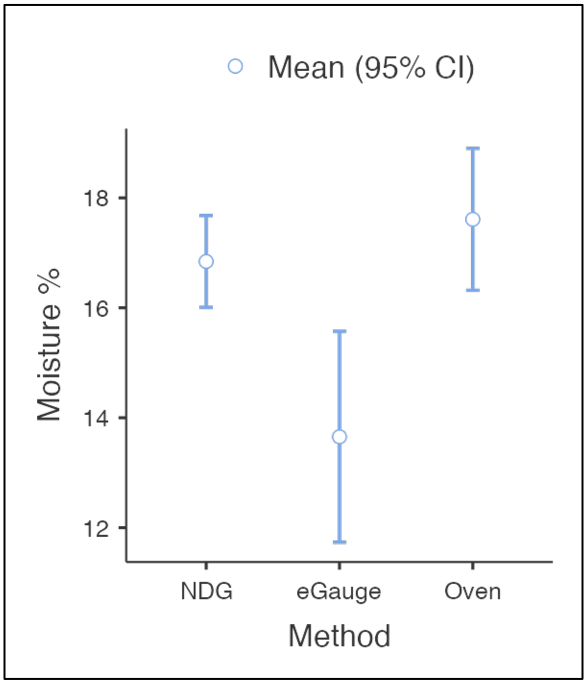

Figure 4.8 Monroe County — Comparison of Moisture Data

Table 4.8 Games-Howell Post-Hoc Test for Monroe County Soil Moisture Data

		NDG Moisture %	eGauge Moisture %	Oven Moisture %
NDG Moisture %	Mean Difference p-value	— —	3.19 0.011	-0.766 0.537
eGauge Moisture %	Mean Difference p-value		— —	-3.956 0.003
Oven Moisture %	Mean Difference p-value			— —

4.4 Scott Co. CID 181239, US 460, New Northwest Bypass Around Georgetown

This project is the final link in a circle that circumnavigates Georgetown. The final graded soil layer was lime stabilized. All tests were performed in the lime stabilized layer prior to seal coat application.

Figure 4.9 Scott Co. CID 181239, US 460

4.3.1 Scott Country — Comparison of NDG and eGauge Density Data

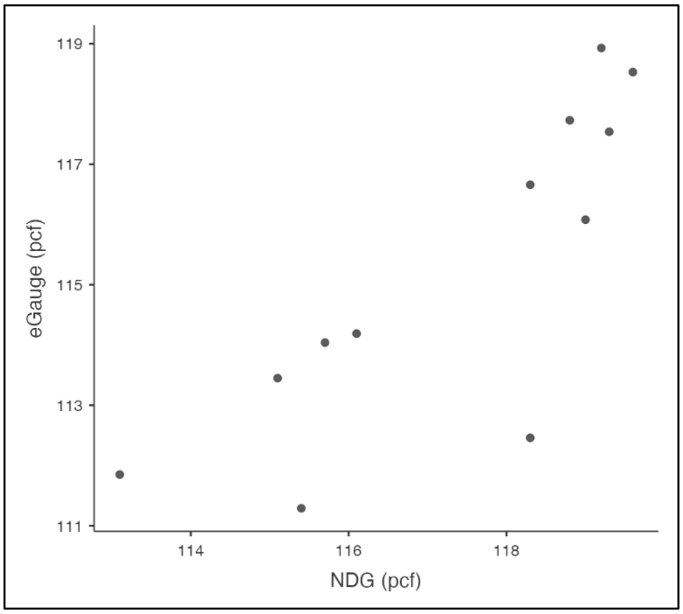

Figure 4.10 Scott County Density Readings (NDG v. eGauge)

Table 4.9 Descriptive Statistics for Scott County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Pass**
NDG	117.33	2.13	115.97	118.68	90.44
eGauge	115.22	2.60	113.67	116.78	90.44

Table 4.10 Correlation and T-Tests for Scott County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.832	0.001	4.75	2.10*	0.0006

* 95% Confidence Interval for Mean Difference: 1.13 – 3.07

4.3.2 Scott County — Comparison NDG, eGauge, and Oven Moisture Data

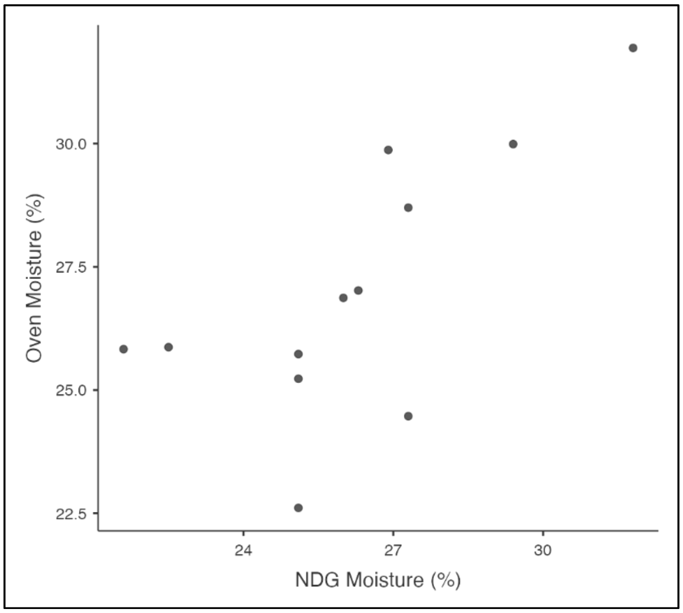

Figure 4.11 Scott County Moisture Scatterplot I (NDG v. Oven)

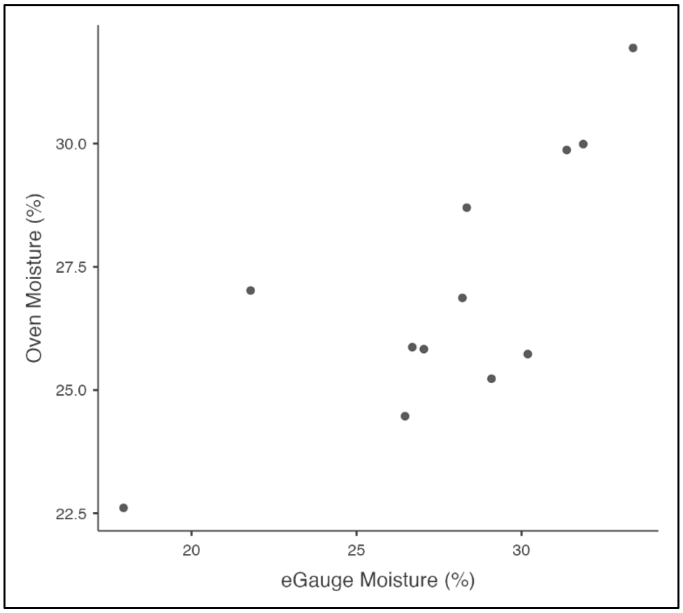

Figure 4.12 Scott County Moisture Scatterplot II (eGauge v. Oven)

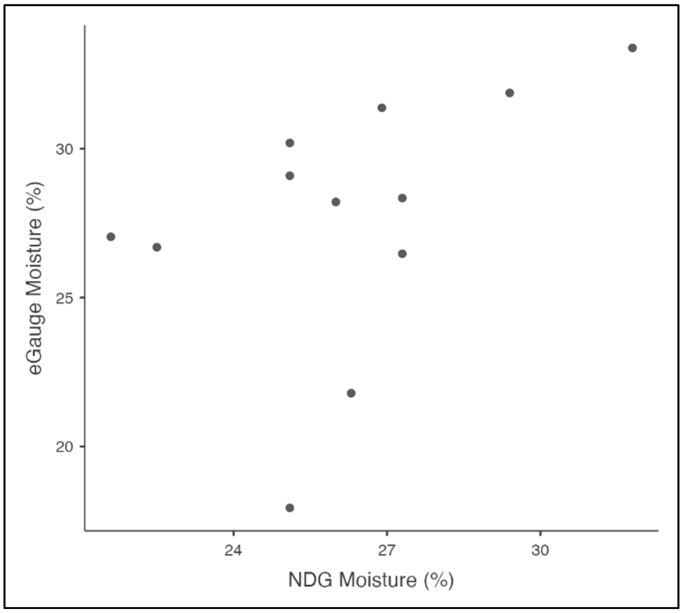

Figure 4.13 Scott County Moisture Scatterplot III (NDG v. eGauge)

Table 4.11 Descriptive Statistics for Scott County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	26.20	2.75	24.25	27.95
eGauge	27.70	4.32	24.95	30.44
Oven	27.01	2.66	25.32	28.70

Table 4.12 Correlation Matrix for Scott County Soil Moisture Data

		NDG Moisture (%)	**eGauge Moisture (%)**	**Oven Moisture (%)**
NDG Moisture (%)	Pearson’s r p-value N	— — —		
eGauge Moisture (%)	Pearson’s r p-value N	0.457 0.135 12		
Oven Moisture (%)	Pearson’s r p-value N	0.699 0.011 12	0.747 0.005 12	

4.3.3 Scott County — ANOVA for Moisture Data

- ANOVA found no statistically significant difference in the mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples (p = 0.576).

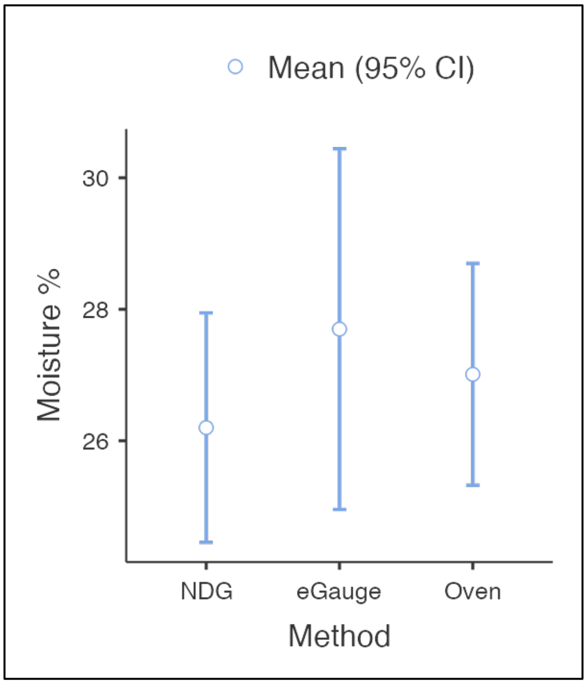

Figure 4.14 Scott County — Comparison of Moisture Data

Table 4.13 Games-Howell Post-Hoc Test for Scott County Soil Moisture Data

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference p-value	— —	-1.50 0.577	-0.811 0.746
eGauge Moisture %	Mean Difference p-value		— —	0.688 0.886
Oven Moisture %	Mean Difference p-value			— —

4.5 Boone Co. CID 191001, I-75, Additional Ramp Lanes at KY 536

This project is adding ramp lanes and an additional outside lane to I-75 to mitigate traffic congestion. On the day testing was scheduled at the site, we observed cement stabilization operations on DGA. This introduced insurmountable complications because the NDG tests were going to be taken using the backscatter method. Although we attempted one reading at the site, our team opted to discontinue testing because the test data would be inconclusive owing to the different methods. Hence, the eGauge is only capable of a direct reading with the probe inserted into the ground. It has no back scatter capability and rock material can greatly affect the density readings in the direct mode of any NDG and NNDG device.

Figure 4.15 Boone Co. CID 191001, I-75, Additional Ramp Lanes at KY 536

4.6 Marion Co. CID 191220, KY 49, Realignment Near KY 52

This project involved realigning KY 49 to improve safety at its intersection with KY 52. The final graded soil layer was cement stabilized. Our tests were conducted after stabilization and compaction operations but before the seal coat was applied. We performed six tests at this location.

Figure 4.16 Marion Co. CID 191220, KY 49, Realignment Near KY 52

4.5.1 Marion Country — Comparison of NDG and eGauge Density Data

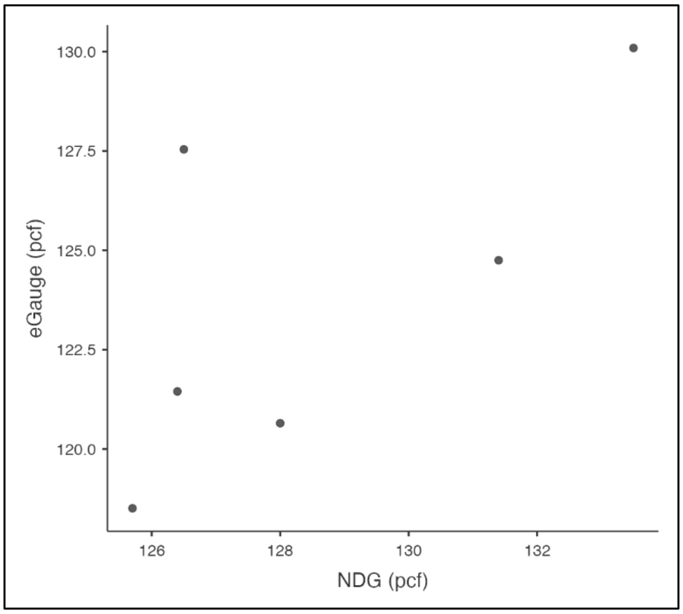

Figure 4.17 Marion County Density Readings (NDG v. eGauge)

Table 4.14 Descriptive Statistics for Marion County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Pass**
NDG	128.58	3.16	125.27	131.90	107.065
eGauge	123.83	4.42	119.19	128.47	107.065

Table 4.15 Correlation and T-Tests for Marion County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.687	0.1312	3.62	4.75*	0.0152

* 95% Confidence Interval for Mean Difference: 1.38 – 8.13

4.5.2 Marion County — Comparison NDG, eGauge, and Oven Moisture Data

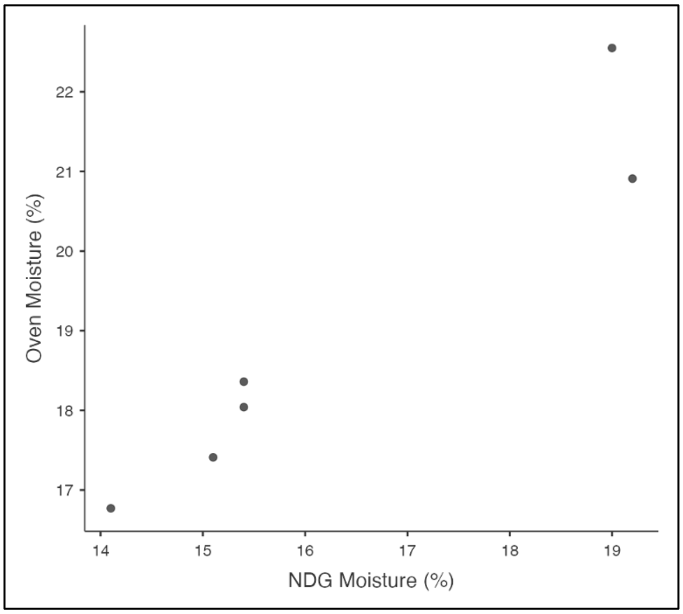

Figure 4.18 Marion County Moisture Scatterplot I (NDG v. Oven)

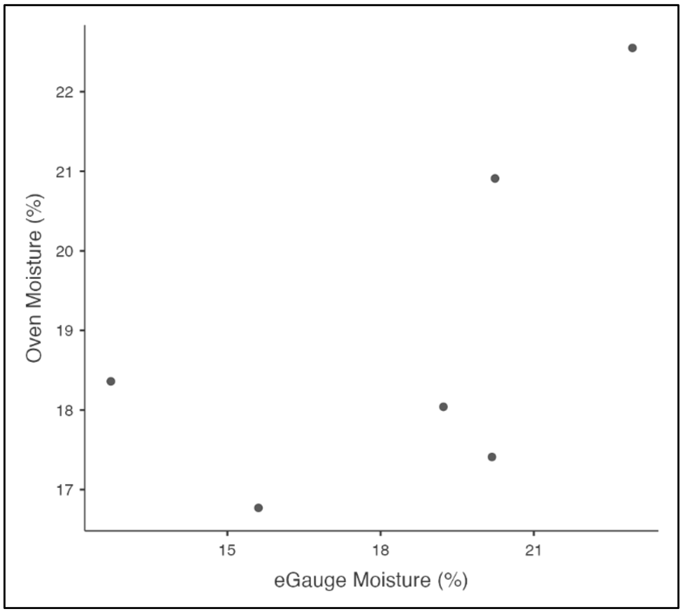

Figure 4.19 Marion County Moisture Scatterplot II (eGauge v. Oven)

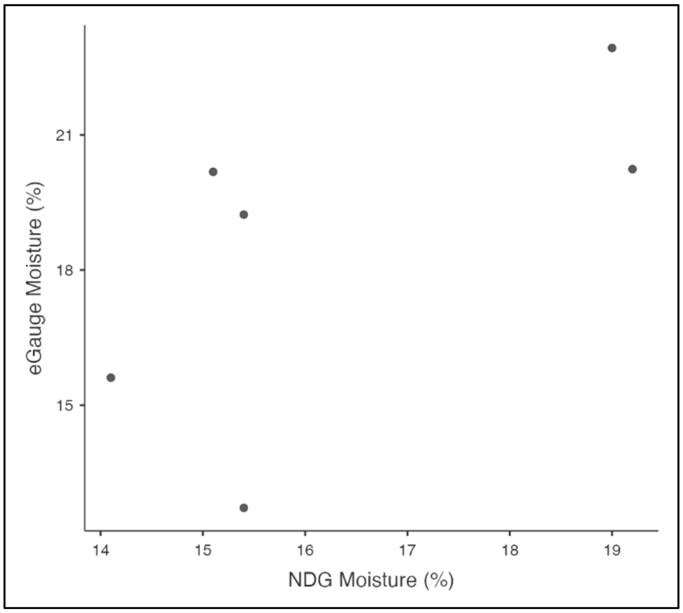

Figure 4.20 Marion County Moisture Scatterplot III (NDG v. eGauge)

Table 4.16 Descriptive Statistics for Marion County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	16.37	2.17	14.09	18.65
eGauge	18.49	3.68	14.62	22.35
Oven	19.01	2.24	16.66	21.36

Table 4.17 Correlation Matrix for Marion County Soil Moisture Data

		NDG Moisture (%)	**eGauge Moisture (%)**	**Oven Moisture (%)**
NDG Moisture (%)	Pearson's r p-value N	— — —		
eGauge Moisture (%)	Pearson's r p-value N	0.648 0.164 6		
Oven Moisture (%)	Pearson's r p-value N	0.961 0.002 6	0.626 0.183 6	

4.5.3 Marion County — ANOVA for Moisture Data

- ANOVA found no statistically significant difference in the mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples (p = 0.171).

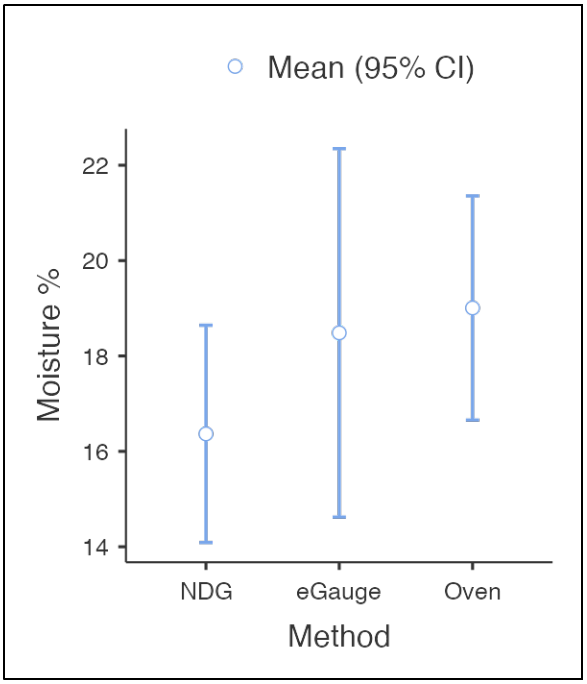

Figure 4.21 Marion County — Comparison of Moisture Data

Table 4.18 Games-Howell Post-Hoc Test for Scott County Soil Moisture Data

		NDG Moisture %	eGauge Moisture %	Oven Moisture %
NDG Moisture %	Mean Difference p-value	— —	-2.12 0.478	-2.640 0.145
eGauge Moisture %	Mean Difference p-value		— —	-0.552 0.953
Oven Moisture %	Mean Difference p-value			— —

4.7 Shelby Co. CID 192383, KY 1779, Full Depth Reclamation of Existing Pavement Structure

Full depth reclamation (FDR) is a newer, lower cost method of reconstructing low-volume roads. The designs associated with this method vary by project and are tailed to produce an adequate result that supports expected reductions in traffic. During testing at this location, we observed that the material being tested was primarily a dry bituminous aggregate mixed with a small amount of cement. No soil was found to in the compacted mixture. Data collected for this site offered more questions than answers. Wet density values obtained from the eGauge were sometimes more than half of the nuclear gauge values. Some direct eGauge tests were compared to nuclear backscatter tests, which we compared to direct nuclear gauge tests. Moisture data from the eGauge was sometimes nearly three times the nuclear moisture values, and nearly five times the oven dry reference. While these data are presented in the following graphs, they are not represented in the final composite data owing to the questionable material and disparate test methods.

Figure 4.22 Shelby Co. CID 192383, KY 1779, Full Depth Reclamation of Existing Pavement Structure

4.6.1 Shelby County — Comparison of NDG and eGauge Density Data

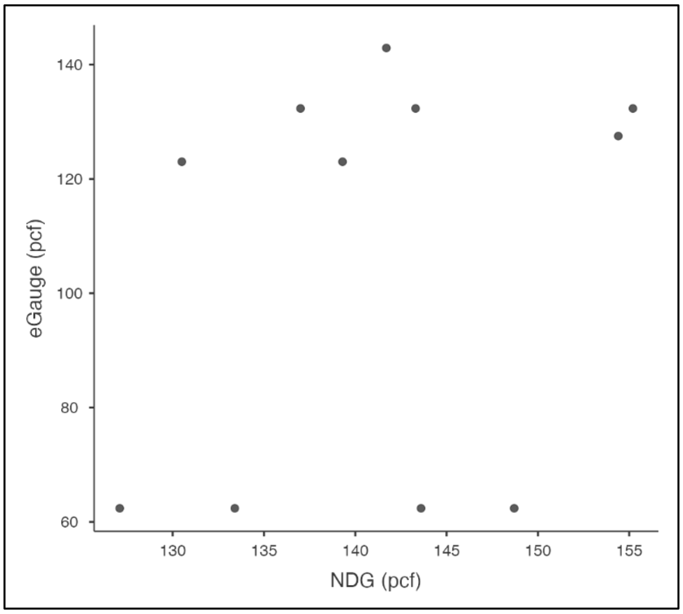

Figure 4.23 Shelby County Density Readings (NDG v. eGauge)

Table 4.19 Descriptive Statistics for Shelby County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Passing**
NDG	141.29	9.12	135.16	147.42	110
eGauge	105.72	34.78	82.35	129.08	110

Table 4.20 Correlation and T-Tests for Shelby County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.292	0.3843	3.54	35.6*	0.0053

* 95% Confidence Interval for Mean Difference: 13.2 – 57.9

4.8 Boone Co. CID 199001, I-275, New Interchange, Alignment of Graves Rd.

This design-build project sought to provide better truck access to a nearby industrial area. The project severed Graves Rd. at the interstate and constructed a new interchange for the industrial area. Eighteen side-by-side tests were performed at this site.

Figure 4.24 Boone Co. CID 199001, I-275, New Interchange, Alignment of Graves Rd.

4.7.1 Boone Country — Comparison of NDG and eGauge Density Data

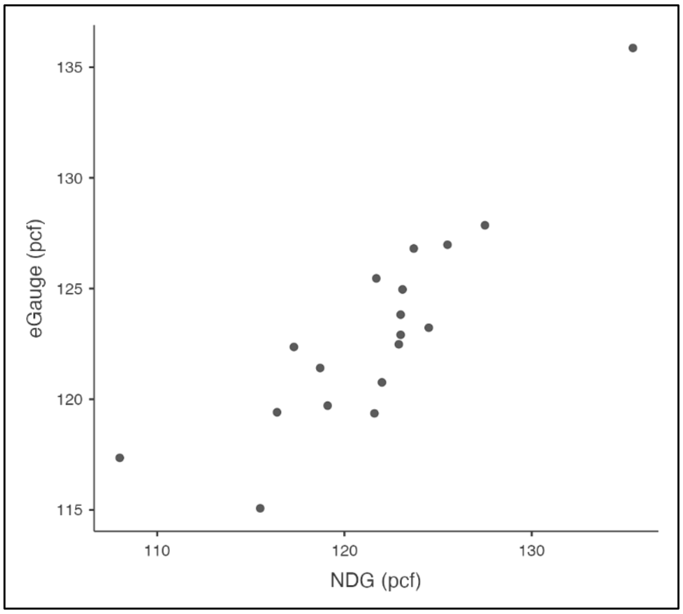

Figure 4.25 Boone County (I-275) Density Readings (NDG v. eGauge)

Table 4.21 Descriptive Statistics for Boone County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Passing**
NDG	121.61	5.66	118.79	124.42	101.65
eGauge	123.10	4.67	120.78	125.42	101.65

Table 4.22 Correlation and T-Tests for Boone County (I-275) Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.875	<0.00001	-2.31	-1.49*	0.034

* 95% Confidence Interval for Mean Difference: -2.86 – -0.127

4.7.2 Boone County — Comparison NDG, eGauge, and Oven Moisture Data

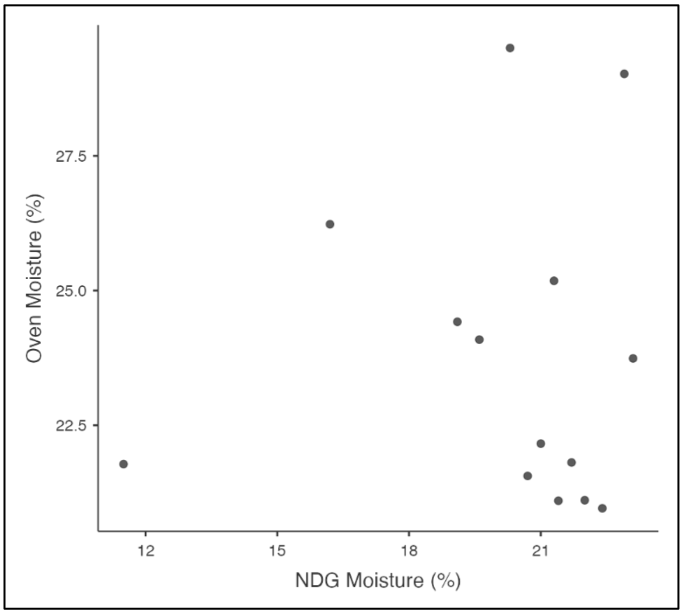

Figure 4.26 Boone County Moisture Scatterplot I (NDG v. Oven)

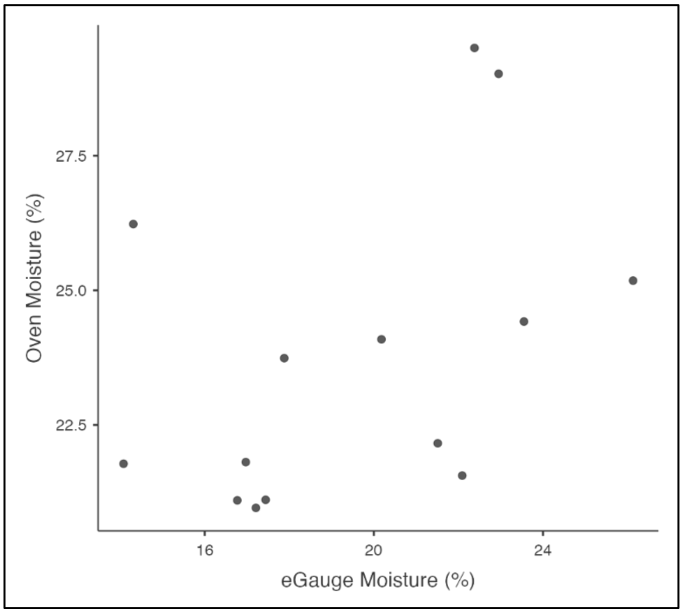

Figure 4.27 Boone County Moisture Scatterplot II (eGauge v. Oven)

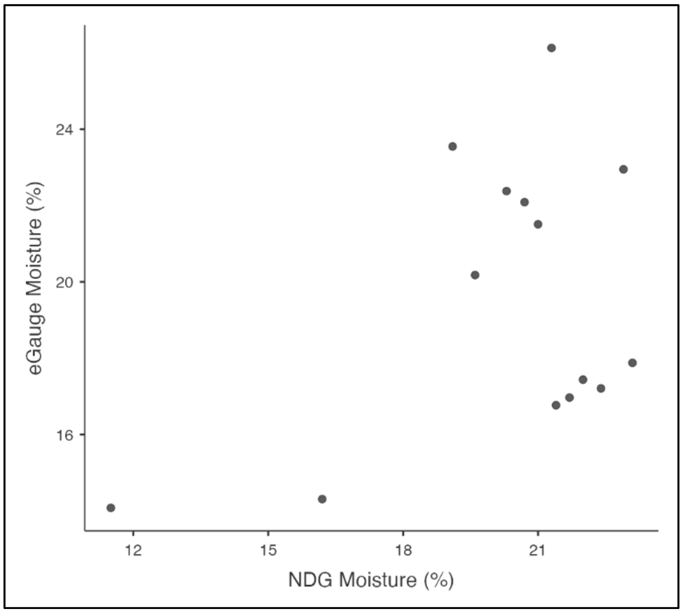

Figure 4.28 Boone County Moisture Scatterplot III (NDG v. eGauge)

Table 4.23 Descriptive Statistics for Boone County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	20.23	3.07	18.45	22.00
eGauge	19.53	3.66	17.42	21.65
Oven	23.76	2.86	22.11	25.41

Table 4.24 Correlation Matrix for Boone County Soil Moisture Data

		NDG Moisture (%)	**eGauge Moisture (%)**	**Oven Moisture (%)**
NDG Moisture (%)	Pearson’s r p-value N	— — —		
eGauge Moisture (%)	Pearson’s r p-value N	0.426 0.129 14		
Oven Moisture (%)	Pearson’s r p-value N	0.029 0.923 14	0.442 0.114 14	

4.7.3 Boone County — ANOVA for Moisture Data

- ANOVA found a statistically significant difference in mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples (p = 0.003). Post-hoc testing indicated that mean moisture values from the NDG and eGauge differed significantly from values measured from oven-dried samples (Table 14).

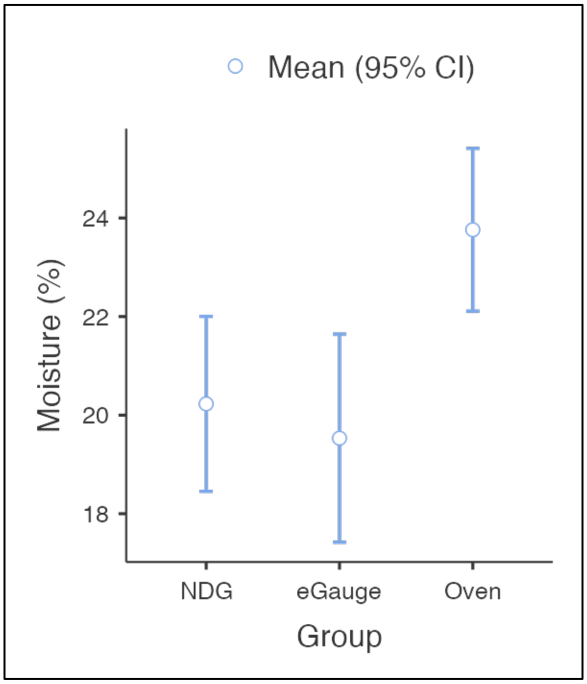

Figure 4.29 Boone County — Comparison of Moisture Data

Table 4.25 Games-Howell Post-Hoc Test for Boone County Soil Moisture Data

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference p-value	— —	0.696 0.850	-3.53 0.011
eGauge Moisture %	Mean Difference p-value		— —	-4.23 0.006
Oven Moisture %	Mean Difference p-value			— —

4.9 Henderson Co. CID 191247, US 60, New Bridge Over Green River at Spottsville, Slight Shift in Alignment

This project constructed a new bridge over the Green River and installed new approaches (Figure 4.33). The approach on the eastern end is approximately a 1/4 mile fill next to the existing approach. The western approach is a cut-and-fill, approximately 1/8 mile in length. Testing was conducted on both approaches.

Figure 4.30 Henderson Co. CID 191247, US 60, New bridge over Green River at Spottsville

4.8.1 Henderson Country — Comparison of NDG and eGauge Density Data

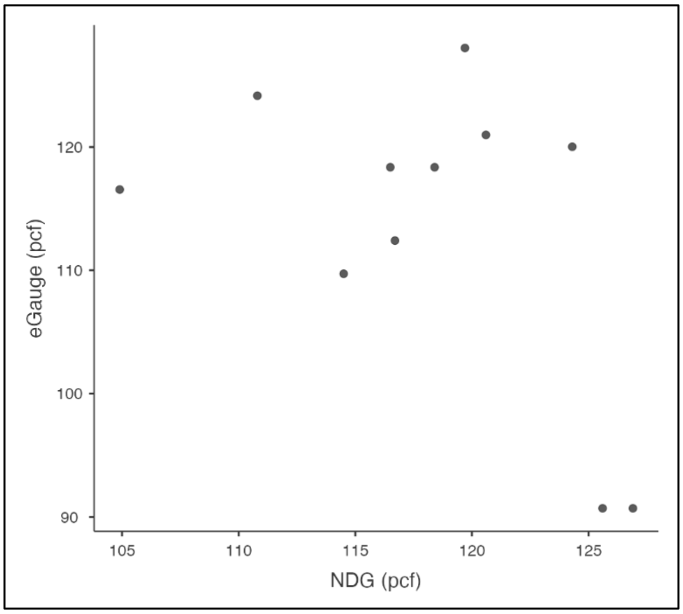

Figure 4.31 Henderson County Density Readings (NDG v. eGauge)

Table 4.26 Descriptive Statistics for Henderson County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Passing**
NDG	118.08	6.53	113.70	122.47	102.41
eGauge	115.01	12.73	106.92	123.10	102.41

Table 4.27 Correlation and T-Tests for Henderson County (I-275) Soil Density Data (NDG v. eGauge)

Correlation		**Paired Samples T-Test**		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
-0.493	0.1235	0.888	4.45*	0.3954

* 95% Confidence Interval for Mean Difference: -6.71 – 15.6

4.8.2 Henderson County — Comparison NDG, eGauge, and Oven Moisture Data

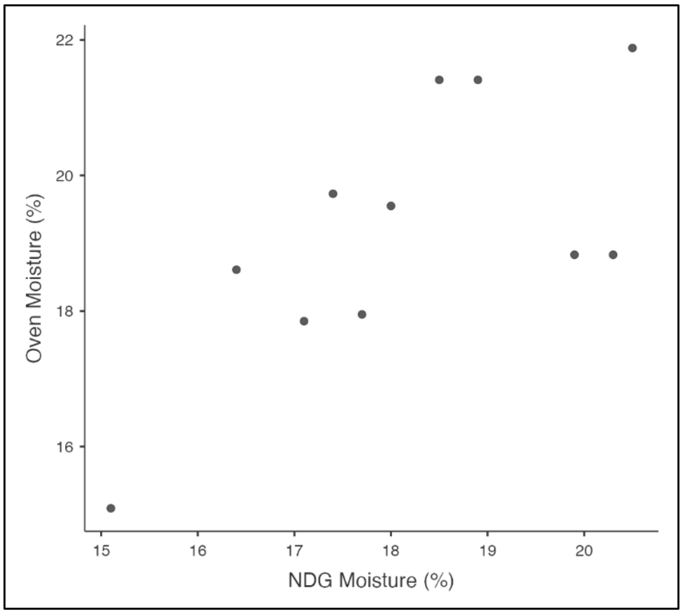

Figure 4.32 Henderson County Moisture Scatterplot I (NDG v. Oven)

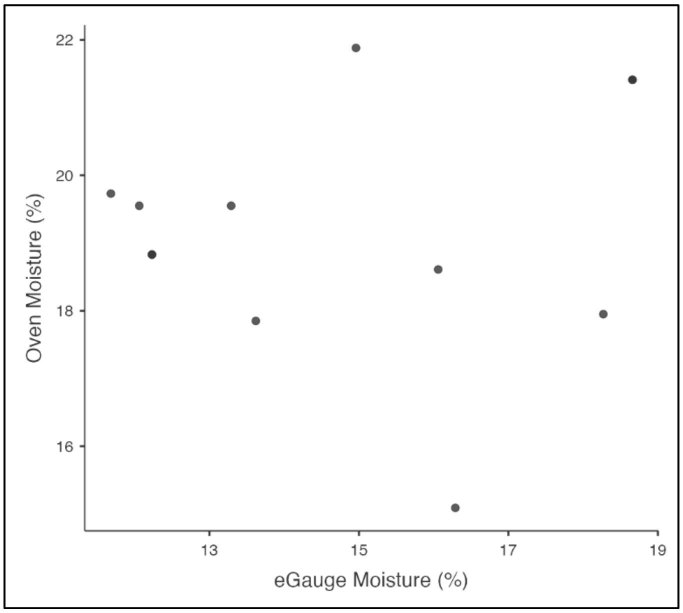

Figure 4.33 Henderson County Moisture Scatterplot II (eGauge v. Oven)

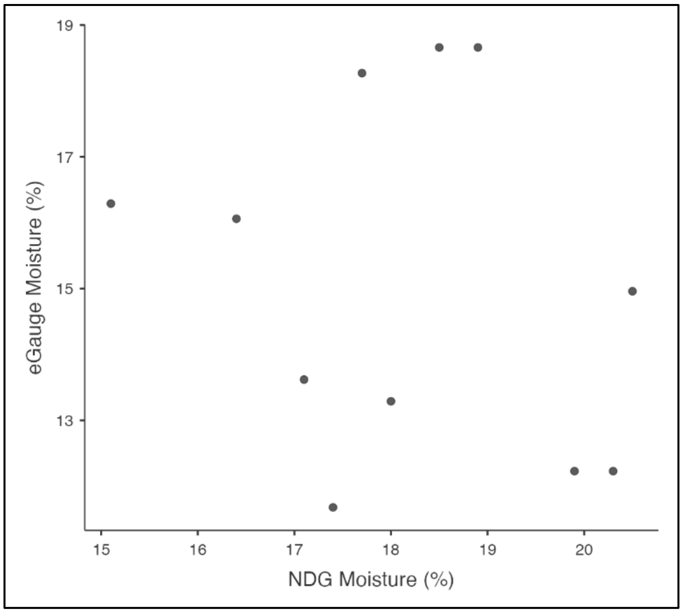

Figure 4.34 Henderson County Moisture Scatterplot III (NDG v. eGauge)

Table 4.28 Descriptive Statistics for Henderson County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	18.16	1.68	17.04	19.29
eGauge	14.83	2.69	13.12	16.55
Oven	19.22	1.87	18.04	20.41

Table 4.29 Correlation Matrix for Henderson County Soil Moisture Data

		NDG Moisture (%)	**eGauge Moisture (%)**	**Oven Moisture (%)**
NDG Moisture (%)	Pearson's r p-value N	— — —		
eGauge Moisture (%)	Pearson's r p-value N	-0.222 0.512 11		
Oven Moisture (%)	Pearson's r p-value N	0.682 0.021 11	0.120 0.711 12	

4.8.3 Henderson County — ANOVA for Moisture Data

- ANOVA found a statistically significant difference in mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples ($p < 0.001$). Post-hoc testing indicated that mean moisture values measured using NDG and those measured from oven-dried samples were statistically similar to one another but differed significantly from eGauge data (Table 17).

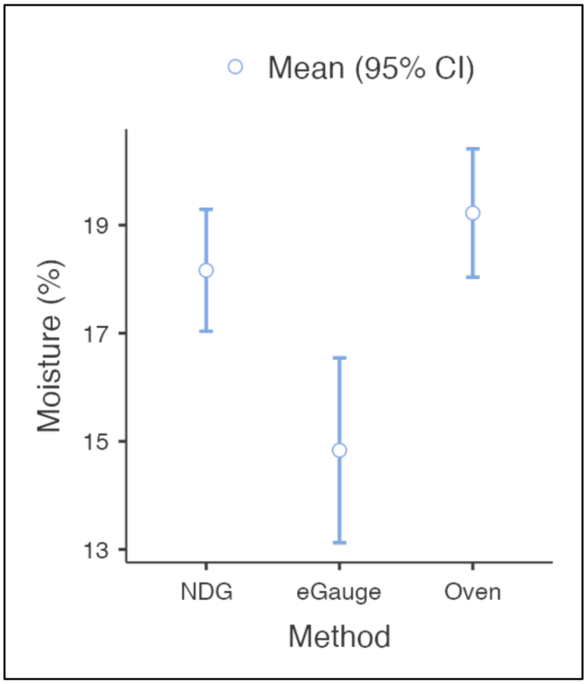

Figure 4.35 Henderson County — Comparison of Moisture Data

Table 4.30 Games-Howell Post-Hoc Test for Henderson County Soil Moisture Data

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference p-value	— —	3.33 0.005	-1.06 0.342
eGauge Moisture %	Mean Difference p-value		— —	-4.39 <0.001
Oven Moisture %	Mean Difference p-value			— —

4.10 Taylor Co. CID 191238, KY 555, New Eastern Campbellsville Bypass

This project is a new alignment on the southeastern side of Campbellsville and is roughly 3 miles in length. We tested several fills, both during fill operations and near final grade. The final grade was evaluated before the stabilization process.

Figure 4.36 Taylor Co. CID 191238, KY 555, New Eastern Campbellsville Bypass

4.9.1 Taylor Country — Comparison of NDG and eGauge Density Data

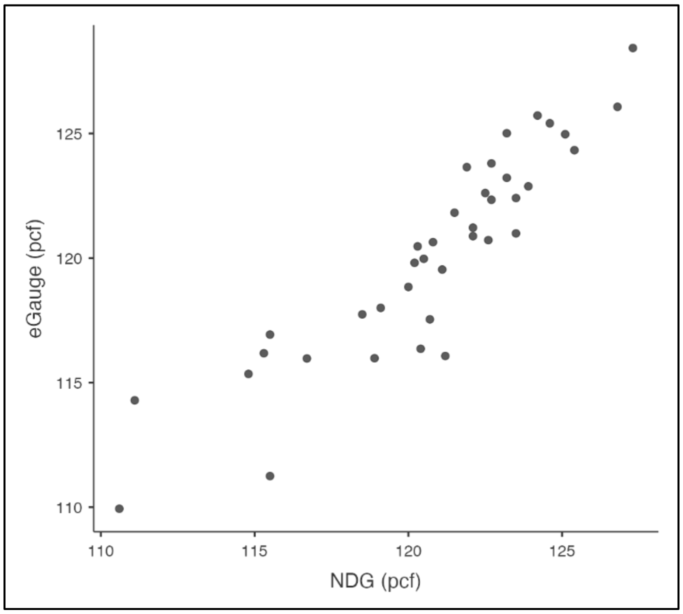

Figure 4.37 Taylor County Density Readings (NDG v. eGauge)

Table 4.31 Descriptive Statistics for Taylor County Soil Density Data

			95% Confidence Interval		Jobsite Proctor
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**	**95% Passing**
NDG	120.79	3.85	119.52	122.06	95.19
eGauge	120.19	4.17	118.82	121.56	95.19

Table 4.32 Correlation and T-Tests for Taylor County Soil Density Data (NDG v. eGauge)

Correlation		Paired Samples T-Test		
Pearson's r	**p-value**	**t-statistic**	**Mean Difference**	**p-value**
0.907	<0.00001	2.09	0.596*	0.043

* 95% Confidence Interval for Mean Difference: 0.0189 – 1.17

4.9.2 Taylor County — Comparison NDG, eGauge, and Oven Moisture Data

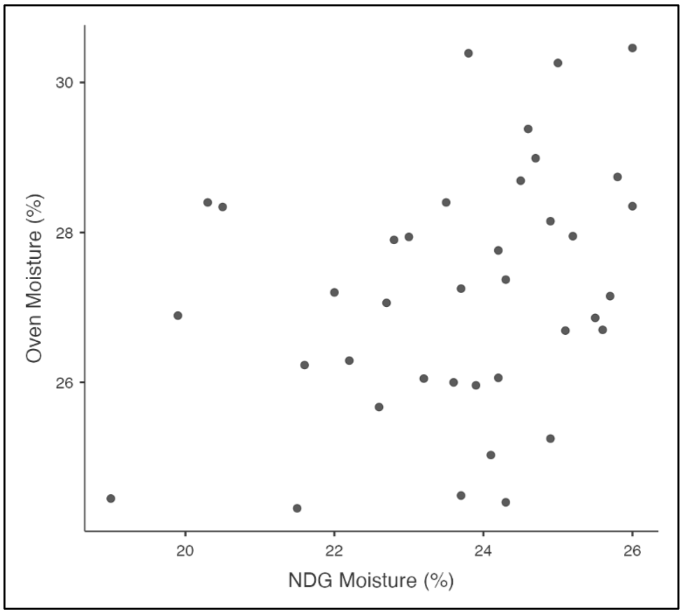

Figure 4.38 Taylor County Moisture Scatterplot I (NDG v. Oven)

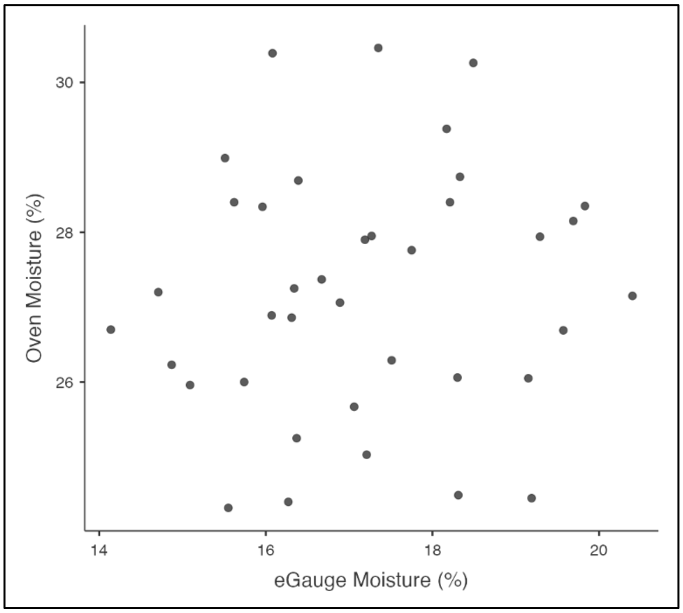

Figure 4.39 Taylor County Moisture Scatterplot II (eGauge v. Oven)

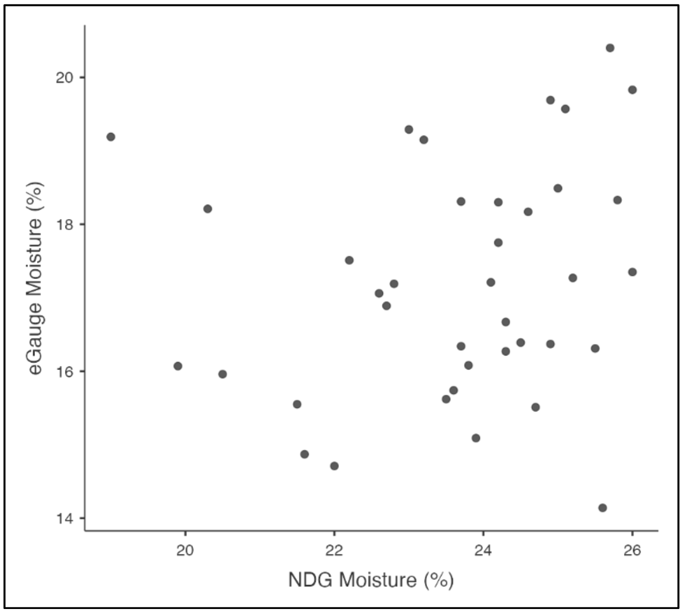

Figure 4.40 Taylor County Moisture Scatterplot III (NDG v. eGauge)

Table 4.33 Descriptive Statistics for Taylor County Soil Moisture Data

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	23.63	1.76	23.06	24.21
eGauge	17.18	1.58	16.66	17.70
Oven	27.20	1.65	26.65	27.74

Table 4.34 Correlation Matrix for Henderson County Soil Moisture Data

		NDG Moisture (%)	eGauge Moisture (%)	Oven Moisture (%)
NDG Moisture (%)	Pearson's r	—		
	p-value	—		
	N	—		
eGauge Moisture (%)	Pearson's r	0.184		
	p-value	0.268		
	N	38		
Oven Moisture (%)	Pearson's r	0.319	0.103	
	p-value	0.051	0.540	
	N	38	38	

4.9.3 Taylor County — ANOVA for Moisture Data

- ANOVA found a statistically significant difference in mean moisture values measured using NDG, eGauge, and those obtained from the oven-dried samples ($p < 0.001$). Post-hoc testing indicated that mean moisture values measured using the NDG and eGauge and those measured in oven-dried samples all differed significantly from one another (Table 20).

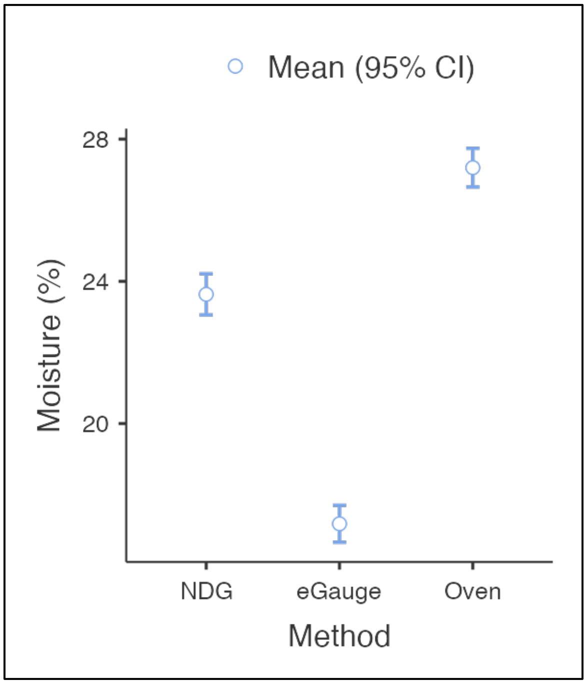

Figure 4.41 Taylor County — Comparison of Moisture Data

Table 4.35 Games-Howell Post-Hoc Test for Taylor County Moisture Data

		NDG Moisture %	eGauge Moisture %	Oven Moisture %
NDG Moisture %	Mean Difference p-value	— —	6.45 <0.001	-3.56 <0.001
eGauge Moisture %	Mean Difference p-value		— —	-10.02 <0.001
Oven Moisture %	Mean Difference p-value			— —

4.11 Composite Soil Density Analysis

To understand how the eGauge's performance in measuring soil density varied relative to the NDG across soil types, we generated four new datasets using the data presented in Sections 4.2 – 4.9. Data were grouped based on soil characteristics into the following categories: (1) silt/clay and shale, (2) stabilized clay, (3) clay, and (4) FDR. We then used paired samples t-tests to detect if the mean differences in the NDG and eGauge's measured values were significantly different. Tables 22 – 29 include descriptive and inferential statistics. At locations with (1) silt/clay and shale (p = 0.098) and (2) stabilized clays (p = 0.974), the mean differences were not significant. For clays (p = 0.034) and FDR (p = 0.005), the mean difference was significant. At four test locations on the FDR site (Shelby County), the eGauge produced four anomalously low readings (62.37 pcf). Excluding these from analysis changes the results of the t-test. Although the difference between the eGauge and NDG remains significant, the mean difference is 12.0 (p = 0.0162). Compared to the confidence intervals for the silt/clay and shale, stabilized clay, and clay soils, the confidence interval for FDR is quite broad, which might suggest that the eGauge is less able to replicate the NDG's baseline performance in these conditions. Further testing FDR sites is necessary to determine if this magnitude of difference is something we should expect for FDR, or if these results are the product of site-specific contingencies.

Table 4.36 Descriptive Statistics for Silt-Clay and Shale Soils (Soil Density)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	121.01	5.90	119.42	122.61
eGauge	119.28	7.44	117.28	121.27

Table 4.37 Paired Samples t-test for Silt-Clay and Shale Soils (Soil Density)

				95% Confidence Interval	
t-statistic	**p-value**	**Mean Difference**	**SE Difference**	**Lower**	**Upper**
1.68	0.098	1.72	1.02	-0.327	3.76

n = 55 (Bullitt, Henderson, Taylor Counties)

Table 4.38 Descriptive Statistics for Stabilized Clay Soils (Soil Density)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	122.76	5.42	120.81	124.71
eGauge	122.39	10.37	118.77	126.01

Table 4.39 Paired Samples t-test for Stabilized Clay Soils (Soil Density)

				95% Confidence Interval	
t-statistic	**p-value**	**Mean Difference**	**SE Difference**	**Lower**	**Upper**
0.033	0.974	0.0462	1.38	-2.77	2.87

n = 32 (Monroe, Scott, and Marion Counties)

Table 4.40 Descriptive Statistics for Clay Soils (Soil Density)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	121.61	5.66	118.79	124.42
eGauge	123.10	4.67	120.78	125.42

Table 4.41 Paired Samples t-test for Clay Soils (Soil Density)

				95% Confidence Interval	
t-statistic	**p-value**	**Mean Difference**	**SE Difference**	**Lower**	**Upper**
-2.31	0.034	-1.49	0.648	-2.86	-0.127

n = 18 (Boone County [I-275])

Table 4.42 Descriptive Statistics for Full Depth Reclamation (Soil Density)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	141.29	9.12	135.16	147.42
eGauge	105.72	34.78	82.35	129.08

Table 4.43 Paired Samples t-test for Full Depth Reclamation (Soil Density)

				95% Confidence Interval	
t-statistic	**p-value**	**Mean Difference**	**SE Difference**	**Lower**	**Upper**
3.54	0.005	35.6	10.0	13.2	57.9

n = 11 (Shelby County)

4.12 Composite Soil Moisture Analysis

As with the wet density data, we stratified our test sites according to soil characteristics to determine whether the three methods (NDG, eGauge, oven drying) performed differently based on soil type. Data were grouped based on soil characteristics into the following categories: (1) silt/clay and shale, (2) stabilized clay, and (3) clay. No moisture data were obtained from the Shelby County site (FDR) and, the results for clay soils are based entirely on the Boone County I-275 data (Section 4.7). Our analysis shows that the mean differences in moisture measurement techniques differ significantly at sites with silt/clay and shale soils (Table 26, Figure 42). Conversely, at sites with stabilized clay soils, there were no significant differences in the mean differences (Table 27, Figure 43), but a mixed picture emerged for clay as the eGauge differed significantly from the NDG and moisture obtained from oven-dried samples (Table 28, Figure 44).

Table 4.44 Descriptive Statistics for Silt-Clay and Shale Soils (Soil Moisture)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	21.85	3.96	20.74	22.97
eGauge	16.35	2.48	15.66	17.04
Oven	24.58	5.16	23.15	26.15

Table 4.45 Games-Howell Post-Hoc Test for Silt-Clay and Shale Soils (Soil Moisture)

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference p-value	— —	5.50 <0.001	-2.73 <0.001
eGauge Moisture %	Mean Difference p-value		— —	-8.23 <0.001
Oven Moisture %	Mean Difference p-value			— —

n = 52 (Bullitt, Henderson, Taylor Counties)

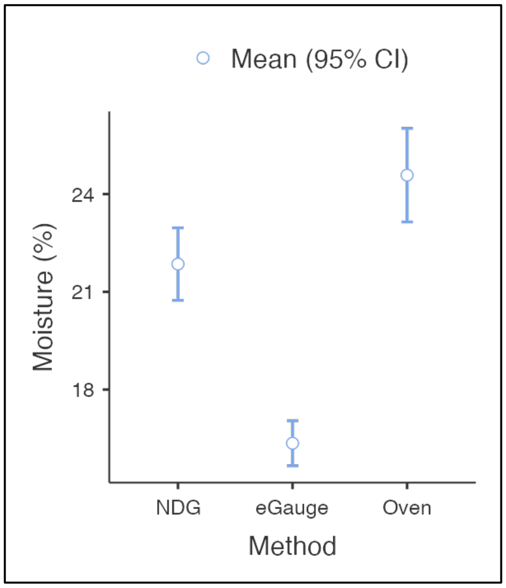

Figure 4.42 Comparison of Moisture Data — Silt-Clay and Shale Soils

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Table 4.46 Descriptive Statistics for Stabilized Clay Soils (Soil Moisture)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	20.26	5.12	18.42	22.11
eGauge	19.83	7.41	17.16	22.50
Oven	21.40	5.02	19.59	23.21

Table 4.47 Games-Howell Post-Hoc Test for Stabilized Clay Soils (Soil Moisture)

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference	—	0.436	-1.13
	p-value	—	0.960	0.645
eGauge Moisture %	Mean Difference		—	-1.57
	p-value		—	0.585
Oven Moisture %	Mean Difference			—
	p-value			—

n = 32 (Monroe, Scott, and Marion Counties)

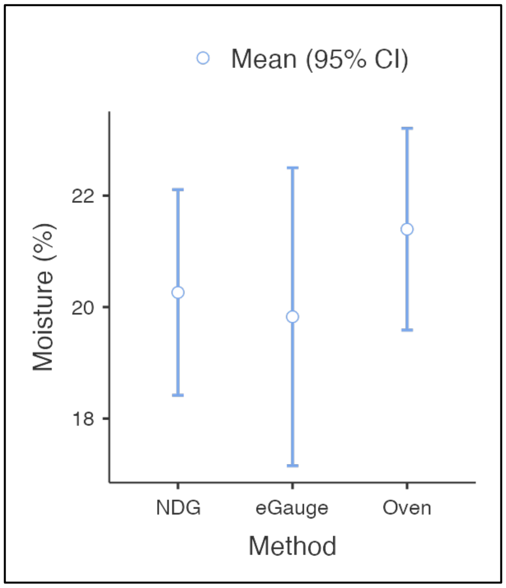

Figure 4.43 Comparison of Moisture Data — Stabilized Clay Soils

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Table 4.48 Descriptive Statistics for Clay Soils (Soil Moisture)

			95% Confidence Interval	
Method	**Mean**	**Standard Deviation**	**Lower**	**Upper**
NDG	20.23	3.07	18.45	22.00
eGauge	19.53	3.66	17.42	21.65
Oven	23.76	2.86	22.11	25.41

Table 4.49 Games-Howell Post-Hoc Test for Clay Soils (Soil Moisture)

		NDG Moisture %	**eGauge Moisture %**	**Oven Moisture %**
NDG Moisture %	Mean Difference p-value	— —	0.696 0.850	-3.53 0.011
eGauge Moisture %	Mean Difference p-value		— —	-4.23 0.006
Oven Moisture %	Mean Difference p-value			— —

n = 14 (Boone County [I-275])

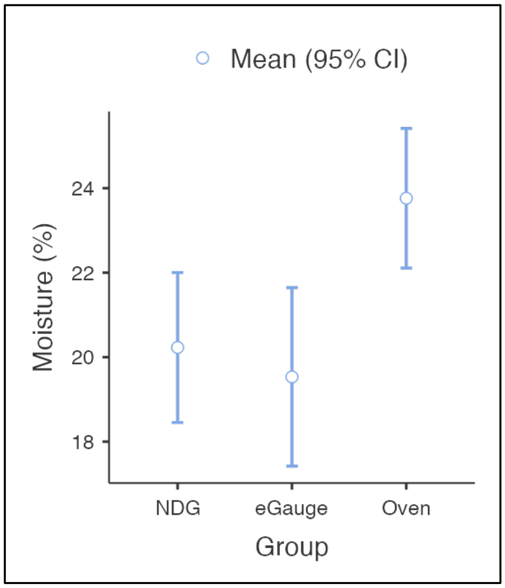

Figure 4.44 Comparison of Moisture Data — Clay Soils

4.13 Key Takeaways

- Our composite analyses found that the mean differences in soil density readings for the NDG and eGauge were not statistically significant at sites characterized by either silt/clay and shale or stabilized clay. Differences were significant for sites with clay or FDR.

- Except for FDR, the confidence intervals for the mean differences were quite narrow, suggesting that even if a finding is statistically significant, it may not be of practical consequence. For the entire dataset, 82.5% of the NDG and eGauge readings were within +/- 5% of one another. If we exclude data from the FDR site, this goes up to 88.1%.

- NDG or eGauge readings are compared to a target soil density value (i.e., the minimum soil density needed for work to proceed). If the measured soil density is 95% of this value or higher, work may proceed. Examining the confidence intervals for the eGauge at individual sites, it appears using the device would not have resulted in crews making a different decision about work proceeding than they would have arrived at using the NDG. At a couple sites, the eGauge produced anomalously low readings (Shelby and Henderson Counties). Although these were likely due to difficulties posed by the sites and challenges with equipment calibration.

- Greater variability characterized the soil moisture data. The mean differences in data obtained from the NDG, eGauge, and from oven-dried lab samples were statistically significant at sites with silt/clay and shale soils but not at sites with stabilized clays. For clay soils, the eGauge produced readings significantly different from the NDG and oven-dried samples. Another way to compare NDG and eGauge moisture data to lab sample moisture data is to (1) calculate differences in raw measurements and (2) compute the percentage differences between raw measurements. For raw data, 88.2% of NDG and 48.0% of eGauge soil moisture readings were within +/- 5 percentage points of the corresponding lab measurement. Conversely, for percentage difference[1] 47.5% of the NDG soil moisture readings were within +/- 10% of lab measurements; this drops to 17.8% for the eGauge.

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[1] For the NDG, percentage difference is: *(NDG Moisture Value – Lab Moisture Value) / Lab Moisture Value*. For the eGauge, substitute the *eGauge Moisture Value* for the *NDG Moisture Value*.

Chapter 5 Stiffness/Strength Devices

A few state DOTs (Minnesota, Indiana, Missouri, and Illinois) have adopted compaction control specifications for soil field stiffness/strength. This chapter describes four stiffness/strength devices which can be used as alternatives to the conventional NDG — Clegg Hammer, GeoGauge, Light Weight Deflectometer, Dynamic Cone Penetrometer.

5.1 Clegg Hammer

The Clegg Hammer — also referred to as a Clegg impact tester — is an impact soil tester device that consists of a flat-ended cylindrical mass (hammer) and guiding tube (Figure 5.1). Applications include testing pavements areas, earthwork construction sites, and turf surfaces. The hammer, which is manually released from a setup height, comes in different weights. Typically, a 10-pound hammer is used for earthwork and roadwork quality control. When the hammer impacts the test surface it creates an electrical pulse. From this pulse is obtained a measure of the hammer's deceleration after it was released onto the test surface. The electrical pulse is converted into units of gravity. Results are quantified in terms of the Clegg Impact Value (CIV), where one unit equals 98.1 m/s^2. The standard protocol entails dropping the mass at least four consecutive times at the same location. The material's percent compaction can be estimated by determining the CIV.

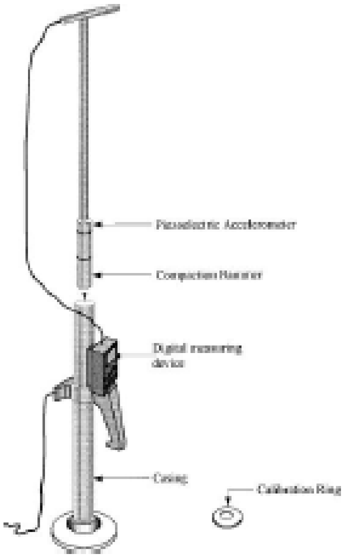

Figure 5.1 Schematic Representation of the Clegg Impact Hammer (Al-Amoudi et al. 2002)

5.2 Soil Stiffness Gauge (GeoGauge)

Originally known as Humboldt Stiffness Gauge, this device consists of an external case which houses an electro-mechanical shaker, upper and lower velocity sensors, and a rigid ring-shaped foot that is fixed at the base of the case (Rathje et al. 2006) (Figure 5.2). The GeoGauge measures the in-place stiffness of compacted soil by vibrating its rigid, ring-shaped foot, which creates vertical frequencies. It evaluates the uniformity of unbound materials based on the variability in stiffness throughout a structure. The stiffness is determined at each frequency, and the average is displayed.

Figure 5.2 Humboldt GeoGauge H-4140 (Ernest S. Berney et al. 2013)

5.3 Light Weight Deflectometer

The light weight deflectometer (LWD) is a rebound device that measures modulus (Figure 5.3) and can be configured to evaluate soil, aggregate, and asphalt. The type of load plate used varies according to the material type, with a standard load plate suitable for soil and aggregate. A LWD can be fitted with a California Bearing Ratio (CBR)–type piston and surcharge weights to generate readings more closely aligned with traditional CBR values. The asphalt device uses a shorter drop distance and small dies for mat depth and mix design.

Figure 5.3 Zorn Lightweight Deflectometer with Attached Data Logger (Berney et al. 2013)

5.4 Dynamic Cone Penetrometer (DCP)

Developed in South Africa, the dynamic cone penetrometer (DCP) is also used in the United Kingdom, Australia, New Zealand, a few US states, and the US Army Corps of Engineers (Abyad 2015) (Figure 5.4). DCP tests measure a material’s in-situ resistance to penetration. Testing is performed by driving a metal cone into the ground by repeatedly striking of a 17.6 lb. hammer from a distance of 22.6 in. The cone’s penetration is measured and recorded after each drop, with a test range of 6-12 in. below the ground surface. Results from DCP tests can be correlated with a soil's in-situ density, resilient modulus, and bearing capacity.

Figure 5.4 Schematic of the Dynamic Cone Penetrometer (Minnesota Transportation "Crossroads")

Table 5.1 summarizes the most salient characteristics of each device (Paez 2018). None of the devices can measure the moisture content of tested material. They differ in their main outputs. While the Clegg Hammer, GeoGauge, and LWD determine the soil's elastic modulus, the DCP obtains the penetration index. Their calibration processes are minimal. Paez (2018) found that the GeoGauge and LWD have been evaluated and are used by almost 50% of state DOTs, while the Clegg Hammer (15%) and DCP (32%) are less widely used.

Table 5.1 Stiffness/Strength Devices

	Clegg Impact Hammer (CIH)	Soil Stiffness Gauge (Geo-Gauge)	Light Weight Deflectometer (LWD)	Dynamic Cone Penetrometer (DCP)
ASTM Standard	ASTM D 5874-16	ASTM D 6758	ASTM E 2583-11	ASTM D 6951
Measurement	%CBR, Elastic Modulus	Structural Stiffness and Elastic modulus	Elastic Modulus	Penetration rate Penetration Index
Calibration of Device	None	Calibration plate	Required	None
Operator Skills and Training	Minimal	Medium	Medium	Minimal
Initial Cost	\$3,000	\$6,720	\$8,705	\$1,895
Influence depth	Up to 10 inches	Up to 8-10 inches	Up to 10-11 inches	48 inches
Data storage	Yes	Yes	Yes	No
Accuracy	Good	-	Good	Good
GPS	Yes	No	Yes	No

	Clegg Impact Hammer (CIH)	Soil Stiffness Gauge (Geo-Gauge)	Light Weight Deflectometer (LWD)	Dynamic Cone Penetrometer (DCP)
Advantages	- Simple - Fast - Non-invasive - Durability - Versatility - Good portability - Fair durability - Data storage	- Simple - Portability - Fast - Non-invasive - Durability - Good portability - Good durability - Data storage	- Simple - Fast - A wide range of modulus values - Not impact by aggregate size - Safer - Fair portability - Good durability - Data storage	- Simple - Fast for shallow depth - Low cost - 4 ft. range - Strong correlation with CBR and Modulus -Used in Many DOTs - Good portability - Good durability
Disadvantages	- Poor portability for 20kg hammer - No moisture measurement	- Sensitive to seating conditions - Inconsistency in test results - Unfavorable findings by several DOT's - No moisture measurement	- Soft soils cause variation in results - High variability - No moisture measurement	- Might require 2 technicians - Max. particle size 2 inches - Deep testing can take up to 15-20 min - Destructive - No moisture measurement - No data storage
Tried by DOTs agencies	15%	46%	49%	32%

Sources: "Construction Materials Testing Equipment" (2018), Nazzal (2014), Kim et al. (2010a)

5.5 State Survey Usage Between Different Compaction Measurements Devices

Paez (2018) surveyed 49 state DOTs to determine each agency's preferred compaction measurement process. About 90% of agencies use the density-moisture procedure for project quality control quality assurance, while just two DOTs have instituted performance-based quality control procedures. Roughly 84% of DOTs use NDGs for in-place density-moisture measurements, while 70% do not use any stiffness-strength method. Nearly 60% of agencies responded that is not necessary to implement new methods of quality control and quality assurance for aggregate subbase.

Chapter 6 Conclusions

Based on our field study, statistical analyses, and literature review we have arrived at the following conclusions and recommendations.

- In silt/clay soils, shales, and stabilized clays, the NDG and eGauge produce statistically indistinguishable density readings. However, the differences were significant for sites characterized by clay or FDR. Across all sites, 82.5% of NDG and eGauge readings were within +/- 5% of one another. If we omit data from the Shelby County (FDR), where the eGauge produced several anomalously low readings, this figure increased to 88.1%.

- Except for the Shelby and Henderson County sites, the confidence intervals for the eGauge at individual sites were narrow enough that had crews used the device they would have correctly decided whether to proceed with construction activities. Before deploying the eGauge at sites with clay or FDR, additional study is warranted to evaluate its performance in those soil conditions.

- The eGauge, unlike the NDG, does not have a back scatter mode. It can only obtain a density reading in the direct reading mode by driving the probe into the soil. Therefore, soil densities obtained on projects mixed with rock and/or FDR projects can vary greatly. The eGauge may not be suitable for projects such as these.

- Compared to soil moisture measurements obtained from laboratory samples, those collected using the eGauge appear less accurate than those acquired using NDGs. Mean differences between NDGs, the eGauge, and lab samples differed significantly for silt/clays and shales, but not for stabilized clays. In clays, although NDGs and lab measurements were comparable, eGauge readings differed significantly from both. Examining raw data, 88.2% of NDG and 48.0% of eGauge soil moisture readings were within +/- 5 percentage points of corresponding lab measurements. In terms of the percentage difference, 47.5% of the NDG soil moisture readings were within +/- 10% of lab measurements. Only 17.8% of the eGauge measurements were. The eGauge tended to return lower measures of soil moisture than NDGs and the lab samples. It therefore may not be the optimal device to collect moisture data.

- A viable non-nuclear alternative for evaluating in-place soil properties is measuring soil stiffness/modulus instead of soil density. State DOTs have been slow to adopt soil stiffness gauges, despite their being promising alternatives. Lightweight portable soil stiffness gauges and LWD produce accurate measurements while being faster, cheaper, and safer to use than NDGs.

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