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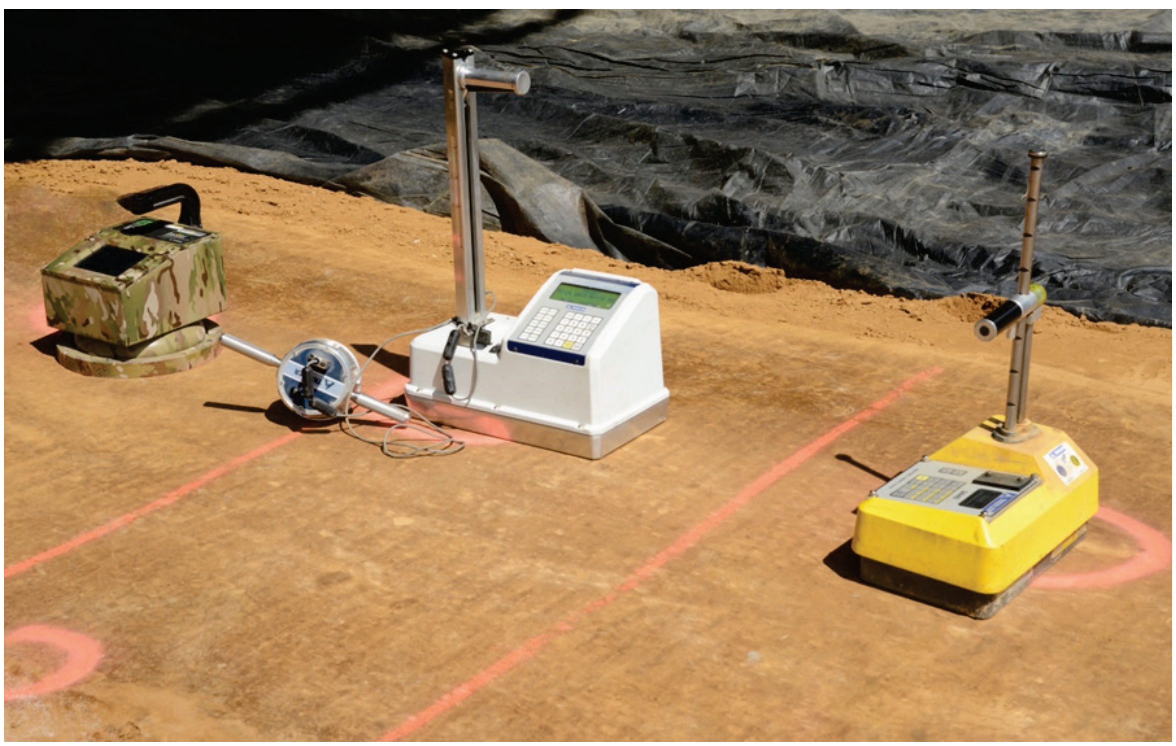
Validation Testing of Non-Nuclear Alternatives to Measuring Soil Density

Ernest S. Berney IV, Mariely Mejías-Santiago, and Matthew D. Norris

November 2016



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Final report

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Under Project 447413

Abstract

During 2015, researchers with the U.S. Army Engineer Research and Development Center (ERDC) validated the effectiveness of the TransTech Combined Asphalt Soil Evaluator (CASE) and the Troxler eGauge as suitable replacements for nuclear density gauge (NDG) technology. Comparisons of soil dry density and moisture content were made between the gauges for six distinct soil types at varying densities and moisture contents. The CASE unit was calibrated using the Sand Cone and hot-plate moisture content prior to its correlation to the NDG; the eGauge was used in its shipped configuration without calibration. Results of both devices were compared to the NDG and core samples to capture asphalt density. Full-scale test sections were constructed for the soil evaluations ranging from crushed limestone to fat clays. Results showed that wet and dry densities obtained with the eGauge very closely matched those of the NDG, but the accuracy of the measured moisture contents was lower. The CASE unit's calibrated accuracy to the NDG moisture content was excellent, but its wet and dry density accuracies were much lower than the eGauge. Based on the ERDC findings, the eGauge is recommended as the best replacement for the NDG for wet/dry density measurements and requires no calibration or transport/licensing restrictions.

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Preface

This report was prepared for Headquarters, Air Force Civil Engineering Center as part of the Air Force Non-Nuclear Density Project 447413. Jeb S. Tingle was the program manager of the Air Force project.

This work was performed by the Airfields and Pavements Branch (APB) and the Concrete and Materials Branch (CMB), Engineering Systems and Materials Division (ESMD), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. Timothy W. Rushing was Chief, APB; Christopher M. Moore was Chief, CMB; Gordon W. McMahon was Chief, ESMD; and Pamela G. Kinnebrew was Technical Director for Military Engineering. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Bartley P. Durst.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square feet	0.09290304	square meters
tons (force)	8,896.443	newtons

1 Introduction

1.1 Background

The U.S. military has identified the need for eliminating the use of nuclear density gauges (NDG) to measure soil moisture and density in the field because of the restrictive requirements for the gauge's transport, use, and storage associated with these instruments containing radioactive materials Cesium and Americium. The military is actively looking for an alternative replacement for use by all of its branches. The preference for the U.S. Air Force is a single instrument that provides asphalt density, soil density, and moisture without licensing of radioactive materials and personnel and has a comparable accuracy to the NDG.

Various studies were conducted at the U.S. Army Engineer Research and Development Center (ERDC) to evaluate different options to replace the NDG. Berney et al. (2013) evaluated a variety of non-nuclear devices for measuring soil density and moisture content in the field. Results showed that the electrical-impedance-based soil density gauge (SDG) by TransTech was the most accurate and precise device measuring soil density compared to the NDG, but only when a field correction factor was applied. A follow-up study on the SDG was conducted by Mejías-Santiago et al. (2013) to collect data for 16 different types of fine-grained soils in order to expand the SDG's capability in fine-grained soils. Results from that study confirmed the SDG's need for a field calibration to provide accurate moisture and density measurements comparable to the NDG. This study also tested another non-nuclear gauge, TransTech's Combined Asphalt and Soil Evaluator (CASE) but only collected data for database development, since at the time of the study it was only in a prototype configuration. The CASE is an electrical impedance-based gauge based on the SDG platform that can provide both asphalt and soil density along with moisture measurements in a single gauge. The electromagnetic characteristics of the CASE are sufficiently different from the current SDG, that it requires a complete characterization for soils and empirical algorithms that are developed to be fully compliant with the range of soils of interest to the Air Force.

Following incorporation of the prior study's soil database into the CASE software, Berney et al. (2014) conducted a field validation study on the performance of the CASE alongside the SDG. The purpose was to verify the accuracy and precision of the CASE in measuring soil density and water content compared to the NDG in a one-to-one setting. Further, the CASE was evaluated to verify its precision and accuracy in measuring asphalt density. The CASE device almost performed as well as the SDG, but like the SDG, it lacked the ability to measure small density changes within a given soil type.

The Troxler eGauge, a low radioactive source gauge, was introduced in the spring of 2015 and prompted the need for a final validation study between its performance and the CASE as the leading candidates for the Air Force to replace the NDG. This report describes the materials, testing procedures, and results of the validation of the CASE and the eGauge to provide Air Force guidance for future equipment procurement.

1.2 Objectives

The objectives of this validation study included:

- Collecting wet and dry density measurements using the CASE and the eGauge from test sections constructed from six different soil types at varying densities to compare their accuracy to the data from the NDG and the sand-cone techniques.
- Collecting moisture content measurements using the CASE and the eGauge from test sections constructed from six different soil types at varying moisture contents to compare their accuracy to data from the NDG and the oven-dried techniques.
- Comparing the ability of a hot plate to adequately capture moisture as compared to the oven-dried methodology. This is a companion study to that discussed in Berney et al. (2013).
- Conducting tests on varying asphalt test sections using the CASE and the eGauge to measure asphalt density with depth and to compare their accuracy to the data from the NDG and core samples at varying thicknesses.
- Summarizing the study's results and recommending the best device for replacing the NDG for measuring moisture and density for construction quality control.

1.3 Scope

This study consisted of evaluating the two functions of the CASE and the eGauge (i.e., 1) soil density and water content measurements and 2) asphalt density measurements).

The CASE and eGauge were evaluated by collecting instrument readings of wet density and moisture content on test sections constructed from six different soil classifications. Standard laboratory tests were conducted prior to the evaluation to determine the engineering properties of the soils, such as grain-size distribution, plasticity characteristics, and compaction properties. The maximum dry density and optimum moisture content (OMC) of each soil were used for construction quality control purposes. Each soil was prepared in the field at two moisture levels, ideally one on the dry side of OMC and the other on the wet side of OMC, for a total of 12 test items. Each test item had final areal compacted dimensions of 16 ft by 8 ft and a thickness of at least 12 in. Each test item was tested at two levels of compaction, with data acquisition occurring between various passes of the compaction roller. Electronic gauge readings were obtained at each compaction level.

Density and moisture readings were obtained at three different locations within each test item with two CASE units and one eGauge. For comparison, NDG density and moisture readings as well as soil samples for moisture content determination for both the oven and hot-plate procedures were collected at each test location. Additionally, sand-cone tests for wet density were performed to compare the electronic and nuclear density measurements to a reference standard.

The asphalt function of the CASE and eGauge were evaluated by collecting measurements of asphalt density on three existing test sections at ERDC. All sections were conventional hot-mix asphalt (HMA). Data were collected at the pavement surface to evaluate backscatter readings between the NDG and CASE and at 2-in., 4-in., and 6-in. depths and to evaluate the down-hole rod measurements between the NDG and the eGauge.

All of the collected data were analyzed to determine the ability of the CASE and the eGauge to adequately measure soil density and moisture content as compared to the NDG and their ability to measure asphalt pavement density.

2 Materials and Instruments

2.1 Soils

Six different soil types ranging from fine-grained to coarse-grained were used for this study in order to provide a wide range of soil properties for validating the effectiveness of the devices in measuring soil density and moisture content. The Unified Soil Classification System (USCS; ASTM International 2011) soil types included high-plasticity clay (CH), low-plasticity clay (CL), clayey sand (SC), clayey-sand with gravel (SC), blended clayey sand (SC), and crushed limestone (GW-GC). While three SC soils were used in the study, only one was intended to be an SC, while the other two were closer to another desired gradation. The clayey-sand with gravel was intended to be a clayey-gravel (GC) soil but had 8 percent more sand than gravel (Table 1). The blended clayey sand was intended to be a silty-sand (SM), but the silt material used in this blend had slightly more plasticity than a true silt (ML) (silt) soil.

Standard laboratory tests were performed at the ERDC Materials Testing Center (MTC) to determine basic geotechnical properties of the soils. Tests conducted on each soil included standard grain-size distribution (ASTM International 2006) with hydrometer analysis (ASTM International 2007c) for dissemination of silt and clay fractions, Atterberg limits (ASTM International 2010c) including liquid limit (LL), plastic limit (PL), and plasticity index (PI), Unified Soil Classification (USCS; ASTM International 2011), and modified proctor compaction (ASTM International 2012c) to determine optimum moisture content (OMC) and maximum dry density (MDD). Details of these test results are in Appendix A. A summary of these properties is shown in Table 1. These properties were used as the initial input data for the CASE and for test section construction purposes. The OMC was used to determine the two different moisture levels for compaction of each soil, and the MDD was used during construction to determine the different compaction levels for data collection.

2.2 Instruments

The list of instruments and methods used in this study is in Table 2; the following sections describe each instrument or method in more detail.

Table 1. Soil properties.

Soil ID	USCS Classification	Atterberg Limits			Grain size (% by weight)			C_u	C_c	MDD (pcf)	OMC (%)
		LL	PL	PI	Fines	Sand	Gravel				
High Plasticity Clay	Clay (CH) Gray	81	23	58	95.6	4.4	0	-	-	104.3	22.4
Low Plasticity Clay	Clay (CL) Brown	35	22	13	97.4	2.6	0	-	-	118.1	13.7
Red Clayey Sand	Clayey Sand (SC), Reddish Brown	19	13	6	34.5	65.4	0	-	-	119.8	12.5
Clay-Gravel	Clayey Sand (SC), with Gravel; Reddish Brown	25	13	12	14.7	46.4	38.9	1714	8.1	133.1	7.4
Blended Clayey Sand	Clayey Sand (SC), Brown	29	19	10	19.1	77.5	0	22.2	8.2	134.8	7.4
Limestone	Gravel (GW-GC), with Silty Clay and Sand; Gray	20	14	6	5.7	21.6	72.7	24.4	2.4	145.7	4.7

C_u = Coefficient of uniformity

C_c = Coefficient of curvature

Table 2. List of instruments used in this evaluation.

Instrument	Standard Method	Description	Output
Model 3430 Roadreader™	ASTM D6938	Nuclear Moisture-Density Gauge	• Wet and Dry Density • % Moisture Content • % Voids • % Compaction
CASE	Not available	Combined Asphalt and Soil Evaluator	• Wet and Dry Density • % Moisture Content • % Compaction
EGauge	ASTM D7830	License Exempt Soil Density Gauge with Moisture Monitoring Probe	• Wet and Dry Density • % Moisture pcf (from probe) • % Voids • % Compaction
Sand Cone	ASTM D1556	Density Determination	• Wet Density
Hot Plate	ASTM D4959	Portable electric stove	• Moisture Content
Laboratory Oven	ASTM D2216	Reference standard	• Moisture Content

2.2.1 Nuclear moisture-density gauge

The Troxler Model 3430 Roadreader™ nuclear moisture-density gauge, shown in Figure 1, was used for this evaluation. This gauge uses the interaction of gamma radiation with matter to measure density through direct transmission or backscatter. It determines the density of a material by counting the number of photons emitted by a cesium-137 source that are read by the detector tubes in the gauge base. In direct transmission, the source rod extends through the base of the gauge into a predrilled hole to position the source at the desired depth, a maximum of 12-in. deep. Photons from the source travel through the material in the test area, collide with electrons present in the material, and reach the photon detectors in the gauge. During a backscatter measurement, the source is lowered near the surface of the test material in the same plane as the photon detectors. The gamma photons that enter the test material must be scattered at least once to reach the detectors in the gauge. Photons emitted from the source penetrate the test material, and the scattered photons are measured by the detectors. A backscatter reading measures material from the surface to a depth of approximately 4 in. (Troxler Electronic Laboratories, Inc. 2016).

Figure 1. Nuclear moisture-density gauge.

A material with a high density increases the number of collisions between the gamma photons and the electrons present in the material. Therefore, the number of photons reaching the detector tubes is reduced. Hence, the lower the number of photons reaching the detector tubes, the higher the material density. The opposite is true for material with a lower density; fewer collisions occur between the gamma photons and electrons present in the material. More photons will reach the detector tubes, increasing the density count. A microprocessor in the gauge converts these counts into a density reading (Troxler Electronic Laboratories, Inc. 2016).

The moisture determination occurs in much the same way as the backscatter density reading. The Americium-241: Beryllium source is located inside of the gauge base. Fast neutrons from this source enter the test material and are slowed by collisions with hydrogen atoms present in the material. The helium 3 detector in the gauge base counts the number of thermalized (slowed) neutrons. This number (known as the moisture count) is directly related to the amount of moisture in the tested area (Troxler Electronic Laboratories, Inc. 2016). The NDG was used according to ASTM D6938 (ASTM International 2010a) with a rod driven 6 in. into the ground to obtain moisture content and wet density.

2.2.2 CASE unit

The Combination Asphalt and Soil Evaluator (CASE) (Figure 2) is used to measure density of asphalt and the density and moisture content of typical construction soils using a multiple concentric ring electrode array configuration (ASTM International 2013). In soil mode, the device uses electrical impedance spectroscopy (EIS) to obtain soil density and moisture content readings non-destructively. As shown in the diagram in Figure 3, the non-contacting sensor in the CASE consists of two rings, a central ring and an outer ring. The central transmit ring injects an electric field into the soil, and the response is received by the outer sensing ring. The density, or compaction level, is measured by the response of the CASE's electrical sensing field to changes in electrical impedance of the material matrix. Since the dielectric constant of air is much lower than that of the other soil constituents, the combined dielectric constant increases as compaction increases, because the percentage of air in the soil matrix decreases. The CASE measures the electromagnetic impedance properties of soil over several frequencies. Using the spectroscopy of the measured impedance over the frequency range, the CASE unit calculates the soil compaction properties (wet density and water content) without the typical soil information, such as grain-size properties, Atterberg limits, etc. The CASE does require a wet density offset, either from a sand cone or another secondary device. For the calculation of the soil's wet density and water content, the CASE unit uses the measured susceptance and resistance between 5 MHz and 25 MHz, respectively. The CASE requires collection of five discrete data points in the cloverleaf pattern shown in Figure 4 for averaging density measurements. The CASE is equipped with a touch screen, a graphical menu interface, and Global Positioning System (GPS).

Figure 2. Combined Asphalt and Soil Evaluator (CASE).

Figure 3. Configuration of the CASE non-contacting sensor.

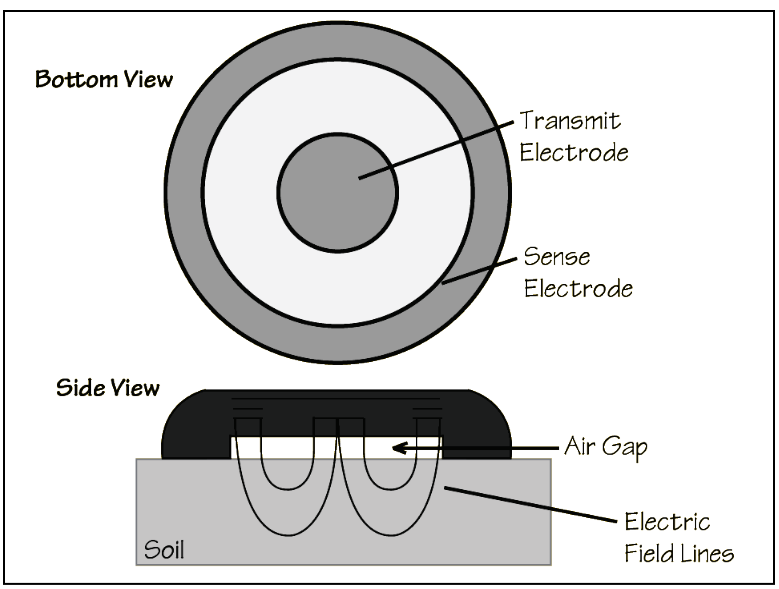
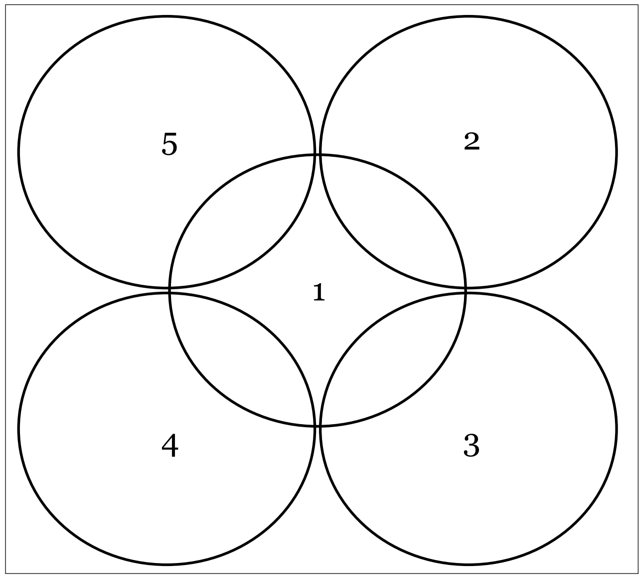


Figure 4. Cloverleaf pattern of readings of the non-nuclear gauges.



In asphalt mode, the outer ring is removed, and the unit operates at a single frequency to determine the density based on the measured impedance (susceptance), a factory calibration, and user inputs of aggregate size and the maximum theoretical density (MTD). This capability is identical to the company's own Pavement Quality Indicator (PQI) technology. The Transtech PQI 301 instrument is used as a standard non-nuclear test device in asphalt construction evaluation. Research has shown that its performance compares well with the nuclear density gauge (Zhuang 2011).

2.2.3 EGauge

The Troxler EGauge (Figure 5) is a new license exempt soil density gauge. The technology of the traditional nuclear density gauge is still utilized in this new model for the measurement of wet density using a Cesium-source tipped rod to produce gamma photons. This device has a larger and more insulated detector plate to mask low level background radiation while still maintaining sensitivity to capture the low photon emittance from the small Cesium source. Licensing is not required with the eGauge, because the Cesium source emits radiation below the Nuclear Regulatory Commission's human safety limits and therefore, the radiation dose to the operator poses no danger. The gauge by itself only measures wet soil density; however, it has the capability to measure moisture content electronically through a secondary probe that is attached by a cable to the main body and is inserted into the ground using the same or different hole drilled for the density source rod. This gauge does not have the backscatter option of the NDG, as it requires penetration of the probe into the ground to measure density. This new gauge features a GPS, a USB port, and backlit display.

Figure 5. Troxler EGauge with Moisture Monitoring Probe.

2.2.4 Sand cone

The sand cone test was used in this study as the reference standard for comparing the effectiveness of the non-nuclear devices in measuring in place soil density. The sand cone density test is a volume replacement test that determines the wet density of a soil. Density is determined by the quotient of soil mass removed from a hole divided by the volume of the hole. The volume of the hole created is indirectly measured by the mass of sand used to fill the hole, with the assumption that the sand fills the hole with a known, uniform density (Sebesta et al. 2006).

The sand cone replacement test was conducted according to ASTM D1556 (ASTM International 2007b). Clay was used to seal the inner ring of the sand cone plate to minimize sand grains being trapped beneath the plate. A #20-#30 grade Ottawa sand was used as the uniform sand. Three sand cone devices were used during testing to expedite the process. Each sand cone bottle was water and sand calibrated prior to the start of the exercise, but no further calibration checks were conducted after the testing began. A field scale accurate to ±0.5 g determined the mass of soil and sand. A surface calibration was performed on every hole dug to account for surface variability at each test location. Holes were dug with a diameter slightly smaller than the ring and a depth of at least 3 in. for all fine-grained soils and up to 4 in. or more for granular materials to produce a representative sample volume. The sand cone density device and accessories are shown in Figure 6.

Figure 6. Sand cone density apparatus and accessories.

2.2.5 Hot plate

In this study, the hot plate method was used as a rapid tool for measuring moisture content in the field and to determine the moisture offset for the CASE. The hot plate method consisted of an electric portable stove (Waring model SB30 1300 Watt single burner) that applied direct heat to the soil (Figure 7). An aluminum specimen container (pan) was initially weighed empty, and then it was weighed with the soil sample before and during heating of the sample. The stove was set in a high heat mode, and the sample container was placed on the stove similar to a conventional stovetop. The soil sample was stirred while heating to expedite the drying process. The specimen container was removed from the heat and weighed at frequent intervals (1 to 5 min.) that depended on the initial moisture of the soil. The heating and weighing process was repeated until a change in soil mass of less than one percent occurred during a 1-min interval. At that point, the moisture content was calculated. Data were monitored using the ERDC Rapid Soil Analysis Kit software (Berney and Wahl 2008) converted to an Android app running on a Motorola Xoom tablet to provide real-time computation of moisture content and change detection during the drying process.

Figure 7. Hot plate, scale, and accessories used to determine soil moisture content.

2.2.6 Laboratory oven

Drying of the soil using the laboratory oven test was the reference standard for comparing the effectiveness of the alternative devices in measuring soil moisture content and the hot plate. The oven temperatures and controls were set to 230 °F ± 9 °F according to ASTM E149 (ASTM International 1994), and the samples were heated overnight (minimum 15 hr) according to ASTM 2216 (ASTM International 2010b).

3 Experimental Procedures

3.1 Soil test section

3.1.1 Test strip construction

A total of 12 test strips were constructed at ERDC under a large covered hangar to help protect the soils from the elements. Each soil was prepared to the desired moisture (as listed in Table 3) by letting it air-dry or by wetting it using a hydro-seeder depending on the current moisture content of the soil at the time of preparation. A skid steer or front-end loader was used to mix the soil to distribute the moisture more consistently. Some of the soils, especially the CH, required the use of a tiller to loosen the soil, expose more surface area, and allow for more uniform moisture distribution. For test strip construction purposes only, constant monitoring of the soil moisture content was performed by using the standard laboratory microwave oven (ASTM International 2008). Once the soil was at the desired moisture content, it was placed in the test section in two lifts using a dump truck and a skid steer (Figure 8).

Table 3. Moisture levels used to prepare each soil for testing.

Test Strip	Soil ID	Moisture Content at time of testing (%)	Compaction Level Tested	
			Low	High
1	High-Plasticity Clay	26.5		X
2	High-Plasticity Clay	33.7		X
3	Clay-Gravel	8.6	X	X
4	Limestone	3.2	X	X
5	Limestone	4.9	X	X
6	Clay-Gravel	6.2	X	X
7	Blended Clayey Sand	7.9	X	X
8	Red Clayey Sand	10.5	X	X
9	Low-Plasticity Clay	19.7	X	X
10	Red Clayey Sand	16.0	X	X
11	Blended Clayey Sand	5.0	X	X
12	Low-Plasticity Clay	12.7	X	X

Figure 8. Placing soil to build a testbed using a) dump truck and b) skid steer.

For each test strip, the first lift placed was approximately two roller widths (10 ft) across to provide a wide enough base to create a top layer at least 8 ft across. The test items were constructed in two 6-in.-thick compacted lifts, such that the final test section was 12 in. thick to provide a suitable thickness of uniform soil above the natural subgrade to ensure that the response of each instrument was not influenced by the subgrade layer's properties. The test items were considered ready for testing when the second lift was at the specified compaction level. The order in which the soil test strips (1 through 6) were constructed is listed in Table 3.

The clay gravel, limestone, blended clayey sand, low-plasticity clay, and red clayey sand were compacted using a Caterpillar CS433E 7-ton vibratory smooth drum roller (Figure 9a). The high-plasticity clay was compacted using an Ingram 35-ton rubber tire compactor (Figure 9b). In order to maintain a smooth surface for testing the gauges, the finer grained soils when compacted on the wet side of optimum required and placement of a plastic sheet over the test section during the compaction process to prevent adherence of the soil to the roller drum (Figure 10).

Figure 9. Soil compaction equipment: a) smooth drum roller and b) rubber tire compactor.

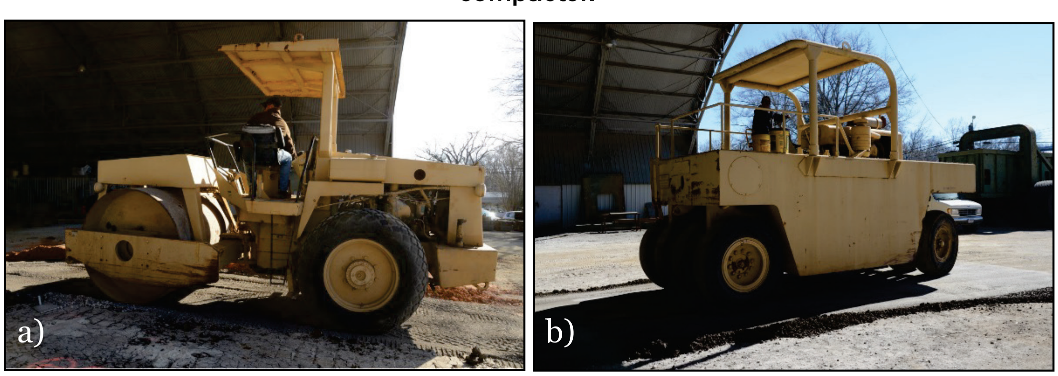


Figure 10. Use of plastic sheet on test strip to prevent soil adhering to the drum.

During the compaction of the first 6-in. lift, NDG readings were obtained after each roller pass or after a series of passes to determine the number of roller passes required to achieve low- and high-compaction levels. This varied for each soil and moisture level. A single sand cone test was conducted at the completion of the first lift along with the CASE and eGauge to provide device calibration for the second lift. Full test data were collected on the second lift at the predetermined low- and high-compaction levels.

3.1.2 Test procedures

Testing was conducted as compaction progressed. Density and moisture content measurements were obtained with two CASE units, the eGauge, and the NDG at two different compaction levels (low and high). Only the high-plasticity clay was tested at one level of compaction. The CH soil compacts very easily when wet making it difficult to identify different compaction levels with the equipment used. Also, when the CH soil is on the dry side of the compaction curve, it is difficult to compact causing a rough compacted surface, which does not allow accurate density measurements. The number of roller coverages required for completing each compaction level varied with soil type and moisture condition. One coverage of the roller consisted of one pass down the test strip and one pass going back.

Figure 11 shows typical test layouts for each test strip. Each test strip was divided into three test areas. At each compaction level, three readings were obtained with each instrument in the three test areas (R_1, R_2, and R_3). A typical instrument layout is shown in Figure 12. Soil samples were obtained from each sand cone test location for standard oven moisture content determination and additional soil samples were collected nearby for moisture content determination using the hot plate (Figure 13 and Figure 14.) Since the soil surface was disturbed after sampling at the low compaction effort, the test locations changed for the high compaction level (i.e., low (L) and high (H)) as shown in Figure 11. The cloverleaf pattern identified in the figures was used once per soil type to observe device precision for the CASE unit by measuring moisture and density in the same location 10 times to note any variance for the same test location (Figure 15).

Figure 11. Typical test item layout.

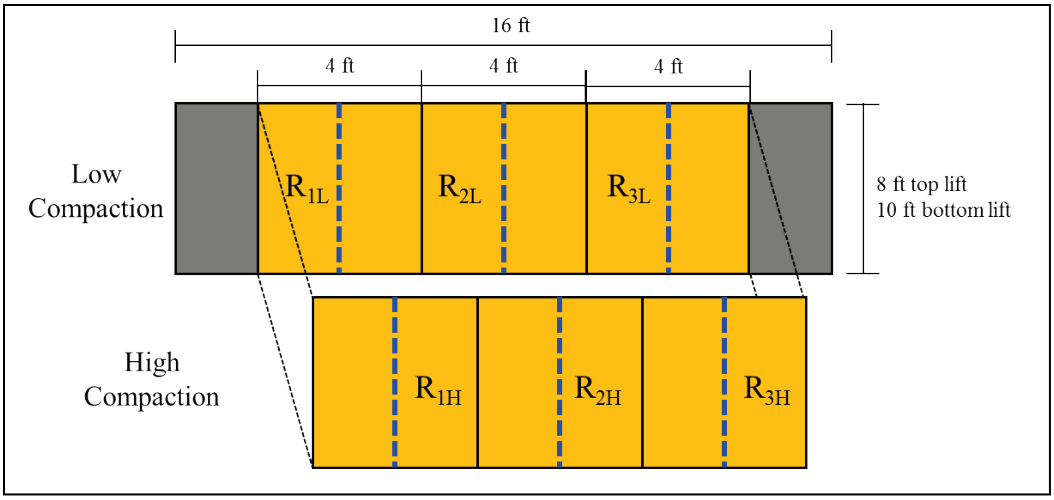


Figure 12. Typical instrument layout.

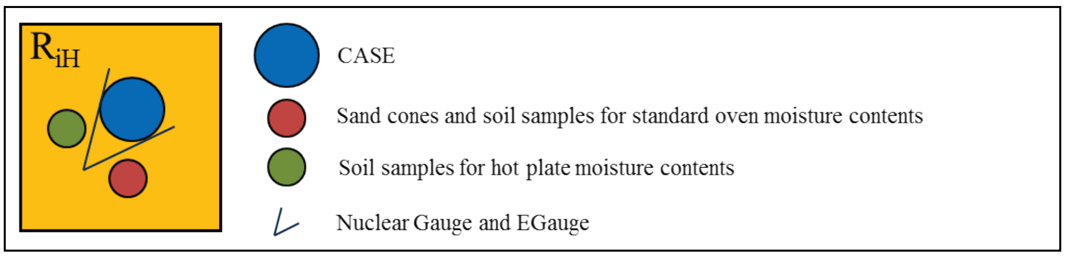
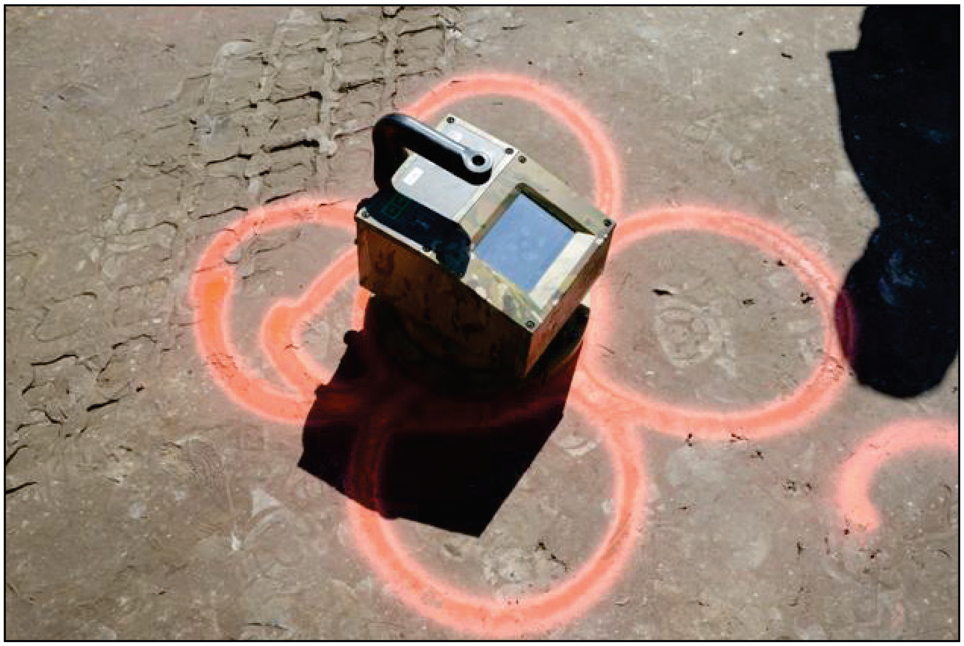


Figure 13. Testing of sand cone density following CASE, NDG, and eGauge measurements and testing of hot plate moisture content inside red ring.

Figure 14. Posttest locations of sand cone and hot plate samples following testing on limestone test section.

Figure 15. Cloverleaf pattern used for precision evaluation of CASE unit.



Sequencing of the test devices began with the CASE unit on the undisturbed surface. This was followed by driving the nuclear gauge compaction rod at each of the three test locations to establish a hole to a depth of at least 8 in. below the compacted surface (Figure 16). The NDG was tested on all three test sites, R1, R2 and R3, at a depth of 6 in., and readings were obtained in two directions around the hole at approximately 90-deg from each other. The NDG was then placed at least 30 ft from the test area before the eGauge was used so as not to influence the low active source in the eGauge device (Figure 17). A wet density was obtained from the eGauge at a rod depth of 6 in., which is a 4-in. depth equivalent for this gauge (Figure 18). Wet densities were obtained in two directions similar to the NDG. Following both the NDG and eGauge density measurements, the moisture probe was then inserted into the hole to obtain the moisture content value that is required to extend at least 8 in. into the soil (Figure 19). The moisture probe was rotated around a 90-deg arc to obtain two moisture readings that coincide with the two eGauge positions.

Figure 16. Driving of the nuclear gauge compaction rod for NDG and eGauge testing.

Figure 17. NDG testing alongside the CASE unit.

Figure 18. eGauge wet density measurement with rod at 6-in. depth.

Figure 19. Insertion of the moisture probe following density eGauge testing.

3.1.3 Internal gauge calibration

The NDG was calibrated each test day prior to use as per ASTM D6938 (ASTM International 2010). This ensured that radiation counts were within the proper limits. The NDG was then used for the remainder of the test day without subsequent calibration.

The combined asphalt and density evaluator (CASE) did not require any pre-calibration prior to collecting data. Its internal software automatically selects the proper regression algorithm to use by analyzing certain features found within the frequency-response curves. The CASE does require calibrated offsets for both wet density and moisture content derived from the sand cone and hot plate. These were obtained from the sand cone wet density and hot plate moisture content on the first completed lift on each test strip and entered into the CASE prior to obtaining data on the completed second lift. This represented a typical field scenario where time to complete an oven moisture content would not be possible to allow operations to continue.

The eGauge requires a standard count be performed on each unique soil to be tested. Therefore, a standard background count was obtained on the completed first lift of each test strip. No moisture calibrations were applied to the readings returned from the eGauge's moisture probe at the time of testing.

3.2 Asphalt test section

3.2.1 Test procedures

To evaluate the ability of the CASE and eGauge to measure asphalt density accurately, measurements were obtained on a series of three different existing dense graded asphalt sections from prior research projects at the ERDC Waterways Experiment Station (WES) campus. Three different sections were selected of varying depth and surface texture. Figure 20 was a well-weathered shoulder section of approximately 4-in. depth with a rough surface texture (RT).

Figure 21 shows a well prepared surface section with a smooth surface texture (ST) and a depth of approximately 4-in. Figure 22 shows a thick asphalt layer (DP) approximately 8-in. thick to evaluate accuracy of the devices with thicker pavement layering. Each asphalt section was marked at three locations where device testing would occur as shown in Figure 22. A generator powered combihammer with a ¾-in.-diameter bit was used to drill a hole for insertion of the NDG and eGauge density rods (Figure 23). The CASE unit was tested adjacent to the hole in a manner similar to Figure 20.

Figure 20. eGauge placed on rough-textured (RT) asphalt section.

Figure 21. Smooth textured (ST) asphalt section (note the transition to RT at top of photo).

Figure 22. Deep (DP) asphalt test section with pencil shown for thickness scale.

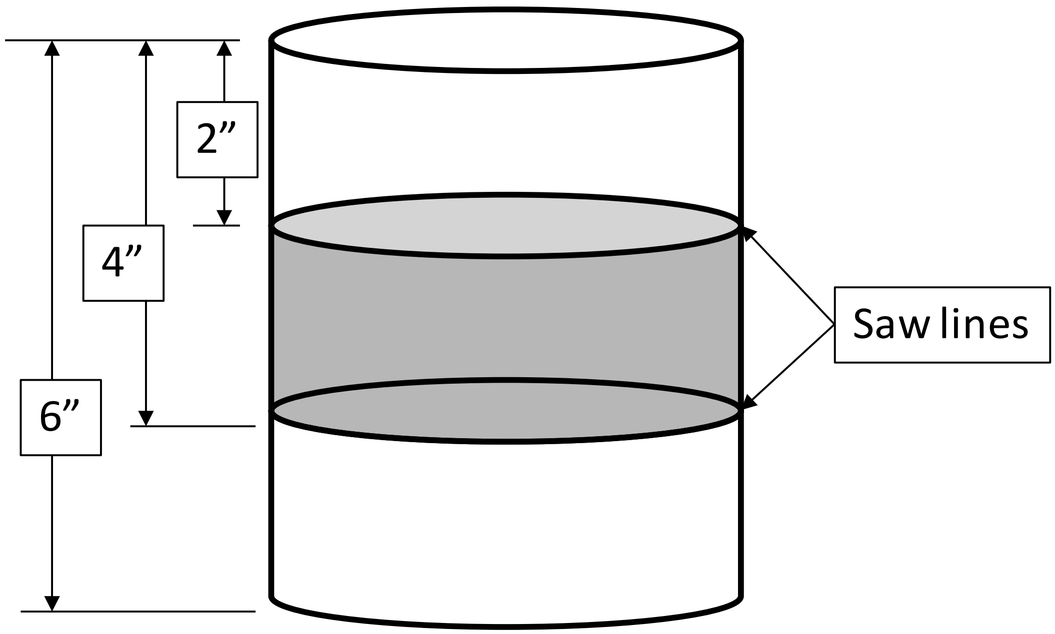
Figure 23. Use of a combihammer to drill holes in asphalt for density probe insertion.

3.2.2 Gauge validation

For this project, core samples for bulk specific gravity determination were obtained at the same test locations as the CASE devices and adjacent to the eGauge and NDG holes following testing of each device. Densities of the asphalt core specimens were obtained according to AASHTO T166 (AASHTO 2011). Four-inch-diam core samples were extracted from the asphalt to the full depth of the layer at each test location (4 in. for ST and RT sections and 6 in. for DP section). Bulk densities were determined from the asphalt cores using the Corelok (ASTM International 2012a) and SSD (ASTM International 2012b) methods in increments of 2 in., 4 in., and 6 in. for the DP samples. For 6-in.-tall cores, the density of the entire sample was obtained, then the bottom 2 in. were sawed off and the 4-in.-

tall core was tested, and finally the last 2 in. were sawed off leaving only a 2-in.-tall core to complete evaluation of the density (Figure 24). A similar approach was taken with the 4-in.-thick core samples where only the 2-in.- and 4-in.-thick densities were obtained. These density values were compared to the backscatter/surface readings of the gauges along with their readings recorded at every 2-in. depth into the pavement. Raw data are listed in Appendix B.

Figure 24. Illustration of core separation to obtain densities at each 2-in. thickness.



4 Data Analysis and Results

4.1 Soil test section

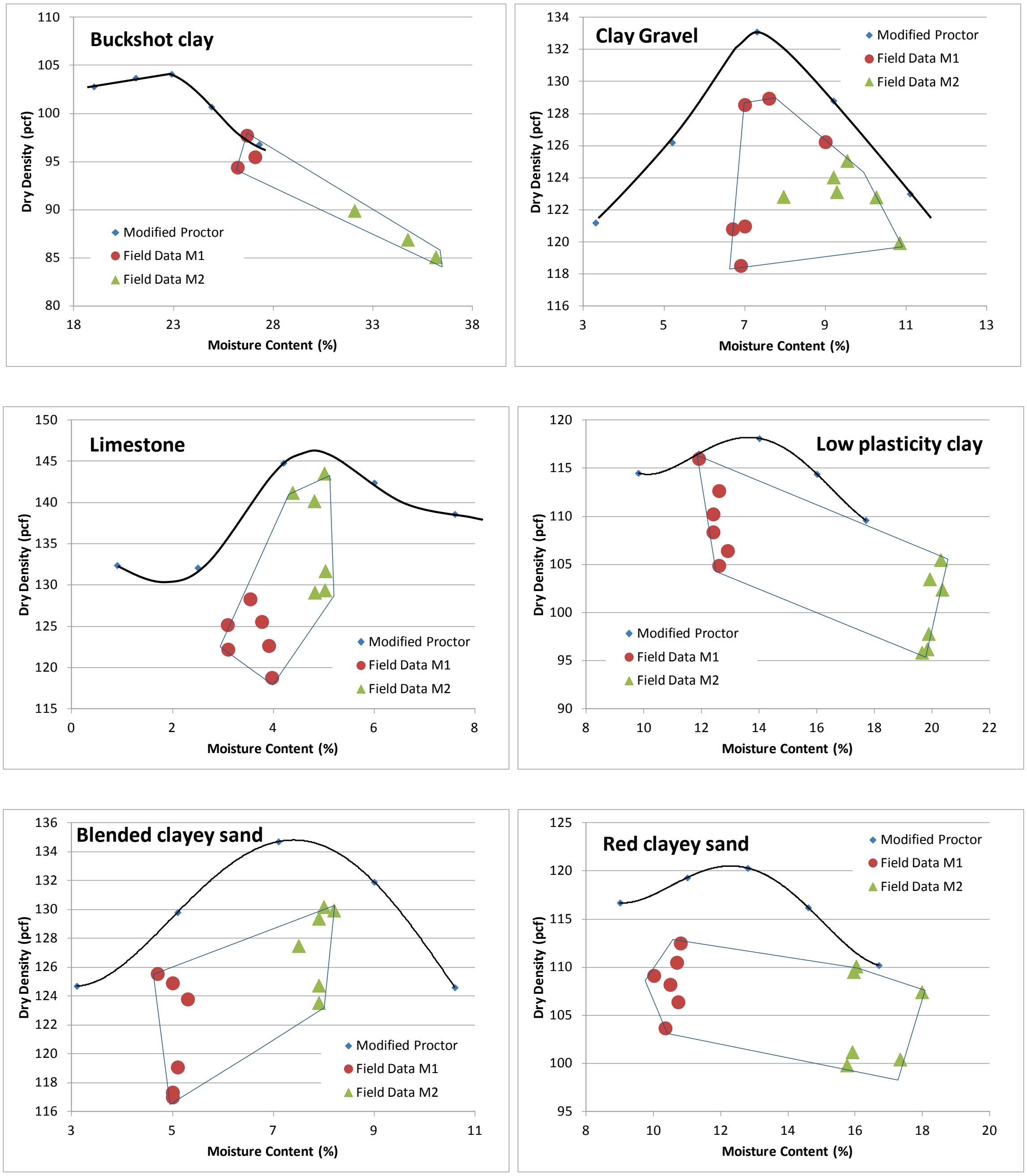
4.1.1 Range of soil conditions evaluated

To provide a means of assessing gauge performance over a range of moisture contents and densities typical of a field construction, each of the six soil types was tested at a high and low moisture along with a high and low density. Attention was paid to ensure that moisture values were near the OMC for all soils except for the Buckshot clay that has inherent constructability problems at dry moisture contents. For all other soils, the relative density ranged from average values of 82 percent to 96 percent of modified MDD for the high-low comparison and an average moisture content range of 1.8 percent below OMC to 3.4 percent above OMC (Table 4). These ranges are considered typical of most horizontal construction activities, and therefore provide a good evaluation of how the devices will capture the necessary data for quality control. Figure 25 illustrates the data points collected during the full scale test section construction with respect to the modified proctor density curve.

Table 4. Range of relative density and moisture content achieved during construction.

				Dry density range		Moisture range	
		MDD	OMC	Max	Min	Low	High
Buckshot	CH	104.3	22.4	94%	82%	-4.3	13.76
Clay Gravel	SC w/gravel	133.1	7.4	97%	89%	0.7	3.44
Limestone	GW-GC	145.7	4.7	99%	82%	1.61	0.33
Low plasticity clay	CL	118.1	13.7	98%	73%	1.3	6.7
Blended sandy clay	Blended-SC	134.8	7.4	97%	87%	2.7	0.8
Red clayey sand	Red-SC	119.8	12.5	94%	83%	2.5	5.5
			Averages:	**96%**	**82%**	**1.8**	**3.4**

Figure 25. Moisture-density range tested for each soil type.

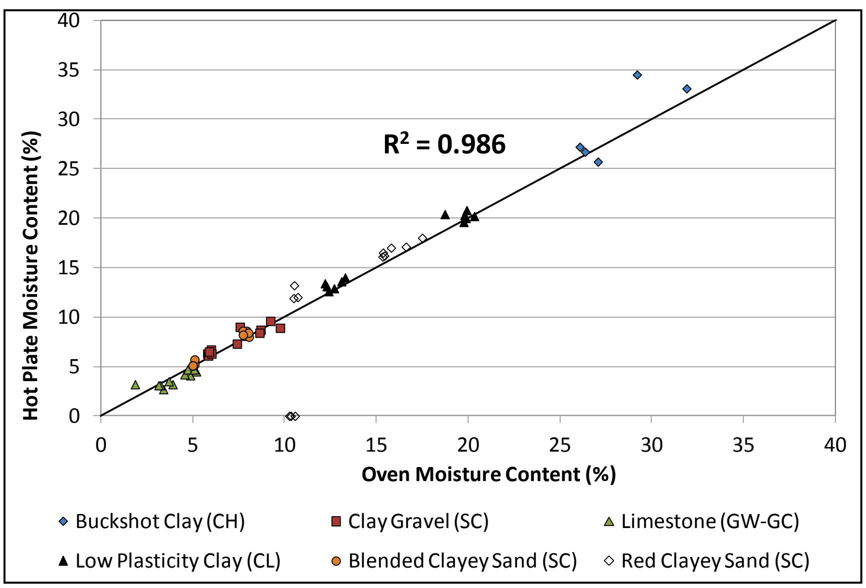


4.1.2 Hot plate moisture correlation to laboratory oven dried procedure

A previous study by Berney et al. (2013) identified a number of alternatives to measure field moisture content without the use of a conventional oven or NDG. The open flame burner was determined to be the most accurate technique of all those tested being superior even to the NDG. At the time of the study, the hot plate method was not tested, but independent studies at ERDC suggest it could be used as a reliable alternative, since it is similar in function to the open flame burner. For each test location used for determining density, a separate soil sample was obtained and split between the oven and a hot plate to provide a one-to-one comparison of moisture content. The hot plate soil sample was dried until less than a 1 percent change in overall soil mass occurred, and the oven dried soil was dried according to ASTM International (2008) as outlined in Chapter 2.

A comparison of moisture contents across all soil samples tested is shown in Figure 26 with a resultant coefficient of determination of 99 percent. This indicates that for soils of both high and low moisture contents, proper use of the hot plate can yield moisture content values with accuracy exceeding that of the NDG. These results compare favorably with the accuracy of the open flame burner. Therefore, the hot plate system can be used as a rapid field technique to validate and calibrate moisture readings obtained from either the CASE or the eGauge to ensure that proper data are obtained from each device.

Figure 26. Comparison of hot plate versus oven dried moisture content techniques.



4.1.3 CASE calibration

It was noted in the literature review that, for the CASE gauge to return moisture content and wet/dry density data in the proper range, it must be calibrated with some secondary moisture and density device. In this study, the sand cone and the hot plate were used for this purpose. To determine the effectiveness of this approach, Figure 27 and Figure 28 illustrate that a one-to-one comparison of sand cone to the NDG for wet density and dry density returned R^2 values of 87 percent and 95 percent, respectively. This suggests that using the sand cone wet density and hot plate moisture content to calibrate the CASE should enable this device to return the correct values.

Figure 27. Comparison of wet density between sand cone and NDG.

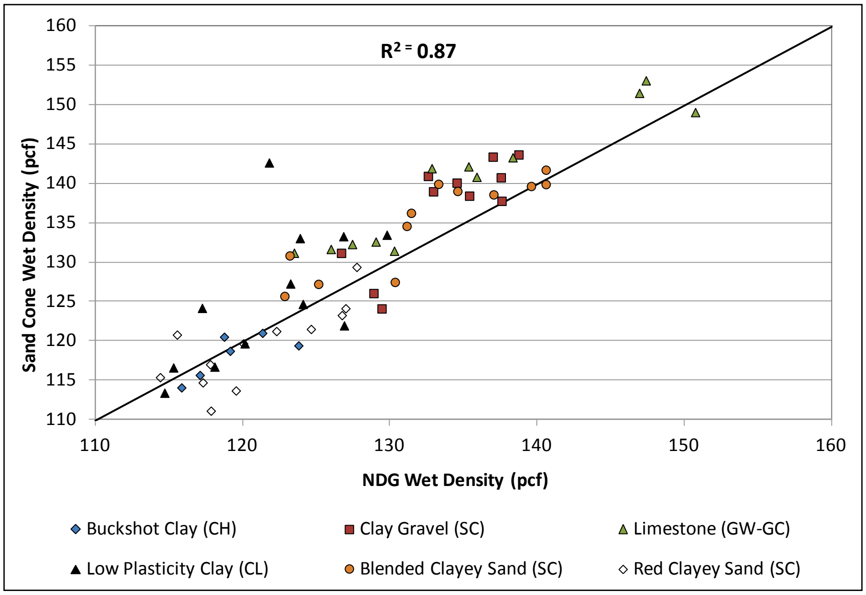
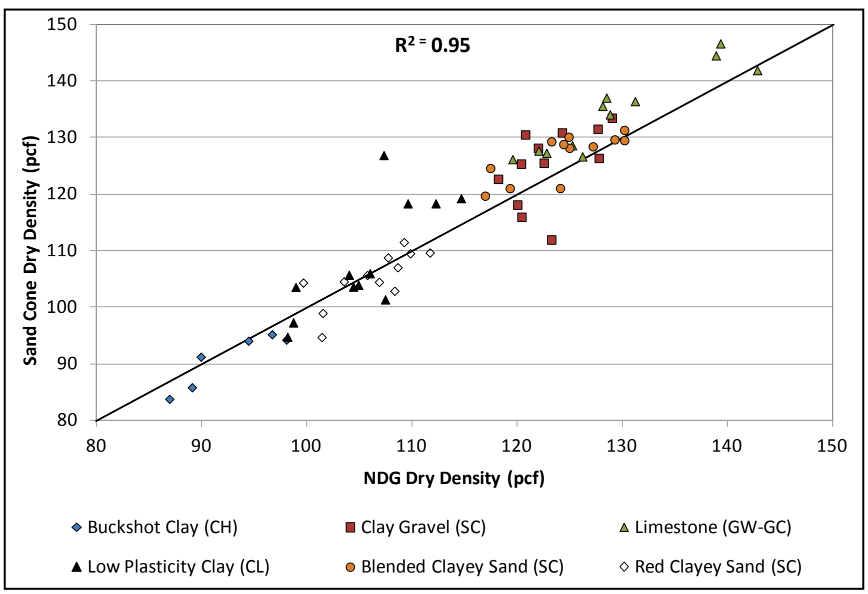


Figure 28. Comparison of dry density between sand cone and NDG.



To calibrate the CASE unit for this study, the device was placed on the soil of interest in a prepared condition similar to expected during construction, in this case following the final roller pass on the first lift. A wet density and moisture content reading were then obtained. A sand cone test was conducted directly below where the CASE gauge was tested, and a sample of soil was obtained from the sand cone spoils to conduct a hot plate moisture content and an oven dried moisture content for validation.

Figure 29 and Figure 30 show the wet density and moisture content differentials occurring between the raw CASE readings for the two replicate gauges CASE 1 and CASE 3 and the calibration method. There exist two distinct trends of the differential; as both wet density and moisture content of the true soil density increase, the magnitude of the offset increases as well. The density and moisture content have opposing parabolic trends in their responses such that when combined in Figure 31, the dry density is represented by a linear offset with a high R^2 of 97 percent. While this calibration seems to provide the proper correction to the CASE readings, it is somewhat disconcerting that the initial readings of the CASE are so far from the true value. This suggests that the internal calibration mechanisms in the gauge lack the ability to properly interpret soil type to correct initial readings.

Figure 29. Wet density differential for CASE gauge during calibration.

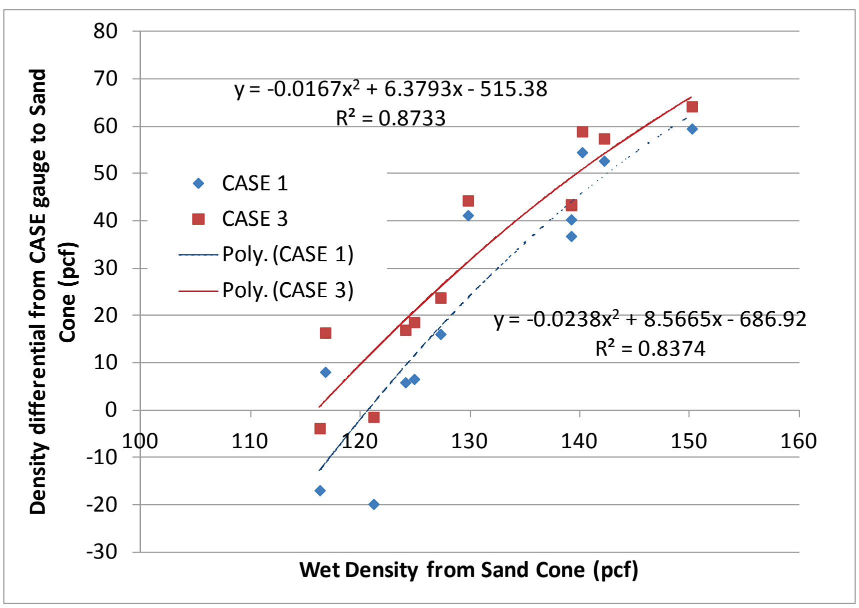


Figure 30. Moisture content differential for the CASE gauge during calibration.

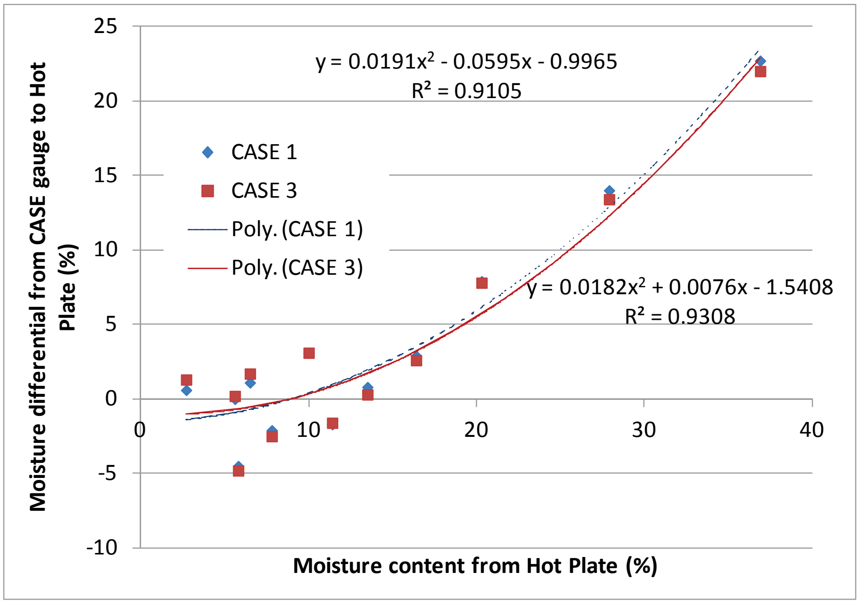
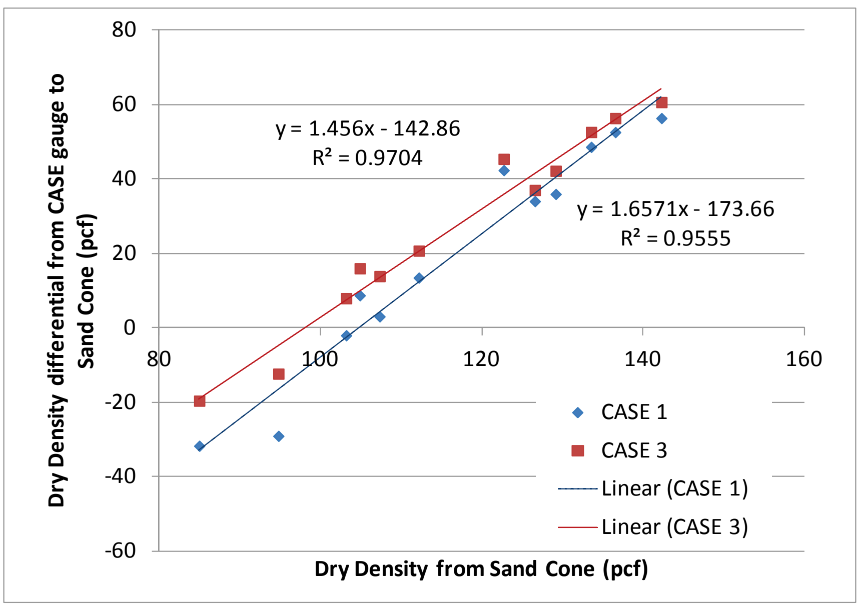


Figure 31. Dry density differential for the CASE gauge during calibration.



4.1.4 eGauge calibration

The eGauge does not require a standard count calibration like the higher radioactive sources in the NDG. However, because the eGauge is so sensitive to background radiation, a standard background radiation count at the test location or soil of interest should be performed prior to collecting wet density data. For this study, the eGauge was placed on the soil of interest prior to testing on the first compacted lift, and a standard background radiation count was obtained on the device. The wet density was performed first, followed by the moisture content reading with the electronic probe. The probe was rotated in the hole, and the highest observed moisture read was noted in the data sheets as this tended to be the closest approximation to the actual moisture content and suggested good sensor contact with the soil face.

The sand cone moisture sample could be used as a calibration tool for the moisture reading on the eGauge. For this study, an observation was made between the moisture content and the eGauge to determine if an offset was necessary and, in most instances, the tested moisture content differential was ± 1.5 percent on average and not considered substantial enough to include as an actual correction. This is similar to the offsets normally encountered in the NDG that are usually ignored during construction operations. When applied, the moisture calibration is similar to the CASE in that the moisture content is computed from the oven or hot plate and a linear offset is applied to the moisture content returned from the eGauge. No calibration offsets were applied to the wet density, similar to the NDG approach, and the resultant wet density was used directly in all comparisons.

4.1.5 CASE and eGauge correlations to NDG

Following data collection, the calibration offsets were applied to the CASE readings, and the eGauge was used without any offsets. Data were obtained from two different CASE gauges. To simplify the analysis, the average of the readings obtained from gauges CASE 1 and CASE 3 were used for comparison to the NDG. Figure 32 and Figure 33 illustrate the overall correlations of wet and dry density for the eGauge and the CASE devices versus the NDG. The eGauge exhibited a high correlation with R^2 = 94 percent for both wet and dry density, whereas the CASE exhibited a lower correlation with 59 percent and 84 percent for wet and dry density, respectively.

Figure 32. Correlation of eGauge density to NDG.

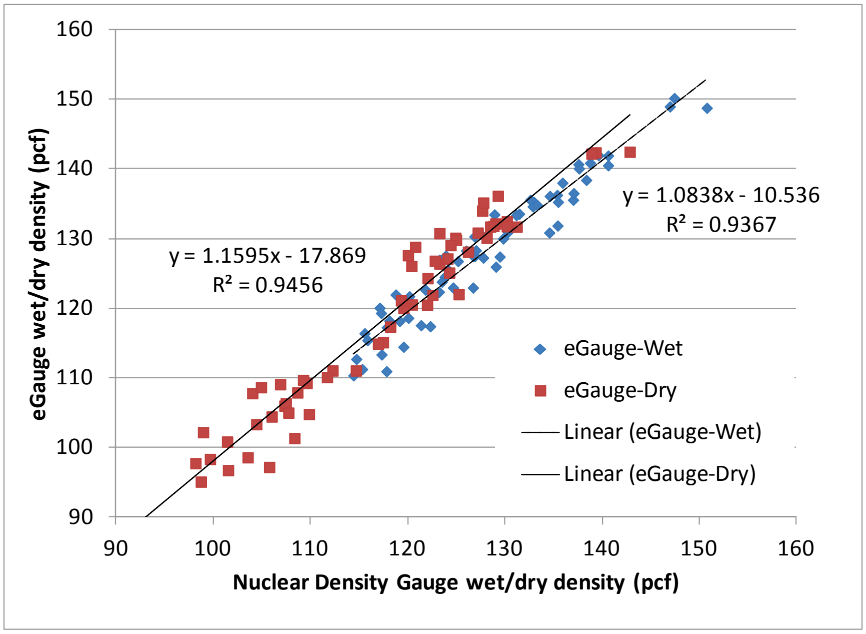


Figure 33. Correlation of CASE density to NDG.

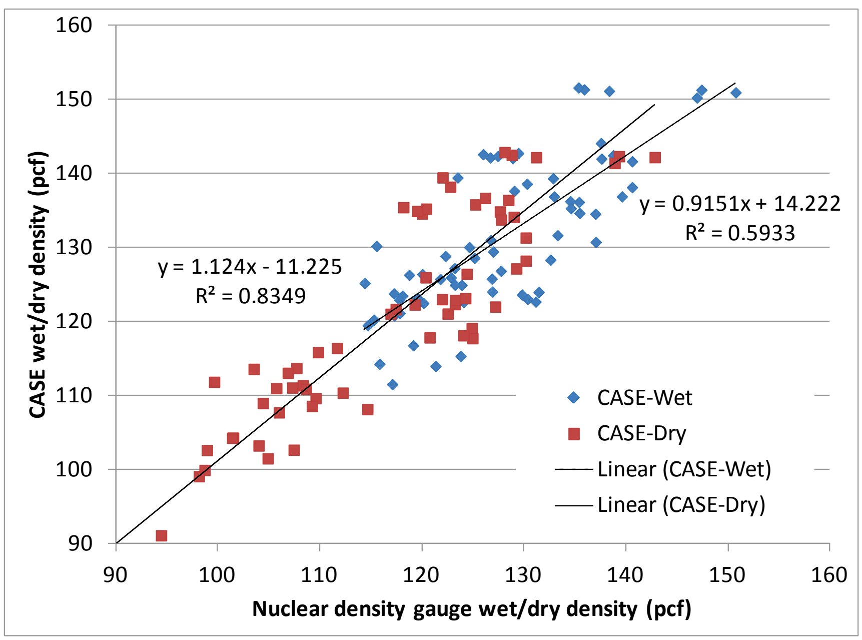


Figure 34 and Figure 35 show the correlation of the device moisture content readings to the NDG and the oven dried moisture technique. The CASE exhibits a high correlation to the oven dried moisture content which helps offset the poor wet density correlation producing a suitable dry density. The eGauge moisture content has a lower correlation near 86 percent with much of this error being attributable to the fluctuation of moisture readings while maneuvering the electronic probe in the ground.

Figure 34. Correlation of eGauge moisture content to NDG/Oven.

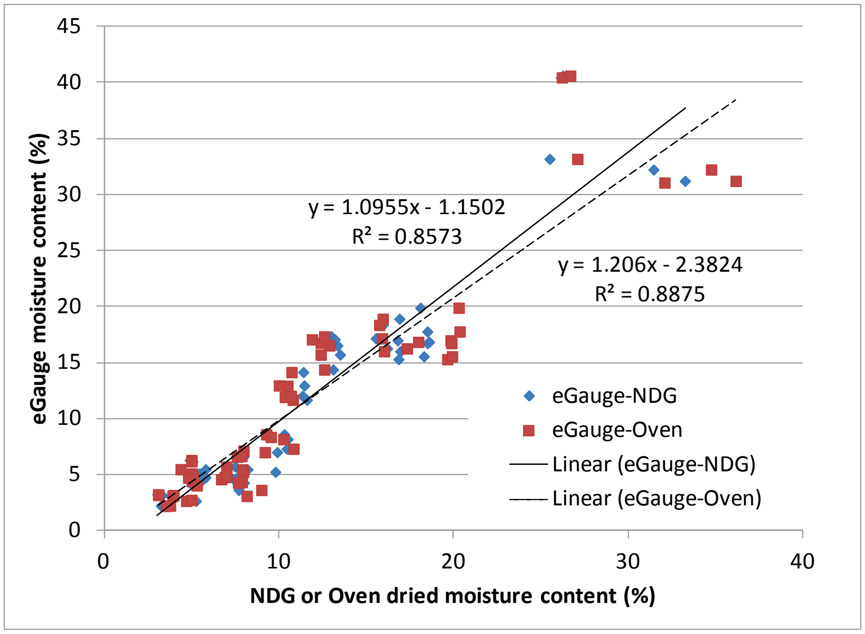
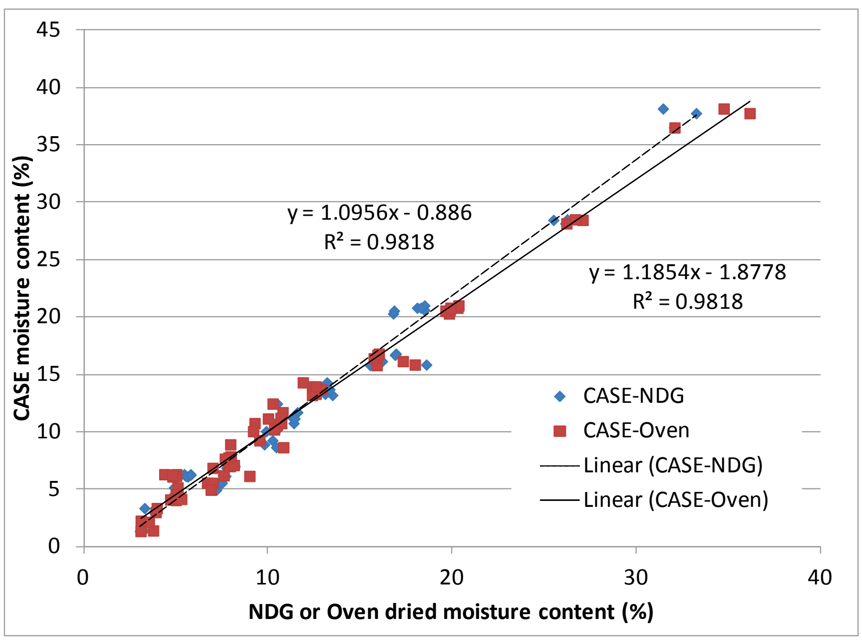
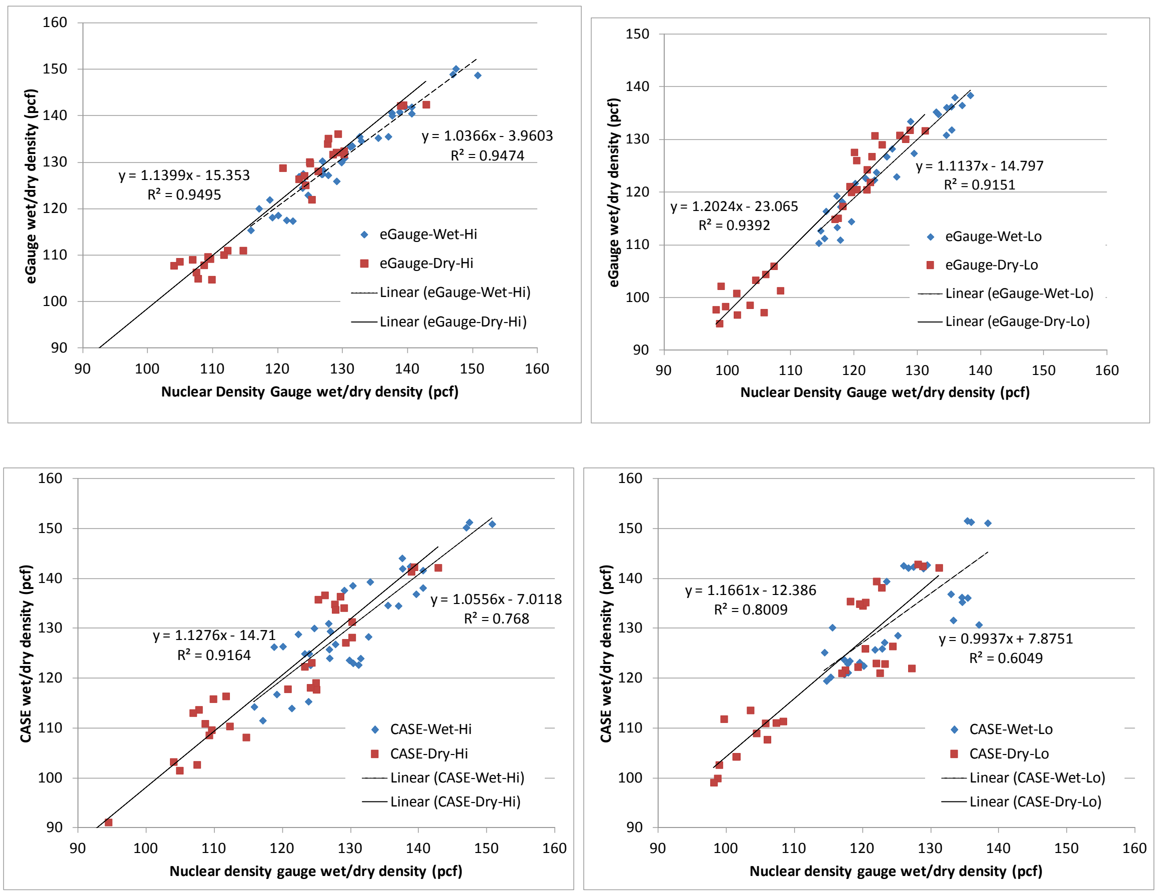


Figure 35. Correlation of CASE moisture content to NDG/Oven.



The prior correlations represent the device response when considering all the varying soil classifications combined. Such high correlation values, when all soils data are considered, indicates the CASE and eGauge are able to accurately distinguish moisture-density response between soil types; for example a clay displays a much lower dry density than a limestone and the reverse is true for moisture content. However, of more importance is the ability of each gauge to measure small changes in density within a single soil as compactor passes or moisture changes from one test section to the next. Figure 36 illustrates the correlations between high and low compaction levels for all soils combined. These plots show a loss of fidelity between the eGauge and the CASE compared to the NDG when testing on the same soil at a few versus many roller passes.

Figure 36. Comparison of density between eGauge and CASE to the NDG at both high (HI) and low (LO) compaction efforts.



The eGauge continues to show a high level of accuracy for both wet and dry density, with a change in correlation from 95 percednt at high compaction to about 92 percent at low compaction. This suggests the eGauge can detect subtle changes in density during compaction operations, a key measure in quality control. The CASE gauge has a larger change in correlation of dry density going from a 92 percent correlation at high compaction but dropping to 80 percent at low compaction efforts. Wet density has an even poorer correlation for the CASE, which does not have the moisture calibration to improve its accuracy.

To assess the measurement capability of each gauge within a unique soil type, comparisons of wet and dry density of the eGauge and CASE to the NDG for each individual soil type tested are shown in Figure 37 and Figure 38. The correlations include both moisture content levels tested (for all soils but CH) and the High-Low density values at varying pass levels.

Figure 37. Comparison of dry density between CASE and eGauge versus NDG by soil type.

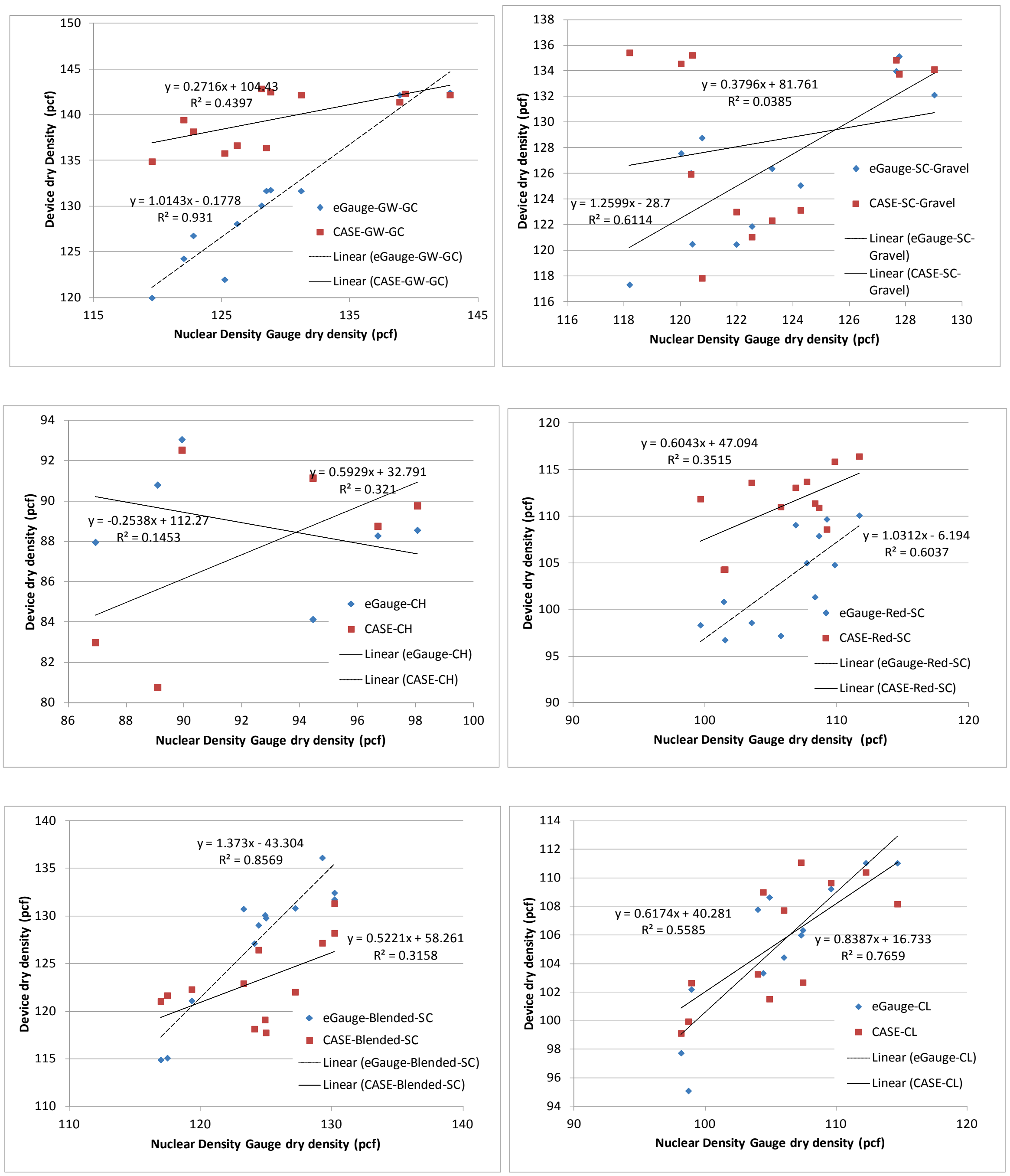


Figure 38. Comparison of wet density between CASE and eGauge versus NDG by soil type.

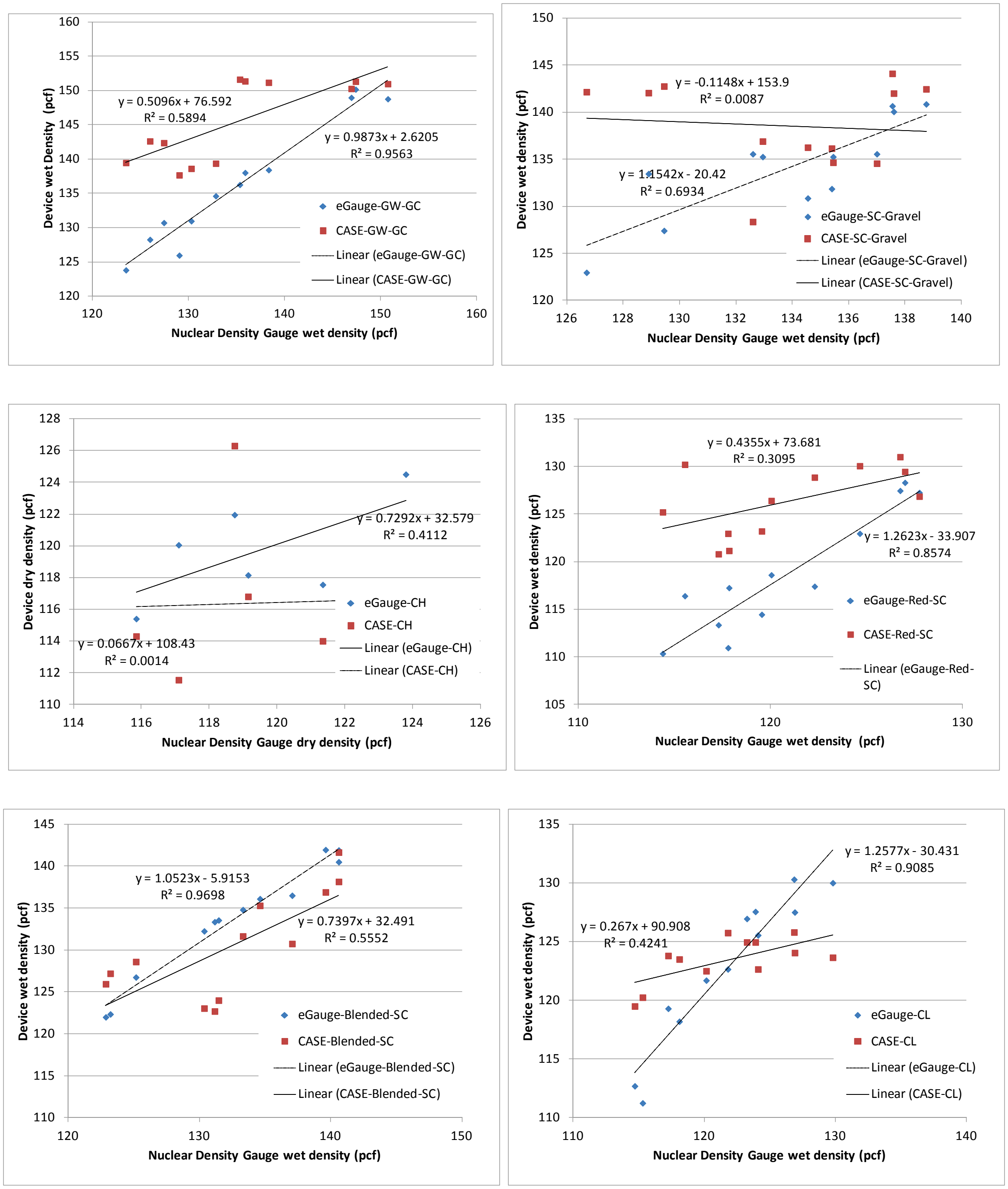
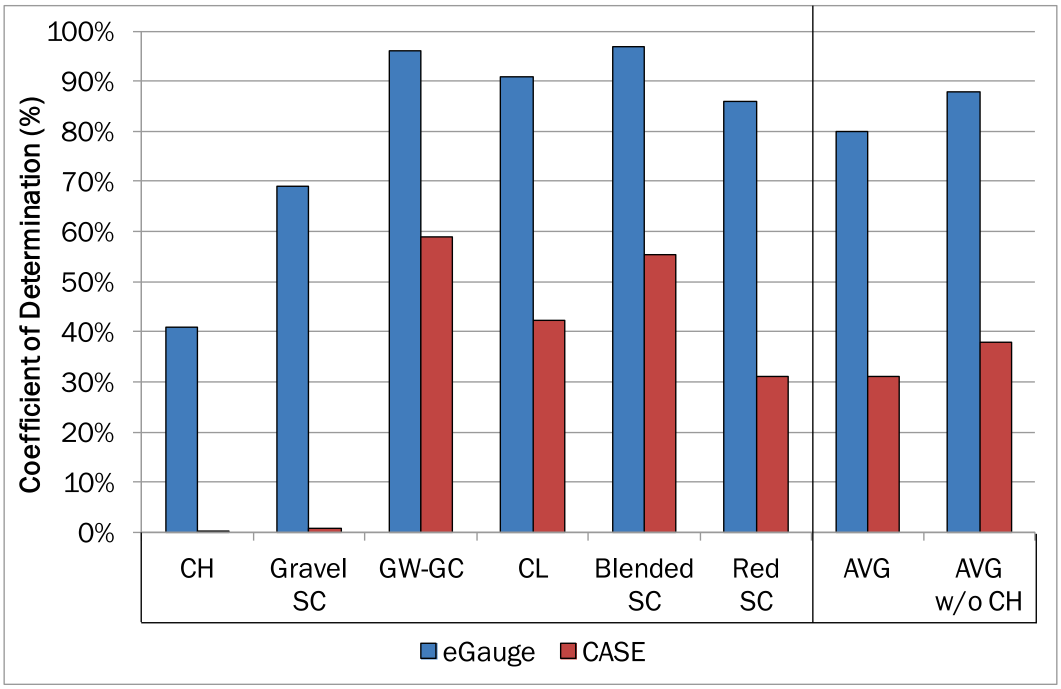


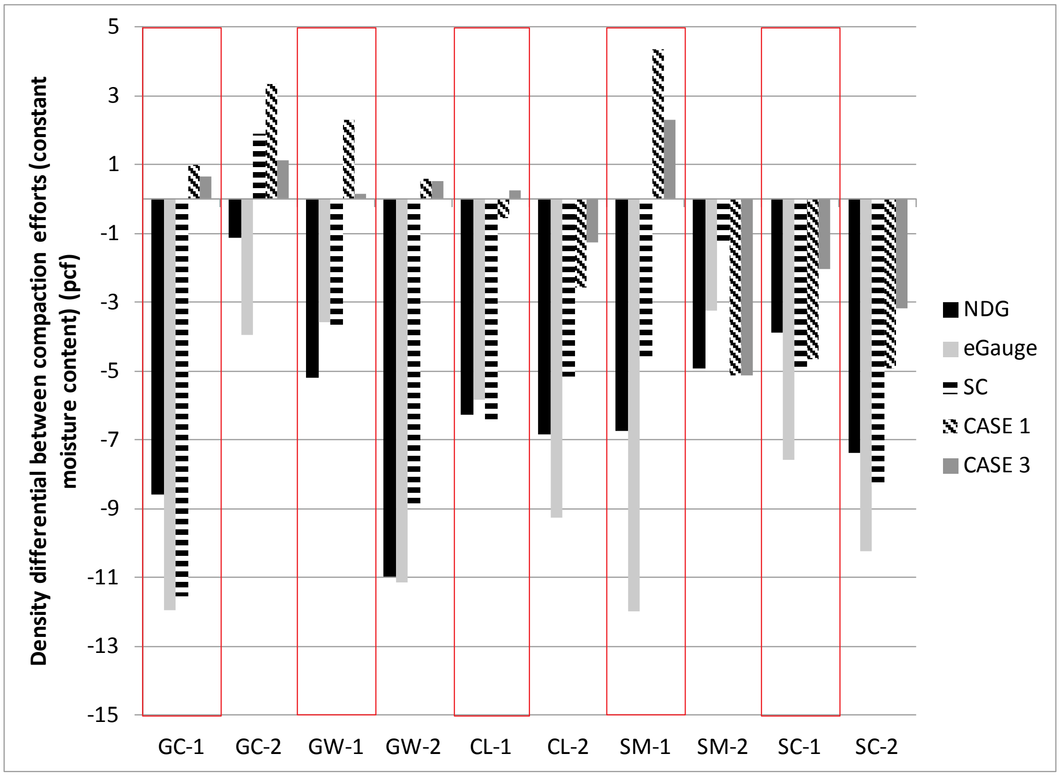
Figure 39 summarizes the coefficients of determination for each gauge and each soil type in both the wet and dry density comparisons. The eGauge was far superior to the CASE unit for all soils tested showing the best correlation in the wet density configuration. The average correlation of the eGauge versus the CASE unit was 75 percent versus 35 percent for dry densities and 88 percent versus 38 percent for wet densities, suggesting the eGauge has the ability to capture small changes in density during compaction operations for a unique soil, whereas the CASE is incapable of providing this type of information. The CASE readings tended to be too random to provide subtle density differences that are critical to establishing end of compaction operations during quality control. Neither gauge was effective at capturing density changes for the heavy Buckshot clay material (CH).

Figure 39. Density correlation by soil type between eGauge and CASE to the NDG.



This behavior is further emphasized in Figure 40, which shows the average change in dry density between the low and high density test items for each soil type and moisture content. All the bars should move in the same direction and be of similar height, as there should be a large change in density and always increasing with passes. However, the CASE data often has little differential or the bars move in the opposite direction to the other density techniques. For most of the test items, the CASE unit recorded a higher density at the low compaction effort and a lower density at the higher compaction effort. This is counter to the actual field response noted in the NDG and sand cone devices. This is a dangerous precedent set by the CASE, as it suggests little confidence can be placed in the density readings it provides during field construction.

Figure 40. Density differential between compaction efforts by soil type for each density test procedure.



4.1.6 Summary of performance

4.1.6.1 Error in moisture sensor for eGauge

The eGauge provides an excellent reproduction of the wet density because of a similarity to the NDG in the radioactive source technology that is used. However, the introduction of a secondary electronic probe for moisture content measurements is a less accurate technology than the neutron emissions from the NDG. In practice, the eGauge can yield an even greater error than that reflected in the correlation plots owing to the technique used to insert the gauge. To properly conduct the moisture experiment, the manufacturer recommends insertion of the moisture probe into the pre-drilled rod hole prior to insertion of the density rod or in a secondary hole adjacent to the density hole. This has the advantage of allowing the moisture probe to have better sidewall contact with the hole which is critical to obtaining the best possible moisture reading. However, extraction of the moisture probe can cause collapse of the sidewalls and prevent obtaining a density reading, as noted by the researchers in preliminary studies on the moisture probe. Friable soils like silts or a dry limestone, as well as many coarse grained soils, tend to have trouble maintaining an open probe hole when disturbed by the moisture probe. To mitigate this effect during the study, the moisture probe was inserted after insertion of the density rod to ensure that moisture and density readings occurred at the same location along with the NDG rod. The moisture probe still maintained good sidewall contact as the density rods did little to disturb the hole, but it was noted that often the initial moisture reading was low compared to the expected value. The operator would then rotate and jostle the moisture probe, continually observing the moisture measurements on the digital display as the probe had better or worse sidewall contact, and noted the highest reading displayed. The correlations shown in Figure 34 were based on the highest reading obtained by the moisture probe in this rotating pattern. This subjectivity to obtaining the moisture reading may put the point-wise accuracy of this feature of the eGauge into question. It is recommended that a hot plate or alternative moisture content be taken on the soil of interest to ensure that the eGauge is obtaining readings in the proper range.

4.1.6.2 Error in the CASE unit

As noted in Berney et al. (2013, 2014), the CASE gauge requires calibration with a secondary moisture and density device prior to its use as the internal algorithms do not provide a valid moisture or density reading. This process was implemented in this study and Figure 29 and Figure 30 show the extent to which the initial CASE readings varied from the sand cone density and hot plate moisture contents before a linear offset was applied.

The CASE exhibited an ability to accurately capture the moisture content across almost all soil types when properly calibrated. The use of electrical impedance in the CASE's frequency band is optimal for this type of reading. However, this same frequency band has difficulty picking up subtle changes in soil density, which is evidenced in Table 5. The CASE unit is not a functional tool for determining changes in density during the compaction process. Readings on the CASE can be misleading to the user as to whether a threshold density has been reached. Because of calibration issues, the CASE cannot be used as a forensic tool but rather only in a continuous duration horizontal construction, which is a similar conclusion to that drawn in Berney et al. (2014).

4.2 Asphalt test section

4.2.1 Summary of performance

Table 5 is a summary of the average bulk density values collected from the ERDC asphalt test sites. A zero-inch depth of measurement refers to a backscatter reading obtained with the NDG or a non-destructive surface reading from the CASE unit. All of the reading depths below 0 in. occurred from the insertion of the density rod into a cored hole in the asphalt for the NDG and eGauge devices. The CASE Corr is the corrected value of density from calibration of the CASE unit to the first core sample taken from each test location similar to the approach recommended in Berney et al. (2014). To provide a comparison between the CASE data and the core samples, the core density for a 2-in.-tall sample was used as this represents the data closest to the surface. All other core densities represent the density of the asphalt over the thickness noted.

Table 5. Average asphalt density readings for the tested devices.

	Depth to	Average Density (pcf)				
Sample Type	easureme	Core	NDG	eGauge	CASE	CASE Corr
RT-Rough Texture	0"		140.2		139.2	143.1
	2"	143.3	139.9	140.8		
	4"	145.1	141.6	144.4		
ST-Smooth Texture	0"		145.7		146.2	145.7
	2"	143.3	141.2	141.0		
	4"	145.1	143.1	142.1		
DP-Deep Sample	0"		123.2		133.8	143.1
	2"	141.8	136.5	138.8		
	4"	141.3	135.8	136.9		
	6"	141.3	135.8	136.9		

For the NDG, the average density differential between the core samples and the NDG readings is approximately 5 pcf in the current study (Table 5).

4.2.2 CASE and eGauge correlations to NDG and core samples

It was noted in Berney et al. (2014) that the calibrated CASE unit performed better than the NDG for warm and hot mix asphalt mixtures placed during construction. The CASE unit exhibited the lowest standard deviation from the core density for these material types. In the current study, the data were scattered when looking at the average density deviation from the core value of each asphalt type, as there were not enough samples taken for a standard deviation comparison (Figure 41). When calibrated, the CASE unit achieves the best results only for the DP asphalt layer whereas the eGauge proved to be the most consistent device across all asphalt types. The CASE gauge's accuracy to the core samples is improved when calibrated, but it results in a poorer correlation to the NDG unit. The eGauge provides an improvement over the NDG in density differential with the cores. Given the consistent offset magnitude of the NDG across asphalt depths and types noted earlier, the eGauge should similarly provide a more accurate estimate of the true core density.

Figure 41. Average deviation of asphalt bulk density between NDG, CASE, and eGauge versus core samples.

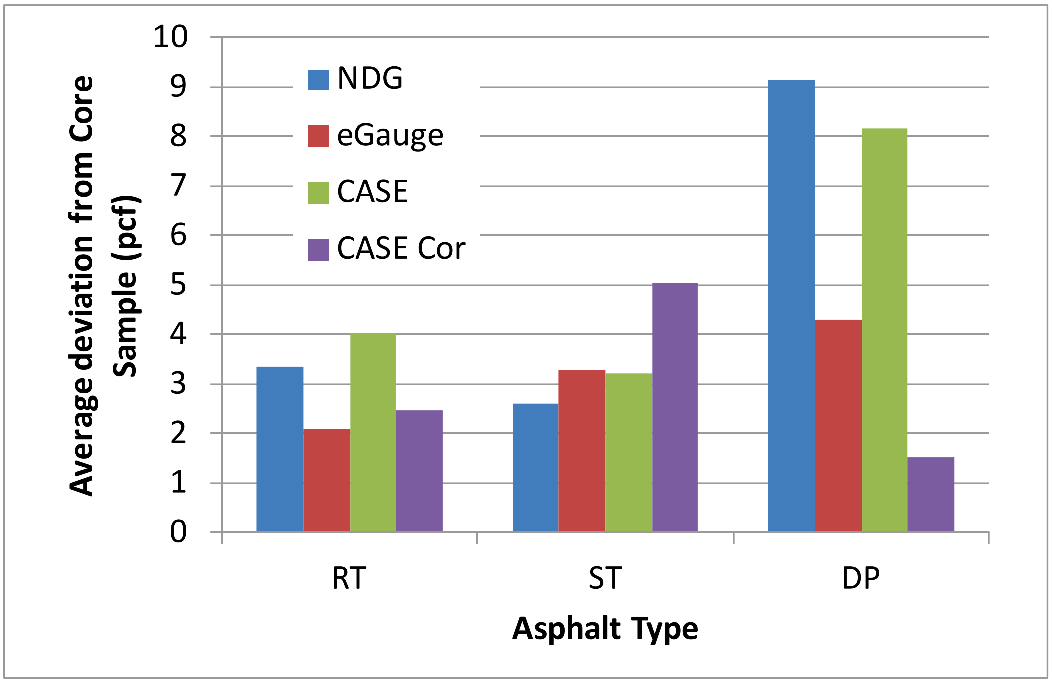


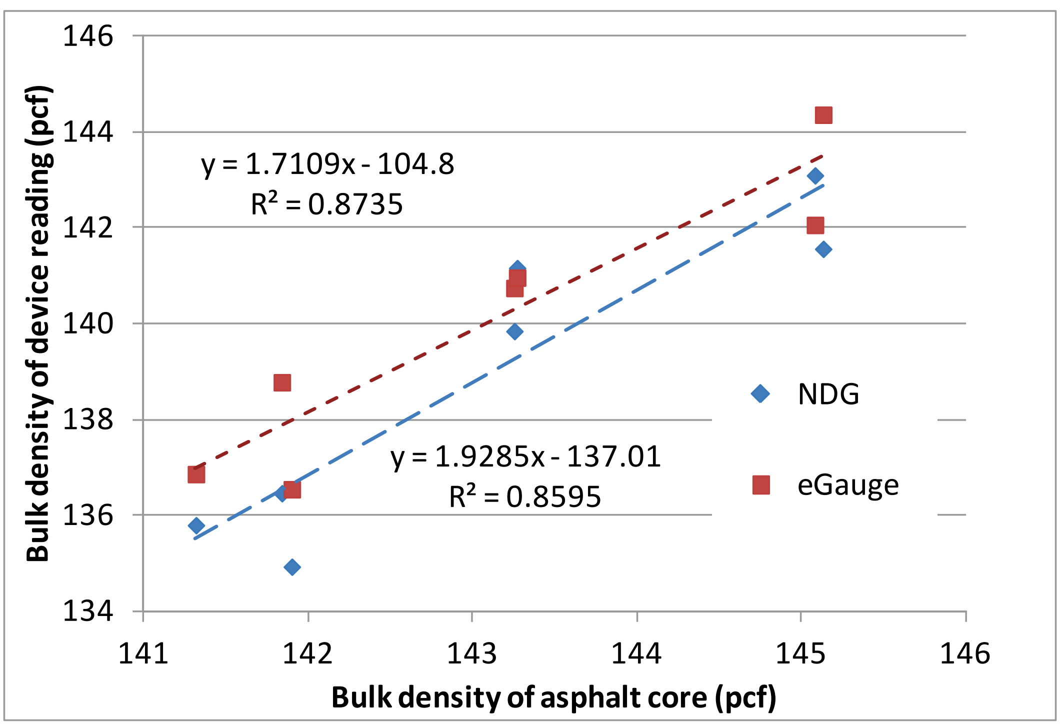
Table 6 displays the summary correlation of determination across all the devices tested along with all the asphalt cores. What is evidenced in this chart is that the eGauge has the highest correlation with the core samples (87 percent), and the NDG has a high correlation with the CASE (87 percent). This is notable in that the CASE was designed to approximate the backscatter readings of the NDG. The raw eGauge and the NDG data do not agree well (49 percent) when comparing density with the probe inserted into the asphalt. However, when comparing the averages across each asphalt type, the eGauge compares similarly to the NDG (Figure 42). It is unclear why the poor correlation when comparing the test items side by side.

Table 6. Coefficient of determination between each test device and the core samples.

Coefficient of Determination between Device Types					
	Cores	NDG	eGauge	CASE	CASE Corr
Cores	--	0.61	0.87	0.18	0.12
NDG		--	0.49	0.87	0.37
eGauge			--	0.63	0.26

For many years, the NDG has been used as the reference standard in the field lending confidence to the eGauge device for down-hole measurements and the CASE device for the surface readings. The advantage of the eGauge is that it can acquire its density without field calibration unlike the CASE unit. The disadvantage is that a hole must be drilled into the asphalt to obtain the reading unlike the non-destructive NDG and CASE units. The eGauge is not the most ideal device to use for obtaining production asphalt densities during construction; this would favor the CASE device although it correlates poorly with core density. When performing site investigations or forensics of existing asphalt structures, the eGauge becomes well-suited, as it does not require an asphalt core for calibration, which is logistically impractical.

Figure 42. Comparison of AVERAGE asphalt bulk density versus NDG and eGauge for all depths tested.

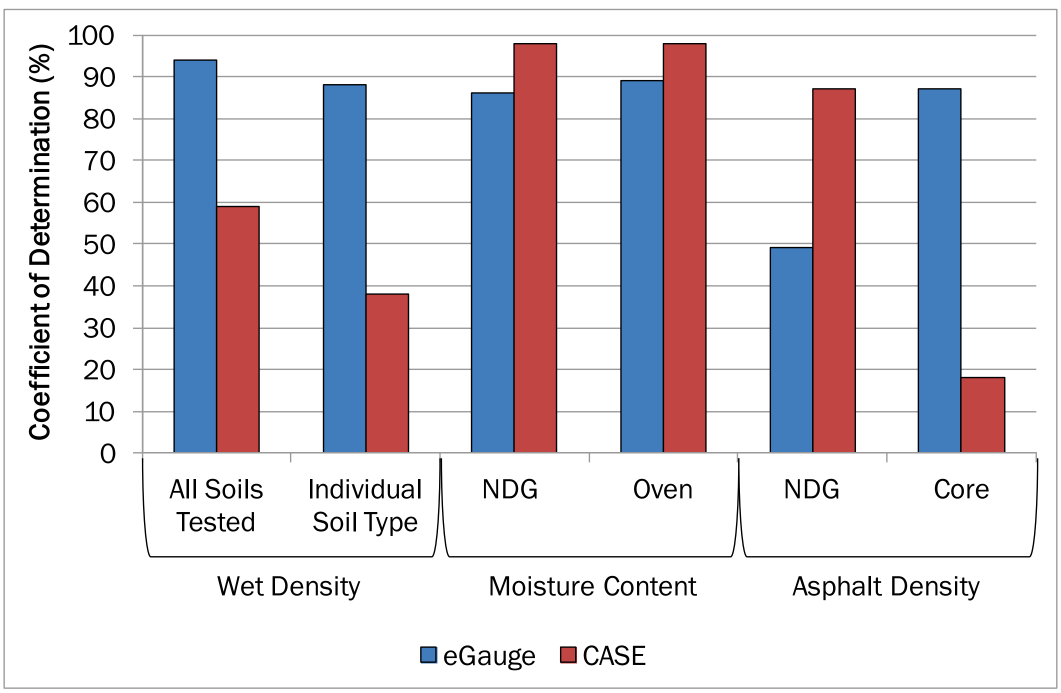


5 Conclusions and Recommendations

5.1 Conclusions

The goal of this research effort was to identify a non-nuclear testing device that could perform the same functions as a nuclear density gauge (NDG), measuring field moisture content and density, with similar accuracy. This report summarized an effort to validate the performance of two non-nuclear device platforms, the TransTech Combined Asphalt Soil Evaluator (CASE) and the Troxler eGauge for determining field moisture content and density. The CASE unit was the leading electronic alternative gauge, and the eGauge was the leading hybrid electronic-low source nuclear device with measuring characteristics mirroring its nuclear density counterpart. One-to-one comparisons were made between the NDG, the eGauge, and the CASE units on six different soil types of varying densities and moisture contents along with three varying asphalt sections. Figure 43 provides a summary of the data findings derived from this validation study.

Figure 43. Summary data from validation study for each device.



5.1.1 Soil density

- The eGauge was found to capture the wet and dry density far more reliably than the CASE and was able to do so without requiring any calibration to a secondary moisture/density test device as was the case for the CASE.
- The eGauge was far superior to the CASE in determining the density of individual soil types during the compaction process. This is a significant finding as the CASE is unable to provide the operator knowledge of when compaction operations have reached their desired state whereas the eGauge does have this ability.

5.1.2 Moisture content

- The calibrated CASE unit (calibrated to soil dried on an electric burner) was able to capture the moisture content more accurately than the eGauge. However, the use of the eGauge without calibration is considered an advantage even with a slightly lower accuracy.
- In many instances, moisture content in the field is obtained through a secondary process, many of which are simple in operation, and so accuracy of this measurement is not as critical as the density.

5.1.3 Asphalt density

- The eGauge matched closest to the density of the core samples and exhibited less variance than the NDG whereas the CASE was the closest match to the NDG readings.
- The requirement to have a drilling device on hand to drill a hole in the asphalt limits the suitability of the eGauge to performing this type of measurement.
- The integrated TransTech Pavement Quality Indicator asphalt density technology incorporated into the CASE device has a proven track record of success in prior studies and should be considered as an advantage over the eGauge.

5.2 Recommendations

Based on the results from this investigation, the following recommendations are made.

5.2.1 Soil density and moisture content

- The eGauge is the superior device for measuring wet and dry density of soil during construction operations comparing most favorably to the NDG.
- The requirement to have a calibration technology on hand to operate the CASE unit in soils for both density and moisture content is considered detrimental to its use, and the CASE should not be considered a viable soil device for military operations
- While moisture measurements are more accurate using a calibrated CASE device, the advantage goes to the eGauge which, without calibration, provides a reasonable estimate of the soil moisture. Calibration of the eGauge to a secondary moisture device can only improve its accuracy.

5.2.2 Asphalt density

- The CASE is the recommended tool for obtaining asphalt density for construction operations when non-destructive methods are preferred or required (calibration of the device to an asphalt core may still be required).
- The eGauge is recommended for scenarios when drilling is available and density without device calibration is required. These scenarios might involve contingency evaluations or spot testing on unknown pavement layers.

5.3 Areas for future study

The process to identify a replacement to the NDG was initiated 5 years ago, and rapid changes in technology have made selecting a commercial device a moving target. A down-selection of modern devices was made in 2010, with the TransTech Soil Density Gauge being selected as the best candidate. However, the CASE device was developed by TransTech prior to the next validation study and was included in a side-by-side analysis with the SDG. The performance of the SDG and CASE devices was found lacking, and a final attempt to understand these device limitations was initiated for the current study. The eGauge was released just one week before the current study began and appeared to be the type of technology the military has been seeking.

Based on the results of this study, the eGauge is currently the best technology to provide a high quality soil moisture-density reading as a replacement to the NDG. However, the eGauge lacks extensive field use in the private and military environments, and its long-term performance could certainly reveal limitations that are not obviated in this study. Once this device has seen placement in a variety of working environments, ERDC should reevaluate its potential use and focus in on solving the limitations identified by its user base to refine any published military guidance.

The military will continue to seek better devices to replace the NDG that are simple, easy to use, easy to calibrate, light, portable, and minimize operational logistics. However, given density remains a difficult property to obtain through alternative means, the possibility exists that the military will redefine how soil performance is assessed based on moisture and modulus response similar to the path the highway industry is moving. This will require updating military criteria to follow the guidelines presented in the Transportation Research Boards's Guide for Mechanistic-Empirical Design for Pavements (MEPDG) (TRB 2011). While a complex challenge to implement, the ability to base soil performance on mechanistic properties may provide a better overall means to design and predict performance.

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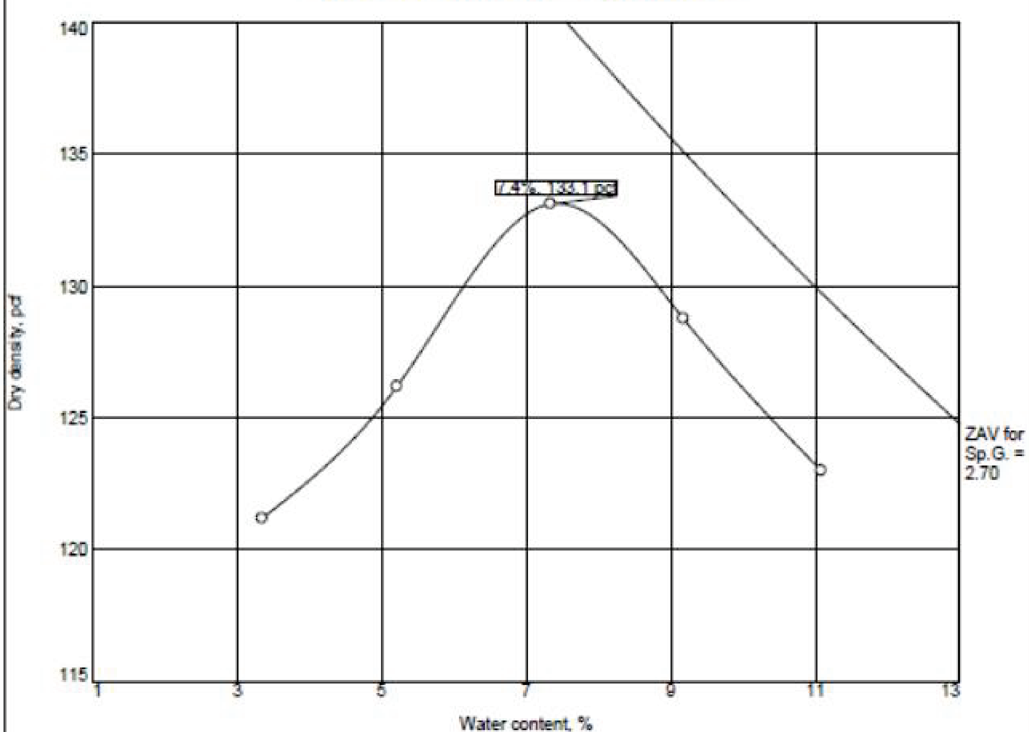
Appendix A: Soil Characterization Data

Clay Gravel

COMPACTION TEST REPORT



Test specification: ASTM D 1557-07 Method C Modified

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/4 in.	% < No.200
	USCS	AASHTO						
				2.70	25	12	13.9	15.3

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 133.1 pcf Optimum moisture = 7.4 %	Clayey Sand (SC) with gravel, Reddish Brown

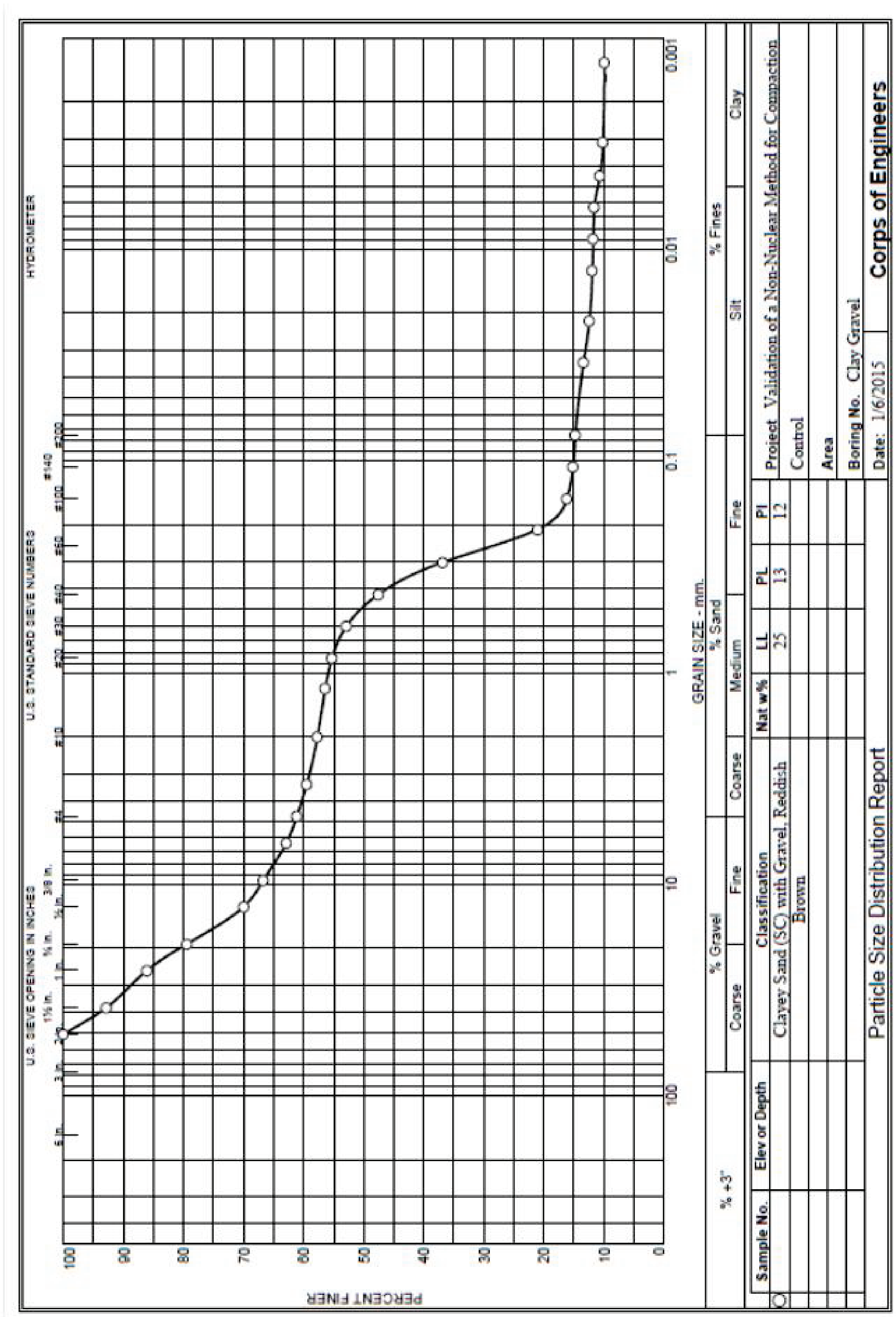
Project No. MD0215 **Client:** Ernest Berney/ Mariely Mejias
Project: Validation of a Non-Nuclear Method for Compaction Control

○ **Source of Sample:** Clay Gravel

Remarks:
Estimated Gravity

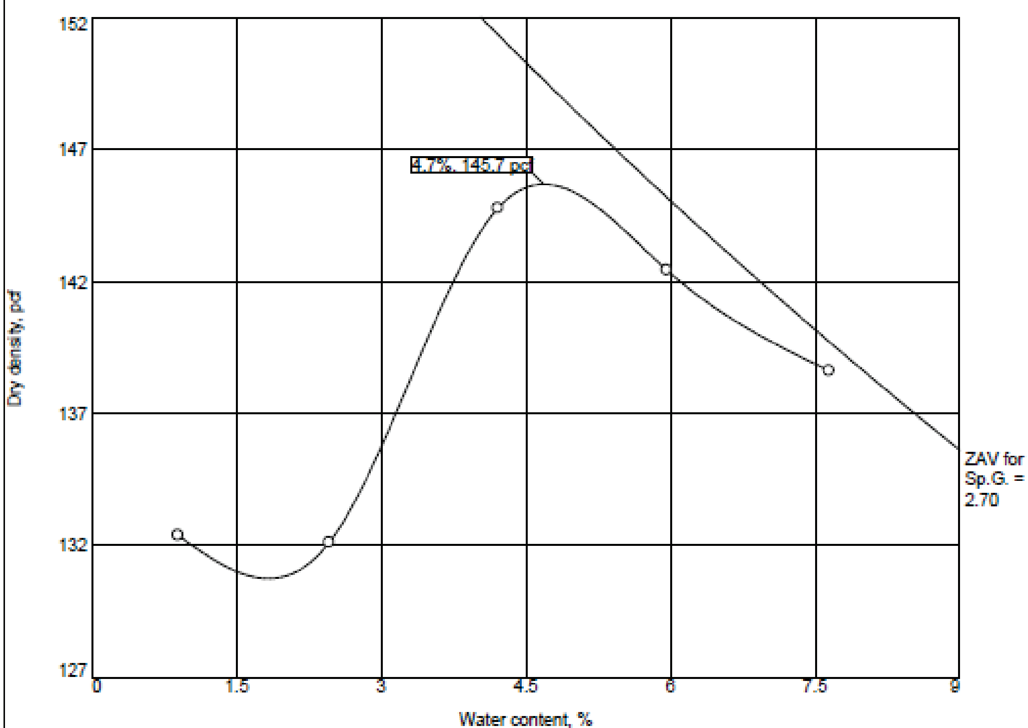
Corps of Engineers
Engineer Research Development Center

Figure


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER
GRAIN SIZE - mm.
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Clayey Sand (SC) with Gravel, Reddish Brown
Nat w%
LL
25
PL
13
PI
12
Project Validation of a Non-Nuclear Method for Compaction Control
Area
Boring No. Clay Gravel
Date: 1/6/2015
Particle Size Distribution Report
Corps of Engineers

Limestone

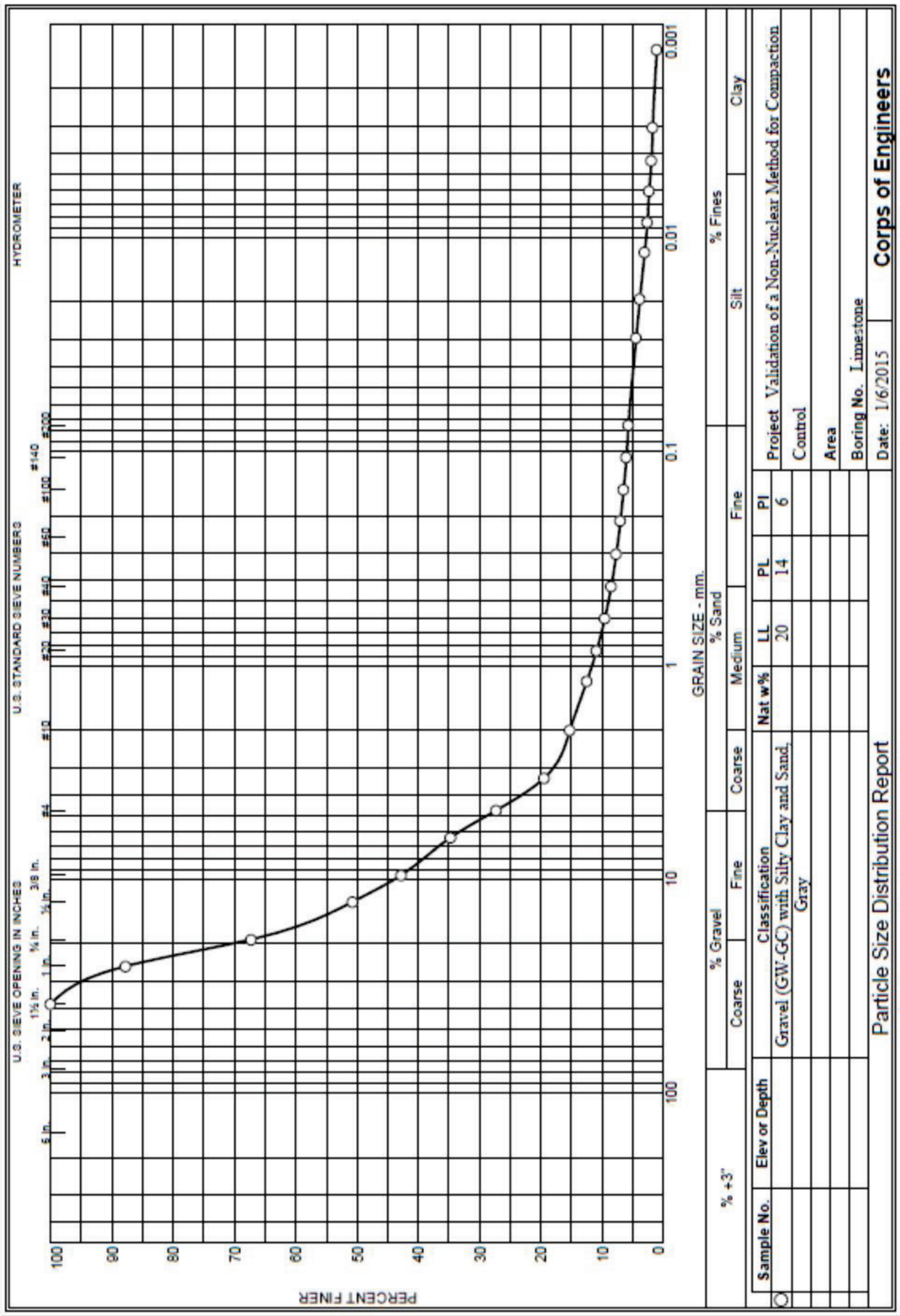
COMPACTION TEST REPORT



Test specification: ASTM D 1557-07 Method C Modified

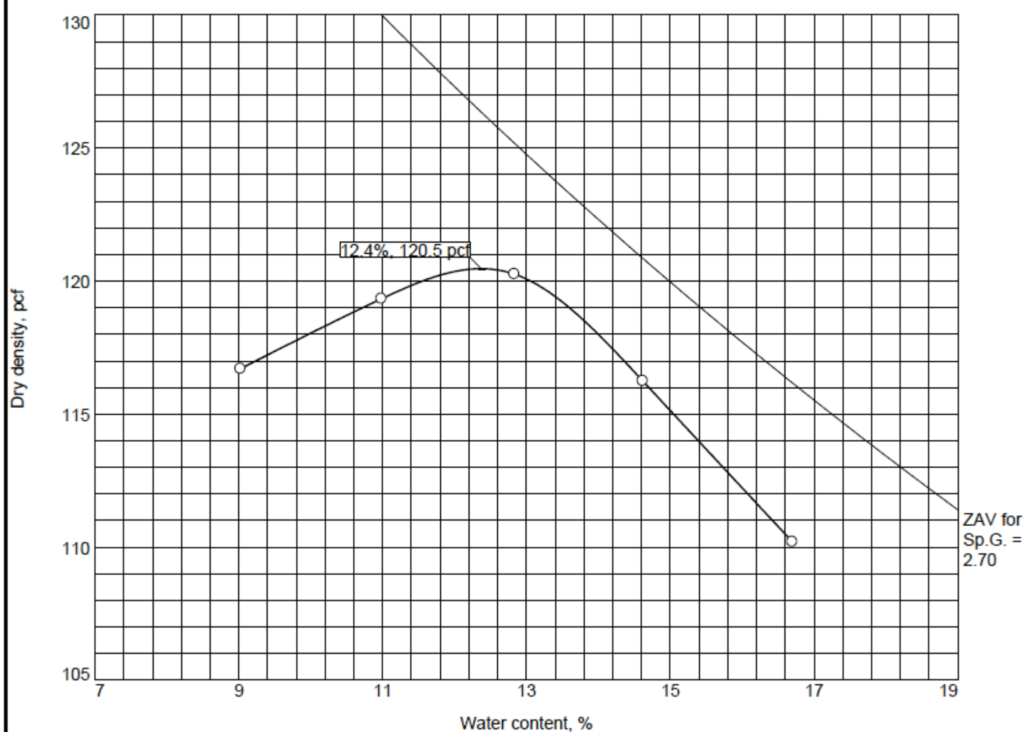
Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/4 in.	% < No.200
	USCS	AASHTO						
				2.70	20	6	32.8	6.7

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 145.7 pcf Optimum moisture = 4.7 %	Gravel (GW-GC) with Silty Clay and Sand, Gray
Project No. MD0215 **Client:** Ernest Berney/ Mariely Mejias **Project:** Validation of a Non-Nuclear Method for Compaction Control ○ **Source of Sample:** Limestone	**Remarks:** Estimated Specific Gravity
Corps of Engineers **Engineer Research Development Center**	**Figure**


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
6 in. 3 in. 2 in. 1½ in. 1 in. ¾ in. ½ in. 3/8 in.
#4 #10 #20 #30 #40 #60 #100 #140 #200
PERCENT FINER
100 90 80 70 60 50 40 30 20 10 0
100 10 1 0.1 0.01 0.001
GRAIN SIZE - mm.
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Gravel (GW-GC) with Silty Clay and Sand, Gray
Nat w%
LL
20
PL
14
PI
6
Project Validation of a Non-Nuclear Method for Compaction
Control
Area
Boring No. Limestone
Date: 1/6/2015
Particle Size Distribution Report
Corps of Engineers

Red Clayey Sand

COMPACTION TEST REPORT



Test specification: ASTM D 1557-07 Method A Modified

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
				2.70				

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 120.5 pcf Optimum moisture = 12.4 %	Clayey Sand, Red

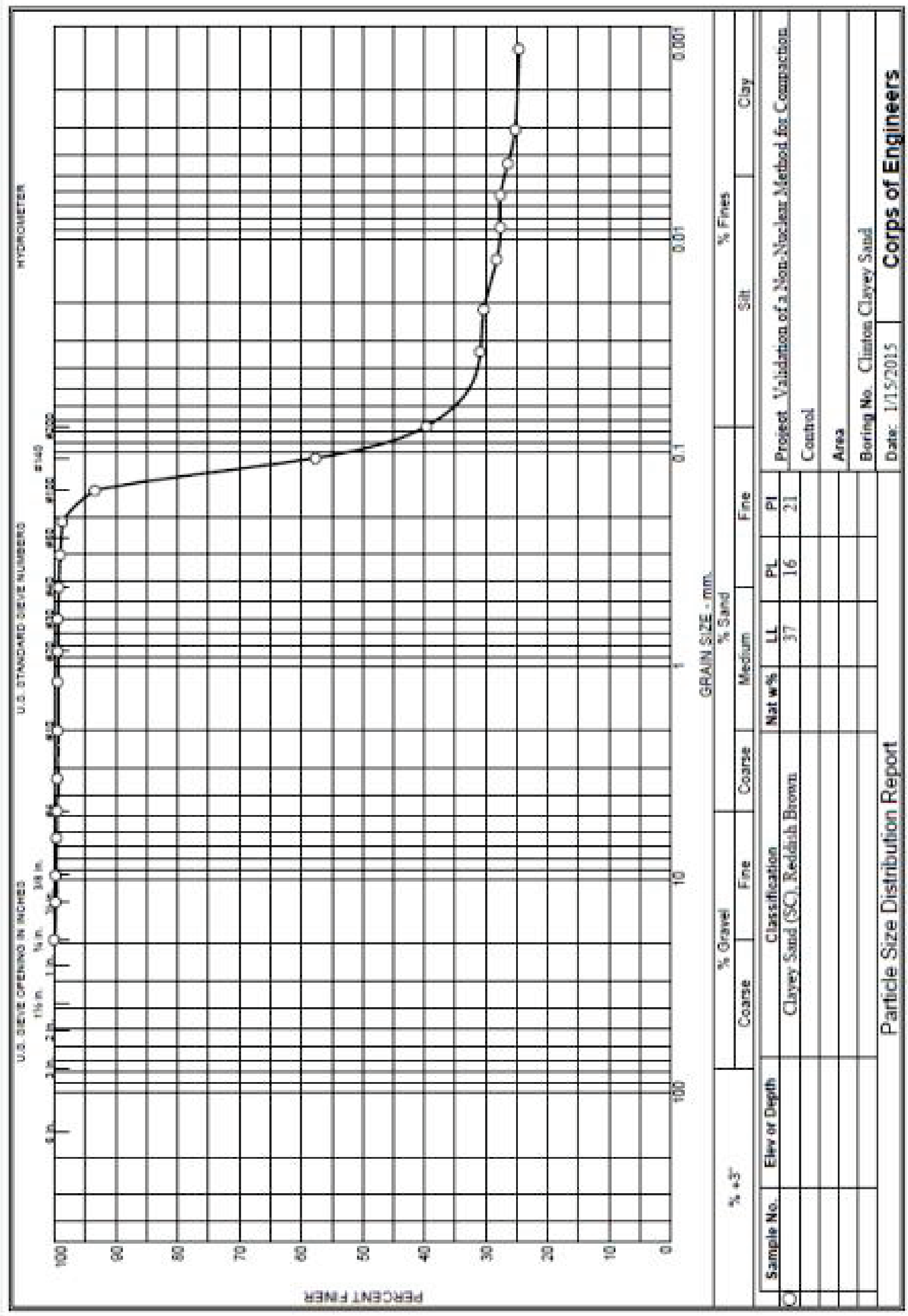
Project No. MD1415 **Client:** Ernest Berney
Project: Validation of a Non-Nuclear Method for Compaction Control

○**Location:** SC Red

Remarks:
Estimated Specific Gravity

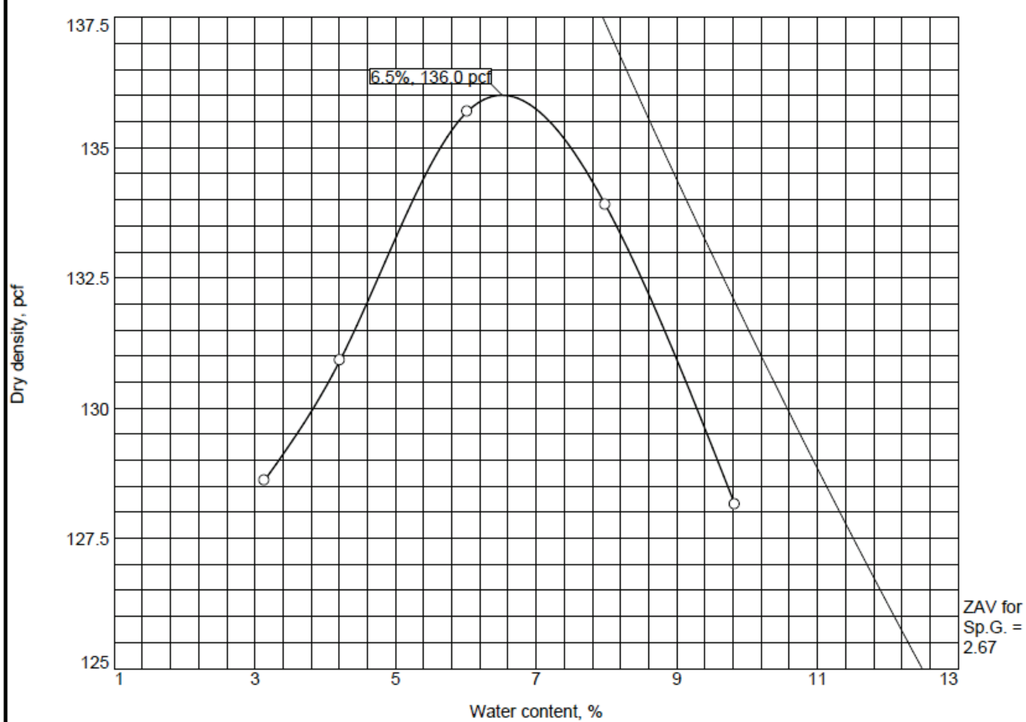
Corps of Engineers
Engineer Research Development Center

Figure


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER
GRAIN SIZE - mm.
100
10
1
0.1
0.01
0.001
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Clayey Sand (SC), Reddish Brown
Nat w%
LL
37
PL
16
PI
21
Project Validation of a Non-Nuclear Method for Compaction
Control
Area
Boring No. Clinton Clayey Sand
Date: 1/15/2015
Particle Size Distribution Report
Corps of Engineers

Blended Clayey Sand

COMPACTION TEST REPORT



Test specification: ASTM D 1557-07 Method A Modified

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
				2.67				

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 136.0 pcf Optimum moisture = 6.5 %	Silty Sand, Brown

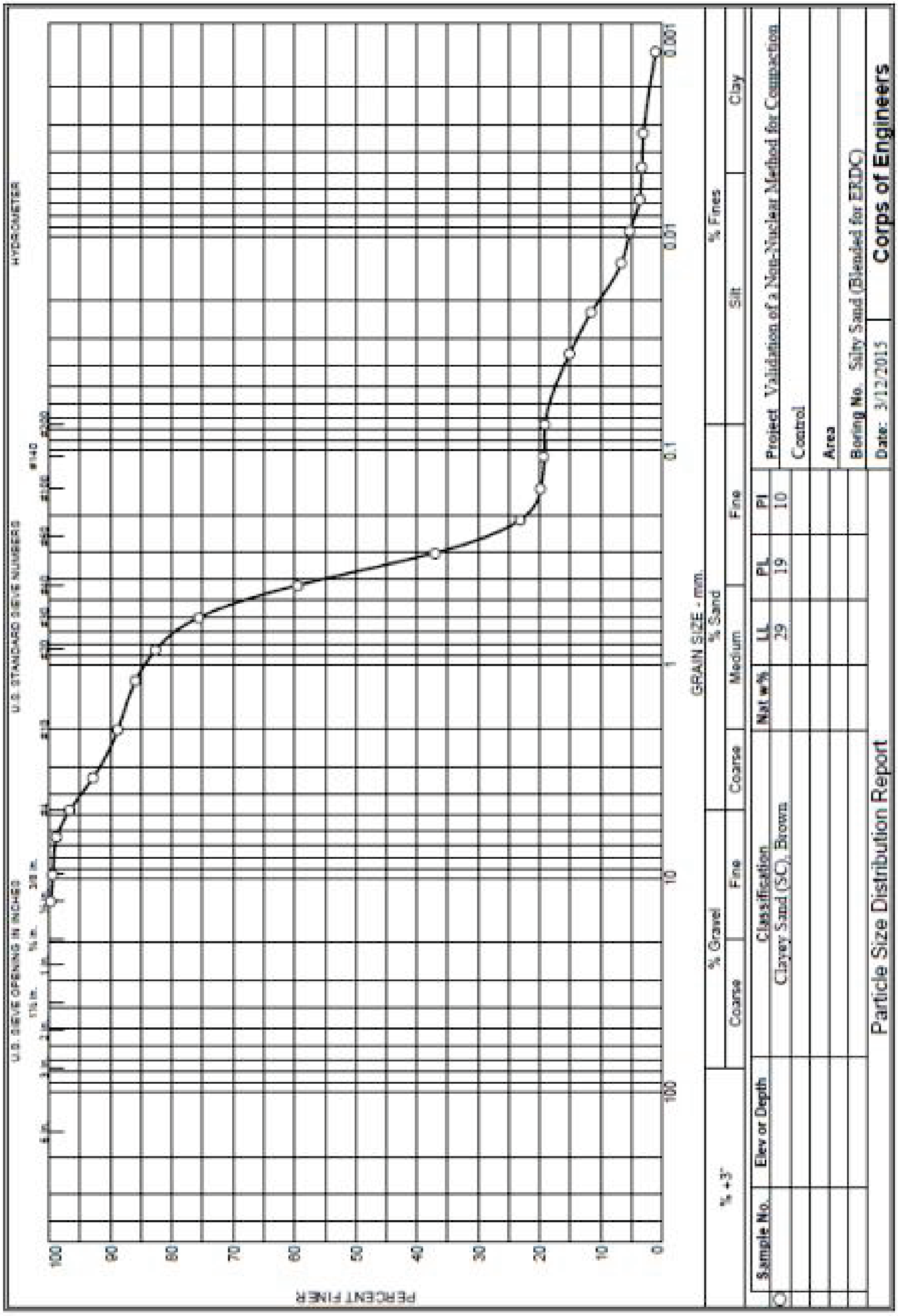
Project No. MD1415 **Client:** Ernest Berney
Project: Validation of a Non-Nuclear Method for Compaction Control

○**Location:** SM Brown

Remarks:
Estimated Specific Gravity

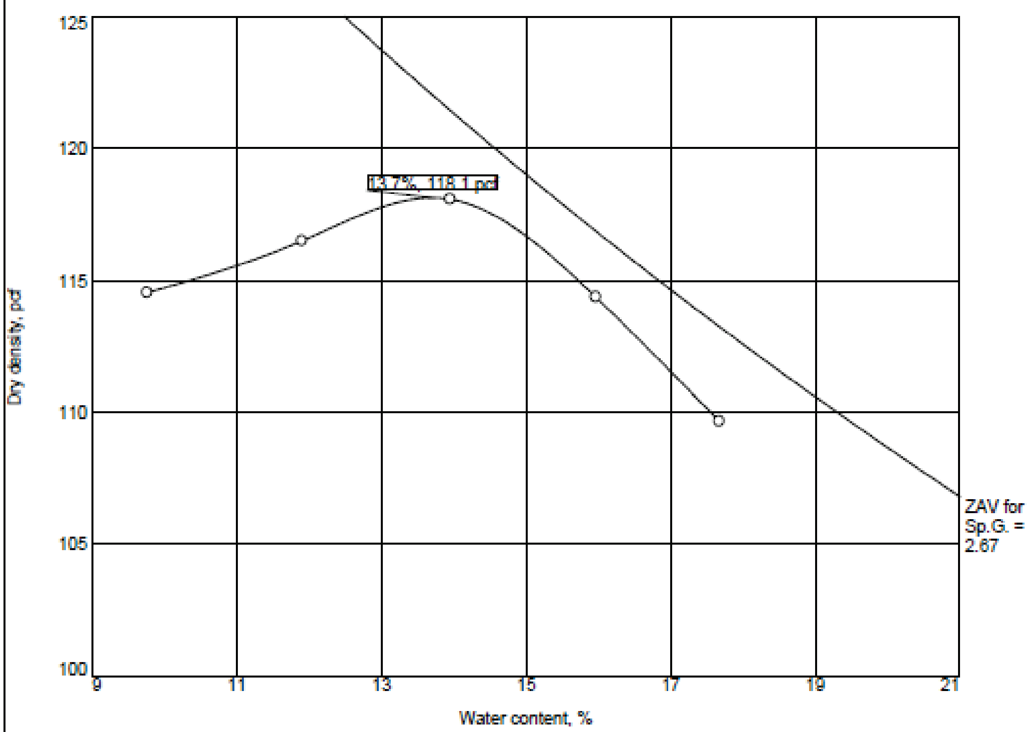
Corps of Engineers
Engineer Research Development Center

Figure


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER
GRAIN SIZE - mm.
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Clayey Sand (SC), Brown
Nat w%
LL 29
PL 19
PI 10
Project Validation of a Non-Nuclear Method for Compaction
Control
Area
Boring No. Silty Sand (Blended for ERDC)
Date: 3/12/2015
Particle Size Distribution Report
Corps of Engineers

Low Plasticity Clay

COMPACTION TEST REPORT



Test specification: ASTM D 1557-00 Method A Modified

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
				2.67	35	13	0	97.4

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 118.1 pcf Optimum moisture = 13.7 %	Clay (CL), Brown

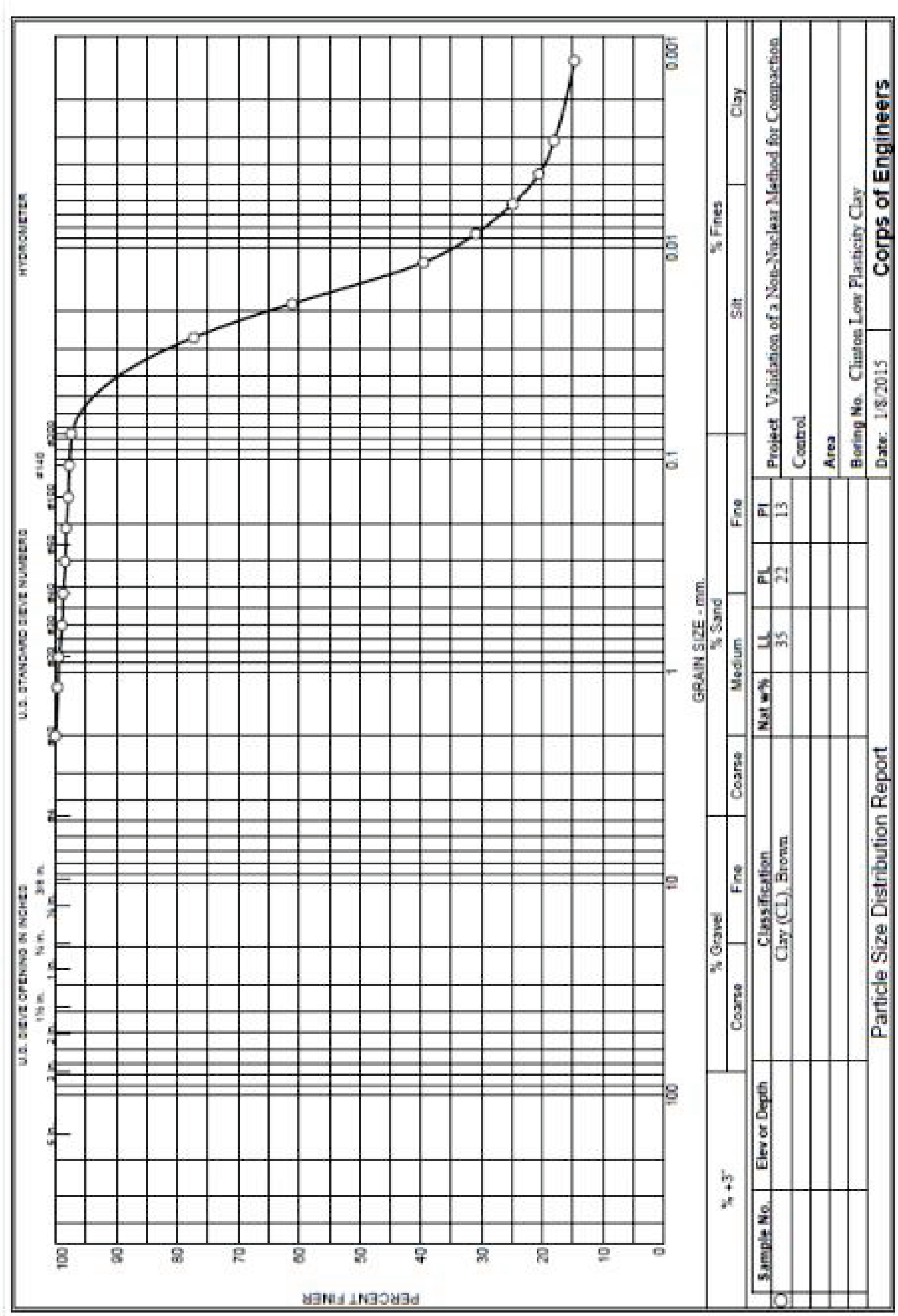
Project No. MD0215 **Client:** Ernest Berney/ Mariely Mejias
Project: Validation of a Non-Nuclear Method for Compaction Control

○ **Source of Sample:** Clinton Clay

Remarks:
Estimated Gravity

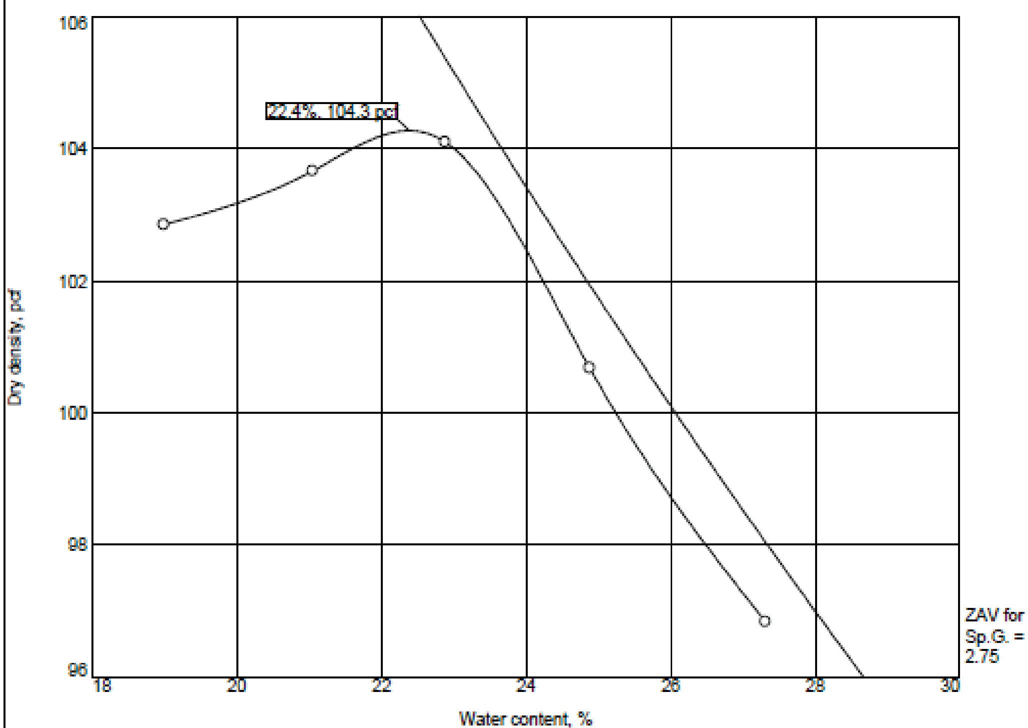
Corps of Engineers
Engineer Research Development Center

Figure


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER
100
90
80
70
60
50
40
30
20
10
0
100
10
1
0.1
0.01
0.001
GRAIN SIZE - mm.
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Clay (CL), Brown
Nat w%
LL
35
PL
22
PI
13
Project Validation of a Non-Nuclear Method for Compaction
Control
Area
Boring No. Clinton Low Plasticity Clay
Date: 1/8/2015
Particle Size Distribution Report
Corps of Engineers

Buckshot Clay

COMPACTION TEST REPORT



Test specification: ASTM D 1557-02 Method A Modified

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
				2.75	81	58	0	95.6

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 104.3 pcf Optimum moisture = 22.4 %	Clay (CH), Gray

Project No. MD0215 **Client:** Ernest Berney/ Mariely Mejias

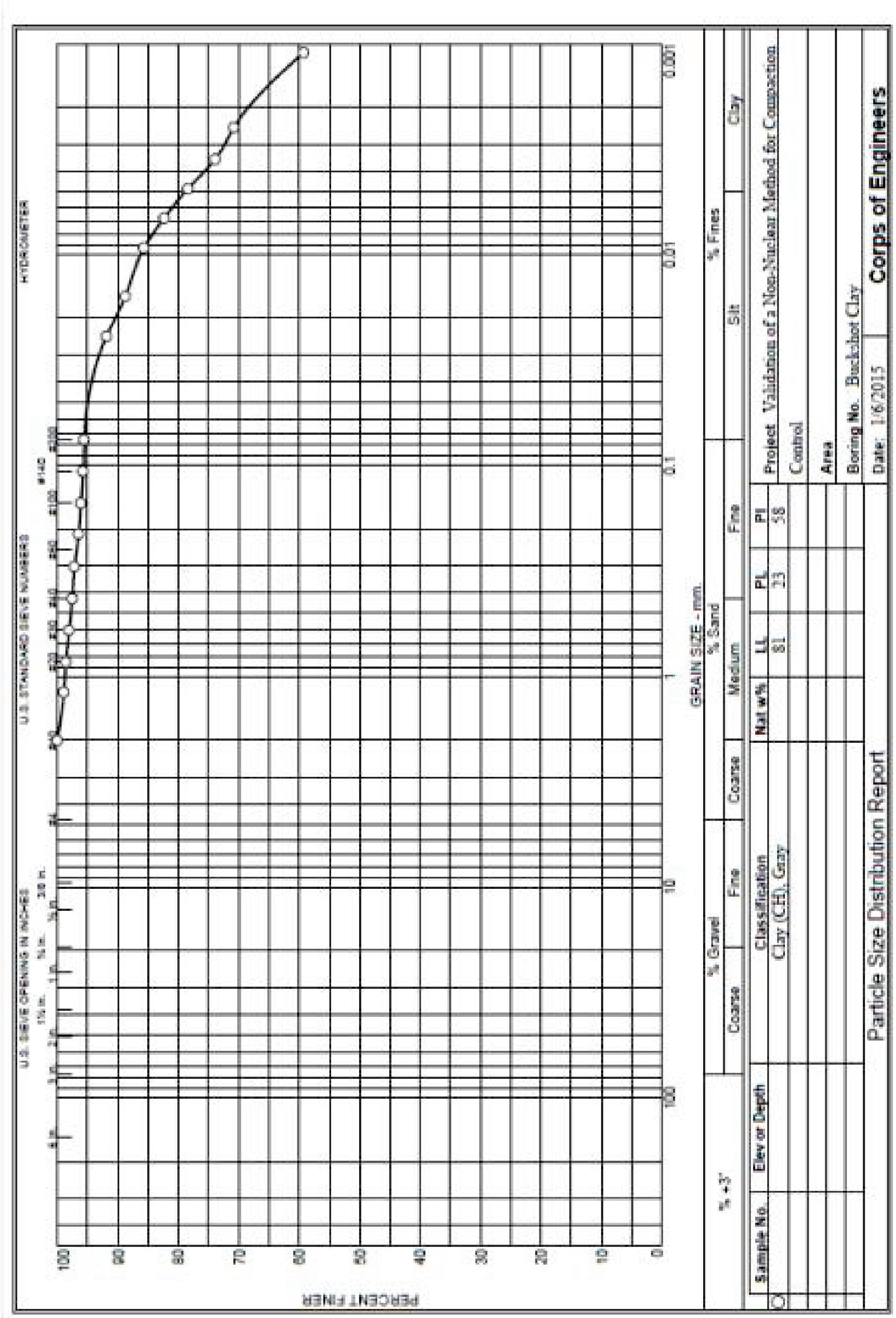
Project: Validation of a Non-Nuclear Method for Compaction Control

○ **Source of Sample:** Buckshot Clay

Remarks:
Estimated Gravity

Corps of Engineers
Engineer Research Development Center

Figure


U.S. SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER
GRAIN SIZE - mm.
% +3"
% Gravel
Coarse
Fine
% Sand
Coarse
Medium
Fine
% Fines
Silt
Clay
Sample No.
Elev or Depth
Classification
Clay (CH), Gray
Nat w%
LL
81
PL
23
PI
58
Project Validation of a Non-Nuclear Method for Compaction Control
Area
Boring No. Buckshot Clay
Date: 1/6/2015
Particle Size Distribution Report
Corps of Engineers

Appendix B: Gauge Comparison Data

Buckshot Clay (CH)																
Method	Moisture Level		*CASE Calibration Point*	Dry						*CASE Calibration Point*	Wet					
	Compaction Level			Lo			Hi				Lo			Hi		
	Test Location			1	2	3	1	2	3		1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*123.6*				118.9	120.9	123.9	*118.9*				117.3	118.2	115.8
		Moisture %	*27*				26.5	25.1	26.4	*30.6*				30.7	32.1	33.1
		Dry Density	*97.3*				94.0	96.6	98.0	*91.0*				89.7	89.5	87.0
	2nd position	Wet Density	*123.1*				119.4	121.8	123.7	*120.5*				116.9	119.3	115.9
		Moisture %	*28.1*				25.8	25.9	26.1	*30.1*				32.2	32.0	33.4
		Dry Density	*96.1*				94.9	96.7	98.1	*92.6*				88.4	90.4	86.9
	Average Wet Density		*123.4*				119.2	121.4	123.8	*119.7*				117.1	118.8	115.9
	Average Moisture		*27.6*				26.2	25.5	26.3	*30.4*				31.5	32.1	33.3
	Average Dry Density		*96.7*				94.5	96.7	98.1	*91.8*				89.1	89.9	86.9
eGauge	1st position	Wet Density	*126.5*				120.6	116.7	123.9	*118.7*				119.3	122.1	116.1
		Moisture pcf	*15.7*				33.9	27.1	35.8	*25.7*				29.6	29.1	27.9
		Moisture %	*14.2*				39.1	30.2	40.6	*27.6*				33.0	31.3	31.6
	2nd position	Wet Density	*122.8*				115.7	118.4	125.1	*120.5*				120.8	121.8	114.7
		Moisture pcf	*15.7*				34.1	31.4	36.1	*25.7*				28.9	28.7	27.0
		Moisture %	*14.7*				41.8	36.1	40.6	*27.1*				31.4	30.8	30.8
	Average Wet Density		*124.7*		Not tested		118.2	117.6	124.5	*119.6*		Not tested		120.1	122.0	115.4
	Average Moisture		*14.4*				40.4	33.2	40.6	*27.4*				32.2	31.1	31.2
	Average Dry Density		*108.9*				84.1	88.3	88.5	*93.9*				90.8	93.0	88.0
CASE 1		Wet Density	*141*				115.9	111.3	114.4	*133.2*				107.9	132.0	112.0
		Moisture %	*13.9*				28.1	28.3	28.2	*14.2*				38.3	36.5	38.0
		Dry Density	*123.8*				90.5	86.7	89.2	*116.6*				78.0	96.7	81.2
CASE 3		Wet Density	*122.6*				117.7	116.7	116.3	*120.1*				115.2	120.6	116.6
		Moisture %	*14.5*				28.2	28.6	28.8	*14.9*				38.0	36.5	37.5
		Dry Density	*107.1*				91.8	90.7	90.3	*104.5*				83.5	88.4	84.8
Sand Cone		Wet Density	*121.2*				118.7	121.0	119.4	*116.3*				115.7	120.5	114.1
		Oven Dry Moisture	*26.5*				26.2	27.1	26.7	*31.14*				34.8	32.1	36.2
		Dry Density	*95.8*				94.1	95.2	94.3	*88.7*				85.8	91.2	83.8
Hot Plate		Moisture %	*27.9*				25.7	27.2	26.7	*36.9*				33.1	34.5	36.2
		Oven Dry Moisture %	*27.03*				27.1	26.1	26.4	*35.95*				31.9	29.2	40.0

Clay Gravel (SC)																
Method	Moisture Level		*CASE*	Dry						*CASE*	Wet					
	Compaction Level		*Calibration*	Lo			Hi			*Calibration*	Lo			Hi		
	Test Location		*Point*	1	2	3	1	2	3	*Point*	1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*136.8*	129.3	131.1	127.5	138.2	138.5	136.9	*138.3*	133.4	136.7	133.8	135.9	137.5	135.2
		Moisture %	*7.6*	7.1	7.3	7.2	7.4	7.5	7.6	*11.5*	10.8	10.4	10.9	9.8	10.0	9.7
		Dry Density	*127.1*	120.7	122.2	118.9	128.7	128.8	127.2	*124.0*	120.4	123.8	120.6	123.8	125.0	123.2
	2nd position	Wet Density	*134.3*	128.5	127.8	125.9	136.9	139.0	138.3	*138.3*	132.5	132.4	137.0	129.3	136.5	135.7
		Moisture %	*7.4*	7.7	7.7	7.2	8.1	7.6	7.8	*10.7*	10.1	10.2	10.1	9.8	10.5	10.1
		Dry Density	*125.0*	119.3	118.7	117.4	126.6	129.2	128.3	*124.9*	120.3	120.1	124.4	117.8	123.5	123.3
	Average Wet Density		*135.6*	128.9	129.5	126.7	137.6	138.8	137.6	*138.3*	133.0	134.6	135.4	132.6	137.0	135.5
	Average Moisture		*7.5*	7.4	7.5	7.2	7.8	7.6	7.7	*11.1*	10.5	10.3	10.5	9.8	10.3	9.9
	Average Dry Density		*126.1*	120.0	120.4	118.2	127.7	129.0	127.8	*124.5*	120.4	122.0	122.5	120.8	124.3	123.2
eGauge	1st position	Wet Density	*136.4*	135.8	129.3	124.9	140.9	140.5	139.7	*138.1*	136.6	132.7	130.7	134.4	134.4	132.5
		Moisture pcf	*8.7*	5.8	5.8	5.6	6.7	8.7	4.9	*10.7*	9.0	10.2	9.6	6.8	10.5	8.5
		Moisture %	*6.8*	4.5	4.7	4.7	5.0	6.6	3.6	*8.4*	7.1	8.3	7.9	5.3	8.5	6.9
	2nd position	Wet Density	*134.3*	131.1	125.5	121.0	140.4	141.2	140.4	*137.4*	133.9	129.0	133.0	136.7	136.7	138.0
		Moisture pcf	*8.9*	5.9	7.9	5.6	6.6	8.7	4.9	*11.1*	9.4	10.5	10.3	6.7	10.4	9.2
		Moisture %	*7.1*	4.7	6.7	4.9	4.9	6.6	3.6	*8.8*	7.6	8.9	8.4	5.2	8.2	7.1
	Average Wet Density		*135.4*	133.5	127.4	123.0	140.7	140.9	140.1	*137.8*	135.3	130.9	131.9	135.6	135.6	135.3
	Average Moisture		*7.0*	4.6	5.7	4.8	5.0	6.6	3.6	*8.6*	7.3	8.6	8.2	5.2	8.4	7.0
	Average Dry Density		*126.5*	127.6	120.5	117.3	134.0	132.1	135.1	*126.8*	126.0	120.5	121.9	128.8	125.1	126.4
CASE1		Wet Density	*89.5*	142.9	142.9	143.4	145.7	142.3	141.7	*98.9*	143.0	136.3	135.0	128.9	135.3	134.4
		Moisture %	*5.4*	5.6	5.4	5.1	6.7	6.1	6.0	*6.9*	9.4	10.3	12.0	9.0	9.1	9.7
		Dry Density	*84.9*	135.3	135.6	136.4	136.6	134.1	133.7	*92.5*	130.7	123.6	120.5	118.3	124.0	122.5
CASE3		Wet Density	*84.8*	141.2	142.6	140.9	142.5	142.6	142.3	*95.7*	130.8	136.2	137.3	127.8	133.8	134.9
		Moisture %	*4.8*	5.5	5.7	4.8	7.0	6.3	6.3	*6.9*	7.9	11.2	12.9	8.8	9.4	10.4
		Dry Density	*80.9*	133.8	134.9	134.4	133.2	134.1	133.9	*89.5*	121.2	122.5	121.6	117.5	122.3	122.2
Sand Cone		Wet Density	*142.2*	126.0	124.1	131.1	140.7	143.6	137.8	*139.2*	139.0	140.1	138.4	140.9	143.4	
		Oven Dry Moisture	*5.7*	6.7	7.0	6.9	7.0	7.6	9.0	*9.8*	10.8	9.3	10.3	8.0	9.5	9.2
		Dry Density	*134.6*	118.1	116.0	122.7	131.5	133.5	126.4	*126.8*	125.4	128.2	125.5	130.5	130.9	112.0
Hot Plate		Moisture %	*6.5*	7.3	6.3	6.1	6.7	6.3	6.5	*10.0*	8.1	8.7	8.4	9.6	8.9	9.0
		Oven Dry Moisture %	*7.2*	7.4	5.8	5.8	6.0	6.0	5.9	*9.7*	7.9	8.7	8.6	9.2	9.8	7.6

Limestone (GW-GC)																
Method	Moisture Level		*CASE Calibration Point*	Dry						*CASE Calibration Point*	Wet					
	Compaction Level			Lo			Hi				Lo			Hi		
	Test Location			1	2	3	1	2	3		1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*134.6*	129.0	125.3	122.5	127.5	132.9	130.3	*147.0*	135.6	134.9	139.0	149.5	151.3	146.9
		Moisture %	*3.8*	3.7	3.2	3.3	3.2	3.5	3.0	*5.3*	5.6	5.8	5.7	5.6	5.4	5.9
		Dry Density	*129.7*	124.4	121.4	118.6	123.5	128.4	126.5	*139.6*	128.4	127.5	131.5	141.6	143.5	138.7
	2nd position	Wet Density	*132.3*	125.9	126.7	124.5	133.1	132.8	127.8	*146.7*	136.2	135.8	137.7	145.3	150.2	147.0
		Moisture %	*3.6*	3.9	3.3	3.3	3.3	3.3	3.1	*5.3*	5.4	5.5	5.2	6.0	5.7	5.7
		Dry Density	*127.7*	121.2	122.7	120.5	128.8	128.6	124.0	*139.3*	129.2	128.7	130.9	137.1	142.1	139.1
	Average Wet Density		*133.5*	127.5	126.0	123.5	130.3	132.9	129.1	*146.9*	135.9	135.4	138.4	147.4	150.8	147.0
	Average Moisture		*3.7*	3.8	3.3	3.3	3.3	3.4	3.1	*5.3*	5.5	5.7	5.5	5.8	5.6	5.8
	Average Dry Density		*128.7*	122.8	122.0	119.6	126.2	128.5	125.2	*139.5*	128.8	128.1	131.2	139.3	142.8	138.9
eGauge	1st position	Wet Density	*134.4*	131.8	129.2	125.1	131.0	136.6	127.5	*145.8*	138.0	135.1	141.9	149.4	150.6	150.6
		Moisture pcf	*9.6*	3.7	4.2	4.0	3.0	3.9	5.4	*5.9*	6.4	6.2	6.7	7.8	8.3	4.4
		Moisture %	*7.7*	2.9	3.4	3.3	2.3	2.9	4.4	*4.2*	4.9	4.8	5.0	5.5	5.8	3.0
	2nd position	Wet Density	*132.1*	129.6	127.3	122.5	130.9	132.6	124.4	*147.4*	138.0	137.4	134.9	150.9	146.9	147.3
		Moisture pcf	*9.0*	4.1	3.7	3.6	2.7	1.9	2.5	*5.4*	6.0	6.1	6.7	7.8	4.3	9.0
		Moisture %	*7.3*	3.3	3.0	3.0	2.1	1.5	2.1	*3.8*	4.5	4.6	5.2	5.5	3.0	6.5
	Average Wet Density		*133.3*	130.7	128.3	123.8	131.0	134.6	126.0	*146.6*	138.0	136.3	138.4	150.2	148.8	149.0
	Average Moisture		*7.5*	3.1	3.2	3.2	2.2	2.2	3.2	*4.0*	4.7	4.7	5.1	5.5	4.4	4.8
	Average Dry Density		*124.0*	126.8	124.3	120.0	128.1	131.7	122.0	*140.9*	131.8	130.1	131.7	142.3	142.4	142.2
CASE 1		Wet Density	*85.7*	144.5	143.1	138.7	137.8	139.4	136.7	*90.7*	152.4	150.2	150.2	151.8	150.2	149.5
		Moisture %	*2.1*	3.0	2.1	3.4	1.3	2.0	1.3	*5.6*	6.2	5.9	6.2	6.4	6.0	6.3
		Dry Density	*83.9*	140.3	140.2	134.1	136.0	136.7	134.9	*85.9*	143.5	141.8	141.4	142.7	141.7	140.6
CASE 3		Wet Density	*81.3*	140.2	142.1	140.2	139.4	139.3	138.6	*86.0*	150.3	153.0	152.1	150.8	151.7	151.0
		Moisture %	*1.4*	3.0	2.4	3.3	1.5	2.3	1.4	*5.4*	6.2	6.3	6.4	6.2	6.3	6.2
		Dry Density	*80.2*	136.1	138.8	135.7	137.3	136.2	136.7	*81.6*	141.5	143.9	143.0	142.0	142.7	142.2
Sand Cone		Wet Density	*140.2*	132.3	131.6	131.2	131.4	141.9	132.6	*150.2*	140.8	142.1	143.3	153.0	149.0	151.5
		Oven Dry Moisture	*3.8*	3.9	3.1	4.0	3.8	3.5	3.1	*4.6*	5.0	4.8	5.0	4.4	5.0	4.8
		Dry Density	*135.1*	127.3	127.7	126.2	126.6	137.0	128.6	*143.6*	134.1	135.6	136.4	146.6	141.9	144.5
Hot Plate		Moisture %	*2.7*	3.2	3.2	3.5	2.7	3.1	3.1	*5.6*	4.1	4.2	4.9	4.5	4.7	4.7
		Oven Dry Moisture %	*3.3*	1.9	3.9	3.7	3.4	3.2	3.1	*4.9*	4.9	4.6	5.0	5.2	4.7	5.1

Low Plasticity Clay (CL)																
Method	Moisture Level		*CASE Calibration Point*	Dry						*CASE Calibration Point*	Wet					
	Compaction Level			Lo			Hi				Lo			Hi		
	Test Location			1	2	3	1	2	3		1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*123.1*	118.1	121.2	116.5	123.8	129.6	131.4	*127.5*	115.3	117.6	113.9	126.9	123.6	124.4
		Moisture %	*12.9*	12.8	13.3	13.5	12.7	12.8	13.2	*17.9*	16.5	17.7	16.8	18.0	18.1	18.3
		Dry Density	*109.0*	104.7	107.0	102.6	109.8	114.9	116.1	*108.1*	99.0	99.9	97.5	107.5	104.7	105.2
	2nd position	Wet Density	*122.7*	118.1	122.4	123.8	124.0	124.1	128.2	*126.7*	115.3	116.9	115.5	126.9	122.9	123.8
		Moisture %	*13.3*	13.4	13.7	13.2	13.4	13.2	13.2	*18.6*	17.1	19.3	16.9	18.2	18.9	18.3
		Dry Density	*108.3*	104.1	107.7	109.4	109.3	109.6	113.3	*106.8*	98.5	98.0	98.8	107.4	103.4	104.6
	Average Wet Density		*122.9*	118.1	121.8	120.2	123.9	126.9	129.8	*127.1*	115.3	117.3	114.7	126.9	123.3	124.1
	Average Moisture		*13.1*	13.1	13.5	13.4	13.1	13.0	13.2	*18.3*	16.8	18.5	16.9	18.1	18.5	18.3
	Average Dry Density		*108.7*	104.4	107.3	106.0	109.6	112.3	114.7	*107.5*	98.7	98.9	98.2	107.5	104.0	104.9
eGauge	1st position	Wet Density	*128.6*	116.6	122.6	119.1	128.0	129.4	131.8	*128.9*	110.8	119.3	110.2	129.5	126.4	125.6
		Moisture pcf	*14.2*	15.0	16.7	17.2	17.3	19.2	19.0	*18.9*	16.1	17.6	14.8	21.3	19.6	17.1
		Moisture %	*12.4*	14.8	15.8	16.9	15.6	17.4	16.8	*17.2*	17.0	17.3	15.5	19.7	18.4	15.8
	2nd position	Wet Density	*126.0*	119.8	122.7	124.3	127.1	131.2	128.2	*128.9*	111.7	119.3	115.2	125.5	127.5	125.5
		Moisture pcf	*13.8*	14.7	16.6	17.3	19.3	19.3	18.9	*20.2*	16.2	16.6	15.1	21.0	18.7	16.7
		Moisture %	*12.3*	14.0	15.6	16.2	17.9	17.2	17.3	*18.6*	17.0	16.2	15.1	20.1	17.2	15.3
	Average Wet Density		*127.3*	118.2	122.7	121.7	127.6	130.3	130.0	*128.9*	111.3	119.3	112.7	127.5	127.0	125.6
	Average Moisture		*12.4*	14.4	15.7	16.5	16.8	17.3	17.1	*17.9*	17.0	16.7	15.3	19.9	17.8	15.6
	Average Dry Density		*113.3*	103.3	106.0	104.4	109.2	111.0	111.0	*109.3*	95.1	102.2	97.7	106.3	107.8	108.6
CASE 1		Wet Density	*112.7*	121.4	126.7	119.9	123.0	125.9	123.0	*118.2*	118.9	121.3	116.7	124.2	123.2	119.8
		Moisture %	*12.7*	13.4	13.3	13.7	14.0	14.0	14.3	*12.4*	20.3	20.5	20.4	20.7	20.9	20.6
		Dry Density	*100.0*	107.1	111.8	105.5	107.9	110.4	107.6	*105.2*	98.8	100.7	96.9	102.9	101.9	99.3
CASE 3		Wet Density	*103.5*	125.6	124.8	125.1	126.9	125.7	124.3	*107.1*	121.6	126.3	122.3	123.9	126.7	125.5
		Moisture %	*13.2*	13.2	13.1	13.7	13.9	13.9	14.3	*12.5*	20.3	20.7	20.7	20.9	21.1	21.0
		Dry Density	*91.4*	111.0	110.3	110.0	111.4	110.4	108.7	*95.2*	101.1	104.6	101.3	102.5	104.6	103.7
Sand Cone		Wet Density	*127.3*	116.7	142.6	119.7	133.0	133.3	133.5	*124.1*	116.6	124.2	113.4	121.9	127.3	124.7
		Oven Dry Moisture	*12.0*	12.6	12.4	12.9	12.4	12.6	11.9	*19.7*	19.8	19.9	19.6	20.3	20.4	19.9
		Dry Density	*113.6*	103.7	126.9	106.0	118.3	118.3	119.3	*103.6*	97.3	103.6	94.8	101.4	105.7	104.0
Hot Plate		Moisture %	*13.5*	13.4	13.6	14.0	13.1	12.6	12.9	*20.3*	20.4	20.2	19.6	20.3	20.0	20.8
		Oven Dry Moisture %	*11.8*	12.2	13.1	13.3	12.3	12.4	12.7	*19.8*	18.7	20.3	19.8	19.8	19.9	19.9

Blended Clayey Sand (SC)																
Method	Moisture Level		*CASE*	Dry						*CASE*	Wet					
	Compaction Level		*Calibration*	Lo			Hi			*Calibration*	Lo			Hi		
	Test Location		*Point*	1	2	3	1	2	3	*Point*	1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*135.8*	125.1	122.7	123.0	131.3	132.3	130.2	*137.4*	137.3	136.0	134.1	139.6	139.9	139.6
		Moisture %	*5.4*	4.9	5.0	5.2	5.5	4.9	4.9	*7.5*	7.7	8.4	7.9	8.1	8.2	7.8
		Dry Density	*128.8*	119.3	116.9	116.9	124.5	126.1	124.1	*127.8*	127.5	125.5	124.3	129.1	129.3	129.5
	2nd position	Wet Density	*134.3*	125.2	123.7	122.7	131.6	130.0	130.5	*138.7*	136.8	133.2	132.5	141.6	141.3	139.6
		Moisture %	*5.3*	4.9	4.8	4.9	5.0	5.0	5.2	*7.1*	7.8	8.0	8.4	7.9	7.8	8.2
		Dry Density	*127.5*	119.4	118.0	117.0	125.3	123.8	124.0	*129.5*	126.9	123.3	122.2	131.2	131.1	129.0
	Average Wet Density		*135.1*	125.2	123.2	122.9	131.5	131.2	130.4	*138.1*	137.1	134.6	133.3	140.6	140.6	139.6
	Average Moisture		*5.4*	4.9	4.9	5.1	5.3	5.0	5.1	*7.3*	7.8	8.2	8.2	8.0	8.0	8.0
	Average Dry Density		*128.2*	119.3	117.4	116.9	124.9	125.0	124.1	*128.7*	127.2	124.4	123.3	130.2	130.2	129.3
eGauge	1st position	Wet Density	*130.3*	126.5	121.7	121.6	132.8	131.7	130.3	*140.8*	136.8	136.3	132.8	143.0	139.0	142.3
		Moisture pcf	*3.5*	7.6	7.3	6.8	3.5	3.9	6.2	*8.1*	7.2	9.7	3.5	9.4	8.8	7.8
		Moisture %	*2.8*	6.4	6.4	5.9	2.7	3.1	5.0	*6.1*	5.6	7.7	2.7	7.0	6.8	5.8
	2nd position	Wet Density	*130.7*	127.0	123.0	122.4	134.3	135.0	134.2	*140.1*	136.2	135.9	136.8	140.8	142.0	141.6
		Moisture pcf	*3.3*	3.6	7.2	7.4	3.4	3.2	4.0	*8.3*	4.1	4.3	4.6	9.5	8.7	3.8
		Moisture %	*2.6*	2.9	6.2	6.4	2.6	2.4	3.1	*6.3*	3.1	3.3	3.5	7.2	6.5	2.8
	Average Wet Density		*130.5*	126.8	122.4	122.0	133.6	133.4	132.3	*140.5*	136.5	136.1	134.8	141.9	140.5	142.0
	Average Moisture		*2.7*	4.7	6.3	6.2	2.7	2.7	4.0	*6.2*	4.3	5.5	3.1	7.1	6.6	4.3
	Average Dry Density		*127.1*	121.1	115.1	114.9	130.1	129.8	127.1	*132.2*	130.8	129.0	130.8	132.4	131.7	136.1
CASE 1		Wet Density	*88.6*	130.1	129.0	124.9	124.3	122.0	122.1	*102.4*	131.2	137.7	132.6	145.2	137.1	138.1
		Moisture %	*10.3*	5.3	4.4	4.2	4.0	4.2	4.1	*9.9*	7.2	7.3	7.3	8.0	7.9	7.8
		Dry Density	*80.3*	123.6	123.6	119.9	119.5	117.1	117.3	*93.2*	122.4	128.3	123.6	134.4	127.1	128.1
CASE 3		Wet Density	*85.5*	127.1	125.4	127.0	123.7	123.4	124.0	*95.9*	130.3	132.9	130.7	138.1	139.2	135.7
		Moisture %	*10.6*	5.0	4.7	3.9	4.2	4.2	4.2	*10.3*	7.1	6.7	6.9	7.7	7.6	7.5
		Dry Density	*77.3*	121.0	119.8	122.2	118.7	118.4	119.0	*86.9*	121.7	124.6	122.3	128.2	129.4	126.2
Sand Cone		Wet Density	*137.4*	127.2	130.8	125.7	136.2	134.6	127.5	*139.2*	138.6	139.0	139.9	139.9	141.7	139.6
		Oven Dry Moisture	*4.9*	5.1	5.0	5.0	4.7	5.0	5.3	*7.5*	7.9	7.9	8.2	8.0	7.9	7.7
		Dry Density	*131.0*	121.0	124.6	119.7	130.1	128.2	121.0	*129.5*	128.4	128.8	129.3	129.5	131.3	129.7
Hot Plate		Moisture %	*5.8*	5.2	5.1	5.1	5.7	5.1	5.1	*7.8*	8.6	8.6	8.1	8.0	8.4	8.2
		Oven Dry Moisture %	*5.2*	5.1	5.0	5.0	5.1	5.0	5.0	*7.7*	7.9	7.7	7.8	8.1	8.0	7.7

Red Clayey Sand (SC)																
Method	Moisture Level		*CASE Calibration Point*	Dry						*CASE Calibration Point*	Wet					
	Compaction Level			Lo			Hi				Lo			Hi		
	Test Location			1	2	3	1	2	3		1	2	3	1	2	3
Nuclear Density Gauge	1st position	Wet Density	*121.4*	119.6	116.1	115.7	125.3	122.0	119.7	*128.2*	116.3	117.8	115.3	127.1	128.0	127.8
		Moisture %	*10.9*	10.6	10.6	10.4	11.1	11.6	11.5	*16.4*	15.7	16.3	16.0	18.8	16.7	16.8
		Dry Density	*109.5*	108.1	105.0	104.8	112.8	109.3	107.4	*110.1*	100.5	101.3	99.4	107.0	109.7	109.4
	2nd position	Wet Density	*121.6*	119.5	119.5	113.1	124.0	122.6	120.4	*128.2*	118.3	117.9	115.8	126.4	127.5	126.2
		Moisture %	*11.6*	10.1	12.2	10.6	12.1	11.1	11.4	*16.6*	15.4	16.1	15.9	18.4	17.2	17.0
		Dry Density	*109.0*	108.5	106.5	102.3	110.6	110.4	108.1	*109.9*	102.5	101.6	99.9	106.8	108.8	107.9
	Average Wet Density		*121.5*	119.6	117.8	114.4	124.7	122.3	120.1	*128.2*	117.3	117.9	115.6	126.8	127.8	127.0
	Average Moisture		*11.3*	10.4	11.4	10.5	11.6	11.4	11.5	*16.5*	15.6	16.2	16.0	18.6	17.0	16.9
	Average Dry Density		*109.2*	108.3	105.7	103.5	111.7	109.8	107.7	*110.0*	101.5	101.4	99.7	106.9	109.2	108.6
eGauge	1st position	Wet Density	*122.2*	115.2	110.1	112.1	122.1	119.5	118.8	*126.5*	112.4	116.2	116.3	128.7	128.9	128.0
		Moisture pcf	*14.0*	13.1	13.6	11.6	12.9	12.6	13.7	*15.6*	16.4	16.3	17.4	17.4	17.3	20.4
		Moisture %	*12.9*	12.8	14.1	11.5	11.8	11.8	13.0	*14.1*	17.1	16.3	17.6	15.6	15.5	19.0
	2nd position	Wet Density	*121.8*	113.7	111.8	108.6	123.8	115.3	118.4	*126.7*	114.3	118.3	116.5	126.2	125.6	128.6
		Moisture pcf	*14.2*	13.1	13.9	11.9	12.8	12.6	13.5	*15.8*	16.8	16.5	18.7	19.3	17.8	20.4
		Moisture %	*13.2*	13.0	14.2	12.3	11.5	12.3	12.9	*14.2*	17.2	16.2	19.1	18.1	16.5	18.9
	Average Wet Density		*122.0*	114.5	111.0	110.4	123.0	117.4	118.6	*126.6*	113.4	117.3	116.4	127.5	127.3	128.3
	Average Moisture		*13.1*	12.9	14.1	11.9	11.7	12.0	13.0	*14.2*	17.2	16.3	18.4	16.8	16.0	18.9
	Average Dry Density		*107.9*	101.3	97.2	98.6	110.1	104.8	105.0	*110.9*	96.8	100.8	98.3	109.1	109.7	107.9
CASE1		Wet Density	*108.7*	125.4	122.2	126.5	131.7	132.5	127.8	*118.3*	119.2	118.8	133.5	131.3	127.0	131.0
		Moisture %	*13.1*	10.8	10.8	10.1	11.6	11.2	11.0	*13.5*	15.9	16.0	16.2	15.6	16.7	16.5
		Dry Density	*96.1*	113.2	110.3	114.9	118.0	119.2	115.1	*104.2*	102.8	102.4	114.9	113.6	108.8	112.4
CASE3		Wet Density	*100.4*	121.0	123.7	123.9	128.4	125.2	125.0	*106.3*	122.4	123.5	126.9	130.7	126.7	127.9
		Moisture %	*13.0*	10.4	10.7	10.3	11.8	11.2	11.3	*13.8*	15.7	16.3	16.6	16.1	16.9	16.9
		Dry Density	*88.8*	109.6	111.7	112.3	114.8	112.6	112.3	*93.4*	105.8	106.2	108.8	112.6	108.4	109.4
Sand Cone		Wet Density	*116.8*	113.7	117.0	115.4	121.5	121.2	119.7	*124.9*	114.7	111.1	120.8	123.2	129.4	124.1
		Oven Dry Moisture	*10.6*	10.5	10.7	10.3	10.8	10.7	10.0	*16.3*	15.9	17.3	15.8	18.0	16.0	15.9
		Dry Density	*105.6*	102.9	105.7	104.6	109.6	109.5	108.8	*107.4*	99.0	94.7	104.3	104.5	111.5	107.0
Hot Plate		Moisture %	*11.4*	11.9	13.2	12.0	Not tested	Not tested	Not tested	*16.4*	16.2	17.1	16.1	18.0	17.0	16.5
		Oven Dry Moisture %	*10.8*	10.5	10.5	10.7	10.3	10.3	10.6	*15.8*	15.4	16.6	15.3	17.5	15.8	15.4

Asphalt Samples								
Sample Type	Depth	Position	Nuke 1st pos. W. Density	Nuke 2nd pos. W. Density	Average W. Density	eGauge 1st pos. W. Density	eGauge 2nd pos. W. Density	Average W. Density
RT-Rough Texture	Backscatter/	1	134	146.1	**140.1**			
		2	141.2	147.0	**144.1**			
		3	137.2	135.6	**136.4**			
	2"	1	140.9	138.9	**139.9**	140.7	143.5	**142.1**
		2	137.1	143.3	**140.2**	143.9	138.6	**141.3**
		3	139.3	139.6	**139.5**	139.8	138	**138.9**
	4"	1	140.6	141.1	**140.9**	145.5	147.3	**146.4**
		2	143.9	143.4	**143.7**	143.4	146.2	**144.8**
		3	140.2	140.2	**140.2**	139.5	144.3	**141.9**
Sample Type	Depth	Position	Nuke 1st pos. W. Density	Nuke 2nd pos. W. Density	Average W. Density	eGauge 1st pos. W. Density	eGauge 2nd pos. W. Density	Average W. Density
ST-Smooth Texture	Backscatter/	1	135.9	146.1	**141.0**			
		2	149.3	149.2	**149.3**			
		3	141.8	151.8	**146.8**			
	2"	1	139.3	143.3	**141.3**	140.2	136.7	**138.5**
		2	139.9	143.1	**141.5**	143.1	142.4	**142.8**
		3	142.1	139.3	**140.7**	140.3	143.1	**141.7**
	4"	1	144	145.8	**144.9**	136.9	141.7	**139.3**
		2	142.5	140.8	**141.7**	145.2	147.7	**146.5**
		3	142.3	143.2	**142.8**	140.1	140.8	**140.5**
Sample Type	Depth	Position	Nuke 1st pos. W. Density	Nuke 2nd pos. W. Density	Average W. Density	eGauge 1st pos. W. Density	eGauge 2nd pos. W. Density	Average W. Density
DP-Deep Sample	Backscatter/	1	126.8	130.0	**128.4**			
		2	126.8	132.7	**129.8**			
		3	110.3	112.6	**111.5**			
	2"	1	134.1	137.1	**135.6**	134.4	137.7	**136.1**
		2	135.6	136.7	**136.2**	137.4	137.2	**137.3**
		3	132.7	133.4	**133.1**	135.7	136.9	**136.3**
	4"	1	136.5	137.3	**136.9**	138.3	138.4	**138.4**
		2	137.3	137.5	**137.4**	140.8	138.5	**139.7**
		3	134.7	135.5	**135.1**	137.9	138.8	**138.4**
	6"	1	136.4	135.3	**135.9**	138.1	137.5	**137.8**
		2	136.1	136.3	**136.2**	136.9	136.8	**136.9**
		3	134.4	136.3	**135.4**	135.1	136.8	**136.0**

Values that have been calculated, all other values not in Bold are raw readings from field/laboratory tests

Asphalt Samples											
Sample Type	Depth	Position	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	SSD B. Density	Core-Lok B. Density	Average B. Density
RT-Rough Texture	Backscatter/	1	138.6	141.5	**140.1**	142.4	145.3	**143.9**			**0.0**
		2	141.6	139.1	**140.4**	145.4	142.9	**144.2**			**0.0**
		3	137.5	137.1	**137.3**	141.3	140.9	**141.1**			**0.0**
	2"	1			Calibration value		-138.6				0.0
		2									0.0
		3									0.0
	4"	1							145.6	144.5	**145.1**
		2							147.1	146.2	**146.7**
		3							144.9	142.5	**143.7**
Sample Type	Depth	Position	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	SSD B. Density	Core-Lok B. Density	Average B. Density
ST-Smooth Texture	Backscatter/	1	143.4	141.6	**142.5**	142.9	141.1	**142.0**			**0.0**
		2	146.7	147.3	**147.0**	146.2	146.8	**146.5**			**0.0**
		3	149.5	148.7	**149.1**	149.0	148.2	**148.6**			**0.0**
	2"	1			Calibration value		-143.4				0.0
		2									0.0
		3									0.0
	4"	1							145.8	145.3	**145.6**
		2							144.7	144.5	**144.6**
		3							145.3	144.9	**145.1**
Sample Type	Depth	Position	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	CASE 1 W. Density	CASE 3 W. Density	Average W. Density	SSD B. Density	Core-Lok B. Density	Average B. Density
DP-Deep Sample	Backscatter/	1	132.5	132.8	**132.7**	141.8	142.1	**142.0**			**141.8**
		2	135.6	134.4	**135.0**	144.9	143.7	**144.3**			**142.1**
		3	133.3	133.9	**133.6**	142.6	143.2	**142.9**			**141.8**
	2"	1			Calibration value		9.3				141.8
		2									142.1
		3									141.8
	4"	1									0.0
		2									0.0
		3									0.0
	6"	1							141.9	141.1	**141.5**
		2							141.4	140.8	**141.1**
		3							141.6	141.1	**141.4**

Values that have been calculated, all other values not in Bold are raw readings from field/laboratory tests

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14. ABSTRACT
During 2015, researchers with the U.S. Army Engineer Research and Development Center (ERDC) validated the effectiveness of the TransTech Combined Asphalt Soil Evaluator (CASE) and the Troxler eGauge as suitable replacements for nuclear density gauge (NDG) technology. Comparisons of soil dry density and moisture content were made between the gauges for six distinct soil types at varying densities and moisture contents. The CASE unit was calibrated using the Sand Cone and hot-plate moisture content prior to its correlation to the NDG; the eGauge was used in its shipped configuration without calibration. Results of both devices were compared to the NDG and core samples to capture asphalt density. Full-scale test sections were constructed for the soil evaluations ranging from crushed limestone to fat clays. Results showed that wet and dry densities obtained with the eGauge very closely matched those of the NDG, but the accuracy of the measured moisture contents was lower. The CASE unit's calibrated accuracy to the NDG moisture content was excellent, but its wet and dry density accuracies were much lower than the eGauge. Based on the ERDC findings, the eGauge is recommended as the best replacement for the NDG for wet/dry density measurements and requires no calibration or transport/licensing restrictions.

15. SUBJECT TERMS
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