ERDC/GSL TR-14-10

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Validation Tests of a Non-Nuclear Combined Asphalt and Soil Density Gauge

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April 2014

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Final report

Prepared for Headquarters, US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

During December 2011, researchers with the US Army Engineer Research and Development Center in Vicksburg, MS validated the effectiveness of the Soil Density Gauge (SDG) and the Combined Asphalt Soil Evaluator (CASE) both of TransTech Systems as a suitable non-nuclear replacement to the Nuclear Density Gauge (NDG). One-to-one comparisons of soil dry density and moisture content were made between the NDG and the SDG and CASE devices for four distinct soil types of varying density and moisture content. The SDG and CASE were tested in a calibrated and uncalibrated condition to establish suitable preparation for field use. Similar comparisons were made between the NDG and the CASE to determine density for two types of asphalt, a warm mix and hot mix at varying surface temperatures. The comparison data were obtained through the construction of two full-scale test sections. The first comprised four soils representing a range of materials encountered in operational construction activities, non-plastic silt, plastic clay, clay-gravel, and crushed limestone. The second comprised a hot mix and warm mix paving operation that was leveraged for this experiment. The test results indicated that the SDG and CASE require field calibration from a secondary device with the CASE being the better of the two devices. For soil, the SDG and CASE are recommended to be only used for military contingency construction activities, because they are not sufficiently accurate compared to the NDG for quality control use in permanent facilities. For asphalt, the CASE is recommended only as a substitute to the NDG for establishing compaction patterns during asphalt construction operations in both contingency and permanent infrastructure projects, as long as it is calibrated to a core density each time it is used in a different asphalt mix.

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Preface

This report was prepared by personnel with the US Army Engineer Research and Development Center (ERDC). Jeb S. Tingle, ERDC Geotechnical and Structures Laboratory (GSL), Engineering Systems and Materials Division (ESMD), was the program manager of the US Air Force-sponsored Non-Nuclear Density project.

The principal investigator for this study was Dr. Ernest S. Berney IV, Airfields and Pavements Branch (APB), ESMD, who was assisted in the preparation of this report by Mariely Mejías-Santiago, APB, and Jeremy J. Beasley of SOL Engineering Services, LLC. Other APB personnel who assisted in this research effort were Quint S. Mason, Jay F. Rowland, Davon A. Mims, and Dr. Jesse D. Doyle. During this study, Dr. Gary L. Anderton was Chief, APB; Dr. Larry N. Lynch was Chief, ESMD; Dr. William P. Grogan was Deputy Director, GSL; and Dr. David W. Pittman was Director, GSL.

COL Jeffrey R. Eckstein was the Commander of ERDC. Dr. Jeffery P. Holland was Director.

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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

Background

The US military has identified the need for eliminating the Nuclear Density Gauge (NDG) used for measuring soil moisture and density in the field because of the restrictive requirements for their transport, use, and storage associated with these instruments containing radioactive materials Cesium and Americium. The military is actively looking for a non-nuclear replacement for use by all of its branches. The US Air Force requirement is for a single instrument that provides asphalt density, soil density, and moisture without the use of radioactive nuclear materials, preferably with a comparable accuracy to the NDG.

Various studies were conducted at the US 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) 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 at ERDC (Mejías-Santiago et al. 2013) to collect data in 16 different types of fine-grained soils to expand its 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 compared to the NDG.

Mejías-Santiago et al. (2013) also tested another non-nuclear gauge, the Combined Asphalt and Soil Evaluator (CASE), but only to collect 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 required a complete characterization on soils and empirical algorithms be developed to be fully compliant with the range of soils of interest to the Army.

Once the database was developed and incorporated in the CASE, the current study was conducted to verify its final version along with the SDG. The purpose was to verify their accuracy and precision 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.

This report describes the materials, testing procedures, and results of the validation of the CASE and the SDG.

Objectives

The objectives of this validation study included:

- Collecting density and water content measurements using the CASE and the SDG 200 to compare to those from standard tests such as NDG, sand cone, drive cylinder, and standard oven tests.
- Conducting tests on an asphalt test section to measure asphalt density with the CASE and comparing to the densities obtained from core samples and the NDG.

Scope

This study consisted of evaluating the two functions of the CASE, 1) soil density and water content measurements and 2) asphalt density measurements. This study also evaluated the performance of the SDG for measuring soil density and water content.

The CASE and the SDG were evaluated by collecting instrument readings of wet density and moisture content from four 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 of each soil were used for construction purposes. Each soil was prepared in the field at two moisture levels, one on the dry side of the optimum moisture content and the other on the wet side, for a total of eight test items. Each test item had final compacted dimensions of 12 ft by 6 ft to a final thickness between 12 and 18 in. Each test item was tested at three varying levels of compaction, with testing occurring between various passes of the compaction roller. Occasionally, based on soil type and moisture levels, only two levels of compaction were obtained. Electronic gauge readings were obtained at each compaction level.

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

The asphalt function of the CASE was evaluated by collecting measurements of asphalt density on two test sections that were constructed for another project at ERDC. One section consisted of conventional hot-mix asphalt (HMA), and the other was warm-mix asphalt (WMA). WMA is asphalt produced at lower temperatures with the help of special additives that keep the viscosity low. Data were collected at two different temperatures (hot and cold) and on two different pavement thicknesses (2 in. and 4 in.).

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

2 Materials and Instruments

Soils

The soils used for the first part of the CASE evaluation study consisted of four different Unified Soil Classification System (USCS) (ASTM D2487 (American Society for Testing and Materials International 2011)) soil types ranging from fine-grained to coarse-grained. The test soils included clay gravel (SC), high-plasticity clay (CH), non-plastic silt (ML), and crushed limestone (GP-GM).

Standard laboratory tests were performed at the ERDC Materials Testing Center (MTC) to determine the geotechnical properties of the soils. Tests conducted on each soil included ASTM C136 (ASTM 2006) and ASTM D422 (ASTM 2007) standard grain-size distribution with hydrometer analysis for dissemination of silt and clay fractions, Atterberg limits (ASTM D4318 (ASTM 2010d)) including liquid limit (LL) and plastic limit (PL), Unified Soil Classification (USCS), and standard proctor compaction (ASTM D698 (ASTM 2012)) 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 SDG 200. 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.

Table 1. Geotechnical properties of the soils used for the first part of the CASE validation.

Soil ID	USCS Classification	Atterberg Limits			Grain size (% by weight)			C_u	C_c	MDD (pcf)	OMC (%)
		LL	PL	PI	Fines	Sand	Gravel				
Silt	Silt (ML), Brown	No Plasticity			93.8	3.5	2.7	-	-	106.6	17.6
Clay-Gravel	Clayey Sand (SC), with Gravel; Reddish Brown	29	14	15	15.5	65.8	18.7	11.4	4.3	125.0	9.2
Limestone	Gravel (GP-GM), with Silt and Sand; Gray	No Plasticity			8.8	37.6	53.6	71.1	3.7	139.6	7.2
Buckshot Clay	Clay (CH) Gray	73	24	49	95.5	5.0	0	-	-	90.5	29.2

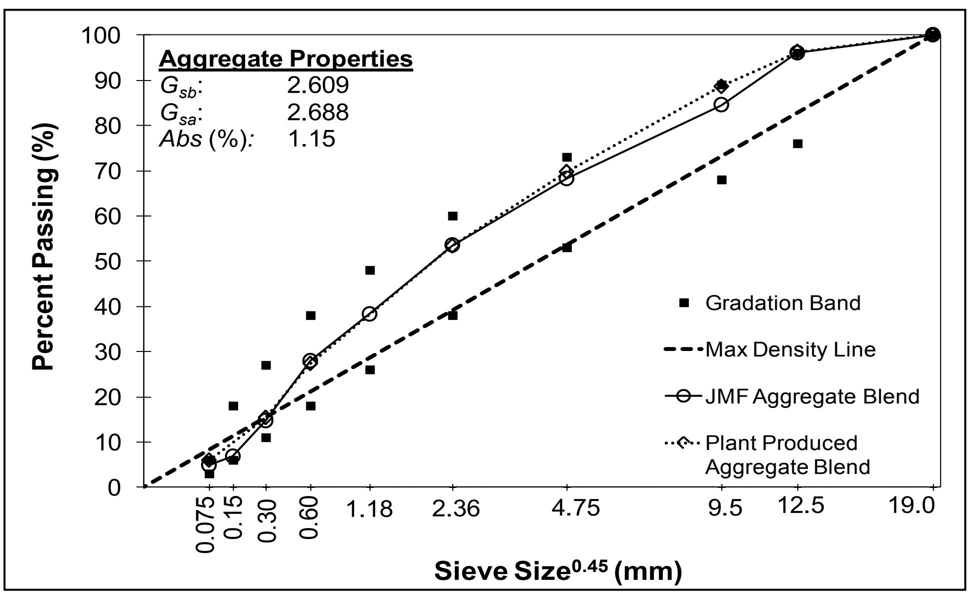
C_u = Coefficient of uniformity

C_c = Coefficient of curvature

Asphalt

The design of the asphalt mix used for the second part of the CASE validation study was performed by the ERDC MTC. An aggregate blend was designed to meet Job Mix Formula (JMF) gradation requirements for a 0.5-in. (12.5-mm) nominal maximum aggregate size according to Unified Facilities Guide Specification (UFGS) 32- 12- 15, *Hot mix asphalt for airfields* (USACE 2010). The blend consisted of 60 percent limestone, 25 percent crushed gravel, and 15 percent sand (maximum allowed by specification). The aggregate sources and blend were selected based on materials available for plant production. Grain-size distribution and aggregate properties for the JMF aggregate blend as well as the grain-size distribution from solvent-extracted material produced at the plant are provided in Figure 1. In the figure, G_{sb} is the aggregate bulk specific gravity, G_{sa} is the aggregate apparent specific gravity, and ABS is the aggregate absorption. The plant-produced aggregate blend was generally close to the JMF target blend. The base binder used was an unmodified Performance Grade (PG) 67-22.

Figure 1. Properties of Job Mix Formula (JMF) aggregate blend.



The asphalt mixtures were designed to 75 gyrations in the Superpave Gyratory Compactor (SGC) according to USACE 2010 specification requirements. The design binder content was selected as the binder content that resulted in a compacted specimen having 4.0 percent air voids. The volumetric properties resulting from the mix designs and the measured volumetric properties from the plant-produced mixtures are listed in Table 2.

Table 2. Volumetric properties of all mixtures.

Mix ID	G_{mm}[a]	G_{se}[b]	G_{mb}[c]	P_b[d]	P_{ba}[e]	P_{be}[f]	V_a[g]	VMA[h]	VFA[i]	D/B[j]
HMA	2.461	2.668	2.362	5.3	0.87	4.48	4.0	14.3	72.0	1.04
WMA	2.467	2.666[k]	2.369	5.1[l]	0.85[k]	4.29[k]	4.0	13.8[k]	71.1[k]	1.08[k]
Target	—	—	—	—	—	—	**4**	**min 14.0**	**65-78**	**0.8-1.2**
HMA-QC[m]	2.444	2.645	2.388	5.3	0.54	4.75	2.3	13.3	83.0	1.20
WMA-QC[m]	2.448	2.638	2.402	5.0	0.43	4.55	1.9	12.5	84.9	1.24

Note: An asphalt binder specific gravity of 1.03 was used for all calculations.

[a] Maximum specific gravity of the asphalt mixture

[b] Effective specific gravity of aggregate

[c] Bulk specific gravity of compacted mixture

[d] Asphalt content, percent by total mass of mixture

[e] Absorbed asphalt, percent by mass of aggregate

[f] Effective asphalt content, percent by total mass of mixture

[g] Air voids

[h] Voids in mineral aggregate

[i] Voids filled with asphalt, percent of VMA

[j] Dust proportion

[k] Calculated using the adjusted total asphalt content.

[l] Total asphalt content was adjusted to account for the water added to the binder. Nominal asphalt content with water included was 5.2.

[m] Average results from producer's Quality Control (QC) testing.

The list of instruments tested is presented in Table 3, and the following sections describe each instrument in more detail.

Table 3. List of instruments used in this evaluation.

Instrument	Description	Output
SDG 200	Soil Density Gauge	• Wet and Dry Density • % Moisture Content • % Compaction
CASE 1 and CASE 2	Combined Asphalt and Soil Evaluator – Units 1 and 2	• Wet and Dry Density • % Moisture Content • % Compaction
Model 3430 Roadreader™	Nuclear Moisture Density Gauge	• Wet and Dry Density • % Moisture Content • % Voids • % Compaction

SDG 200

The Soil Density Gauge is an electrical impedance-based gauge that is manufactured by TransTech Systems, Inc. to be used as a quality control tool during soil compaction. The Model 200 (Figure 2) used in this evaluation is equipped with a touch screen, a graphical menu interface, and Global Positioning System (GPS). 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 SDG 200 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 SDG'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 density/compaction increases because the percentage of air in the soil matrix decreases. The SDG processes the data and uses algorithms to calculate and report the soil's density and moisture content (TransTech Systems, Inc.). The SDG uses the cloverleaf pattern shown in Figure 4 for averaging density measurements.

Figure 2. SDG 200 (www.transtechsys.com).

Figure 3. Configuration of the SDG 200 non-contacting sensor (www.transtechsys.com).

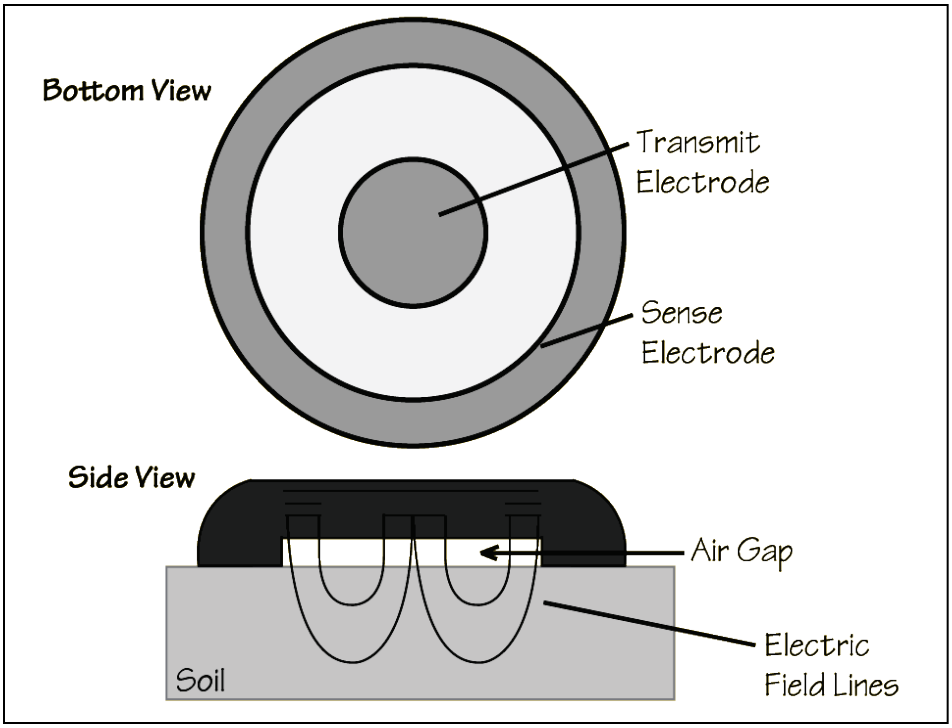
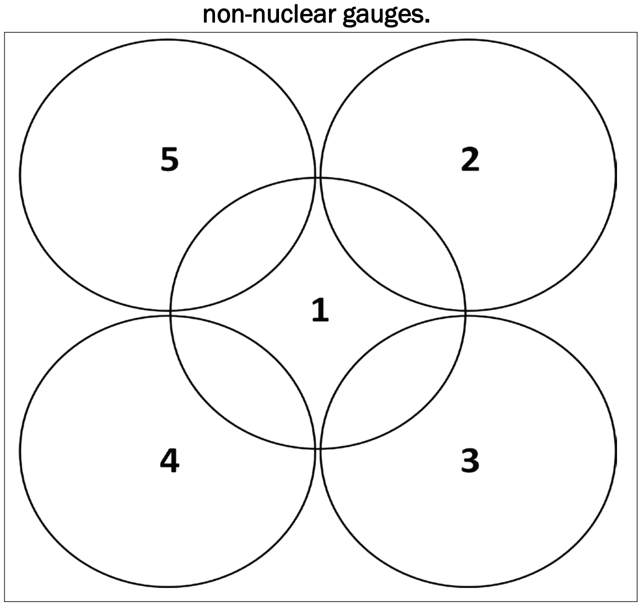


Figure 4. Cloverleaf pattern of readings of the non-nuclear gauges.



CASE unit

The Combination Asphalt and Soil Evaluator (CASE) 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.

In asphalt mode, 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).

In soil mode, the unit 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 unit 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. It uses the same cloverleaf pattern for averaging density measurements as the SDG.

The CASE (Figure 5) has the same case design as the SDG 200 and is also equipped with touch screen, graphical menu interface, and GPS.

Figure 5. Combined Asphalt and Soil Evaluator (CASE).

Nuclear gauge

The Troxler Model 3430 Roadreader™ nuclear moisture-density gauge, Model 3430, shown in Figure 6, was also 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. 2007).

Figure 6. 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. 2007).

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. 2007). The NDG was used according to ASTM D6938 (ASTM 2010b) with a rod driven 6 in. into the ground to obtain moisture content and wet density.

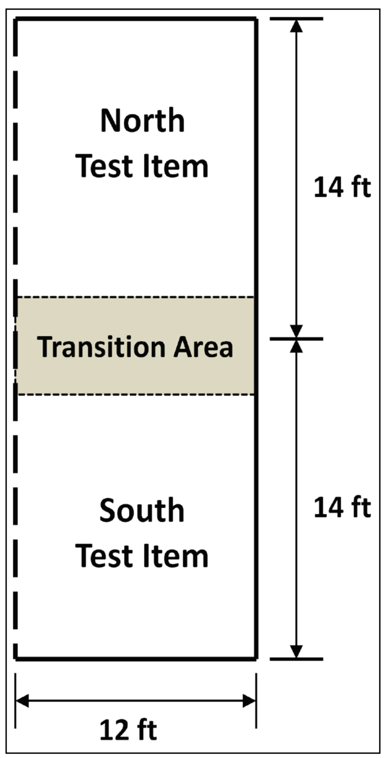
3 Experimental Procedures

Soil test section

Test strips construction

Four soil test strips were constructed at ERDC under Hangar 2 to help protect the soils from the elements. Each test strip consisted of two test items (North and South) consisting of two different soils or the same soil but at two different moisture levels. Figure 7 shows a typical test strip layout with the typical dimensions. The transition area at the boundary between two test items was about 4 ft wide and was not used for testing.

Figure 7. Typical test strip layout.



The order in which the soil test strips (1 through 4) were constructed is listed in Table 4, which also provides a description of each test item, the moisture content tested and the compaction level tested. Each test strip was tested as construction was completed. The original plan was to construct one test strip at a time consisting of two test items of the same soil prepared at the two moisture levels. Due to issues during construction, Test Strip 1 was constructed using two different soils, silt and clay-gravel (Figure 8), as their initial moisture condition was at the first desired moisture level for each one. Test Strip 2 was constructed as planned using the limestone material at two different moisture levels. Test Strip 3 was constructed by removing the silt and the clay gravel used in Test Strip 1 and spraying them to achieve the "wet" moisture level. Once the soils were ready, they were placed back in the same location for construction of Test Strip 3. The last test strip was constructed using the Buckshot Clay at two moisture levels.

Table 4. Test item description.

Test Strip	Test Item	Soil Type	Moisture Content (%)[a]	Compaction Level Tested		
				Low	Medium	High
1	North	Clay-Gravel	7	X	X	X
	South	Silt	17	X	X	X
2	North	Limestone	4	X	X	X
	South	Limestone	6	X	X	X
3	North	Clay-Gravel	12	No data	No data	X
	South	Silt	20	X	No data	X
4	North	Buckshot Clay	28	No data	No data	X
	South	Buckshot Clay	37	No data	No data	X

[a] Average soil moisture content from at least 3 samples tested with the standard oven test (%) (ASTM D2216 (ASTM 2010c)).

Figure 8. Test Strip 1 consisting of silt in the South Test Item (back) and clay-gravel in the North Test Item (front).

Each soil was prepared to the desired moisture by letting it air-dry or by wetting it using a hydro-seeder (Figure 9a) depending on the current moisture content of the soil at the time of preparation. A skid steer was used to mix the soil to distribute the moisture more consistently as shown in Figure 9b. Some of the soils, especially the Buckshot Clay, required the use of a tiller (Figure 10) to loosen the soil, so that the moisture could be distributed more uniformly. For test section construction purposes only, constant monitoring of the soil moisture content was performed by using the standard laboratory microwave oven (ASTM D4643 (ASTM 2008)). Once the soil was at the desired moisture content, it was placed in the test section in three lifts using a skid steer (Figure 11) or a bucket loader and shovels.

Figure 9. Soil preparation: a) wetting soil using a hydro-seeder and b) mixing soil using a skid steer.

Figure 10. Tiller used to loosen the soil during soil preparation.

Figure 11. Placing a soil in the test section using a skid steer.

For each test strip, the first lift placed was approximately two roller widths (12 ft) across to provide a wide enough base to create a top layer at least 6 ft across. The test items were constructed in three 6-in.-thick compacted lifts such that the final test section was 18in. 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. This was true for all soils except the wet clay-gravel and the buckshot. These soils were only placed in two lifts because of lack of material and difficulty in smoothing these substantially wet soils.

To accelerate construction and testing in all test strips except Test Strip 3, both test items (North and South) were compacted simultaneously (Figure 12). In Test Strip 3, the clay-gravel was too wet and could not be compacted simultaneously with the wet silt because the soil was sticking to the roller. All of the soils were compacted using a Caterpillar CS433E 7-ton vibratory smooth drum roller (Figure 12) with the exception of the Buckshot clay, which was compacted using an Ingram 35-ton rubber tire compactor (Figure 13).

Nuclear gauge density readings down to 12 in. were obtained at the center of the test items after the second lift was compacted (Figure 14). This was to ensure that the desired density was obtained before placing and compacting the third lift. The test items were considered ready for testing when the third lift was at the specified compaction level.

Figure 12. Compacting both test items (North and South) of Test Strip 1 simultaneously.

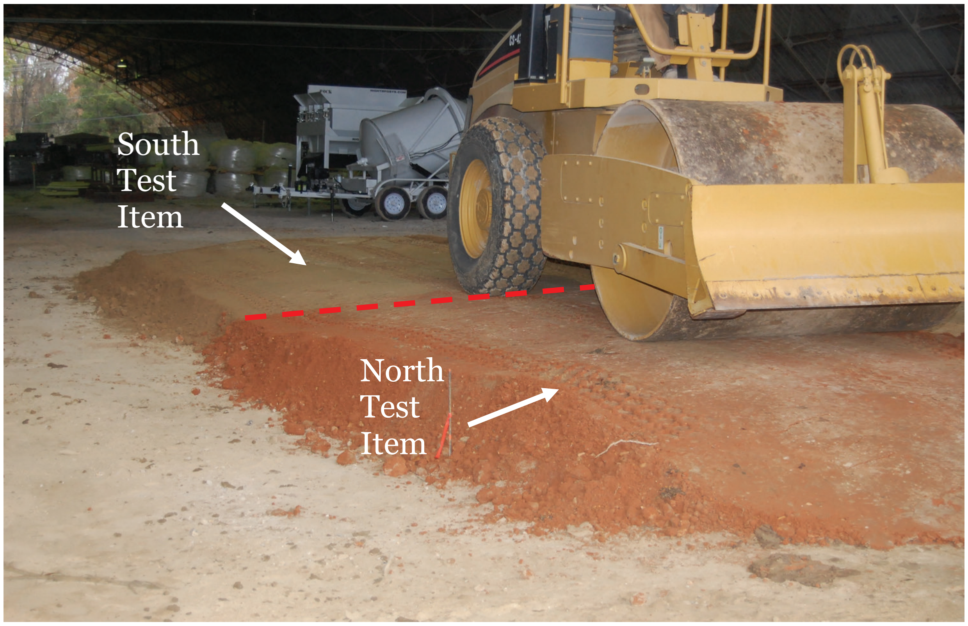
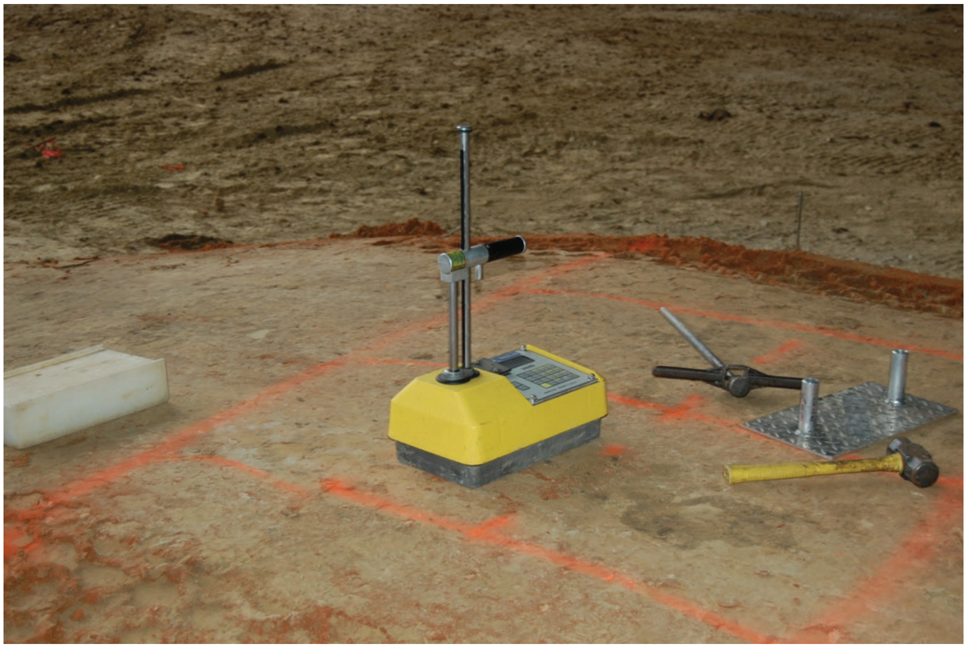


Figure 13. Rubber-tire compactor with a 35-ton capacity.

Figure 14. Obtaining nuclear gauge readings at the center of the second lift of soil.

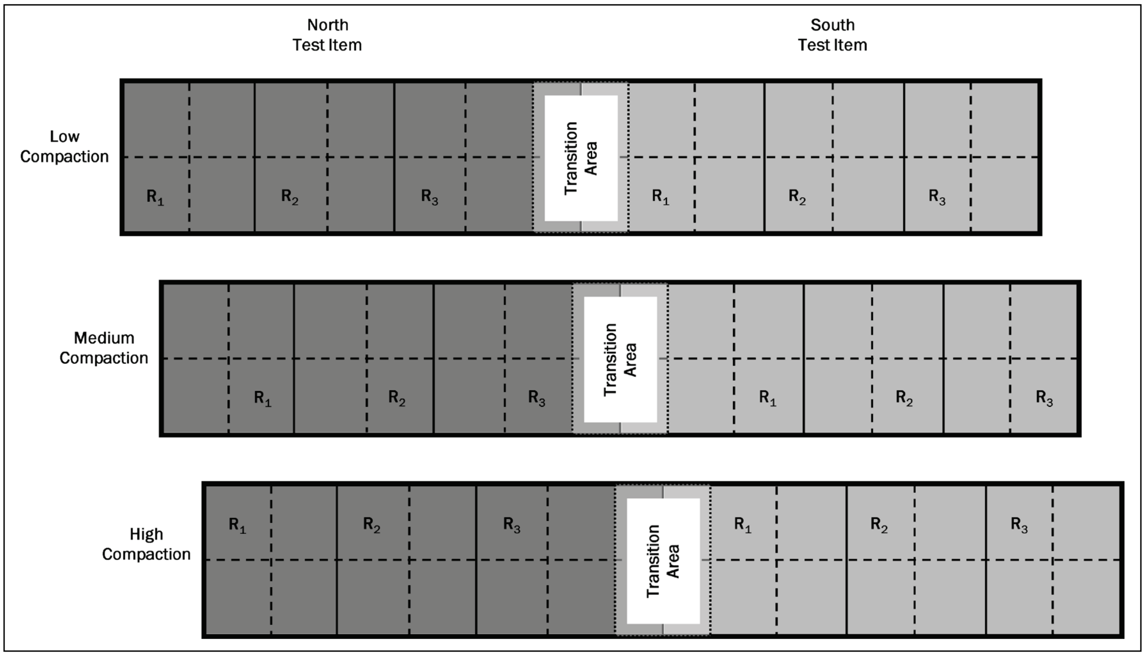


Test procedures

Testing was conducted as compaction progressed. Density and moisture content measurements were collected with two CASE units, the SDG 200, and the NDG at three different compaction levels (low, medium, and high). Occasionally, based on soil type and moisture levels, only one or two levels of compaction were obtained. 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 on each side plus two passes on the middle of the strip.

Figure 15 shows typical test layouts for each test strip. Each test item was divided into three test areas. At each compaction level, three readings were obtained with each instrument in the three test locations (R_1, R_2, and R_3) on each test item (North and South). Soil samples were obtained from each test location for moisture content determination after all four instruments were tested. Since the soil was disturbed and could not be used for further testing, the test locations changed for each compaction level as shown in Figure 15.

Figure 15. Typical test layout.



When testing was completed at the last compaction level, standard density tests were conducted for comparison. The standard test used for the coarse-grained soils (limestone and clay-gravel) was the sand-cone method (ASTM D1556 (ASTM 2007)), shown in Figure 16. The drive-cylinder method (ASTM D2937 (ASTM 2010a)) was used in the fine-grained soils (silt and buckshot clay), as shown in Figure 17.

Figure 16. Conducting sand cone test in the clay-gravel.

Figure 17. Conducting drive cylinder test in the buckshot clay.

Internal gauge calibration

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

The soil density gauge (SDG) required material inputs based on the soils' grain-size distribution and Atterberg limits to function properly. It used this information to select the proper regression algorithm based on soil classification to correlate the measured frequency data to density and moisture content. Data obtained from the laboratory investigation were used to input the percent material greater than the ¾-in. sieve, the percentage of sand (#4-#200 sieve), and the percentage of fines (minus #200-sieve fraction), along with the liquid limit and plastic limit if applicable. This approach was considered as if this device was to be used on a construction project for quality control where the material properties were known prior to construction.

In situations when no soil data may be available prior to testing, the user has two options. First, an SDG test could be conducted, obtaining the internal frequency response and then calibrating the device posttest with soil obtained from the site and analyzed later. Second, an expedient process to establish the general properties at the site could be conducted such as the Rapid Soils Analysis Kit (Berney et al. 2007) or guidance on field classification given in Army FM 5-472. Either way, the internal calibration process extends the time to conduct a test well beyond the 2 min. it takes for the SDG operation in the field.

The combined asphalt and density evaluator (CASE) did not require any setup or pre-calibration information 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. This simplifies the CASE unit for use as opposed to the SDG and enables its use in situations where no soil property information may be available.

Asphalt Test Section

Construction

The asphalt test section used for this evaluation was constructed for another ERDC project. It consisted of two different test items; one was hot-mix asphalt (HMA), and the other was warm-mix asphalt (WMA). Two different pavement layer thicknesses were tested, 2 in. and 4 in. The asphalt mixes were produced in a local asphalt plant. The mixes were delivered from the plant to the lay-down site and placed and compacted using typical construction equipment. Table 5 lists the test items and the actual mix plant production and field placement temperatures.

Table 5. Asphalt test items descriptions.

Test Item	Mix Type	Mix Production Temperature (°F)	Mix Compaction Temperature (°F)
1	HMA	330	270
2	WMA	290	230

The tests for the 2-in.-thick pavement were conducted on the first lift of each test item. Tests for the 4-in.-thick pavement were conducted in the second lift of the test items. Asphalt paving operations were conducted as shown in Figure 18. Once the first lift was finished, the paver started the second lift about 5 ft away from the starting point of the first lift. This allowed for testing the first lift when it cooled down and for the collection of core samples from the first lift for density determination.

Figure 18. Asphalt paving operations layout.

Test procedures

Asphalt density measurements were obtained once compaction operations were completed. The test layout shown in Figure 19 was used on each of the two test items. Testing consisted of obtaining 10 consecutive readings without picking up the gauges at each test location (1 through 6). Two CASE units were used.

Two layer thicknesses and two different temperature levels were used to provide different test conditions and a wider range of densities. The high temperature used was the temperature of the mat immediately behind the finish roller, and the low temperature was tested after the mat had cooled considerably. The approximate temperatures measured at each location during each test are in Table 6. The exact testing locations (Figure 19) were marked so that the same locations could be tested after the mat had cooled and to obtain the core samples from the exact same locations where the measurements occurred.

Figure 19. Typical asphalt test layout.

Table 6. Asphalt test temperatures.

Test Item	Test Locations	Pavement Thickness (in.)	Average High Temperature (°F)	Average Low Temperature (°F)
HMA	1 - 3	2	136	77
	4 - 6	4	130	81
WMA	1 - 3	2	120	79
	4 - 6	4	125	80

Gauge calibration

A critical step in using electrical impedance-based gauges effectively is to calibrate them in a manner that will increase the accuracy of their results. Different methods are available for use in calibrating electrical impedance-based gauges. The American Association of State and Highway Transportation Officials (TP68 (AASHTO 2008)) method outlines three methods, 1) a relative density method recommended for establishing rolling patterns during compaction, 2) a screed calibration, in which the density behind the screed is estimated and used to generate an offset for the mix, and 3) a core calibration method. This last method is the one recommended by AASHTO. In this procedure, one to five locations are chosen to obtain gauge readings, and core samples are obtained at each location for bulk specific gravity determinations. The offset is calculated based on the average differences between the gauge readings and the core densities.

In this project, core samples for bulk specific gravity determination were obtained at the end of all testing at exactly the same test locations shown in Figure 19. Densities of the asphalt core specimens were obtained according to AASHTO T166 (AASHTO 2011). The asphalt density readings from the CASE units were compared to the core densities to determine the calibration factors applicable to the asphalt pavements tested.

4 Data Analysis and Results

Soil test section

Nuclear Density Gauge performance

It was first necessary to establish the capability of the NDG as a suitable device for measuring dry density and moisture content in the soils chosen for this research. Since the NDG was considered the standard by which to compare the performance of the electronic gauges, a one-to-one comparison was made between the dry density and moisture content readings returned from the NDG to those of either the sand cone or drive cylinder samples taken adjacent to the NDG hole. A representative soil sample was then obtained from the sand cone sampled soil or from the drive cylinder and dried in an oven as per ASTM D2216 (ASTM 2010c) to obtain the reference moisture content. Figure 20 shows this comparison for the dry density of soils with data grouped according to soil type. Figure 21 shows the comparison of moisture content using the same layout as density. The soil types in Figure 21 plot in reverse order along the diagonal from those in Figure 20, because the wettest soils had the lowest density and the driest soils the highest density. A linear trendline is presented on each plot to illustrate the coefficient of determination, R^2, found for each of the data sets.

Figure 20. Comparison of dry density between NDG and sand cone or drive cylinder.

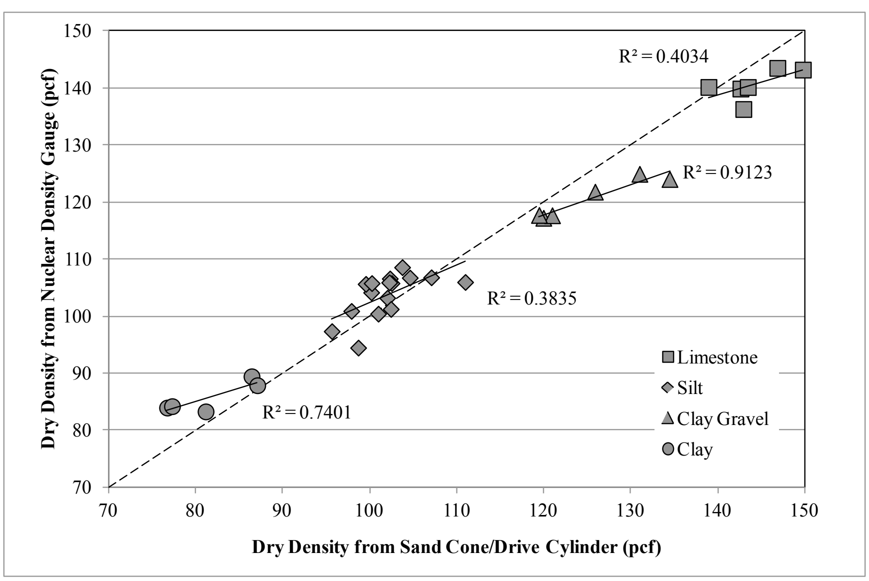
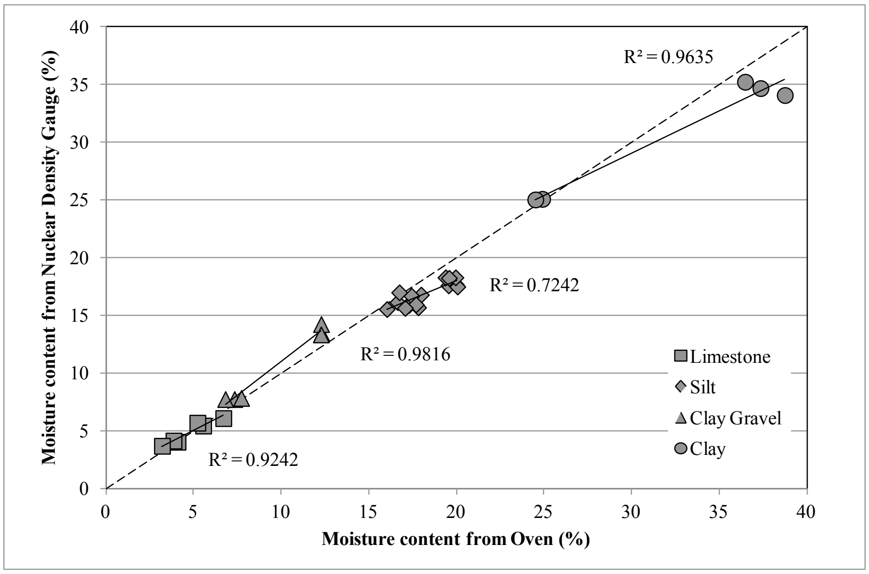


Figure 21. Comparison of moisture content between NDG and oven dried.



What is evident from the NDG response is that this device is capable of obtaining the dry density of the soil with some trouble distinguishing small changes in density within the limestone and silt soils. However the overall trend between soils has a moderate degree of correlation and little variability is seen from the one-to-one correspondence line. With regard to moisture content, the NDG performed even better with an even higher degree of correlation for each soil independent of the density, illustrating the NDG's good sensitivity to small changes in moisture within the same soil type.

External device calibration

To consider the use of the SDG and CASE devices as a replacement to the NDG required a one-to-one comparison of wet density, dry density, and moisture content based on the data obtained from the various soil test sections. This one-to-one comparison was conducted based on one of two conditions for the electronic devices, the first with no external calibration (uncalibrated) whereby the data provided by the device was based on internal parameters only, and the second with external calibration (calibrated), which provided a single reference point to scale the returned density and moisture readings. The second technique varied as per the soil type tested; the sand-cone density and oven-dried moisture content were used for the limestone and clay-gravel sections, and the drive cylinder density and oven-dried moisture content were used for the silt and buckshot clay sections. Side-by-side data are shown in Appendix B.

A calibration factor for the NDG was developed based on the average deviations of the wet density and moisture content for each soil from the sand cone or drive cylinder density and oven-dried moisture values. This process shifted the measured data points closer to the one-to-one correspondence line improving the overall correlation but did not improve the correlation within a given soil type. The calibrated NDG response that was used as a basis for one-to-one comparison with the electronic gauges is shown in Figures 22 and 23 for the wet density and moisture content, respectively. The combination of these two calibrations provides an overall dry density correlation of 88 percent as shown in Figure 24.

SDG and CASE correlations to NDG

The SDG and CASE devices allow for input of a known dry density and moisture content from a sample location in which the electronic device obtained frequency response data. Each soil test section involved multiple test locations; however, for each soil type tested, only one test location was used as the input point for the device, either using a sand cone or drive cylinder density and its associated oven-dried moisture content. This calibration point was not selected as the first data point in the collection sequence which would be the typical approach in an applied field setting, but rather the point at which there was the least differential between the NDG and the secondary device. This approach was used in order to minimize the influence of any error inherent in the secondary device.

Figure 22. Calibrated NDG wet density readings from sand cone/drive cylinder.

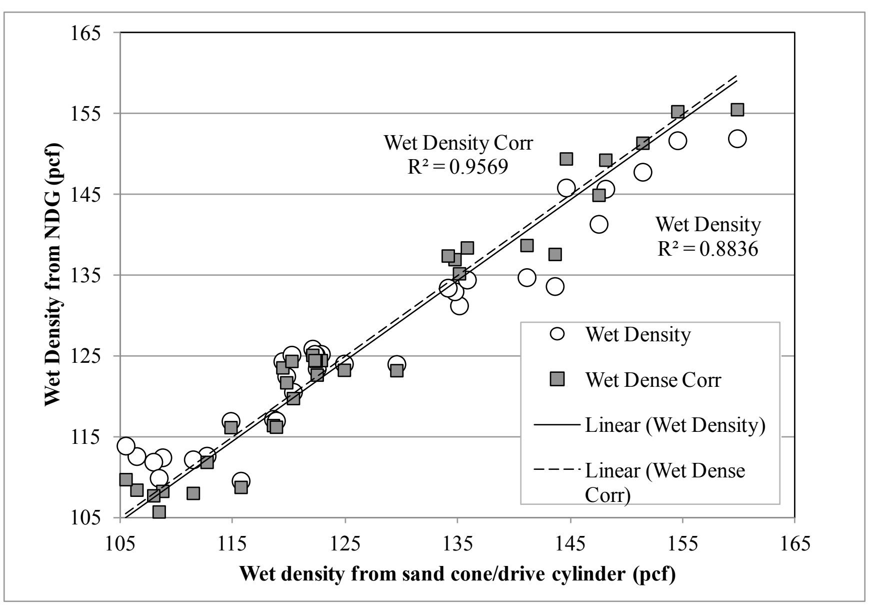


Figure 23. Calibrated NDG moisture content readings from oven dried.

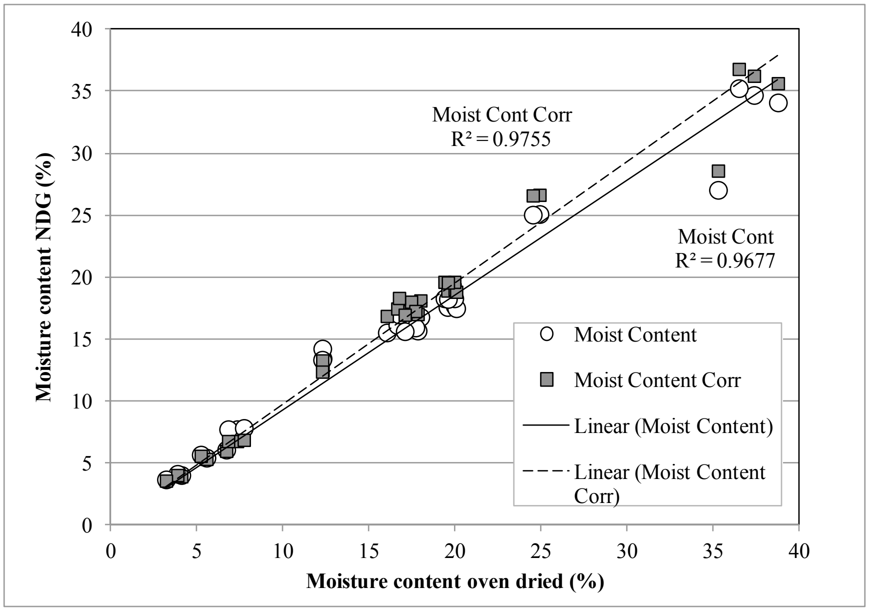
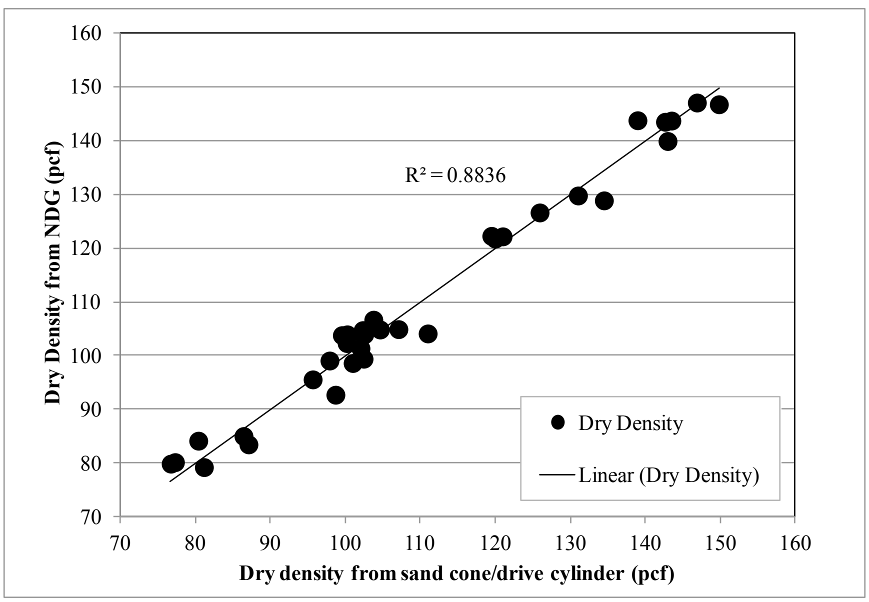


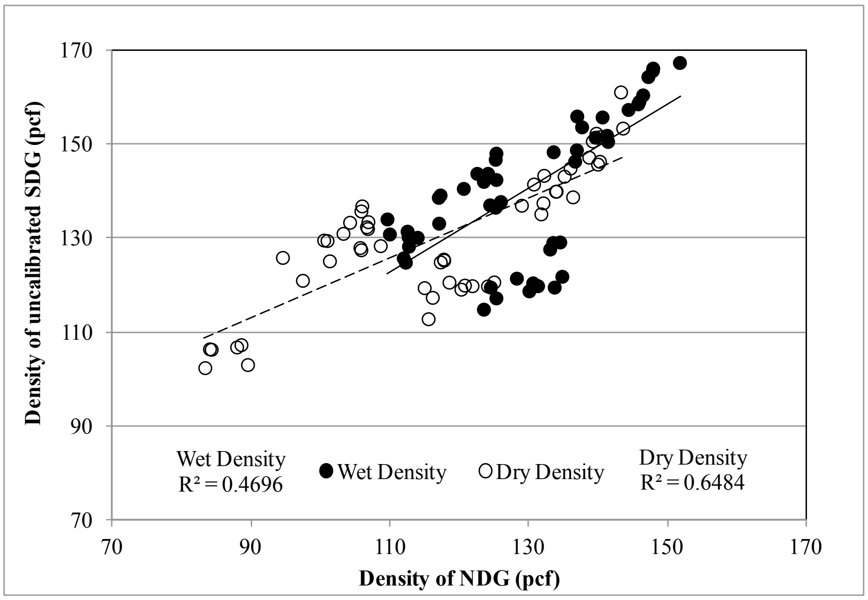
Figure 24. Calibrated dry density correlation between NDG and sand cone/drive cylinder.



Density comparison to the NDG

Figures 25 and 26 are the one-to-one comparisons of wet and dry density measured with the calibrated NDG to that of the SDG and CASE devices, respectively. The upper plot is in an uncalibrated state showing the device response if it were to be used without any density or moisture information provided to the device. The lower plot is the response of each device when calibrated with a known density and moisture value. Two CASE devices were tested at each sample location, and their values for moisture and density were averaged to represent a single device response in the following figures. Appendix B contains the side-by-side comparisons of each CASE device.

Figure 25. Dry and wet density comparison between SDG and NDG for uncalibrated (top) and calibrated (bottom) conditions.



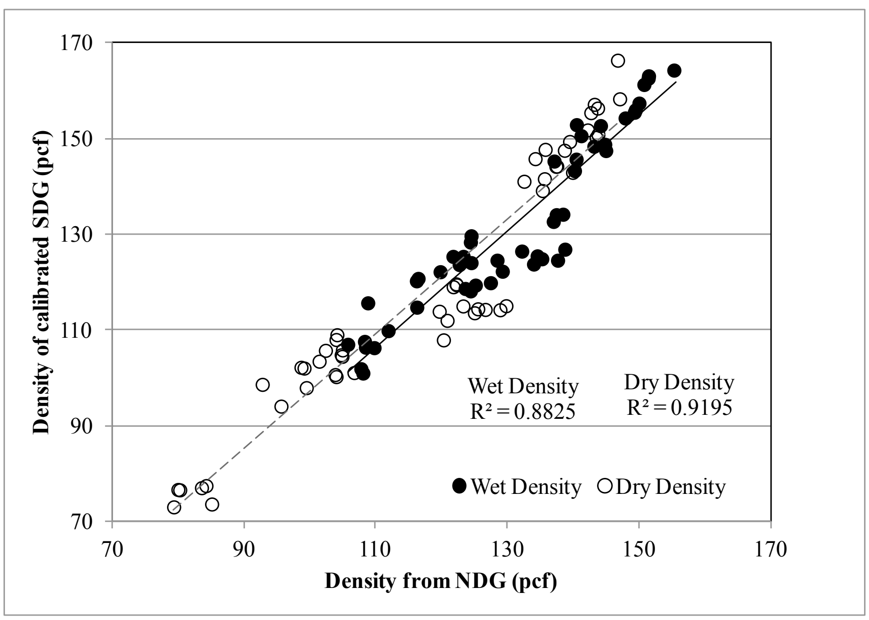
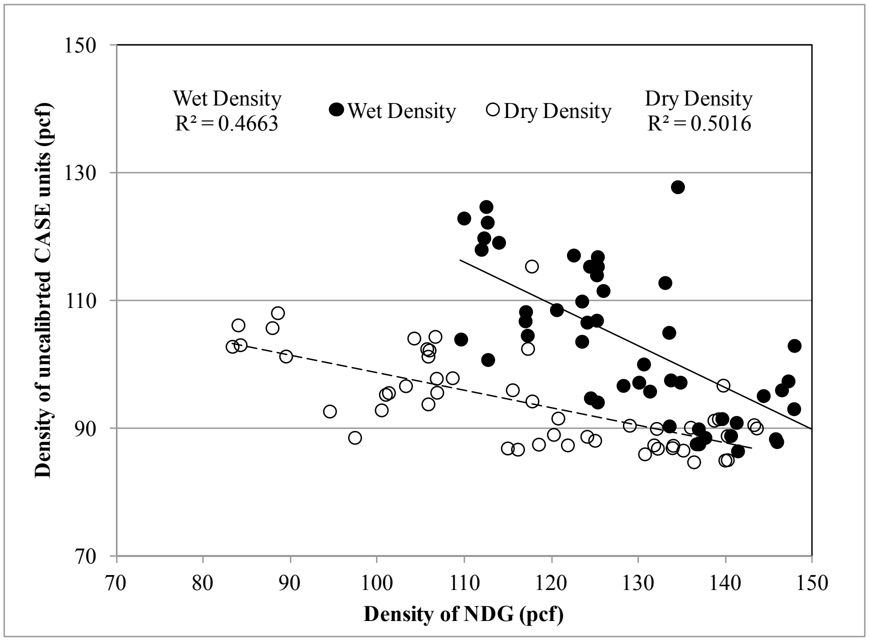
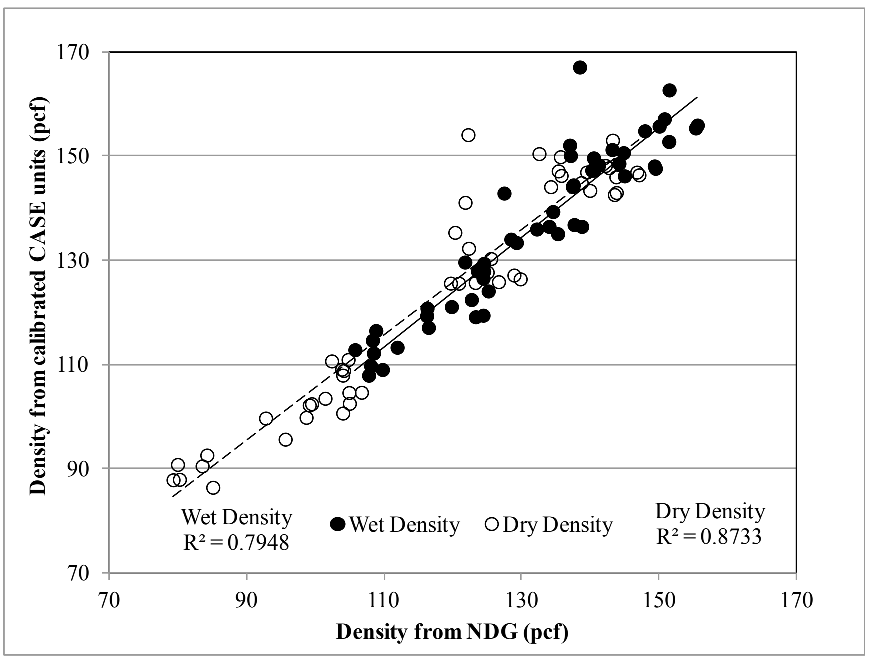


Figure 26. Dry and wet density comparison between CASE units and NDG for uncalibrated (top) and calibrated (bottom) conditions.





The trends shown in these data sets indicate that external calibration is a key feature in improving the effectiveness of the electronic devices in providing dry density accurately. R^2 values for the CASE units increased from 50 percent to 87 percent and for the SDG from 65 percent to 92 percent. A 90 percent coefficient of determination represents an excellent correlation when dealing with granular material due to the high variability in material characteristics. When calibrated, both electronic devices were able to differentiate wet and dry density responses for all soils in general. However, without calibration, the CASE units provided a reverse trend in behavior where wet and dry density both decreased as the NDG values increased. The fact that the CASE devices even exhibit such a response shows that their performance is highly dependent on being calibrated. Both calibrated plots (CASE in particular) show some deviation from the equality line, which suggests that some sort of additional offset is needed for the SDG and CASE machines to truly return similar values to the NDG.

Moisture content comparison to the NDG

Figures 27 and 28 illustrate the one-to-one comparisons of moisture content obtained with the NDG to that from the SDG and CASE devices, respectively. Each plot contains data in both an uncalibrated and calibrated condition. The trends shown in these data sets indicate again that external calibration is a key feature in improving the effectiveness of the electronic devices in measuring moisture content accurately. R^2 values for the CASE units increased 74 percent to 90 percent and for the SDG from 42 percent to 93 percent. When calibrated, both electronic devices were able to differentiate moisture content between soils very well. Without calibration, the CASE still provided a reasonable correlation; however, the magnitudes of the measured moisture contents decreased with increasing true moisture content. The SDG had a difficult time predicting moisture contents without calibration.

Figure 27. Moisture comparison between the NDG and SDG gauges.

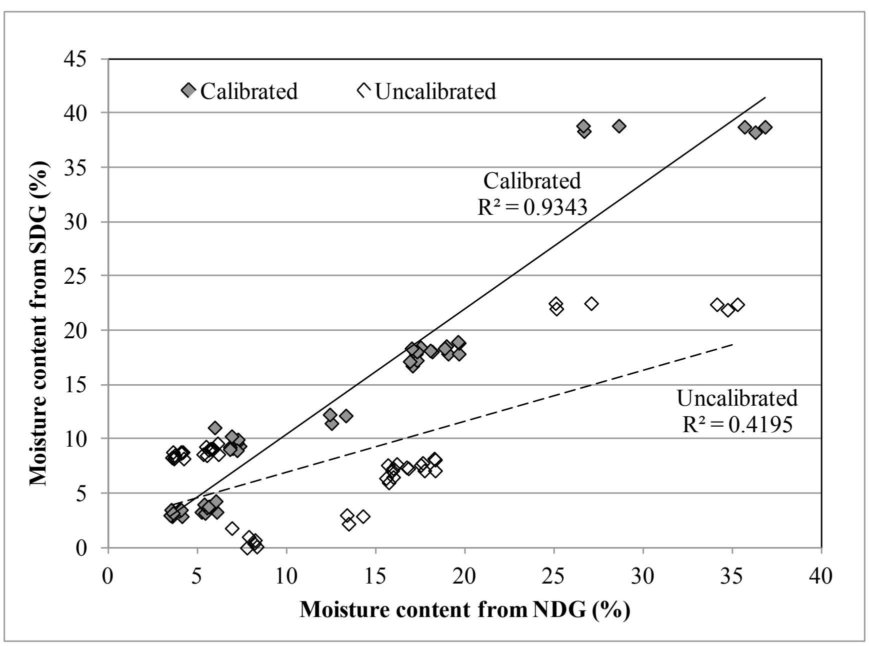
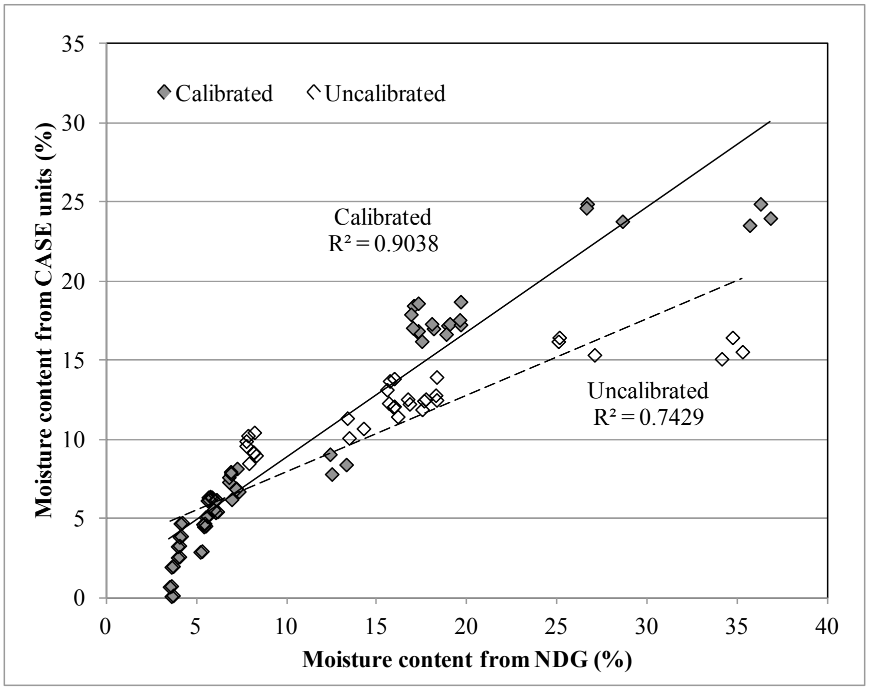


Figure 28. Moisture comparison between the NDG and CASE gauges.



Correlations by soil type

The key to assessing the ability of the SDG and CASE devices for use as quality control tools for construction operations requires determining the sensitivity of each electronic device when detecting changes in moisture and density for a given soil type undergoing compaction. In the previous section, Figures 20 and 21 indicated that the NDG performed well in distinguishing moisture content and density between incremental changes in compaction effort as well as changes in moisture between test sections of similar material. Figures 29 and 30 highlight the R^2 correlation between the SDG and CASE device measurements of dry density and moisture content to that of the NDG. The SDG and CASE devices had a much lower sensitivity and in some cases were unable to differentiate changes in compaction characteristics for certain soil types. An illustration of the correlations is shown in Figures 31 and 32.

What can be noted in the figures is a banding response that is horizontal with respect to density and both horizontal and vertical with respect to moisture content. This indicates a difficulty of the electronic units to measure incremental changes in density and moisture for a given soil type. In general, the fine grained soils (silt and clay) proved to be the most difficult materials to measure density changes between roller passes and moisture content between test levels. Between the SDG and CASE, the

Figure 29. R^2 value for dry density differential by soil for each device (NDG compared to sand cone/drive cylinder).

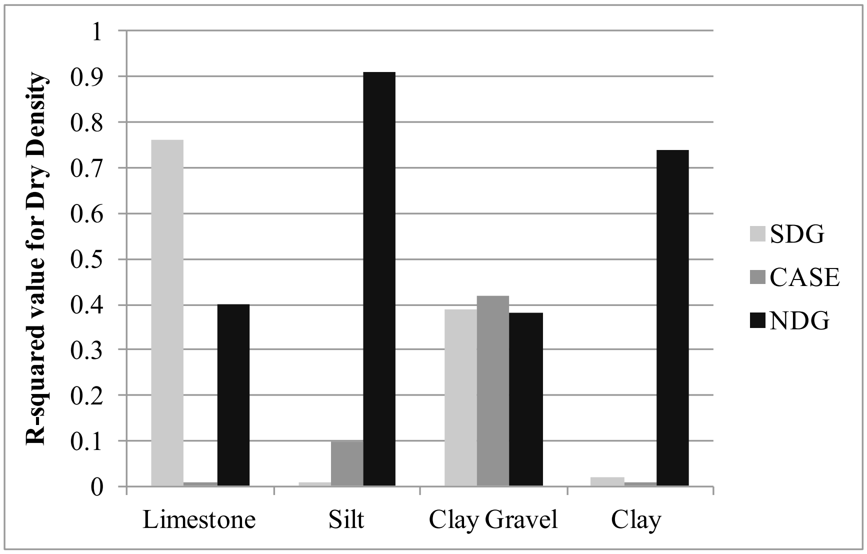


Figure 30. R^2 value for moisture content differential by soil for each device (all devices compared to oven-dried moisture content)

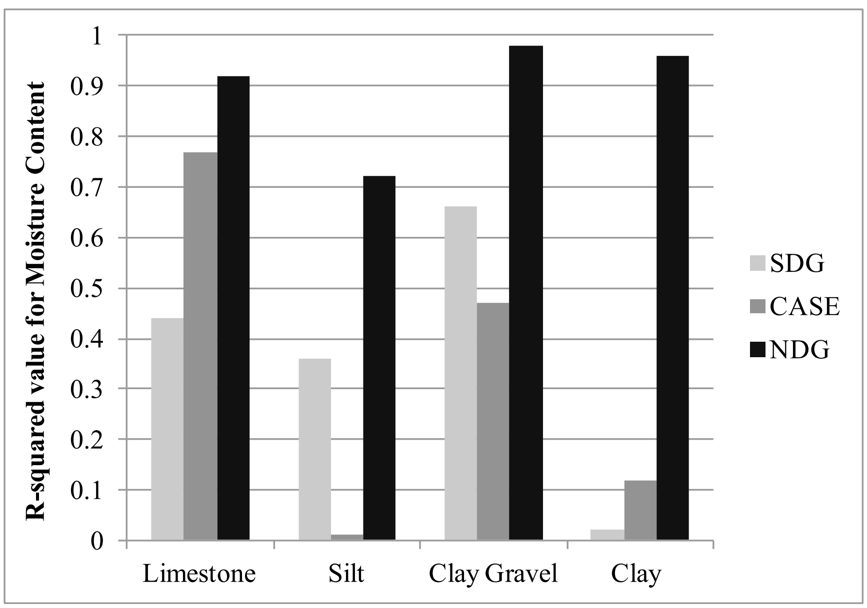
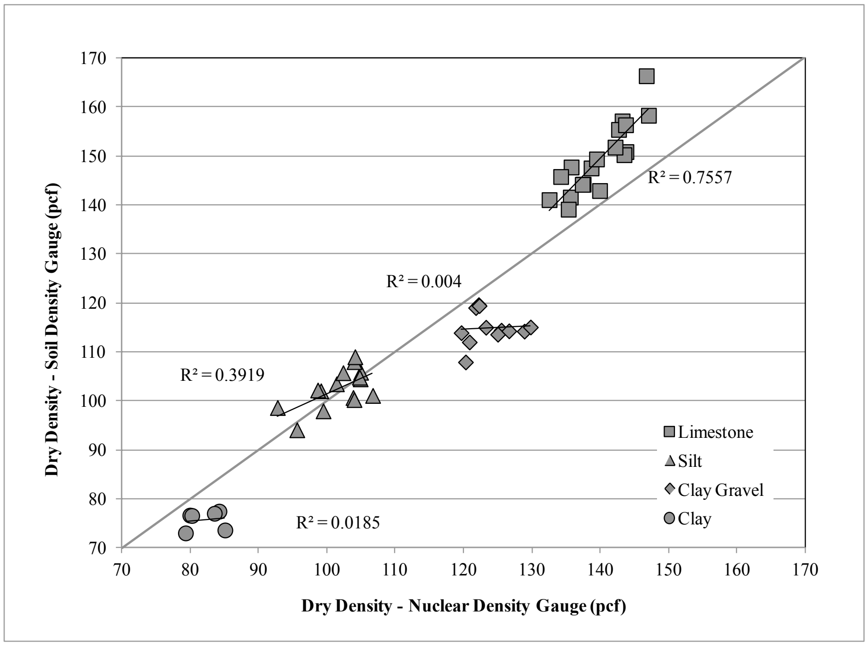


Figure 31. Dry density (top) and moisture content (bottom) comparison between SDG and NDG by soil type.



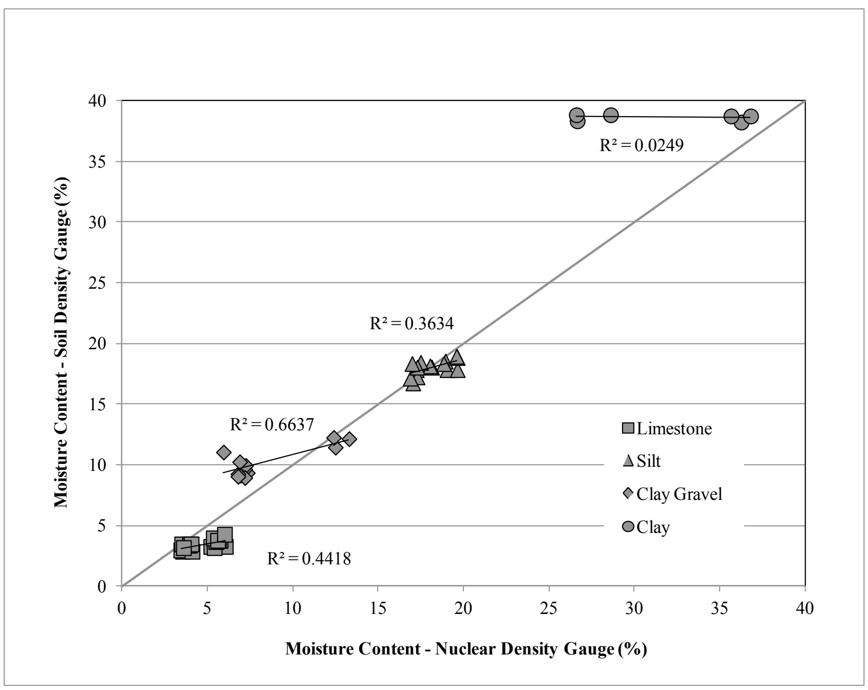
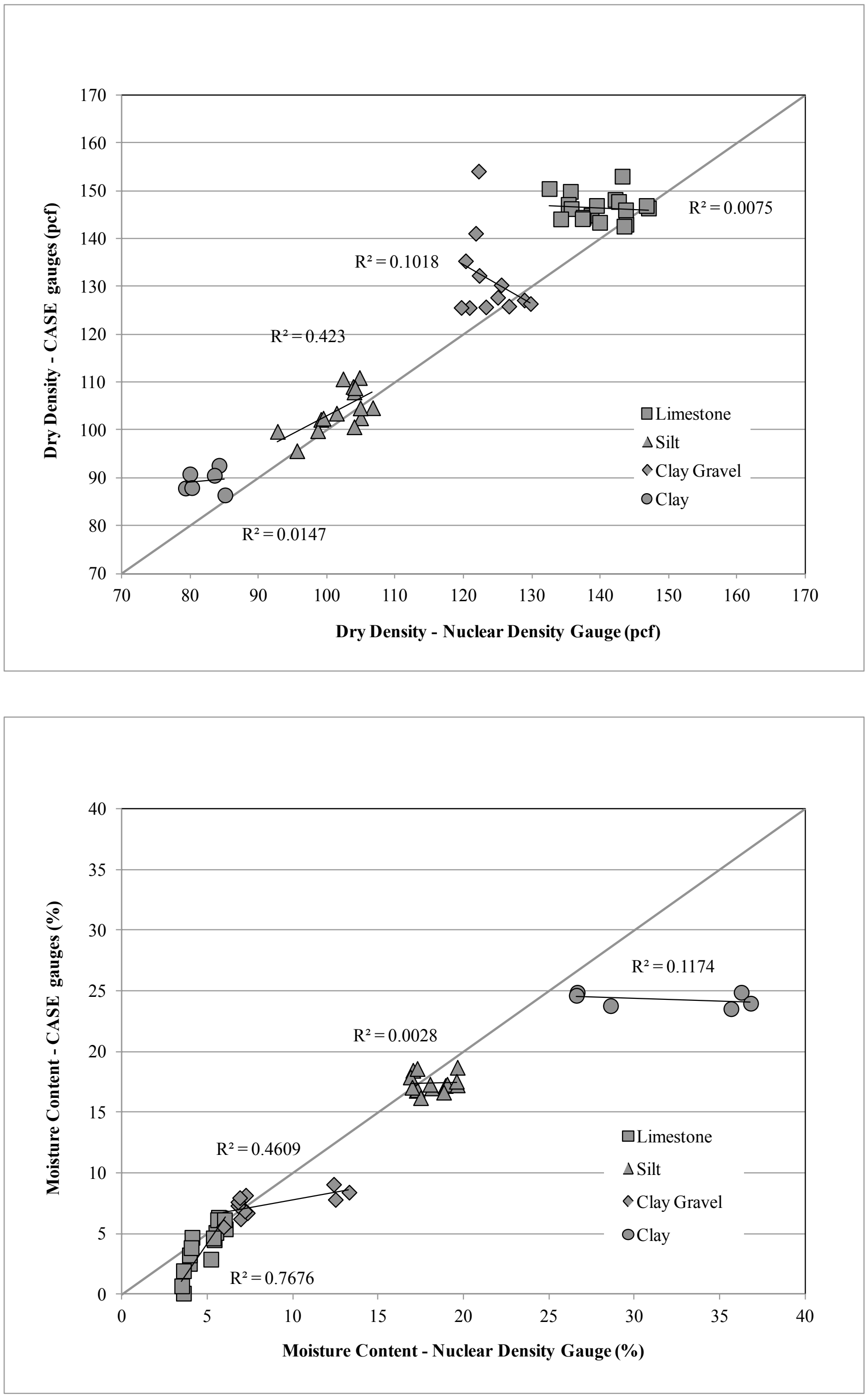


Figure 32. Dry density (top) and moisture content (bottom) comparison between CASE and NDG by soil type.



highest R^2 value was 40 to 45 percent in the silt soil, but less than 20 percent for the other clayey soils (buckshot and clay-gravel) suggesting that, for these electronic devices, these soils all appear similar in condition independent of their site specific characteristics. The devices performed better in measuring moisture content in the coarse grained soils (limestone and clay gravel) but still performed poorly on density. In the coarse soils, these devices may be able to provide a qualitative measure of density to determine whether the soil has met some minimum density criteria (i.e., gross changes in response), but are unreliable for establishing a quantitative density measure for analysis (i.e., small changes in response). These devices do not have sufficient provision for measuring incremental improvements in soil density during rolling operations and, therefore, are best applied when compaction is considered final for a given soil lift.

The CASE units had difficulty in establishing the moisture content at the extremes exhibited by the limestone and clay. On the dry end using limestone, the CASE moisture readings in some instances were 0 percent and tended to vary greatly compared to a near constant NDG reading. On the opposite extreme in the wet clay, the device recorded the same moisture for all samples and at a magnitude much less than the oven value. This behavior was noted only in the clay soil response for the SDG measurements, but the measured magnitude was more in line with that of the oven moisture content. Intermediate moistures contents resulted in somewhat better correlations. Based on these observations, it is difficult to rely on accurate moisture content measurements for these soil types with the CASE units, because their variability could easily exceed the tolerances imposed in a typical field compaction specification.

Standard deviation by soil type

Previously established was that the electronic devices had difficulty determining changes in density and moisture content within a given soil type. To determine whether the calibrated devices achieved the correct magnitude of density and moisture content and to establish their accuracy, Figure 33 presents a summary of a one-standard-deviation offset between the magnitude of the sand cone dry density and the electronic device dry density for each soil. Figure 34 displays a one-standard-deviation offset between the magnitude of the oven-dried moisture content and the electronic-device measured moisture content for each soil.

In all cases, the NDG had a 68 percent probability (one standard deviation) that its value was within 3 pcf for any soil type measured, and a 95 percent probability (two standard deviations) that the value is within 7 pcf. Since the NDG is the reference standard, any deviations exceeding this would render the use of the electronic devices subject to question. In Figure 33, the SDG has either the same or greater deviation than the NDG with a differential

Figure 33. Standard deviation of calibrated dry density differential from sand cone.

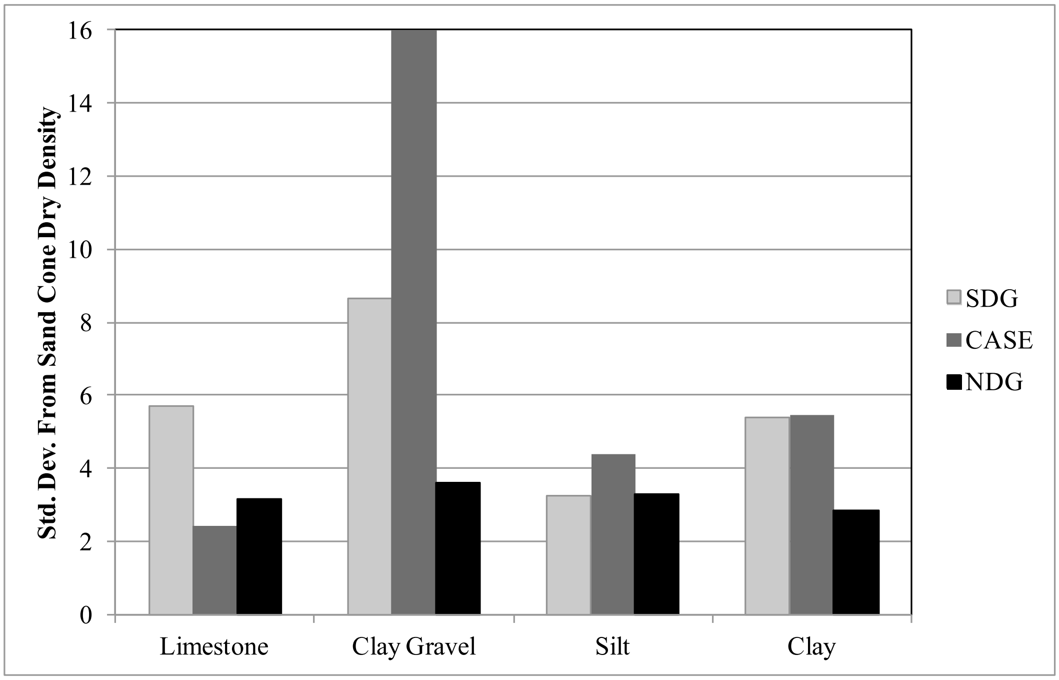
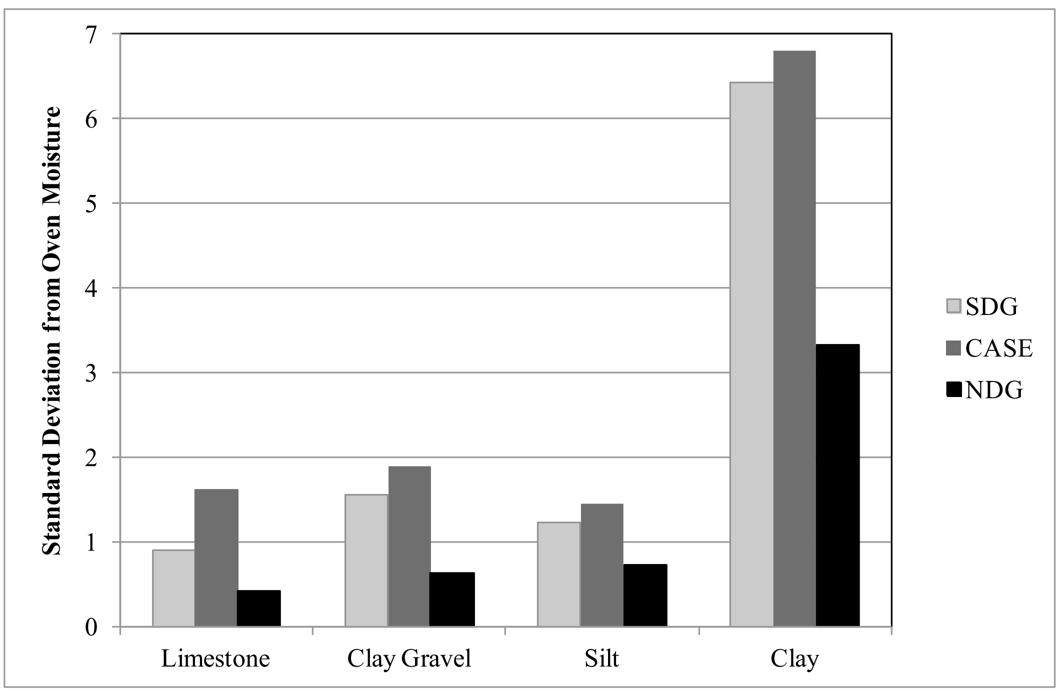


Figure 34. Standard deviation of oven-dried moisture from calibrated moisture content.



in the 7-10 pcf range for all but the clay gravel at 95 percent confidence. The CASE units fared slightly better for the limestone and silt, but did poorly in the clay gravel and clay materials. Unfortunately from a density standpoint, these devices have difficultly capturing the magnitudes appropriately with errors in the 8-10 pcf range; this poses the question of whether they can be relied on for quality control. It is possible that an alternative sand cone reference point could be chosen that might change the magnitude of these offsets. However in a practical field setting, the operator will likely only conduct one test, and it will be the value relied on for all subsequent testing.

In Figure 34, the NDG has a low deviation in moisture content for all but the clay soil with a 95 percent probability of being less than 1 percent off in moisture content reading from the oven-dried value. It appears that the NDG is less accurate in determining precise values when moisture contents are high. The CASE units all exceeded the NDG deviation including for the clay. However, for all other soils, the CASE values are still within 4 percent or less of the oven-dried value with 95 percent confidence. Thus, from a moisture content standpoint, these devices are relatively accurate and could be relied on as quality control tools for moisture content in field construction.

Summary

The SDG and CASE devices performed best in soils that have a more coarse-grain size and intermediate moisture content, i.e., not trending towards the extreme dry or wet conditions. However, in fine-grained soils, their performance is poor enough that they should not be used until further product development has occurred. In coarser soils, the SDG and CASE devices could potentially be used as quality control devices; however, their large standard deviations in both density and moisture content restrict their ability to provide accurate quantitative data. This is an important consideration when selecting these devices for field use as tolerances in compaction specifications typically vary by only 1 or 2 percent plus or minus optimum moisture content. It is recommended that the SDG and CASE be routinely calibrated against a secondary density and moisture device to ensure accuracy of the field readings.

The SDG outperformed the CASE units based on its ability to better identify the proper internal regression model due to grain size and material property inputs along with external calibration. However, this advantage may be offset by the requirement that some soil property information must be known prior to testing, which introduces added expense and time. With a more diverse database developed through continued field testing, the CASE unit may be able to provide similar correlations with the NDG.

The best use of these devices is in field construction scenarios where multiple field tests are to be conducted on a single soil. Unlike the NDG that can be used for point-wise determinations of moisture content and density for any soil under most conditions, the CASE and SDG require a secondary moisture-density input. Therefore, for spot checking density in unique soils, the time invested in calibrating the device already yields the moisture content and density data sought. This prevents the use of the CASE and SDG for survey use to identify existing soil or ground conditions and for inspection of existing soil structures.

Asphalt test section

Gauge variation

The raw data obtained with both the CASE 1 and the CASE 2 were compared to determine gauge variability and is presented in Appendix B. The variability of the individual gauges seemed to be greater when used on the 2-in.-thick pavement than when they were used on the 4-in.-thick pavement for the WMA. For the HMA, the opposite was observed; the variability of the individual gauges was greater when used on the 4-in.-thick pavement than when they were used on the 2-in.-thick pavement. However, the variability was still within acceptable ranges. The standard deviations between the gauges varied from 0.1 to 1.5 for the WMA and from 0.1 to 2.9 for the HMA which translate into coefficients of variation (COV) of approximately 1 percent for WMA and 2 percent for HMA. The low COV suggests a constant error over the working range of the device and therefore for the remaining analyses presented, the uncalibrated and calibrated data from both gauges were combined and averaged for use in characterizing the overall performance of the CASE.

Temperature and pavement thickness effects

Figures 35 and 36 show the effects of the temperature and pavement thickness on the density readings from the CASE and NDG, respectively. The values in the plots are expressed as the standard deviation of the measured densities from the cores' densities. In terms of temperature effects, the figures show small differences between the standard deviation of the density readings taken at the low temperature and the ones taken at the high temperature for both devices. In terms of pavement thickness effects, no trends were observed on the data that could indicate either negative or positive impact of the pavement thickness on the density measurements. The differences between the 4-in. thick pavement and the 2-in. thick pavement were relatively small for both devices.

Figure 35. Temperature effects on CASE density readings.

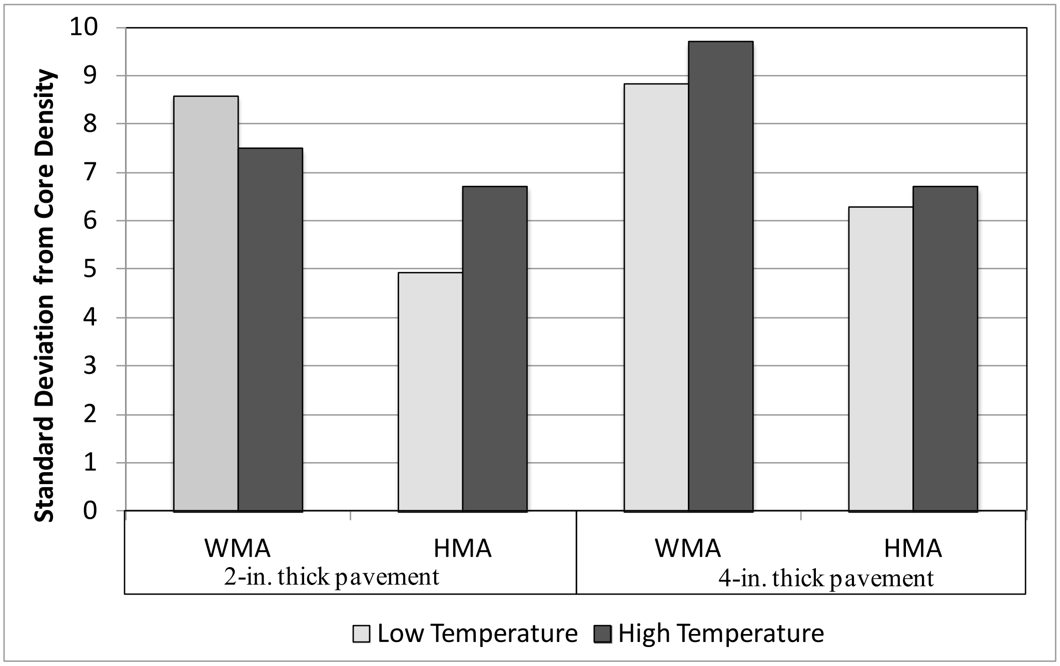
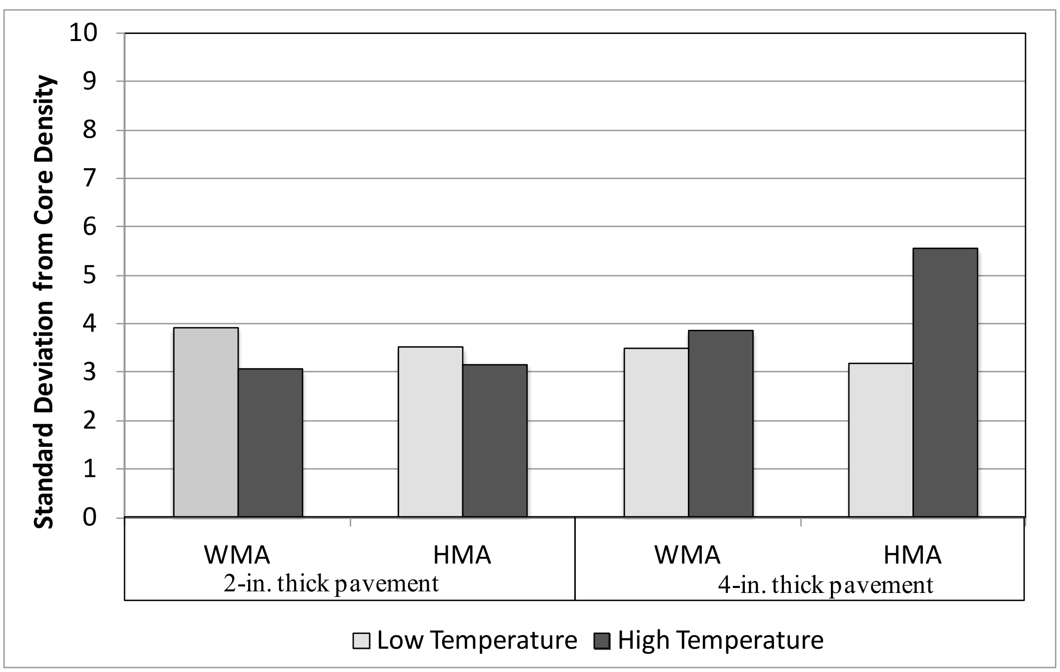


Figure 36. Temperature effects on NDG density readings.



CASE calibration results

The data calibration process was as follows. The ten density readings obtained at each test location were combined to obtain an average density for each test location. Then, the average densities from the center test locations (2 and 5) on each pavement section were used to determine the calibration factors. These locations were less susceptible to edge effects during compaction. Test Location 2 was used for the 2-in.-thick pavement section (Test Locations 1-3), and Test Location 5 was used for the 4-in.-thick pavement section (Test Locations 4-6). The calibration factors were determined by calculating the difference between the average CASE densities at these locations and the corresponding core densities. The factors were then added to the average density readings at each test location.

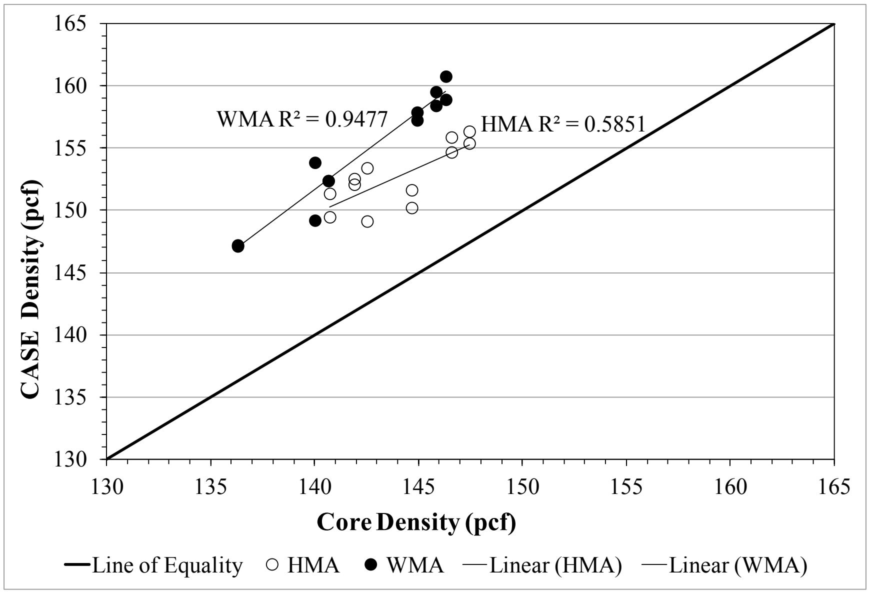
The plots in Figure 37 show comparisons between uncalibrated (top) and calibrated (bottom) CASE densities and core densities. Linear trend lines are presented on each plot to illustrate the coefficients of determination, R^2, found for each data set. Without any calibration, the overall data shows that the CASE tends to overpredict asphalt density in both HMA and WMA. On WMA, the CASE had a high R^2 (0.95), which showed that the CASE density increases at a similar rate as the core density. When the CASE was used on HMA, it showed poor correlation with the standard core densities, but the density values were closer to the line of equality for HMA than for WMA. The CASE seemed to detect better the changes in density in the WMA than in the HMA pavement.

The calibration factors improved the density predictions of the CASE considerably, moving the trend lines over the line of equality as shown in Figure 37 (bottom). The R^2 values also improved showing that calibration improved the CASE's ability to detect changes in density in both the WMA and the HMA.

Comparison to NDG

The standard asphalt density measurement is determined from core samples. This core density is used for Quality Control (QC) and Quality Assurance (QA) procedures during asphalt construction. However, during asphalt paving operations, nuclear density gauges are commonly used to establish compaction patterns and to provide an idea of the compaction achieved. To determine the suitability of the CASE to replace the NDG for this application, a one-to-one comparison between the CASE and the NDG is necessary. For this, the NDG data were calibrated to core densities using the same procedure that was used with the CASE data. This provided a better understanding of the performance of the NDG predicting asphalt density. Figure 38 shows the correlation between the uncalibrated (top) and calibrated (bottom) NDG densities and the core densities.

Figure 37. CASE uncalibrated (top) and calibrated (bottom) densities compared to core densities.



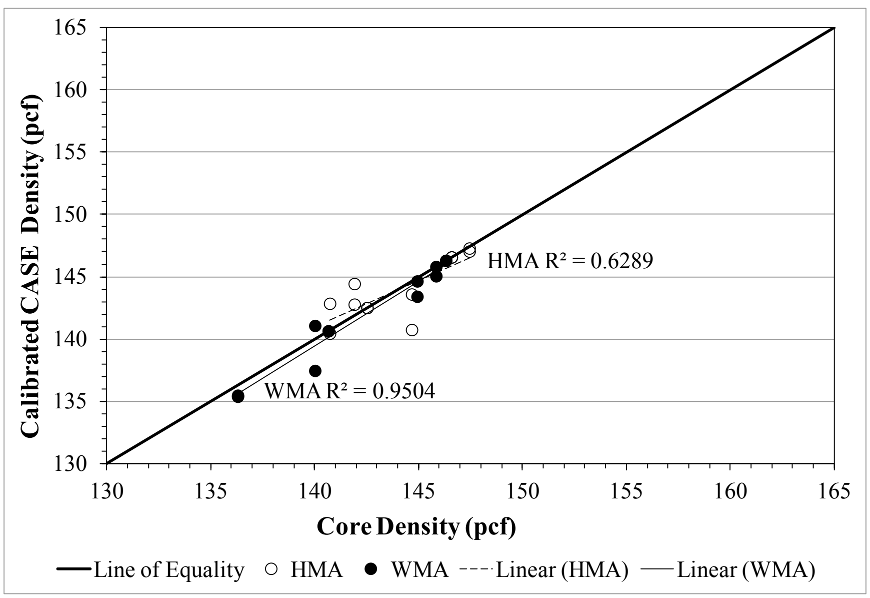
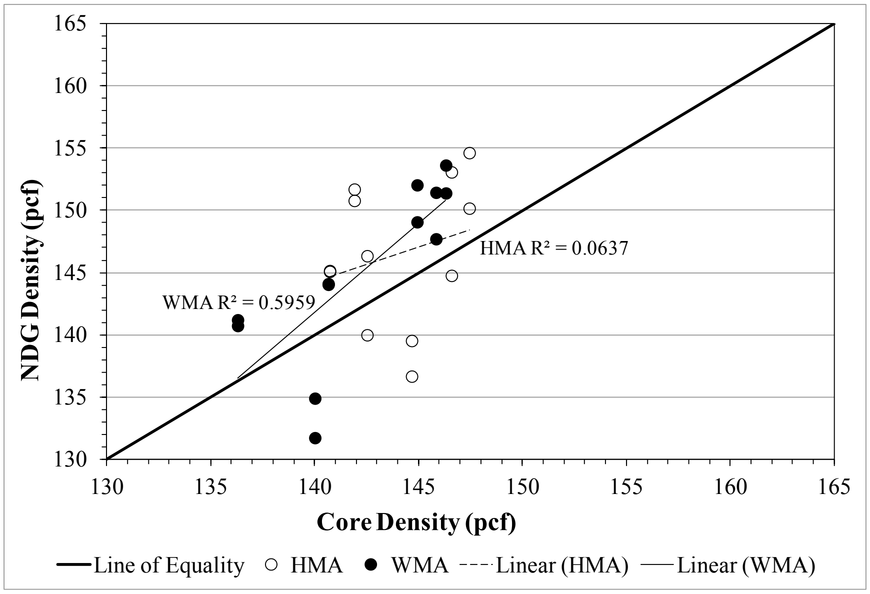
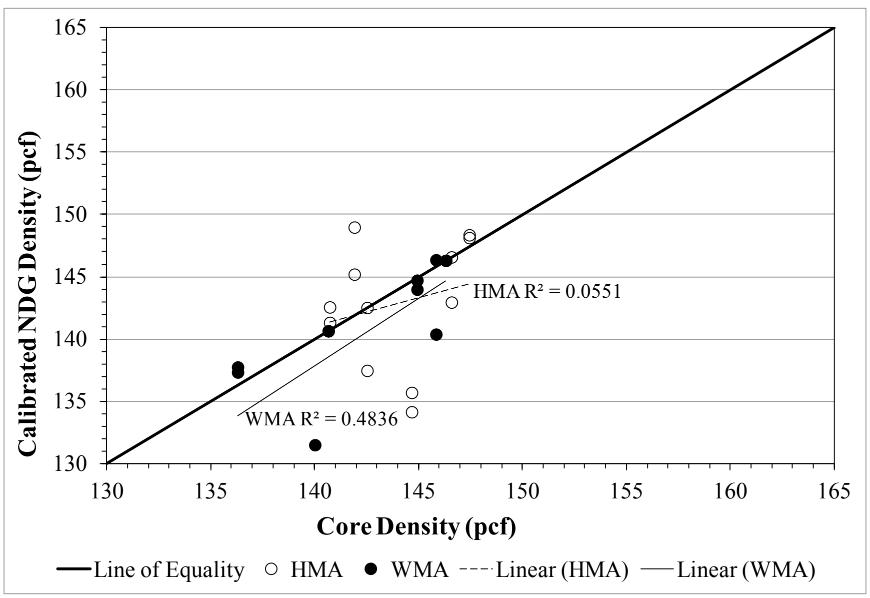


Figure 38. NDG uncalibrated (top) and calibrated (bottom) density compared to core density.





Data scatter was observed in both plots showing a poor correlation between the NDG densities and the core densities for both WMA and HMA. Calibration brought the prediction lines closer to the line of equality. This shows that the NDG also requires calibration to a core density. However, the correlation between the calibrated NDG densities and the core densities did not improve. Comparing results in Figure 37 to the ones in Figure 38, the CASE predicted the asphalt density better than the NDG when it was calibrated to a core density.

Average asphalt density data from the CASE and the NDG are compared in Figures 39 and 40 for the HMA and WMA data sets, respectively. The comparisons were based on the standard deviation of the average CASE and NDG density from the core density. The uncalibrated CASE data shows a greater difference to the core density than the uncalibrated NDG. Once the data were calibrated, the CASE's difference to the core density was considerably smaller than that for the NDG. This shows that using one calibration point in the field improves the CASE's prediction of asphalt density and makes it a more accurate density measurement than the calibrated NDG.

In summary, the uncalibrated CASE tended to overpredict the asphalt densities in both HMA and WMA. When the CASE data were calibrated, the predictions improved considerably, and the average difference between CASE and core density was less than 1 percent. When compared to the NDG, the CASE uncalibrated densities correlated better to the core densities than the uncalibrated NDG, although the CASE tended to overpredict the density. When calibrated, the CASE outperformed the calibrated NDG, and both the correlation and the proximity to equality to the core densities were improved. This showed that the CASE is a viable substitute to the nuclear density gauge for measuring asphalt density during paving operations. The CASE still requires calibration to a core density every time it is used in a different asphalt mix.

Figure 39. Standard deviation of calibrated densities from core densities on the HMA.

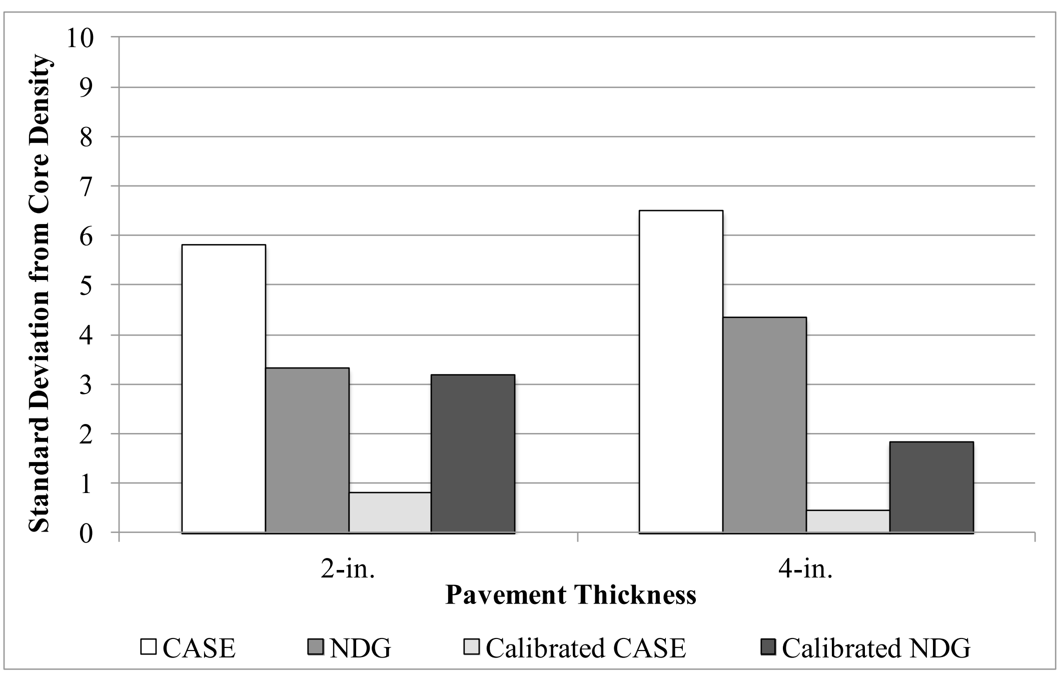
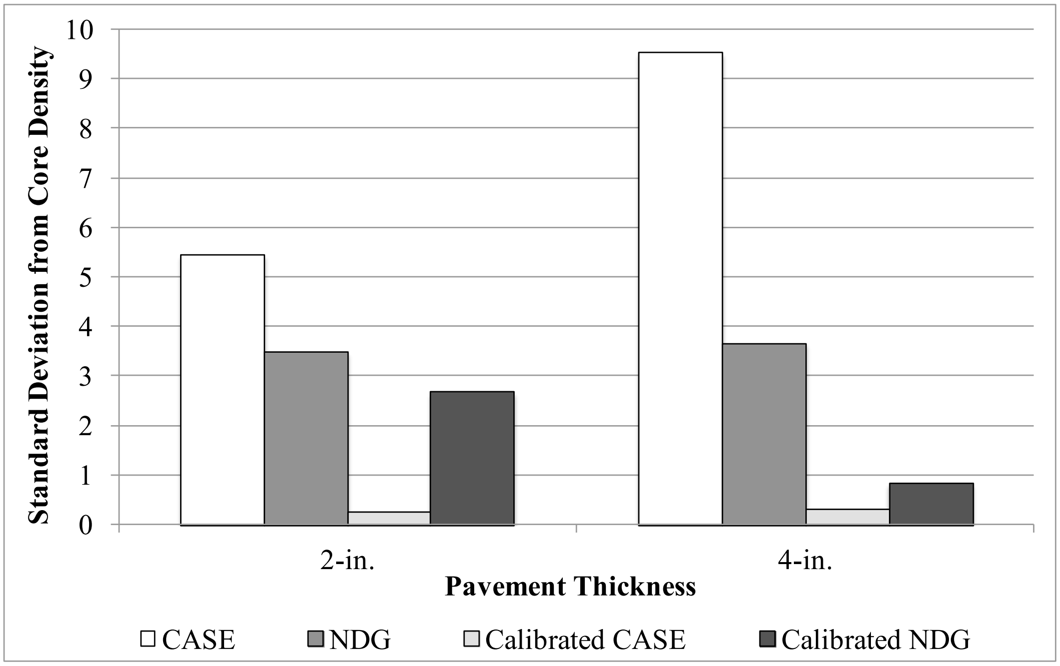


Figure 40. Standard deviation of calibrated densities from core densities on the WMA.



5 Conclusions and Recommendations

Conclusions

This report summarized the research effort to validate the Soil Density Gauge (SDG) and the Combined Asphalt Soil Evaluator (CASE), both of TransTech Systems, as a suitable non-nuclear replacement to the nuclear density gauge (NDG). One-to-one comparisons of soil dry density and moisture content were made between the NDG and each of the aforementioned devices on four distinct soil types of varying densities and moisture contents. Comparisons were made based on uncalibrated and calibrated conditions for the SDG and CASE. Similar comparisons were made between the NDG and CASE to determine density for two types of asphalt, i.e., warm mix and hot mix at varying surface temperatures. The following conclusions were derived from this validation study.

Soil density and moisture content

- When compared to the NDG, both moisture content and dry density data obtained with the SDG and CASE in an uncalibrated state provided a poor correlation, with the dry density having the poorest response. The CASE unit's data provided an inverse relationship with the NDG, and the SDG had considerable data scatter. Therefore, these devices are not suitable for field work without including a field calibration point.
- A field calibration point is a single density and moisture content value obtained with a secondary device (NDG, sand cone, etc.). With the SDG and CASE calibrated with a single moisture-density value from the NDG for each soil tested, the comparisons showed a much improved and useful data response over the range of soils tested suggesting this is a necessary aspect of these devices operation.
- Correlations between the NDG and the non-nuclear devices for soil-specific response revealed that the SDG and CASE had difficulty distinguishing between density changes occurring during the compaction process as well as moisture content changes between test items. In general, the fine-grained soils (silt and clay) proved to be the most difficult materials to measure density changes between roller passes and moisture content between test levels but with a better response for the coarser-grained soils.

- In the clay and clay-gravel soils, the SDG and CASE had standard deviations double that of the NDG, but in the silt and limestone, the SDG and CASE had similar standard deviations, with the CASE being the better of the two tested devices. Therefore, the error associated with these alternatives is such that they cannot be relied on over the range of soils tested to be an acceptable quality control substitute for the NDG for non-contingency construction.
- The SDG and CASE had a standard deviation for the measured moisture content 2 to 3 times greater than that for the NDG. The moisture content measured by the NDG was typically within 1 percent of the actual moisture content at a 95 percent reliability level, with the other devices being off by 2 to 3 percent. Most construction specifications have moisture tolerances of 1-2 percent plus or minus optimum moisture content, which is a tighter range of response than can be relied on for the SDG and CASE.

Asphalt density

- When compared to the NDG, the CASE uncalibrated asphalt densities correlated better to the core densities than the uncalibrated NDG. The CASE tended to overpredict the density, which shows that calibration to a core density is critical for the effective use of the CASE.
- No trends were observed on the data that could indicate significant effects of pavement temperature and thickness on the performance of the CASE or the NDG.
- When compared to the NDG, the CASE asphalt densities calibrated to a core density had a better correlation and proximity to the core densities than the calibrated NDG.
- The CASE, both uncalibrated and calibrated, was able to detect changes in density, supporting its suitability as a tool for establishing compaction patterns during asphalt construction as verified through more in-depth research studies (Zhuang 2011).
- The CASE, both uncalibrated and calibrated, predicted density better for WMA than for HMA.

Recommendations

Based on the comparisons between the SDG, CASE and the NDG data, the following is recommended.

Soil density and moisture content

- The CASE and SDG are only recommended for military contingency construction scenarios, as long as their density prediction is calibrated to at least one independent density sample obtained in the field with an alternative device such as the NDG, sand cone, etc.
- The CASE and SDG are not recommended as QC/QA tools in critical or permanent infrastructure construction scenarios where more precise measurements of soil density are required.
- Future research in the use of electronic devices such as the SDG and CASE will require development of a larger database of soil properties to improve the accuracy of the internal regression algorithms that drive the correlated measurements. Developing techniques to minimize the need for a secondary field calibration device will optimize their suitability for deployment.

Asphalt density

- The CASE is recommended only as a substitute to the NDG for establishing compaction patterns during asphalt construction operations in both contingency and permanent infrastructure projects, as long as the CASE is calibrated to a core density each time it is used in a different asphalt mix.
- Core densities are the standard QC/QA method for determining in-place asphalt density. A more detailed study would be required to collect enough data to determine if the CASE could be used as a standard measurement for asphalt density. Therefore, based on the limited results of this study, the CASE is not recommended as a substitution for the core density method.

References

American Association of State and Highway Transportation Officials, 2008. *Standard method of test for density of in-place hot mix asphalt (hma) pavement by electronic surface contact devices*. Washington, DC: AASHTO Designation TP 68-04.

_______. 2011. Standard test method for bulk specific gravity of compacted asphalt mixtures using saturated surface-dry specimens. Washington, DC: AASTHTO Designation T 166.

American Society for Testing and Materials (ASTM) International. 2006. *Standard test method for sieve analysis of fine and coarse aggregates*. Designation C 136. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2007a. *Standard test method for density and unit weight of soil in place by sand cone method*. Designation D 1556-07. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2007b. *Standard test method for particle-size analysis of soils*. Designation D 422-63. West Conshohocken, PA: American Society for Testing and Materials International.

_______. 2008. *Standard test methods for determination of water (moisture) content of the soil by the microwave oven heating*. Designation D 4643-08. West Conshohocken, PA: American Society for Testing and Materials International.

_______. 2010a. *Standard test method for density of soil in place by the drive-cylinder method*. Designation D 2937-10. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2010b. West Conshohocken, PA. *Standard test method for in-place density and water content of soil and soil- aggregate by nuclear methods (shallow depth)*. Designation D 6938-10. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2010c. *Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass*. Designation D 2216-10. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2010d. Standard test methods for liquid limit, plastic limit, and *plasticity index of soils*. Designation D 4318. West Conshohocken, PA: American Society for Testing and Materials International.

______. 2011. *Standard practice for classification of soils for engineering purposes (unified soil classification system)*. Designation D 2487 West Conshohocken, PA: American Society for Testing and Materials International.

______. 2012. *Standard test methods for laboratory compaction characteristics of soil using standard effort*. Designation D 698. West Conshohocken, PA: American Society for Testing and Materials International.

Berney, E. S., M. Mejías-Santiago, and J. D. Kyzar.2013. *Non-nuclear alternatives to monitoring moisture-density response in soils*. ERDC/GSL TR-13-6,. Vicksburg MS: US Army Engineer Research and Development Center.

Berney IV, E. S. and Wahl, R.E. 2008. *A rapid soils analysis kit*. ERDC/GSL TR-08-3, US Army Engineer Research and Development Center. Vicksburg, MS: US Army Engineer Research and Development Center.

Headquarters, Department of the Army. 2001. Materials Testing FM 5-472/NAVFAC MO 330/AFJMAN 32-1221. Washington, DC: Department of the Army.

Mejías-Santiago, M., E. S. Berney, and C. Bradley.2013. *Evaluation of a non-nuclear soil density gauge on fine-grained soils*. ERDC/GSL TR-13- 20. Vicksburg MS: US Army Engineer Research and Development Center.

TransTech Systems, Inc. Soil Density Gauge Brochure. http://www.transtechsys.com, (accessed 07/12/11).

Troxler Electronic Laboratories, Inc. 2007. Application Brief: Troxler Model 3430 Roadreader™ Nuclear Moisture Density Gauge.

US Army Corps of Engineers (USACE). 2010. Hot-Mix Asphalt (HMA) for Airfields. Unified Facilities Guide Specification UFGS-32 12 15.

Zhuang, Ziqing. 2011. Effectiveness study of non-nuclear gauge for hot mix asphalt (hma) pavement construction. University of Nebraska Construction Systems - *Dissertations & theses*. Paper No. 5. Lincoln NE: University of Nebraska.

Appendix A: Soil Characterization Data

Silt

COMPACTION TEST REPORT

Test specification: ASTM D 698-07 Method A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
				2.60	NP		3.4	92.1

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 106.6 pcf Optimum moisture = 17.6 %	Silt (ML), Brown

Project No. MD0412 **Client:** Mariely Meji'as
Project: Non-Nuclear Gage

○ **Source of Sample:** Silt

Remarks:
Estimated Gravity

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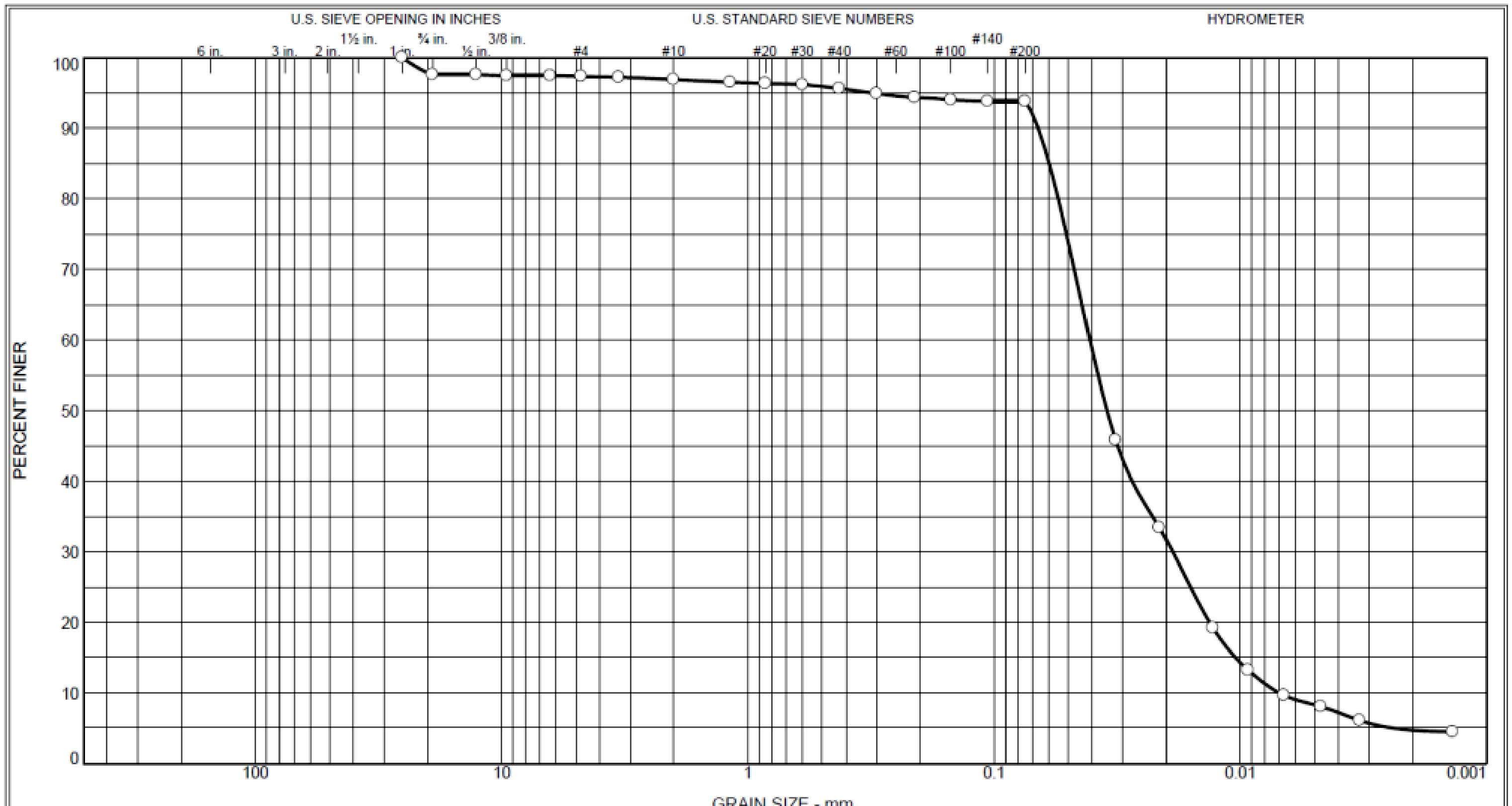
Figure



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○			Silt (ML), Brown		NV	NP	NP

Project Non-Nuclear Gauge

Area

Boring No. Silt

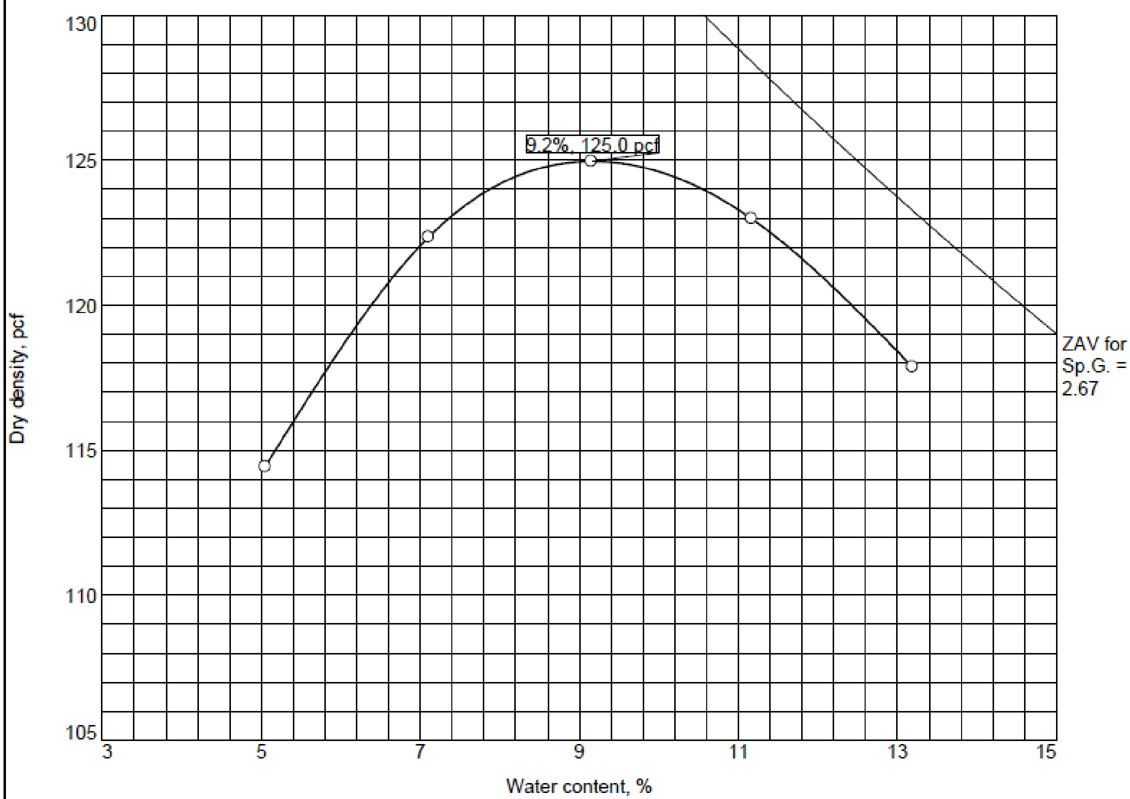
Date: 12/2/2011

Corps of Engineers

Particle Size Distribution Report

Clay-Gravel

COMPACTION TEST REPORT



Test specification: ASTM D 698-07 Method C Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/4 in.	% < No.200
	USCS	AASHTO						
				2.67	29	15	2.3	

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 125.0 pcf Optimum moisture = 9.2 %	Clay (CL), Reddish Brown

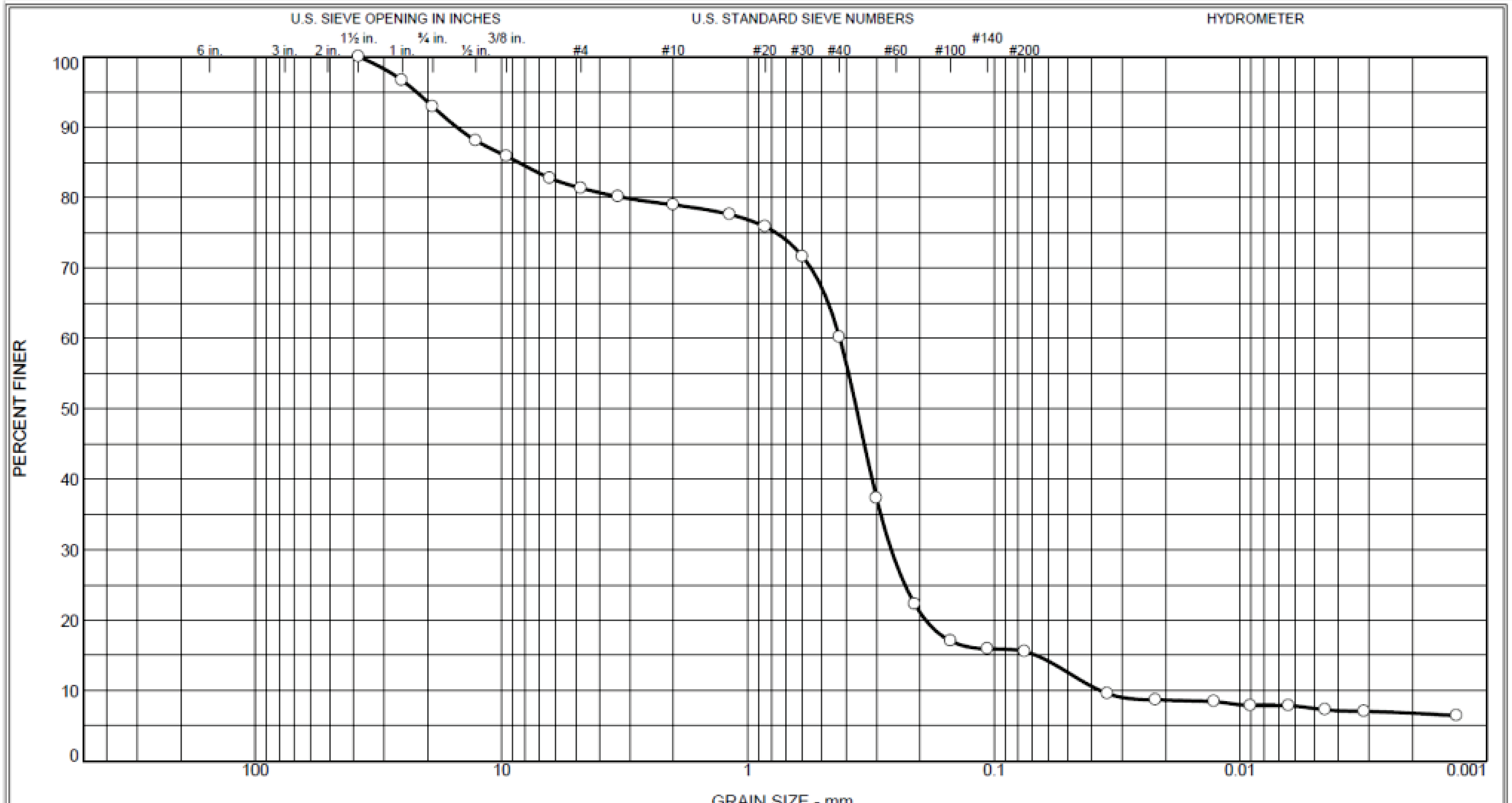
Project No. MD0412 **Client:** Mariely Meji'as
Project: Non-Nuclear Gage

○ **Source of Sample:** Clay Gravel

Remarks:
Estimated Gravity

Corps of Engineers
Engineer Research Development Center

Figure



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○			Clayey Sand (SC), with Gravel; Reddish Brown		29	14	15

Project Non-Nuclear Gauge

Area

Boring No. Clay Gravel

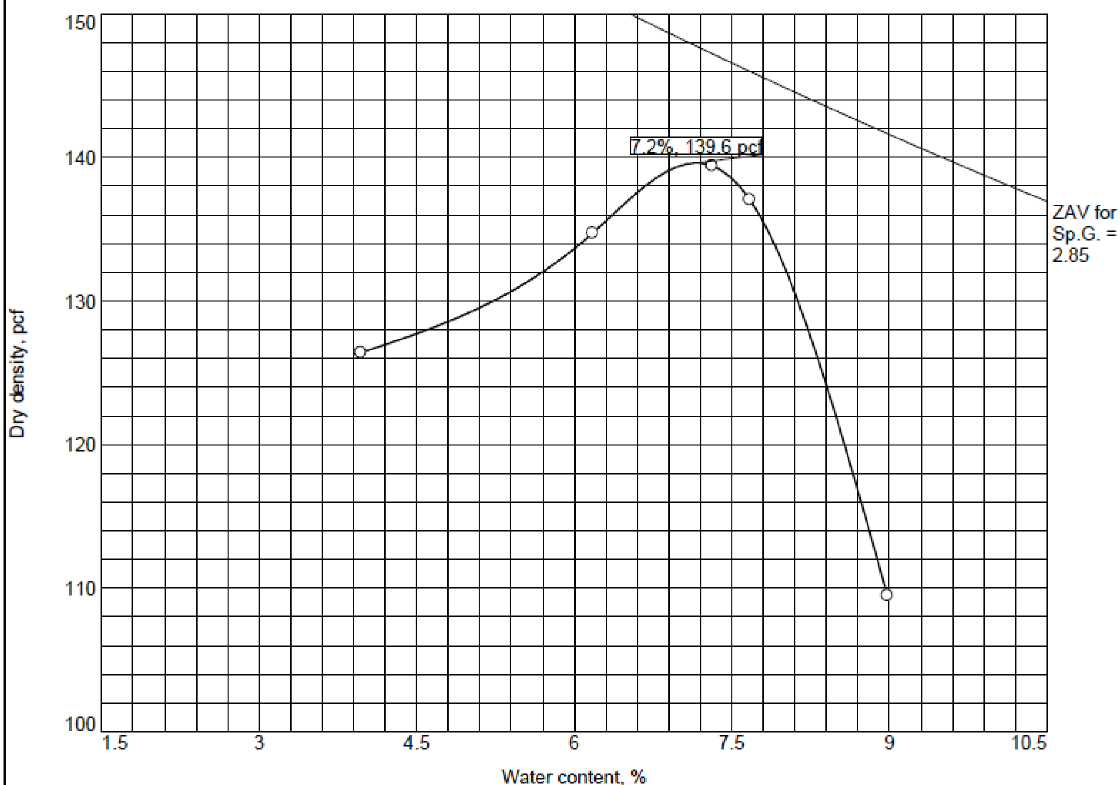
Date: 12/6/2011

Particle Size Distribution Report

Corps of Engineers

Limestone

COMPACTION TEST REPORT



Test specification: ASTM D 698-07 Method C Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/4 in.	% < No.200
	USCS	AASHTO						
				2.85	NP		2.0	

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 139.6 pcf Optimum moisture = 7.2 %	Silt (ML), Gray

Project No. MD0412 **Client:** Mariely Meji'as

Project: Non-Nuclear Gage

○ **Source of Sample:** Limestone

Remarks:
Estimated Gravity Lost water at the botton of mold during compaction at 10% and 12%. Also had free water on top of mold after compaction at 10% and 12%.

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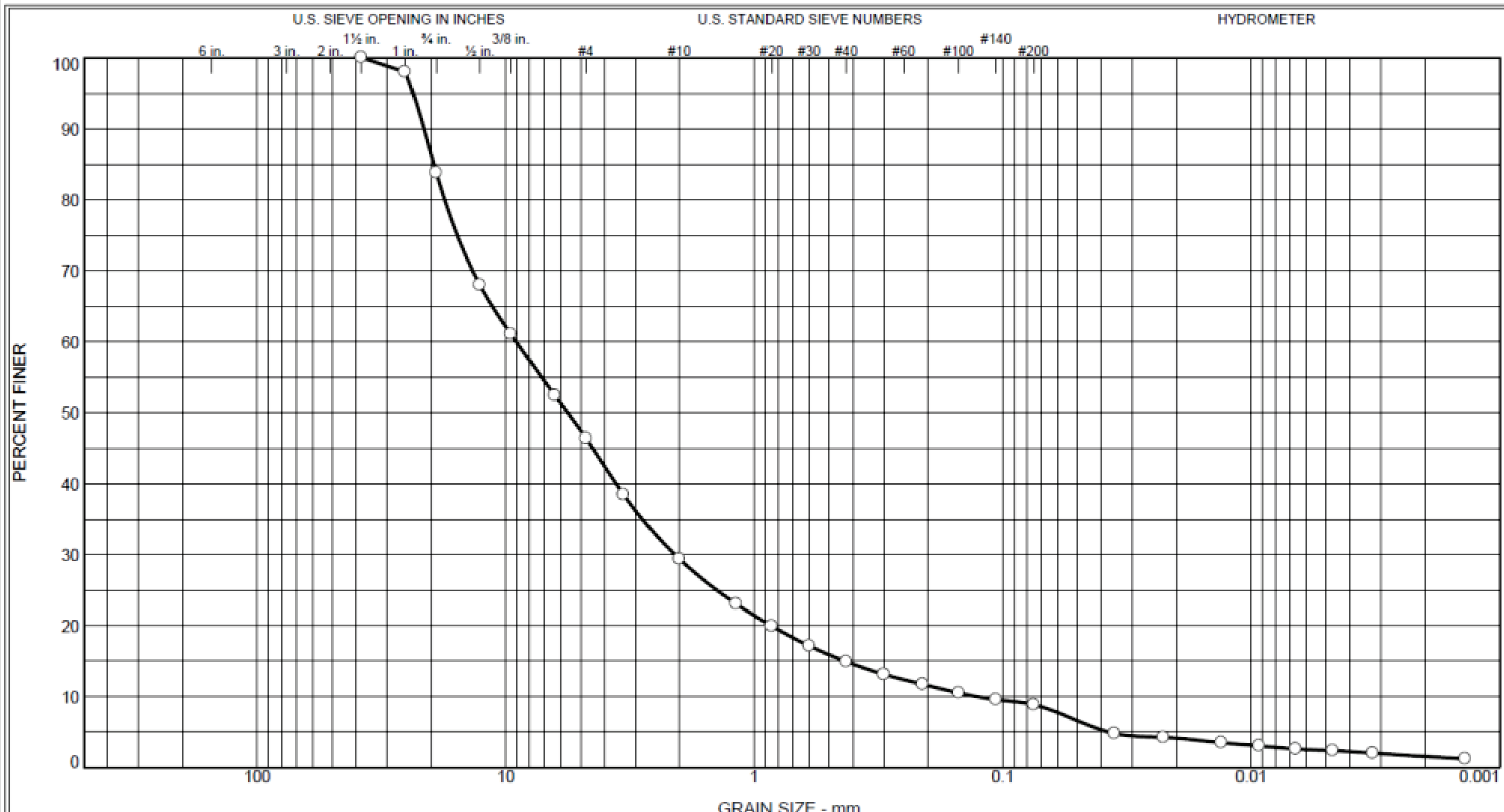
Engineer Research Development Center

Figure

Tested By: CEC **Checked By:** LRC



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○			Gravel (GP-GM), with Silt and Sand; Gray		NV	NP	NP

Project Non-Nuclear Gauge

Area

Boring No. Limestone

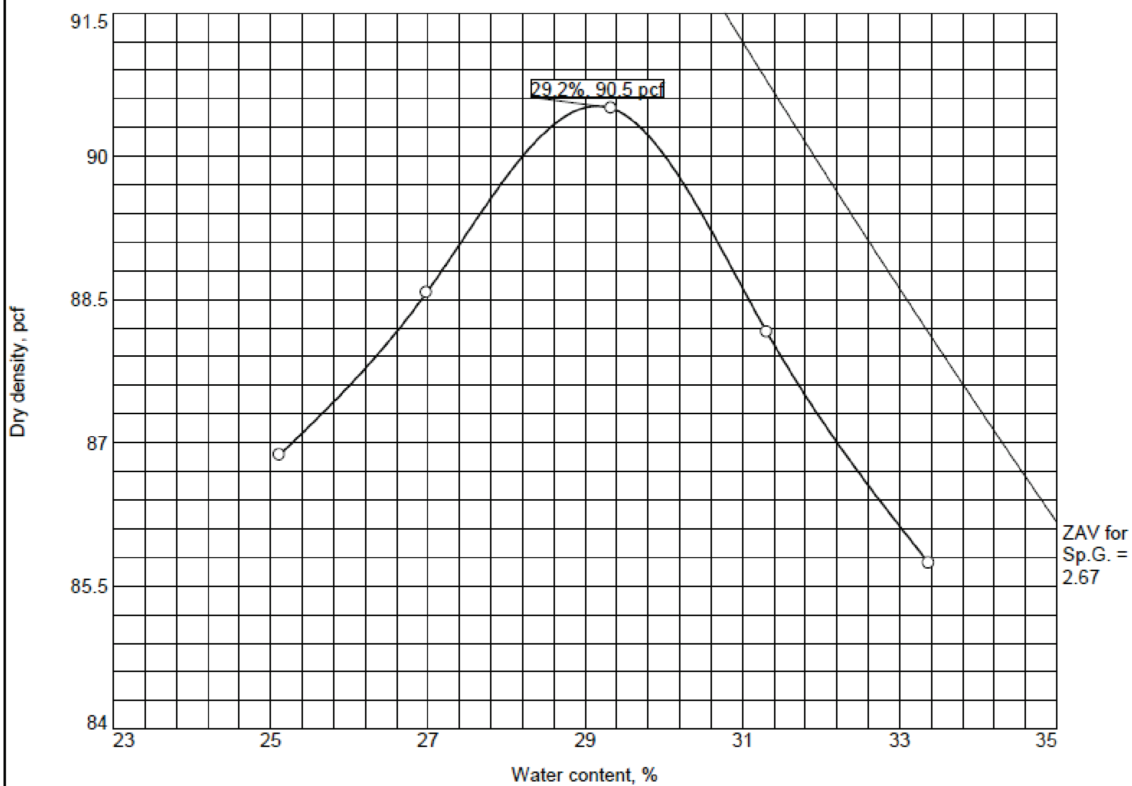
Date: 12/6/2011

Particle Size Distribution Report

Corps of Engineers

Buckshot Clay

COMPACTION TEST REPORT



Test specification: ASTM D 698-07 Method B Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/8 in.	% < No.200
	USCS	AASHTO						
			10.5	2.67 est.	77	55	0.3	89%

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 90.5 pcf Optimum moisture = 29.2 %	Clay(CH), Gray

Project No. MD2411 **Client:** Mariely Mejias
Project: Non Nuclear Gauge

○ **Source of Sample:** C1

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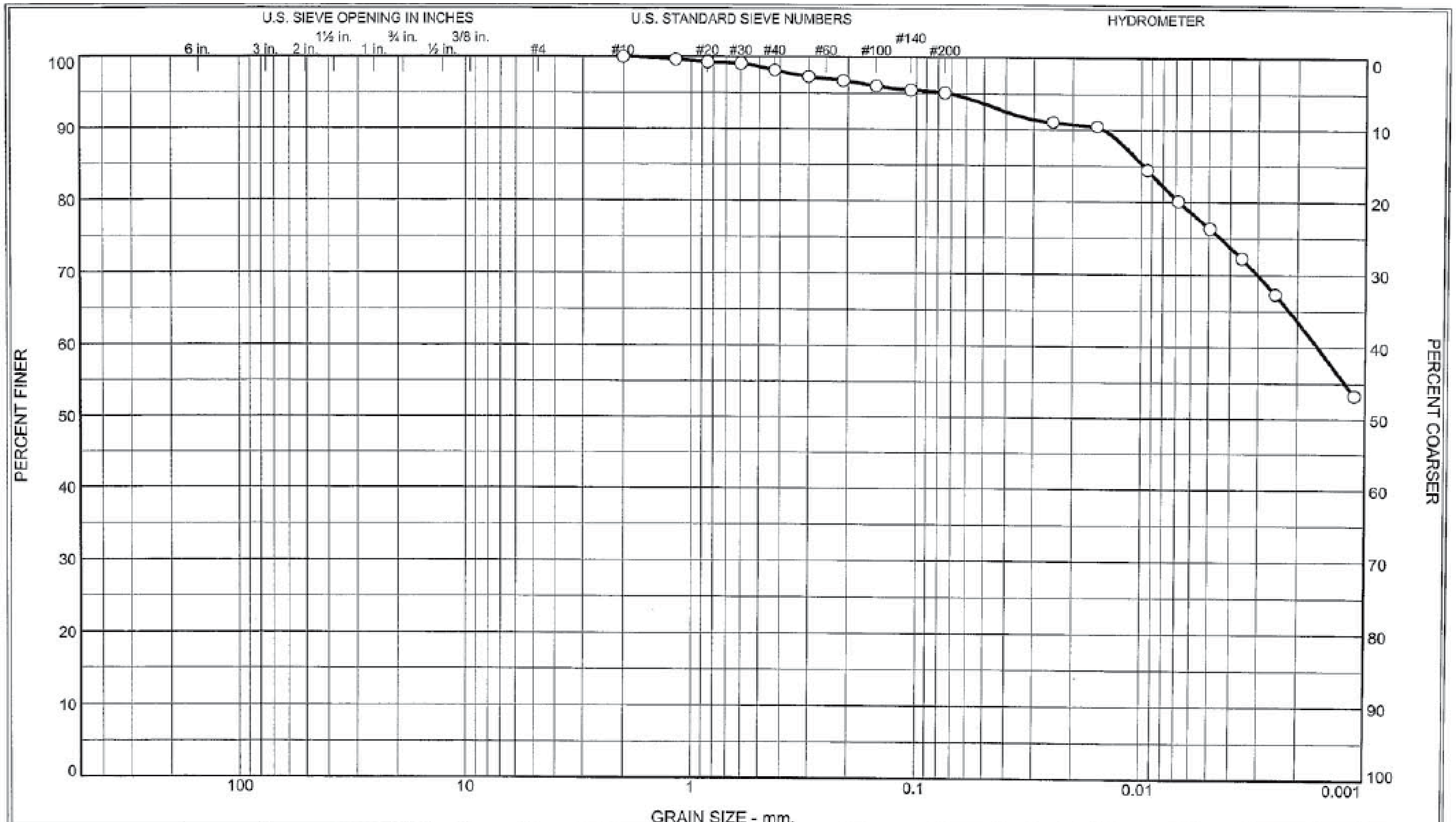
Remarks:
Estimated gravity 2.67

Figure



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
O			Clay (CH), Gray		73	24	49

Particle Size Distribution Report

Project Non-Nuclear Gauge Study

Area

Boring No. Buckshot

Date: 5/17/2010

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Appendix B: Gauge Comparison Data

CASE side-by-side comparison of uncalibrated soil data

	Dry Density				Moisture Content			
Soil Type	CASE 1	CASE 2	Avg.	STDEV	CASE 1	CASE 2	Avg.	STDEV
Limestone	149.3	150.5	149.9	0.85	0.0	-0.3	-0.2	0.14
Dry	148.0	146.3	147.2	1.17	0.2	0.0	0.1	0.07
	154.3	146.7	150.5	5.39	0.0	-0.5	-0.3	0.28
	146.8	143.0	144.9	2.68	2.5	2.7	2.6	0.14
	146.8	145.8	146.3	0.67	0.9	0.6	0.7	0.21
	145.6	143.3	144.5	1.58	4.6	4.9	4.7	0.21
	142.7	143.3	143.0	0.42	3.2	3.4	3.3	0.14
	142.6	142.6	142.6	0.00	3.9	3.9	3.9	0.00
	143.9	142.9	143.4	0.74	1.7	2.3	2.0	0.42
AVG	146.7	144.9	145.8	1.5	1.8	1.9	1.9	0.2
STDEV	3.7	2.6	2.9	1.6	1.7	2.0	1.8	0.1
Limestone	145.0	143.2	144.1	1.26	2.8	3.1	2.9	0.21
Wet	151.3	142.5	146.9	6.20	5.2	5.7	5.4	0.35
	143.6	144.7	144.2	0.77	3.8	5.3	4.5	1.06
	152.3	144.1	148.2	5.82	5.1	5.2	5.1	0.07
	157.3	148.8	153.1	5.95	6.5	6.2	6.3	0.21
	152.6	143.0	147.8	6.78	6.5	6.3	6.4	0.14
	148.8	143.2	146.0	3.98	4.6	4.8	4.7	0.14
	147.9	144.9	146.4	2.06	6.1	6.3	6.2	0.14
	149.0	144.8	146.9	2.99	6.0	6.4	6.2	0.28
AVG	149.8	144.4	147.1	4.0	5.1	5.4	5.3	0.3
STDEV	4.2	1.9	2.7	2.3	1.3	1.1	1.1	0.3

Soil Type	Dry Density				Moisture Content			
	CASE 1	CASE 2	Avg.	STDEV	CASE 1	CASE 2	Avg.	STDEV
Silt	107.6	96.8	102.2	7.58	16.2	17.5	16.8	0.92
Dry	99.0	92.3	95.7	4.70	18.2	18.8	18.5	0.42
	103.7	95.7	99.7	5.63	16.6	17.2	16.9	0.42
	107.4	99.7	103.5	5.45	16.8	17.3	17.0	0.35
	103.5	96.2	99.8	5.18	16.8	17.9	17.3	0.78
	109.9	95.0	102.5	10.56	17.9	18.0	17.9	0.07
	102.4	102.7	102.5	0.17	15.9	16.6	16.2	0.49
	114.4	94.9	104.7	13.84	18.4	18.9	18.6	0.35
	104.6	104.6	104.6	0.00	17.1	17.1	17.1	0.00
AVG	105.8	97.5	101.7	5.9	17.1	17.7	17.4	0.4
STDEV	4.6	4.0	2.9	4.4	0.9	0.8	0.8	0.3
Silt	120.8	100.5	110.7	14.38	16.6	17.9	17.2	0.92
Wet	120.0	98.2	109.1	15.37	16.8	17.9	17.3	0.78
	118.7	103.2	111.0	10.90	16.3	17.1	16.7	0.57
	106.7	94.6	100.7	8.52	18.0	19.5	18.7	1.06
	114.7	101.2	107.9	9.56	17.0	17.6	17.3	0.42
	115.3	102.4	108.8	9.15	17.0	18.2	17.6	0.85
AVG	116.0	100.0	108.0	11.3	16.9	18.0	17.5	0.8
STDEV	5.2	3.2	3.8	2.9	0.6	0.8	0.7	0.2

	Dry Density				Moisture Content			
Soil Type	CASE 1	CASE 2	Avg.	STDEV	CASE 1	CASE 2	Avg.	STDEV
Clay Gravel	122.7	128.5	125.6	4.09	6.1	6.3	6.2	0.14
Dry	125.4	125.8	125.6	0.33	6.7	6.7	6.7	0.00
	132.1	128.5	130.3	2.54	7.0	6.8	6.9	0.14
	139.5	131.3	135.4	5.80	5.6	5.5	5.6	0.07
	127.7	123.8	125.7	2.73	8.4	7.9	8.2	0.35
	129.7	125.8	127.7	2.77	6.7	7.0	6.9	0.21
	125.9	125.9	125.9	0.00	7.3	7.3	7.3	0.00
	127.6	126.7	127.2	0.69	7.7	7.5	7.6	0.14
	126.0	126.8	126.4	0.55	8.6	7.3	8.0	0.92
AVG	128.5	127.0	127.8	2.2	7.1	6.9	7.0	0.2
STDEV	4.9	2.2	3.2	2.0	1.0	0.7	0.8	0.3
Clay Gravel	148.7	133.5	141.1	10.74	7.1	8.5	7.8	0.99
Wet	160.1	148.1	154.1	8.47	8.6	8.2	8.4	0.28
	132.7	131.9	132.3	0.52	9.2	8.9	9.1	0.21
AVG	147.2	137.9	142.5	6.6	8.3	8.6	8.4	0.5
STDEV	13.8	8.9	11.0	5.4	1.1	0.4	0.6	0.4
Clay	96.9	88.3	92.6	6.04	23.6	24.0	23.8	0.28
Dry	86.4	86.4	86.4	0.00	24.9	24.9	24.9	0.00
	91.0	90.0	90.5	0.72	24.5	24.8	24.6	0.21
AVG	91.4	88.3	89.9	2.3	24.3	24.6	24.4	0.2
STDEV	5.2	1.8	3.1	3.3	0.7	0.5	0.6	0.1
Clay	88.5	87.2	87.9	0.93	25.1	24.7	24.9	0.28
Wet	94.2	87.4	90.8	4.80	23.5	23.6	23.5	0.07
	91.5	84.4	87.9	4.96	23.6	24.4	24.0	0.57
AVG	91.4	86.3	88.9	3.6	24.1	24.2	24.1	0.3
STDEV	2.8	1.7	1.7	2.3	0.9	0.6	0.7	0.2

All soil data collected

Soil Type	Moisture Level	Compaction Level	Pos.	Nuclear Density W. Dense (pcf)	Nuclear Density MC (%)	Soil Density (SDG) W. Dense (pcf)	Soil Density (SDG) MC (%)	CASE 1 W. Dense (pcf)	CASE 1 MC (%)	CASE 2 W. Dense (pcf)	CASE 2 MC (%)	SC/DC W. Dense (pcf)	Oven Dry MC (%)
Limestone	Dry	Lo	1	136.85	3.65	148.8	8.2	94.6	0.7	85.3	-0.9		4.07
			2	136.6	3.7	146.4	8.3	93.6	0.9	81.6	-0.6		4.31
			3	133.5	3.55	148.4	8.3	99.6	0.7	81.2	-1.1		3.84
		Med	1	140.55	4.05	155.8	8.8	95.8	3.2	82	2		3.98
			2	136.9	3.6	156	8.8	93.4	1.6	81.8	-0.1		3.98
			3	139.55	4.2	151.5	8.2	97.6	5.3	85.5	4.2		4.17
		Hi	1	145.85	4.05	159.1	8.7	92.6	3.9	83.3	2.7	144.6	4.08
			2	145.7	4.15	158.6	8.8	93.5	4.6	83.3	3.2	148.1	3.85
			3	141.35	3.7	150.6	8.5	91.7	2.4	81.3	1.6	147.5	3.19
Limestone	Wet	Lo	1	137.6	5.3	153.7	8.6	94.4	3.5	82.8	2.4		4.99
			2	144.3	6.15	157.4	8.6	104.5	5.9	85.8	5		5.58
			3	141.2	5.5	151.9	8.5	94.4	4.5	87.5	4.6		6.02
		Med	1	146.4	5.6	160.5	9	105.4	5.8	86.7	4.5		6.12
			2	147.85	5.85	166.2	9.1	112.8	7.2	93.2	5.5		6.94
			3	147.15	5.75	164.4	9.1	107.8	7.2	87.1	5.6		5.96
		Hi	1	147.8	5.45	165.7	9.3	101	5.3	85.2	4.1	151.4	5.54
			2	151.7	5.7	167.4	9.1	102.2	6.8	89.2	5.6	154.5	5.21
			3	151.95	6.1	176.6	9.6	103.3	6.7	89.2	5.7	159.8	6.69
Silt	Dry	Lo	1	116.95	15.9	138.7	7.1	119.9	12.2	93.8	11.9	114.8	17.28
			2	112.65	15.7	128.3	6	111.9	14.2	89.7	13.2	112.7	17.81
			3	109.55	15.95	134.1	6.5	115.8	12.6	92.2	11.6	115.7	17.25
		Med	1	120.55	16.8	140.6	7.3	120.3	12.8	96.9	11.7	120.3	17.97
			2	117.2	16.7	139.2	7.4	115.8	12.8	93.4	12.3	118.6	17.43
			3	117	15.55	133.2	6.4	124.5	13.9	92.1	12.4	118.8	16.02
		Hi	1	124.05	16.15	143.8	7.7	113.6	11.9	99.7	11	124.9	16.63
			2	125.9	15.95	137.8	7.3	130.4	14.4	92.8	13.3	122.1	17.68
			3	123.45	15.65	142.1	7.6	117.4	13.1	102.5	11.5	122.5	17.06
Silt	Wet	Lo	1	122.5	17.6	143.8	7.8	135.8	12.6	98.5	12.3	119.7	19.54
			2	124.35	17.7	137.1	7.1	135	12.8	95.8	12.3	119.4	19.96
			3	125.25	17.5	142.5	7.6	132.9	12.3	100.9	11.5	122.8	20.05
		Hi	1	125.15	18.3	136.6	7.1	120.8	14	93.1	13.9	120.2	19.94
			2	125.15	18.3	146.8	8.1	129.1	13	99	12	122.4	19.37
			3	125.25	18.25	148.1	8.2	129.8	13	101	12.6	122.3	19.57
Clay-Gravel	Dry	Lo	1	125.25	7.9	117.3	-0.1	98.2	8.8	90.1	8.2		7.07
			2	124.45	8.3	119.6	0.1	101.8	9.4	87.8	8.6		6.92
			3	130.55	8.15	120.5	0.4	109.4	9.7	90.8	8.7		7.63
		Med	1	123.45	6.9	114.9	1.8	115.3	8.3	92	7.4		6.15
			2	128.2	8.2	121.5	0.7	106.4	11.1	87.1	9.8		6.96
			3	130	8.15	118.8	-0.3	106.4	9.4	88.1	8.9		6.21
		Hi	1	131.25	7.75	119.9	0	103.1	10	88.6	9.2	135.1	7.32
			2	133.65	7.75	119.6	-0.2	105.5	10.4	89.7	9.4	143.6	6.8
			3	134.75	7.85	121.9	1	104.9	11.3	89.6	9.2	141.1	7.71
Clay-Gravel	Wet	Hi	1	133	13.45	127.7	2.2	127.3	9.8	98.4	10.4	134.7	12.29
			2	134.45	14.25	129.2	2.9	141.9	11.3	113.8	10.1	135.8	12.27
			3	133.45	13.35	129.1	3	112.9	11.9	97.2	10.8	134.1	12.26
Buckshot	Dry	Hi	1	112.45	27.05	131.5	22.5	142.3	15.5	107.2	15.2	108.7	35.26
Clay			2	111.9	25.1	125.8	22	130.5	16.8	105.6	16.1	107.9	24.89
			3	109.9	25.05	130.9	22.5	135.9	16.4	110	16	108.4	24.5
Buckshot	Wet	Hi	1	112.2	34.7	124.9	21.9	133.3	17	106.4	15.9	111.4	37.35
Clay			2	112.6	34.1	130.3	22.4	138.9	15.4	105.7	14.8	106.4	38.74
			3	113.9	35.25	130.2	22.4	135.6	15.5	102.7	15.6	105.5	36.47
Chosen as calibration point from sand cone based on proximity of sand cone to nuke value as best available													
SC/DC: Sand Cone or Drive Cylinder as appropriate; W. Dense: wet density; MC: moisture content													

Calibrated soils data and device calibration factors

				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
				Nuclear Gauge		3.1	5.31	-54.6	0.75	-64.8	-0.65
Soil Type	Moisture Level	Compaction Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Limestone	Dry	Lo	1	140.4	3.6	145.7	2.89	149.2	-0.05	150.1	-0.25
			2	140.2	3.6	143.3	2.99	148.2	0.15	146.4	0.05
			3	137.1	3.5	145.3	2.99	154.2	-0.05	146	-0.45
		Med	1	144.1	4.0	152.7	3.49	150.4	2.45	146.8	2.65
			2	140.5	3.5	152.9	3.49	148	0.85	146.6	0.55
			3	143.1	4.1	148.4	2.89	152.2	4.55	150.3	4.85
		Hi	1	149.4	4.0	156	3.39	147.2	3.15	148.1	3.35
			2	149.3	4.1	155.5	3.49	148.1	3.85	148.1	3.85
			3	144.9	3.6	147.5	3.19	146.3	1.65	146.1	2.25
Limestone	Wet	Lo	1	141.2	5.2	150.6	3.29	149	2.75	147.6	3.05
			2	147.9	6.1	154.3	3.29	159.1	5.15	150.6	5.65
			3	144.8	5.4	148.8	3.19	149	3.75	152.3	5.25
		Med	1	150.0	5.5	157.4	3.69	160	5.05	151.5	5.15
			2	151.4	5.8	163.1	3.79	167.4	6.45	158	6.15
			3	150.7	5.7	161.3	3.79	162.4	6.45	151.9	6.25
		Hi	1	151.4	5.4	162.6	3.99	155.6	4.55	150	4.75
			2	155.3	5.6	164.3	3.79	156.8	6.05	154	6.25
			3	155.5	6.0	173.5	4.29	157.9	5.95	154	6.35

				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
				Nuclear Gauge		18.40732	-10.75	-5.0552	-3.96	-19.9552	-5.56
Soil Type	Moisture Level	Compaction Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Silt	Dry	Lo	1	116.2	17.2	120.2927	17.85	124.9552	16.16	113.7552	17.46
			2	111.9	17.0	109.8927	16.75	116.9552	18.16	109.6552	18.76
			3	108.8	17.3	115.6927	17.25	120.8552	16.56	112.1552	17.16
		Med	1	119.8	18.1	122.1927	18.05	125.3552	16.76	116.8552	17.26
			2	116.4	18.0	120.7927	18.15	120.8552	16.76	113.3552	17.86
			3	116.2	16.9	114.7927	17.15	129.5552	17.86	112.0552	17.96
		Hi	1	123.3	17.5	125.3927	18.45	118.6552	15.86	119.6552	16.56
			2	125.1	17.3	119.3927	18.05	135.4552	18.36	112.7552	18.86
			3	122.7	17.0	123.6927	18.35	122.4552	17.06	122.4552	17.06
Silt	Wet	Lo	1	121.7	18.9	125.3927	18.55	140.8552	16.56	118.4552	17.86
			2	123.6	19.0	118.6927	17.85	140.0552	16.76	115.7552	17.86
			3	124.5	18.8	124.0927	18.35	137.9552	16.26	120.8552	17.06
		Hi	1	124.4	19.6	118.1927	17.85	125.8552	17.96	113.0552	19.46
			2	124.4	19.6	128.3927	18.85	134.1552	16.96	118.9552	17.56
			3	124.5	19.6	129.6927	18.95	134.8552	16.96	120.9552	18.16

				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
	Moisture	Compaction		Nuclear Gauge		-5	-9.26	-32	2.68	-46.5	1.88
Soil Type	Level	Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Clay-Gravel	Dry	Lo	1	129.2	6.9	122.3	9.16	130.2	6.12	136.6	6.32
			2	128.4	7.3	124.6	9.36	133.8	6.72	134.3	6.72
			3	134.5	7.2	125.5	9.66	141.4	7.02	137.3	6.82
		Med	1	127.4	5.9	119.9	11.06	147.3	5.62	138.5	5.52
			2	132.2	7.2	126.5	9.96	138.4	8.42	133.6	7.92
			3	134.0	7.2	123.8	8.96	138.4	6.72	134.6	7.02
		Hi	1	135.2	6.8	124.9	9.26	135.1	7.32	135.1	7.32
			2	137.6	6.8	124.6	9.06	137.5	7.72	136.2	7.52
			3	138.7	6.9	126.9	10.26	136.9	8.62	136.1	7.32
Clay-Gravel	Wet	Hi	1	137.0	12.5	132.7	11.46	159.3	7.12	144.9	8.52
			2	138.4	13.3	134.2	12.16	173.9	8.62	160.3	8.22
			3	137.4	12.4	134.1	12.26	144.9	9.22	143.7	8.92
				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
	Moisture	Compaction		Nuclear Gauge		23.86	-16.34	22.57	-8.09	-2.33	-8.79
Soil Type	Level	Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Buckshot	Dry	Hi	1	108.3	28.6	107.6377	38.84	119.7315	23.59	109.5315	23.99
Clay			2	107.7	26.7	101.9377	38.34	107.9315	24.89	107.9315	24.89
			3	105.7	26.6	107.0377	38.84	113.3315	24.49	112.3315	24.79
Buckshot	Wet	Hi	1	108.0	36.3	101.0377	38.24	110.7315	25.09	108.7315	24.69
Clay			2	108.4	35.7	106.4377	38.74	116.3315	23.49	108.0315	23.59
			3	109.7	36.8	106.3377	38.74	113.0315	23.59	105.0315	24.39

				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
	Moist	Comp		Nuclear Gauge		-5	-9.26	-32	2.68	-46.5	1.88
Soil Type	Level	Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Clay-Gravel	Dry	Lo	1	129.2	6.9	122.3	9.16	130.2	6.12	136.6	6.32
			2	128.4	7.3	124.6	9.36	133.8	6.72	134.3	6.72
			3	134.5	7.2	125.5	9.66	141.4	7.02	137.3	6.82
		Med	1	127.4	5.9	119.9	11.06	147.3	5.62	138.5	5.52
			2	132.2	7.2	126.5	9.96	138.4	8.42	133.6	7.92
			3	134.0	7.2	123.8	8.96	138.4	6.72	134.6	7.02
		Hi	1	135.2	6.8	124.9	9.26	135.1	7.32	135.1	7.32
			2	137.6	6.8	124.6	9.06	137.5	7.72	136.2	7.52
			3	138.7	6.9	126.9	10.26	136.9	8.62	136.1	7.32
Clay-Gravel	Wet	Hi	1	137.0	12.5	132.7	11.46	159.3	7.12	144.9	8.52
			2	138.4	13.3	134.2	12.16	173.9	8.62	160.3	8.22
			3	137.4	12.4	134.1	12.26	144.9	9.22	143.7	8.92
				Corrected Data		SDG Offset		CASE 1 Offset		CASE 2 Offset	
	Moist	Comp		Nuclear Gauge		23.86	-16.34	22.57	-8.09	-2.33	-8.79
Soil Type	Level	Level	Pos.	W. Dense	MC	W. Dense	MC	W. Dense	MC	W. Dense	MC
Buckshot	Dry	Hi	1	108.3	28.6	107.6377	38.84	119.7315	23.59	109.5315	23.99
Clay			2	107.7	26.7	101.9377	38.34	107.9315	24.89	107.9315	24.89
			3	105.7	26.6	107.0377	38.84	113.3315	24.49	112.3315	24.79
Buckshot	Wet	Hi	1	108.0	36.3	101.0377	38.24	110.7315	25.09	108.7315	24.69
Clay			2	108.4	35.7	106.4377	38.74	116.3315	23.49	108.0315	23.59
			3	109.7	36.8	106.3377	38.74	113.0315	23.59	105.0315	24.39

Hot asphalt data collected with CASE and NDG

HOT TEST					
	Pavement	Instrument Density Readings (pcf)			
Test Location	Thickness	NDG	CASE 1	CASE 3	Core Density (pcf)
1	2 in.	134.1	148.7	148.5	140.0
Avg. Temp.	2 in.	135.7	148.7	148.5	140.0
112.7	2 in.	135.2	149.0	149.1	140.0
°F	2 in.	134.8	149.2	149.8	140.0
	2 in.	134.6	149.9	149.0	140.0
	2 in.	134.4	148.8	149.6	140.0
	2 in.	134.5	148.9	148.7	140.0
	2 in.	135.7	149.6	150.2	140.0
	2 in.	135.5	150.0	149.0	140.0
	2 in.	134.6	150.0	148.9	140.0
2	2 in.	142.1	152.6	152.2	140.7
Avg. Temp.	2 in.	142.9	151.7	152.3	140.7
119.5	2 in.	144.5	152.7	152.3	140.7
°F	2 in.	143.6	152.5	152.0	140.7
	2 in.	145.3	152.3	152.1	140.7
	2 in.	145.0	152.9	152.3	140.7
	2 in.	144.1	152.3	152.6	140.7
	2 in.	144.3	152.9	152.6	140.7
	2 in.	144.1	152.2	152.8	140.7
	2 in.	144.6	152.3	152.1	140.7
3	2 in.	139.4	147.0	143.1	136.3
Avg. Temp.	2 in.	140.9	147.2	145.4	136.3
129.2	2 in.	141.0	147.3	145.5	136.3
°F	2 in.	141.8	147.6	146.1	136.3
	2 in.	141.2	147.8	146.3	136.3
	2 in.	139.9	148.1	146.9	136.3
	2 in.	141.3	148.7	146.5	136.3
	2 in.	142.4	147.6	147.7	136.3
	2 in.	140.1	149.4	147.3	136.3
	2 in.	139.4	149.3	147.8	136.3

HOT TEST					
	Pavement	Instrument Density Readings (pcf)			
Test Location	Thickness	NDG	CASE 1	CASE 3	Core Density (pcf)
4	4 in.	147.6	159.7	158.9	145.8
Avg. Temp.	4 in.	147.6	159.5	158.9	145.8
117.3	4 in.	147.4	160.1	158.9	145.8
°F	4 in.	147.9	159.8	159.0	145.8
	4 in.	147.8	159.9	159.2	145.8
	4 in.	148.1	160.3	159.1	145.8
	4 in.	146.8	160.1	158.7	145.8
	4 in.	147.4	160.3	159.2	145.8
	4 in.	147.9	160.1	159.2	145.8
	4 in.	148.6	160.2	159.4	145.8
5	4 in.	152.9	161.5	159.9	146.3
Avg. Temp.	4 in.	153.0	161.5	159.8	146.3
121.5	4 in.	152.6	161.6	160.1	146.3
°F	4 in.	152.3	161.7	160.0	146.3
	4 in.	153.4	161.8	160.0	146.3
	4 in.	155.0	161.7	160.1	146.3
	4 in.	154.8	161.7	159.4	146.3
	4 in.	153.8	161.7	159.7	146.3
	4 in.	153.4	161.6	160.1	146.3
	4 in.	155.1	161.7	159.8	146.3
6	4 in.	151.1	158.0	157.9	144.9
Avg. Temp.	4 in.	152.8	157.8	157.9	144.9
137.5	4 in.	152.6	157.7	157.5	144.9
°F	4 in.	152.2	157.8	157.7	144.9
	4 in.	153.0	158.2	158.0	144.9
	4 in.	151.3	157.9	157.6	144.9
	4 in.	151.6	158.0	157.9	144.9
	4 in.	152.1	158.0	158.0	144.9
	4 in.	151.9	158.7	157.6	144.9
	4 in.	151.8	157.8	157.7	144.9

Cold asphalt data collected with CASE and NDG

COLD TEST					
	Pavement	Instrument Density Readings (pcf)			
Test Location	Thickness	NDG	CASE 1	CASE 3	Core Density (pcf)
1	2 in.	131.0	152.8	154.1	140.0
Avg. Temp.	2 in.	130.9	151.8	154.2	140.0
80.2	2 in.	131.5	152.5	154.3	140.0
°F	2 in.	131.5	152.8	154.3	140.0
	2 in.	131.6	154.5	153.3	140.0
	2 in.	132.3	154.7	153.0	140.0
	2 in.	132.8	154.8	153.3	140.0
	2 in.	133.3	154.7	153.6	140.0
	2 in.	131.0	154.9	153.7	140.0
	2 in.	131.5	155.0	153.4	140.0
2	2 in.	144.7	153.5	148.9	140.7
Avg. Temp.	2 in.	144.0	153.3	149.8	140.7
79.1	2 in.	143.4	153.4	150.3	140.7
°F	2 in.	144.1	153.5	150.8	140.7
	2 in.	143.1	153.4	152.1	140.7
	2 in.	143.7	153.4	152.0	140.7
	2 in.	143.9	153.7	152.1	140.7
	2 in.	145.1	153.3	152.3	140.7
	2 in.	144.5	153.3	152.4	140.7
	2 in.	144.6	153.4	152.8	140.7
3	2 in.	141.0	146.8	147.3	136.3
Avg. Temp.	2 in.	141.2	145.8	147.3	136.3
79.0	2 in.	140.1	146.0	147.3	136.3
°F	2 in.	140.8	146.8	147.4	136.3
	2 in.	142.0	147.2	147.7	136.3
	2 in.	141.5	147.2	147.7	136.3
	2 in.	142.6	147.2	147.7	136.3
	2 in.	140.5	147.4	147.4	136.3
	2 in.	140.9	147.5	147.2	136.3
	2 in.	141.5	147.6	147.9	136.3

COLD TEST					
	Pavement	Instrument Density Readings (pcf)			
Test Location	Thickness	NDG	CASE 1	CASE 3	Core Density (pcf)
4	4 in.	150.8	159.0	157.9	145.8
Avg. Temp.	4 in.	150.3	159.2	157.5	145.8
80.2	4 in.	150.0	159.3	157.4	145.8
°F	4 in.	150.4	159.2	157.9	145.8
	4 in.	152.8	159.4	158.0	145.8
	4 in.	151.8	159.2	157.8	145.8
	4 in.	152.7	159.2	158.1	145.8
	4 in.	151.8	159.2	157.8	145.8
	4 in.	151.5	159.5	157.4	145.8
	4 in.	152.3	159.4	155.9	145.8
5	4 in.	152.7	158.3	158.2	146.3
Avg. Temp.	4 in.	150.9	158.8	158.2	146.3
80.5	4 in.	152.6	159.4	158.3	146.3
°F	4 in.	150.7	159.4	158.4	146.3
	4 in.	152.3	159.4	158.0	146.3
	4 in.	151.3	160.0	158.2	146.3
	4 in.	151.1	159.8	158.6	146.3
	4 in.	150.5	159.8	158.5	146.3
	4 in.	151.9	159.8	158.6	146.3
	4 in.	149.9	159.7	158.7	146.3
6	4 in.	149.2	157.9	156.7	144.9
Avg. Temp.	4 in.	149.0	157.5	156.6	144.9
80.6	4 in.	148.8	157.7	156.2	144.9
°F	4 in.	150.2	157.6	156.6	144.9
	4 in.	149.4	157.7	156.6	144.9
	4 in.	148.5	157.8	156.9	144.9
	4 in.	148.0	157.7	156.9	144.9
	4 in.	149.2	157.4	157.1	144.9
	4 in.	148.5	157.7	157.3	144.9
	4 in.	149.9	157.6	157.5	144.9

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2014	Final report	

4. TITLE AND SUBTITLE
Validation Tests of a Non-Nuclear Combined Asphalt and Soil Density Gauge

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ernest S. Berney IV, Mariely Mejías-Santiago, and Jeremy Beasley

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GSL TR-14-10

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U S Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Researchers at ERDC evaluated the Soil Density Gauge (SDG) and the Combined Asphalt Soil Evaluator (CASE) both of TransTech Systems as suitable non-nuclear replacements to the nuclear density gauge (NDG) in a series of full scale test sections. One-to-one comparisons of soil dry density and moisture content were made between the NDG, SDG and CASE over four unique soil types of varying density and moisture content. The SDG and CASE were tested both calibrated and uncalibrated to establish suitable field preparation. A similar comparison of asphalt density was conducted between the NDG and the CASE on both warm mix and hot mix asphalt at varying surface temperatures. Test results concluded that the CASE unit was the most suitable replacement device however both the SDG and CASE require field calibration from a secondary density technique to be effective. In soil, the SDG and CASE are recommended only for contingency construction activities, because each lacks sufficient accuracy for quality control use in permanent facilities. For asphalt, the CASE is recommended only as a substitute to the NDG for establishing compaction patterns in asphalt so long as it is calibrated to a core density sample for each unique asphalt mixture.

15. SUBJECT TERMS

Soil	Nuclear gauge	Non-destructive
Electronic gauge	Asphalt	Field tests
	Density	Moisture content

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		75	