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Device Comparison for Determining Field Soil Moisture Content

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Abstract: During the period May 2010-August 2010, researchers of the U.S. Army Engineer Research and Development Center in Vicksburg, MS, tested the effectiveness of various devices in determining the moisture content of soil for horizontal construction. These tests were conducted to determine a usable alternative to the nuclear soil density gauge. The accuracy and precision of the different testing devices was compared to the standard laboratory oven soil moisture determination. The devices and techniques tested are grouped into four broad families: gravimetric, electrical, chemical, and nuclear. Gravimetric devices and techniques tested were the laboratory oven, gas stove and fry pan, standard microwave oven, battery-powered field microwave oven, and moisture analyzer. Electrical devices tested were the electrical density gauge, and the soil density gauge. The chemical device tested was the Speedy Calcium Carbide soil moisture test. The nuclear device tested was the nuclear density gauge, included for comparison purposes. This investigation consisted of full-scale construction of seven soils representing a range of materials encountered in operational construction activities. Soils ranged from fine-grained silts and clays to coarse-grained gravels and crushed limestone. This testing showed that the devices showing the optimal combination of precision and accuracy compared to the laboratory oven are the soil density gauge and the gas stove with fry pan technique.

Results of the moisture content tests are presented and include (a) comparison of the individual moisture contents to the results obtained using the standard laboratory oven, and (b) ranking of devices versus laboratory oven. Results will be used to provide further guidance for selection of appropriate devices for field determination of soil moisture content.

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Preface

This report was prepared by the U.S. Army Engineer Research and Development Center (ERDC). Jeb Tingle, ERDC, Geotechnical and Structures Laboratory, was the manager of the U.S. Air Force Non-Nuclear Density Device project.

This publication was prepared by personnel of the ERDC Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. The principal investigator for this study was Dr. Ernest S. Berney IV, Airfields and Pavements Branch (APB), Engineering Systems and Materials Division (ESMD), and was assisted in preparation of this report by Lawrence Oyelami of the ESMD Concrete Materials Branch (CMB) and James Kyzar (APB). Dr. Gary L. Anderton, Chief, APB; Toney Cummins, Chief, CMB; Dr. Larry N. Lynch, Chief, ESMD; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL, provided direct supervision.

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1 Introduction

Problem

The compactive effort applied during soil construction has been established as the primary indicator of the strength and performance of the constructed layer. The currently accepted "best" method of ensuring adequate soil strength design is through constant sampling of moisture content and dry density throughout the construction process. This quality control (QC) activity is most commonly and expediently conducted using a nuclear densometer or sand cone for density and a nuclear densometer or laboratory oven for moisture content determination. However, the moisture content measured with the nuclear densometer requires recurring calibration against the standard laboratory oven. Numerous hurdles exist with the ownership, operation, transport, and disposal of nuclear gauges. As such, commercial alternatives to the nuclear densometer are being sought, but no military guidance exists to direct the engineer as to proper device selection, usage and limitations resulting in acquisition of devices at considerable expense that may not provide the required QC control needed for construction.

Development of soil moisture content devices and techniques have been episodic, with new techniques developed followed by a lull in product development. One of the first techniques developed was the oven drying method (Buchanan 1939). This method is still viewed as the standard method for determining moisture content of soils. The main drawback to using the laboratory oven for moisture content is the long time to return results, which is not desirable in expedient construction scenarios. Several chemical methods, such as the calcium carbide method (Engineer Manual-479, Department of the Interior 1957), have been studied. All chemical methods developed require calibration curves for each specific soil, which can be difficult in field construction if little knowledge of the native soil exists. The next progression in measurement of moisture content was the simultaneous development of the nuclear soil density and moisture gauge (Visvalingam et al., 1972) and the microwave oven moisture content test (Miller et al., 1974). Once developed, microwave and nuclear moisture methods were the leading technologies due to ease of use in field applications; however, the nature of both methods imposes significant challenges to their use in expeditionary field construction. The safety implications of using the nuclear gauge require certification of users and make transporting the device troublesome. While producing results faster than the standard oven, the microwave oven test still requires removal of the soil from the field and analysis in a facility with a power supply for the microwave, capabilities often unavailable in field applications. More recently, devices based on measuring electrical properties of the soil have emerged (Gamache et al. 2009; Freeman et al. 2008). These new technologies include Time Domain Reflectometery (TDR) and Dielectrics (DI). Many of these technologies are already being fielded by DOTs across the nation. These devices are able to return moisture content in the field without the regulatory burden imposed by use of the nuclear gauge. As with chemical methods, soil physical data must be determined to properly calibrate the electronic moisture content methods.

Objective

The U.S. Air Force in concert with the U.S. Army Engineer Research and Development Center (ERDC) sought to identify a technology that could effectively measure soil moisture content in the field without the use of a nuclear source (a nuclear density gauge) or a standard laboratory oven. The research effort entailed evaluation of a wide range of commercially available technologies that could serve as an expedient, non-nuclear alternative for measuring moisture content during construction.

Scope

The work began with procurement of several common and emerging devices commercially available for use in identifying soil moisture content in the field. These devices fell into two general categories: electrical devices which infer the soil moisture in-situ (similar to a nuclear density gauge) and heating devices that dry out soil samples so that the mass loss due to moisture evaporation can be recorded (similar to the laboratory oven). Identification of the desired set of devices to be tested was based on their frequency of mention in research publications and ready availability in the commercial market.

To evaluate the regional effectiveness of each device, tests were conducted on a range of soil types that covered both fine-grained soils (clays and silts) and coarse-grained soils (sands and gravels) typical of those found in a variety of soil construction scenarios. Each device was tested for each soil at one field moisture contents to determine the sensitivity of each device to grain size distribution. All techniques were compared to the results obtained using a laboratory oven, the current military standard for field quality control (QC) and quality assurance (QA).

Correlations between measured moisture contents were made to:

- Determine the accuracy and precision of various commercially available non-nuclear moisture devices.
- Determine the ability to prescribe methods for measuring compliance with construction moisture specifications using commercially available non-nuclear moisture devices.
- Provide written guidance as to the suitability of the test devices for quality control/quality assurance in contingency operations and the proper utilization criteria for these devices.

The most promising device(s) will be further explored to refine correlations between device output and achieving the desired moisture-density state.

Outline of report

This report describes the research in the following sequence:

1. Description of operation and use of the selected moisture content technologies
2. Description of the soils selected for study
3. Summary of data collected from the laboratory study
4. Analysis procedures to down select devices for recommendation for field use and/or future study.

2 Methodology

Test overview

Eight moisture content measurement devices, including the nuclear density gauge (NDG), were selected for comparison to the standard laboratory oven in determining moisture content of construction soils. These devices were tested against seven soils of differing unified soils classification system (USCS) classes including fine grained, high plasticity clay, loess, silty-sand, concrete sand, clay-gravel, silty-gravel, and crushed limestone. These materials are described in greater detail in the following sections.

Instrument descriptions

The devices selected for testing were grouped into four general categories: gravimetric, chemical, nuclear and electronic. The gravimetric devices all provide for direct measurement of the moisture content based on drying of the soil specimens. The latter three categories all provide for indirect measures of moisture content with the devices requiring calibration to some known standard prior to their effective use. A description of each test device follows.

Gravimetric techniques

The following techniques directly determine the moisture content of soil by determining the mass of a collected soil sample, applying energy to the sample to evaporate free water in the sample, and then determining the mass of the dried sample. The moisture content is then determined by Equation 1.

$$w(\%) = \left(\frac{M_{cms} - M_{cds}}{M_{cds} - M_c}\right) * 100 = \frac{M_w}{M_s} * 100 \tag{1}$$

where:

w = moisture content, %,
M_{cms} = mass of container and moist specimen, g,
M_{cds} = mass of container and dry specimen, g,
M_c = mass of container, g,

M_w = mass of water ($M_w = M_{cms} - M_{cds}$), g, and
M_s = mass of dry specimen ($M_s = M_{cds} - M_c$), g

Laboratory oven

The laboratory oven represents the reference standard for determining field moisture content. The oven temperature and controls were set to 110°C +/- 5°C according to ASTM E149 (ASTM 1994), and the sample heated for several hours according to ASTM 2216 (ASTM 2010a). If gypsum or calcium carbonate minerals are present in the soil, the ASTM suggests that the oven be set at 60°C and the sample dried over a longer time period to avoid evaporating bound mineral water. No gypsum or calcium carbonate enriched soil was tested during this experiment, so the higher oven temperature setting was used. The large oven shown in Figure 1 was used to determine the average true moisture content for each soil tested.

Figure 1. Laboratory oven.

Standard microwave oven

The microwave oven represents the gravimetric technique with the quickest operation. As per ASTM 4643-08 (ASTM 2008a), a soil sample is repeatedly heated and weighed at 1-min intervals until a limiting change in total mass between readings occurs, signifying a “dried” sample. Unlike the oven, which brings the sample into a steady state moisture condition with the ambient oven temperature, the microwave can continue imparting energy into the sample. As a result of this property, if not used in accordance with the ASTM standard, the microwave can drive outbound water in clay minerals, resulting in higher measured values for moisture content. Conversely, internal studies at ERDC have shown that the microwave does not dry out the bound mineral water in gypsum and calcium carbonate soils, making it a superior option for those types of soils over the laboratory oven.

ASTM specifies that a 700-W microwave oven be used for testing, and one of that power was the selected device for this study (Figure 2). Larger and smaller microwaves can be used, but the intermittent drying times should be adjusted to prevent over-drying of the soil. Also, drying times do not scale linearly with wattage. Rather, an exponential decrease in drying time occurs with increased wattage. A small concrete brick was used to absorb excess energy to extend the life of the microwave. Soil samples were placed in a porcelain dish and weighed on an 800-g +/- 0.01-g balance.

Figure 2. 700-W microwave oven.

Field portable microwave oven

Presently, the only battery-operated microwave oven available commercially is the WaveBox, a variable wattage microwave designed to work on AC current, 12-V battery current, or 9-V car adapter current shown in Figure 3. Each condition limits the wattage output of the microwave, with AC being the greatest (near 650 W), the battery the next highest (based on longer drying times) and the 9-V option being around 200 W, impractical for field use. A 12-V marine battery and recharger were used to simulate battery power from a running vehicle. The principle of the WaveBox operation is identical to that of the standard microwave discussed previously. As per ASTM 4643-08, the test was conducted and soil specimens were weighed on an 800 g +/- 0.01 g balance.

Figure 3. Variable wattage, 12-V powered WaveBox portable microwave oven.

It was noted that when connected to the battery the microwave operated with a decreasing wattage output due to the power depletion from the discharging battery. This is due to the decline in current as the battery is being discharged. Therefore, the recharge was used frequently to ensure that constant amperage was maintained to impart constant energy to the soil specimen with each time increment. In field operation, connecting the microwave into the vehicle electrical system would supply constant power while the vehicle is running.

Moisture analyzer

The moisture analyzer is a tabletop-drying device designed primarily for the agricultural and pharmaceutical industries. The device selected for testing is a Sartorius MA 150 model, which consists of a 1,200-g scale and an overhead ceramic heating element as shown in Figure 4. Samples are placed on small, disposable aluminum foil dishes and the material must fit between the dish and the ceramic heating element. The small sample volume automatically eliminates use of this device for soils with aggregates exceeding 1-in. in diameter.

Figure 4. Sartorious *model MA 150* 1,200-g moisture analyzer.

The device functions by a simple one button test sequence that tares the aluminum dish, weighs the moist sample and then proceeds to record the mass of soil as the heating element warms and dries the soil sample from the top. Once the mass reaches a steady-state value, the test ends and the final gravimetric moisture content is returned to the user.

Open flame gas burner

The open flame gas burner selected for testing was a typical Coleman duel fuel burner (Figure 5), which burns either Coleman camp fuel or unleaded gasoline. Similar diesel fuel stove models are available, which would be optimal for use in contingency situations. This technique combines the

Figure 5. Coleman open-flame duel fuel gas burner.

heating of the laboratory oven and the convenience of the microwave oven test. The open flame gas burner (gas stove) was used in accordance with ASTM D 4959 (ASTM 2000). The frying pan serves as the specimen container; with mass taken of the empty pan, of the pan and its contents after adding the soil sample, and of the pan and its contents during heating of the sample. The burner is ignited and the flame adjusted to a high heat. The frying pan is placed on the burner like cooking on a conventional stovetop and the sample is stirred while heating. Like the standard microwave procedure in ASTM, the specimen and pan are removed from the heat and weighed at 1-min intervals. The process continues until a change in soil mass of less than one percent occurs during the 1-min interval, at which point the moisture content is calculated.

Chemical moisture testing device

The Speedy moisture tester indirectly measures the moisture content of soil by determining the amount of gas produced by a reactant material and the free moisture in the soil. The Speedy moisture tester was used in accordance with ASTM 4944-04 (ASTM 2004), using calcium carbide as the reactant material. The device measures the amount of gas produced by recording the pressure change in a steel vessel resulting from the production of carbon dioxide during the water-chemical reaction. This pressure change is then related to the amount of water and ultimately the gravimetric moisture content assuming all free water in the soil has reacted with the calcium carbide. Figure 6 shows the equipment selected for this experiment. A small 20 g sample of soil is placed into the Speedy moisture container along with a specified amount of calcium carbide powder. Two steel balls are placed into the device and then it is sealed. The operator then shakes the Speedy in a

Figure 6. Calcium-carbide Speedy moisture tester.

circular fashion so that the steel balls break up the soil mass and distribute calcium carbide to as much exposed moisture as possible. A continuous reading of pressure is shown on the top of the Speedy, with the value recorded when stabilized. In accordance with FM 5-472 (Department of the Army 2001) a chart is then consulted for conversion of the recorded container pressure to moisture content, considering whether the soil is fine grained (silts or clays) or coarse grained (sands or gravels). This is the final recorded moisture content of the sample.

Nuclear density gauge (NDG)

The Troxler nuclear density gauge (NDG) uses emissions from radioactive materials to determine wet density and moisture content of a material. To determine wet density, gamma radiation from a Cesium (Cs^{137}) source is emitted into the material of interest. The gamma radiation is then either scattered or reflected by the test material. A detector on the gauge determines the amount of radiation reflected back, which is then related to wet density of the soil. The gauge also uses a neutron source, Americium (Am^{241}) to determine moisture content of the test material. Since the emitted neutrons react with the hydrogen in water, the detector senses neutrons reflected back to the gauge. The percentage of neutrons reflected back is then related to the water content of the soil. The device analyzes the moisture neutron reflection and returns a moisture content (Mooney et. al 2008).

The NDG was used according to ASTM D6938 (2010b) with a rod driven 6-in. into the ground to obtain moisture content and wet density. The NDG is shown in Figure 7.

Figure 7. Nuclear density gauge.

Electrical moisture content devices

The following described devices all pass an electric field through a soil of interest, measuring the change in the field as a result of interactions with the soil matrix. These devices measure moisture content indirectly by determining the different electrical properties of the soil and relating those properties to the properties of calibrated soil samples. These devices require additional input about the soil of interest in order to return useful moisture information.

Electrical density gauge (EDG)

The Humboldt electrical density gauge (EDG) measures density and moisture content of a material using high frequency radio energy transmitted into the material. The device transmits the radio frequency energy through tapered darts driven into the soil in a specific geometry.

The device then analyzes the radio frequency transmitted through the soil to produce a soil dielectric constant. The EDG then converts the value into density and moisture content output, based upon comparison of results to a calibration soil model. The soil model is built in the field by taking readings of the material when uncompacted and dry, uncompacted and saturated, compacted and dry, and compacted and saturated. The model effectively bounds the analysis of the field data (Brown 2007).

The EDG was used according to ASTM D 7698 (ASTM 1998) by driving the four metal darts into the ground using the supplied template. The electrical alligator clips were then attached to opposing darts and a reading was taken. Then the clips were reversed and another reading was taken. These steps were repeated for the other pair of opposing darts. The EDG is shown in Figure 8.

Figure 8. Electrical density gauge.

Soil density gauge (SDG)

The TransTech soil density gauge (SDG), shown in Figure 9, measures density and moisture content of a material using electrical impedance spectroscopy (EIS) allowing for non-contact measurements of soil density and moisture content. EIS works by forming an electric field within the soil of interest and measuring the electrical impedance of the soil, which is then

Figure 9. TransTech soil density gauge SDG200.

related to a dielectric constant. A sample reading of the material is required as an initial condition from which the soil density and moisture content is projected by the dielectric constant of the test material. The SDG was used per the manufacturer's instructions as an ASTM standard for this device does not yet exist. The device was placed on the soil, and testing began using the onscreen menu. The device was then moved diagonally in a clover pattern (Figure 10) with additional readings taken at each "leaf".

Durham GeoSlope moisture + density indicator

In a parallel project for determining soil density, the Durham GeoSlope moisture + density indicator (M+DI) was tested. Those tests found that the device would return null moisture content readings for 30% of the measurements taken (Berney et al., in preparation). That level of error was determined to be unacceptable in a moisture content device. Therefore, the M+DI was not considered in this evaluation.

Soils tested

This experiment used seven different soil types to approximate typical soils encountered during horizontal construction efforts. Table 1 presents a summary of the soils selected for testing and their associated engineering

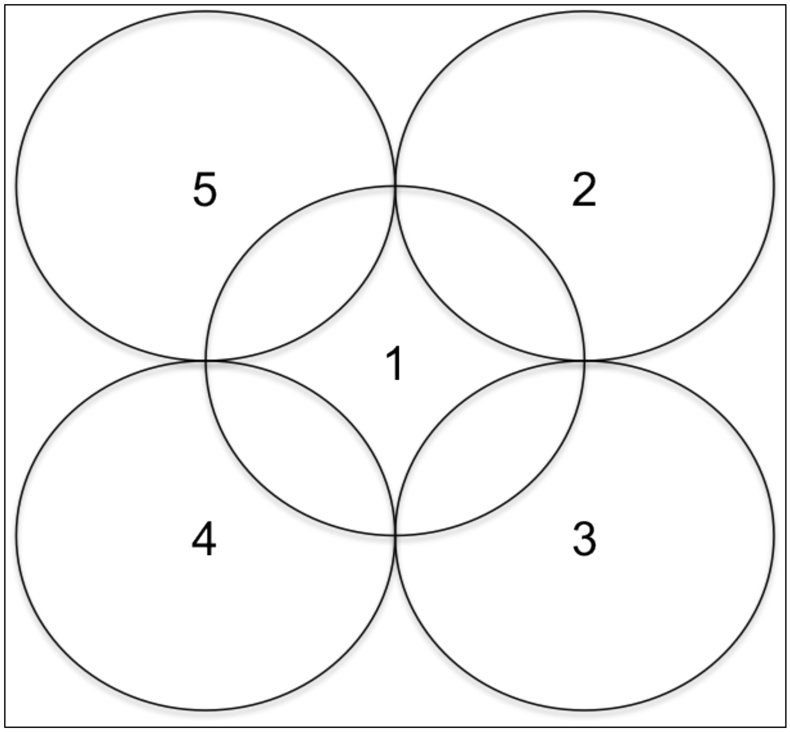

Figure 10. Testing pattern for TransTech SDG.

Table 1. Properties of soils selected for testing.

	USCS	Grain size percentage by weight				Atterberg Limits		Standard Proctor	
Descriptor	Class.	Gravel	Sand	Silt	Clay	LL	PL	OMC (%)	MDD (pcf)
Crushed Limestone	GP-GM	52.8	40.9	3.9	2.4	15	12	6.8	136.3
Silty Gravel	SM	29.2	45.9	21.1	3.8	NP	NP	7.8	129.7
Clay Gravel (Sub)	SP-SC	41.3	50.7	3.1	4.9	23	13	8	128.8
Silty Sand	ML-2	2.7	47	43.9	6.4	NP	NP	10	121.8
Concrete Sand	SP	4.9	36.1	2.3	0.8	NP	NP	9.5	109
Vicksburg Loess	ML-1	1.2	11	78.4	9.4	NP	NP	15.8	109.5
Buckshot Clay	CH	0	4.9	18.6	76.5	73	24	24.6	85.7

properties. Tests conducted on each soil included grain size distribution with hydrometer analysis for dissemination of silt and clay fractions, Atterberg limits including liquid limit (LL) and plastic limit (PL), Unified Soil Classification (USCS) and standard proctor compaction to determine optimum moisture content (OMC) and maximum dry density (MDD). Details of these test results can be found in Appendix B.

The silty-sand (ML-2) and silty-gravel (SM) were manufactured blends of proper proportions of the Vicksburg loess and concrete sand with some washed rounded gravel introduced for the silty gravel gradation. These manufactured blends were mixed on a hardened concrete surface on-site by a front-end loader and a bulldozer. The desired USCS classification was that of an SM and GM respectively. However, because these were not naturally occurring materials, significant point-to-point variability is present owing to segregation occurring during the mixing process. Similarly, the crushed limestone ordered from a local aggregate supplier classified as a GP-GM when, ideally, a GW or SW classification was desired.

The intent of using a variety of selected soils was to provide a spectrum of behaviors necessary to validate moisture content response:

1. A series of fine grained soils that included clay, silt and sandy-clay/silt blends were required to provide soils with high moisture retention to test the ability of the devices to measure high moisture contents.
2. A series of coarse soils that included crushed limestone, silty-gravel and clay gravel provided large aggregates that could adversely influence certain moisture measurement devices.
3. Lastly, the range of soils tested considered a wide range of fines content, aggregate content and were soils typical of those used in various horizontal construction activities.

Sampling protocol

A sample was taken from the stockpile of each soil used in a companion field density study. The samples were placed in 1-gal metal paint cans and sealed until moisture measurements were conducted. Each paint can held about 4-5 kg soil, which was enough to provide at least three replicate experiments using 200-250 g of material for each of six test devices: the two microwaves, gas stove, moisture analyzer, Speedy and laboratory oven. The NDG, EDG and SDG were all tested in an outdoor field setting during a large-scale density study (Berney et al., in preparation).

The paint cans remained sealed for 4 to 6 weeks, during which time the moisture had an opportunity to equilibrate throughout the bulk soil specimen. When testing began on a particular soil, three random samples of soil were extracted from the can for determination of moisture content by the laboratory oven method. The average moisture content of these samples was considered to be the reference moisture content for the bulk sample within the can. All the remaining samples were treated similarly, with three random samples of soil drawn from the can and tested.

The field tested devices all had moisture samples extracted from the upper 4-in. of compacted soil at the point where a unique device reading was taken. Therefore, multiple points of comparison were obtained for these devices providing a more precise standard deviation.

Properties measured

Electrical moisture-density devices

Calibration of the EDG was performed with field data points measured with the nuclear density gauge as described in the next section. The EDG returns to the user the gravimetric moisture content of the soil. Similarly, the SDG was calibrated with physical soil properties such as grain size and Atterberg limits and corrected with one field data point from the field. The SDG also returns gravimetric moisture content to the user.

Heating devices

These devices consisted of drying technologies ranging from convection heating (laboratory oven), microwaves (standard and field) and direct heating from a ceramic heating element (moisture analyzer) or a gas flame burner (gas stove). With the exception of the moisture analyzer, each drying technique required a series of manual measurements to be made during the drying process to determine the final constant dry mass of the soil. This technique was assisted by the use of software developed specifically for these types of drying scenarios used in ERDC's Rapid Soils Analysis Kit (Berney et al. 2007). The software prompts the user for weights of the soil at 1-min drying increments and internally calculates the mass differential between drying times until a prescribed minimum difference is obtained. For field use this threshold is considered as less than 1% of the total wet mass. For the associated microwave ASTM this is nearer to 0.1% of the total wet mass. The 1% value was used for military consideration based on an outdoor scenario where wind and environmental conditions prevent measurement accuracy consistent enough to measure down to a 0.1% differential, especially with small soil specimens.

Instrument calibrations

Electrical density gauge (EDG)

According to the manufacturer, the ideal calibration scenario for the EDG is to measure data in the laboratory at nine distinct points bounding the moisture-density Proctor curve. A 3x3 matrix of points would be taken consisting of each combination of three moisture contents, optimum moisture content, dry of optimum and wet of optimum and three densities, low, medium and maximum. A reduced set of calibration data using a 2x2 matrix of points is a next best option. However for deployment of this device in a military scenario, a field capable calibration scheme was desired. It was decided to compromise and provide a three point calibration scheme making use of the various pass levels and the stockpiled material for each soil type. Calibration occurred as follows:

1. A data point was taken after the first roller pass on each soil in a field constructed test section representing a low density-optimum moisture content and correlated to an NDG wet density and an oven dried moisture content
2. A data point was taken after the final roller pass on each soil representing a maximum density-optimum moisture content correlated to an NDG wet density and an oven dried moisture content
3. A small pad of soil 6 to 8-in. deep was placed to the side of each soil stockpile, left to dry during the day with frequent remixing to allow moisture removal, and compacted with one pass of the roller representing a low density-low moisture content correlated to an NDG wet density and oven dried moisture content.

This technique provided two data points for moisture calibration, one moisture content near optimum and one moisture content dry of optimum. All soils sampled from the stockpile were at a moisture condition within these bounds.

Table 2 represents a summary of the field data collected for each soil type.

Soil density gauge (SDG)

The soil density gauge is calibrated based on input properties of the grain size distribution and Atterberg limits. The advantage of this approach is the device uses data obtained from traditional laboratory tests without requiring the device to be calibrated in the laboratory. Because of a delay in laboratory results versus when the field-testing was executed, for several soils, historical data on past soil types similar to those used in the section were used to calibrate the SDG. As laboratory data became available the true gradation and Atterberg limit data could be input into the device. Appendix B shows the grain size and Atterberg values determined by lab analysis. An offset for the device measured moisture content was determined from one field data point dried in the laboratory oven, collected at the first test point on the first roller pass for each soil.

Table 2. Electrical density gauge calibration points.

	Microwave	NDG	Calculated		Microwave	NDG	Calculated
ML	Water Content	Wet Density	Dry Density	**SM**	Water Content	Wet Density	Dry Density
	(%)	(pcf)	(pcf)		(%)	(pcf)	(pcf)
Stockpile	15.6	113.4	98.1	Stockpile	11.94	118.2	105.5
Lift 2-Pass 1	20.0	122.4	102.0	Lift 3-Pass 1	12.29	120.8	107.6
Lift 2-Pass 8	20.1	123.7	103.0	Lift 2-Pass 8	13.05	131.6	116.4
	Microwave	NDG	Calculated		Microwave	NDG	Calculated
SP	Water Content	Wet Density	Dry Density	**SP-SC/SM**	Water Content	Wet Density	Dry Density
	(%)	(pcf)	(pcf)		(%)	(pcf)	(pcf)
Stockpile	0.93	102.7	101.8	Stockpile	9.80	125.6	114.4
Lift 2-Pass 1	5.45	109.3	103.7	Lift 2-Pass 1	7.17	130.9	122.1
Lift 2-Pass 8	5.06	109.9	104.6	Lift 1-Pass 8	5.99	139.1	131.2
	Microwave	NDG	Calculated		Microwave	NDG	Calculated
GM	Water Content	Wet Density	Dry Density	**GW**	Water Content	Wet Density	Dry Density
	(%)	(pcf)	(pcf)		(%)	(pcf)	(pcf)
Stockpile	6.34	130.1	122.3	Stockpile	2.00	123.5	121.1
Lift 2-Pass 1	9.03	134.4	123.3	Lift 2-Pass 1	3.30	136.3	131.9
Lift 2-Pass 8	8.24	136.9	126.5	Lift 2-Pass 8	3.21	142.1	137.7
	Microwave	NDG	Calculated				
CH	Water Content	Wet Density	Dry Density				
	(%)	(pcf)	(pcf)				
Stockpile	21.77	106.7	87.6				
Lift 2-Pass 1	27.41	110.8	87.0				
Lift 1-Pass 8	27.43	117.5	92.2				

3 Results

Comparison of laboratory data

The following series of plots (Figures 10-15) represent the average of the three laboratory oven dried moisture content samples as compared to the individual samples tested with each specific device. These results are from the samples collected and stored in paint cans for a period of time. Figure 11 shows the laboratory oven versus soil-average laboratory oven as a reference for highly accurate and precise method. The slope reported compares the overall accuracy of the device compared to the laboratory oven. Slopes approaching m=1 indicate overall agreement with the values from the laboratory oven, whereas m<1 indicates under-prediction and m>1 indicates over-prediction of moisture content. Individual data points collected for each soil and device (not including the SDG, EDG and NDG) are tabulated in Appendix A.

Comparison of field data

The following plots (Figures 17-20) represent data from full-scale field-testing. Samples for the laboratory oven were collected for every device reading at the exact location of the device reading to allow for one-to-one comparison of device values to standard lab oven values. The slope

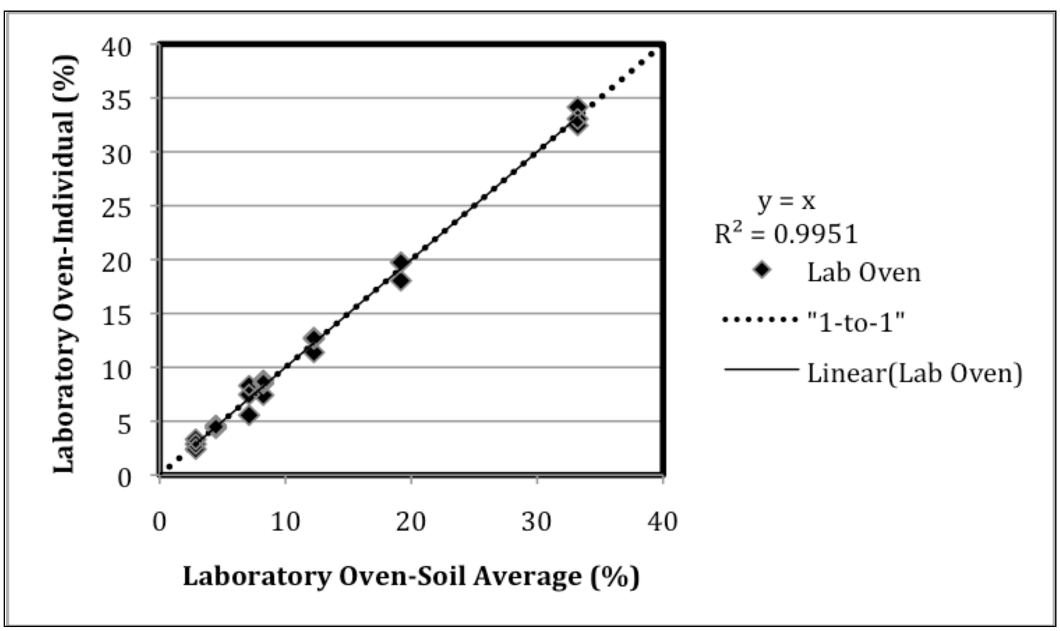

Figure 11. Comparison of individual laboratory oven moisture content to soil-average laboratory oven moisture content.

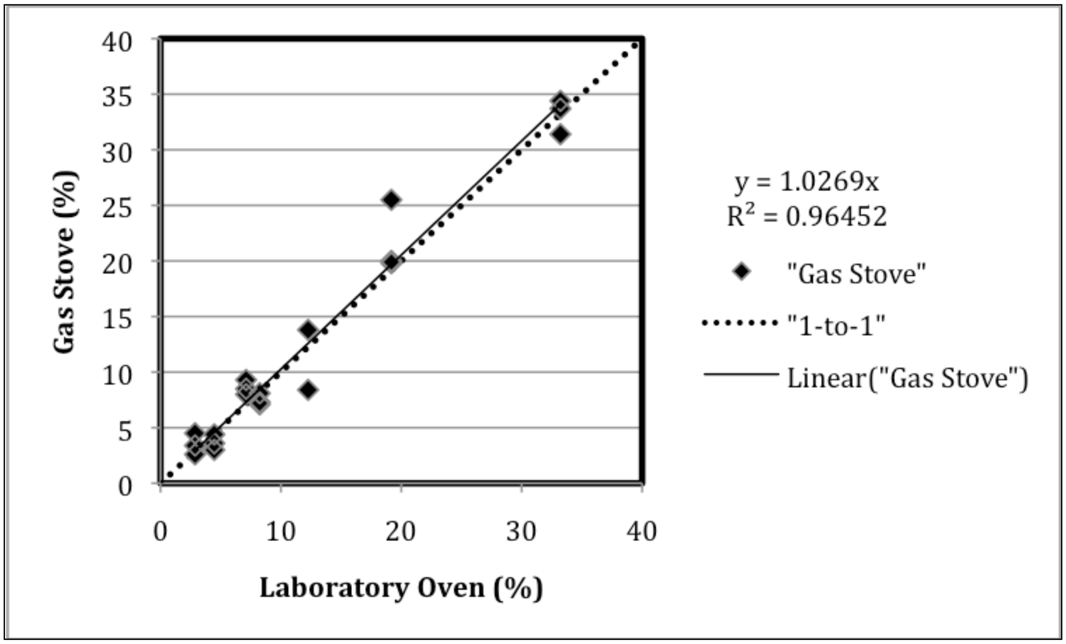

Figure 12. Comparison of individual gas stove moisture content to soil-average laboratory oven.

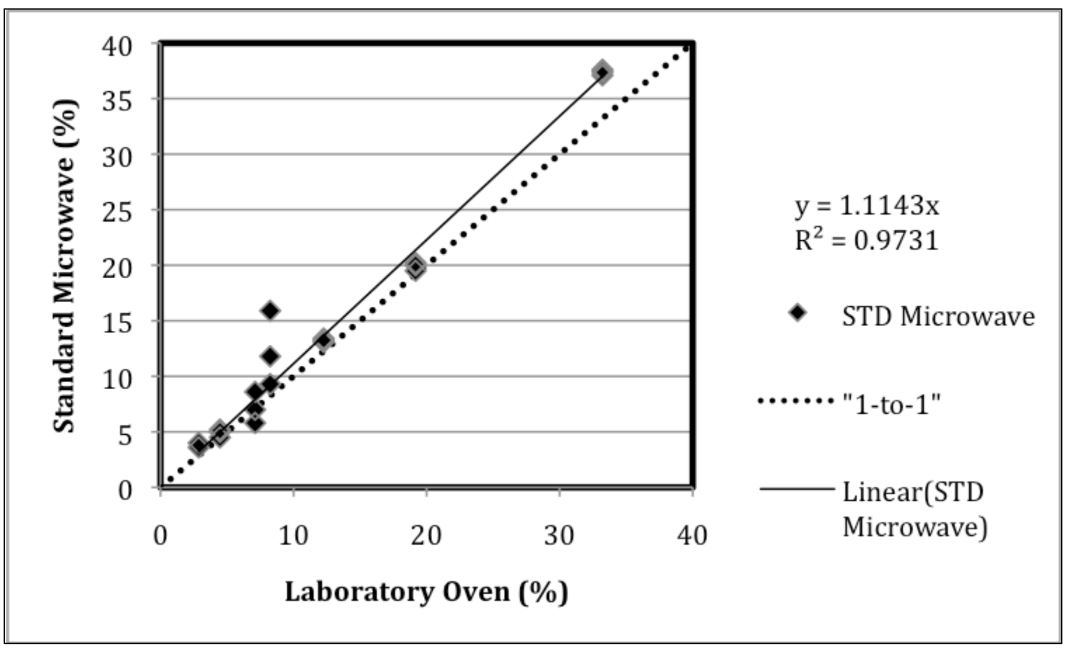

Figure 13. Comparison of individual standard microwave moisture content to soil-average laboratory oven.

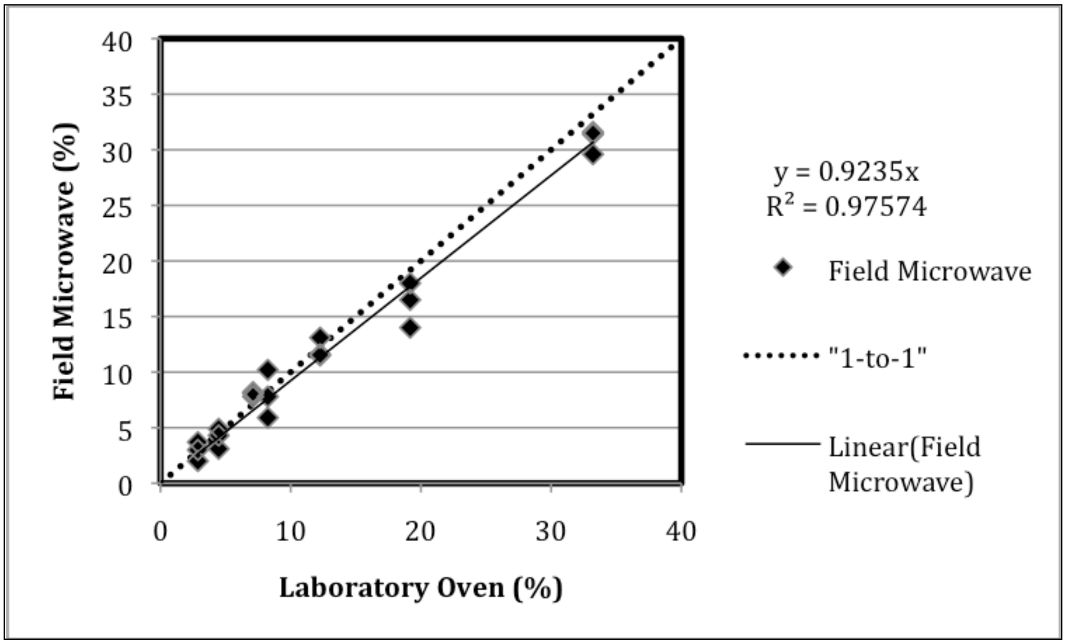

Figure 14. Comparison of individual field microwave moisture content to soil-average laboratory oven.

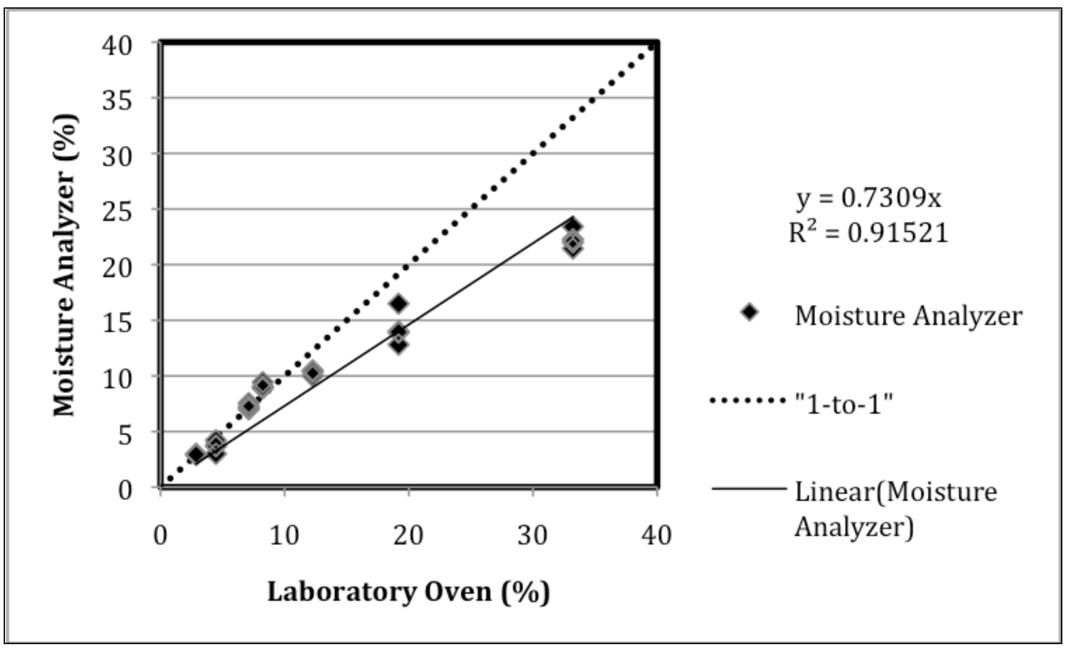

Figure 15. Comparison of individual moisture analyzer moisture content to soil-average laboratory oven.

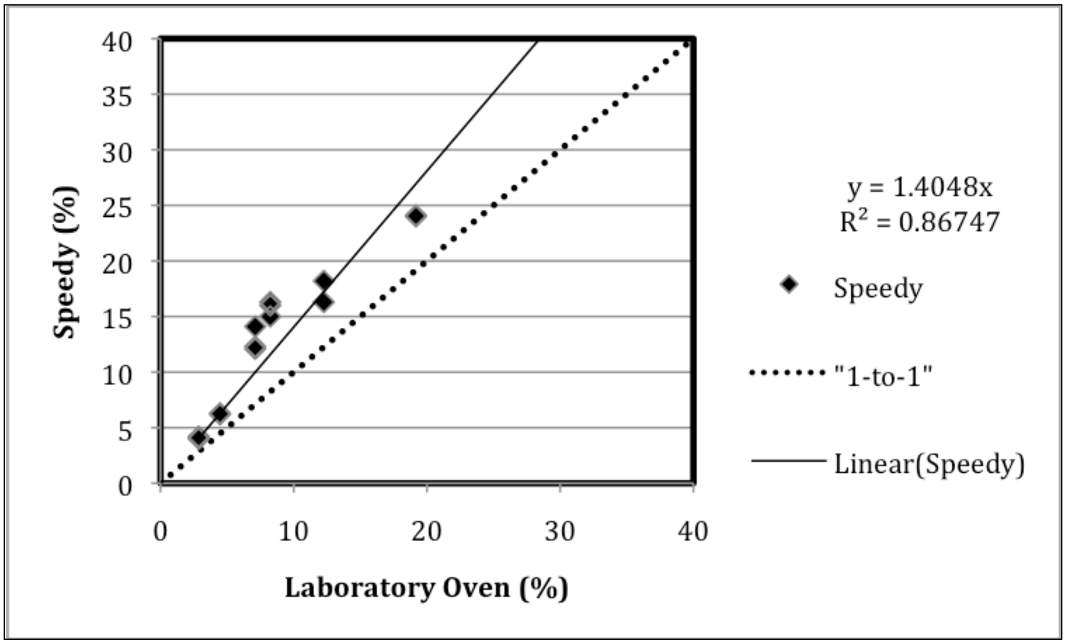

Figure 16. Comparison of individual speedy moisture content to soil-average laboratory oven.

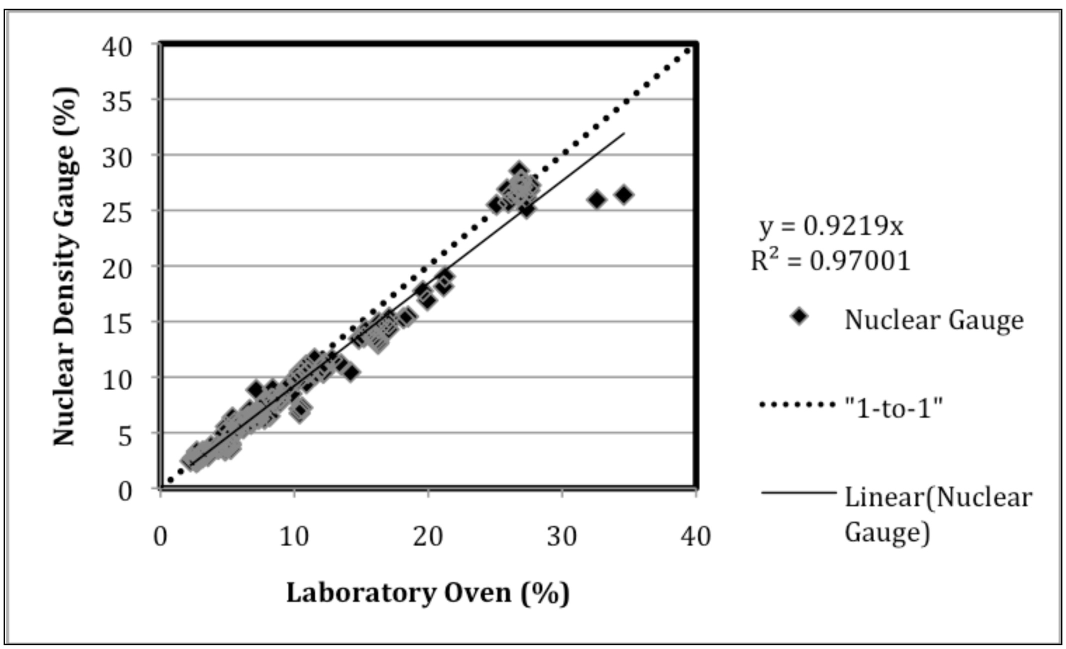

Figure 17. Comparison of all field measured moisture contents for nuclear density gauge (NDG) to the laboratory oven.

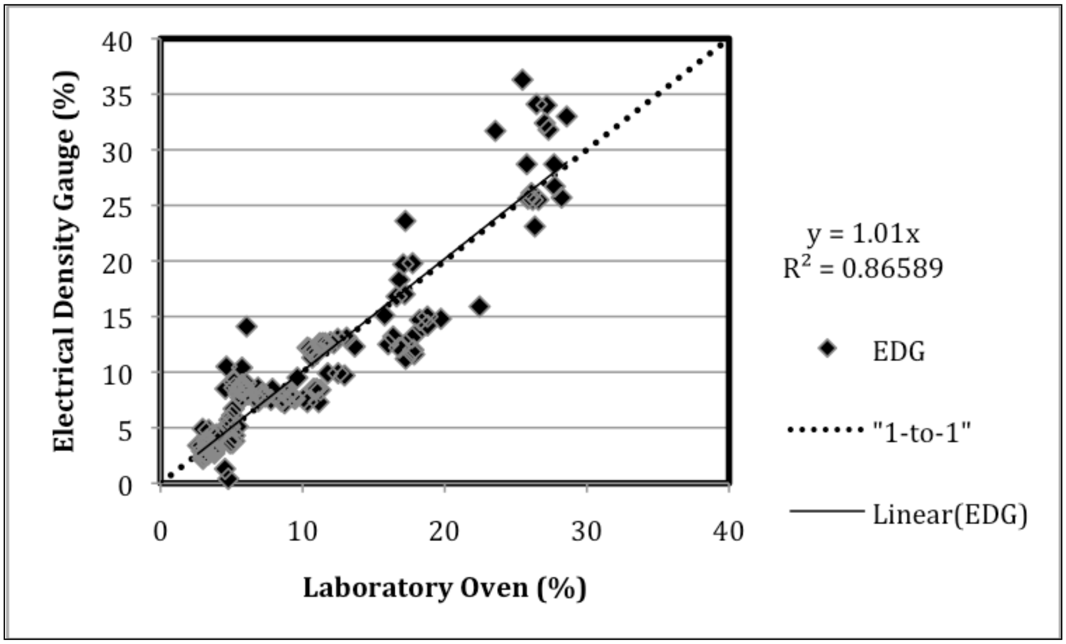

Figure 18. Comparison of all field measured moisture contents for electrical density gauge to the laboratory oven.

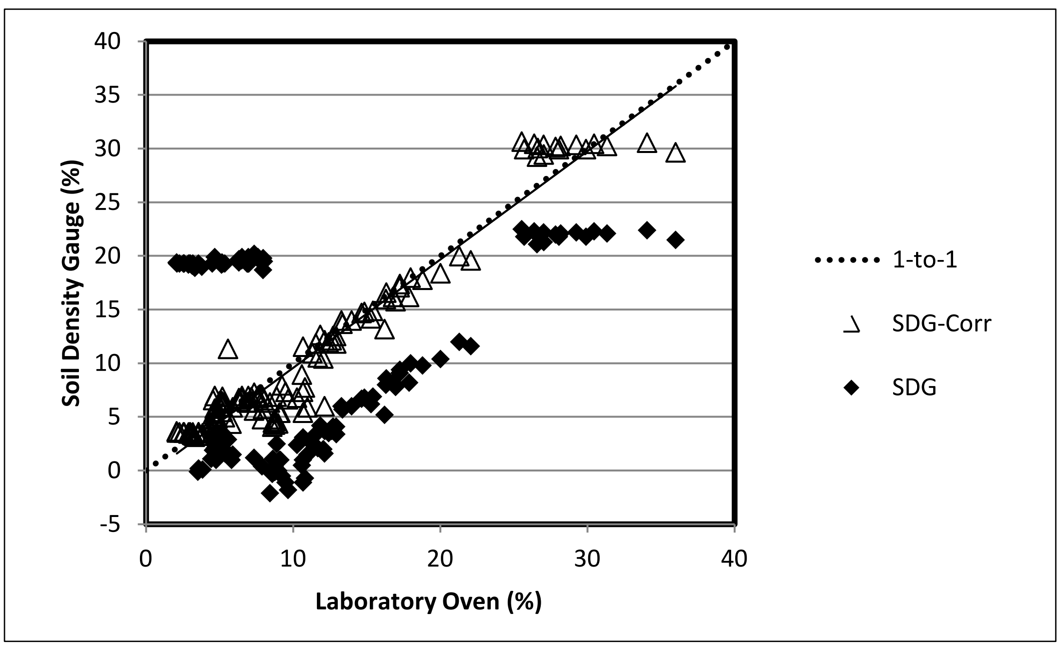

Figure 19. Comparison of both field-measured and corrected moisture content of soil density gauge (SDG) to the laboratory oven.

reported compares the overall accuracy of the device compared to the laboratory oven. Slopes approaching m=1 indicate overall agreement with the values from the laboratory oven, whereas m<1 indicates under-prediction and m>1 indicates over-prediction of moisture content.

Data initially collected from the SDG provided poor consistency and poor relationship with the laboratory oven. However a simple linear offset was applied to the data per the manufacturer's guidance. This step involved independently determining the oven moisture content for the soil of interest and finding the difference between the independent value and the first value recorded for that soil. This difference was then used as a linear offset for that soil to provide SDG-corrected data. The linear offset process is shown in Equations 2 and 3. The corrected data show significant improvement in correlation to the laboratory oven as shown in Figure 19.

$$L.O. = STD_{Oven} - MC_{SDG\#1} \quad (2)$$

$$SDG_{Corr} = MC_{SDG} + L.O. \quad (3)$$

where:

$L.O.$ = the linear offset
STD_{Oven} = Moisture Content from Laboratory Oven (or other standard)
$MC_{SDG\#1}$ = first SDG moisture content for that soil
SDG_{Corr} = Corrected moisture content for SDG
MC_{SDG} = SDG device reading for moisture content

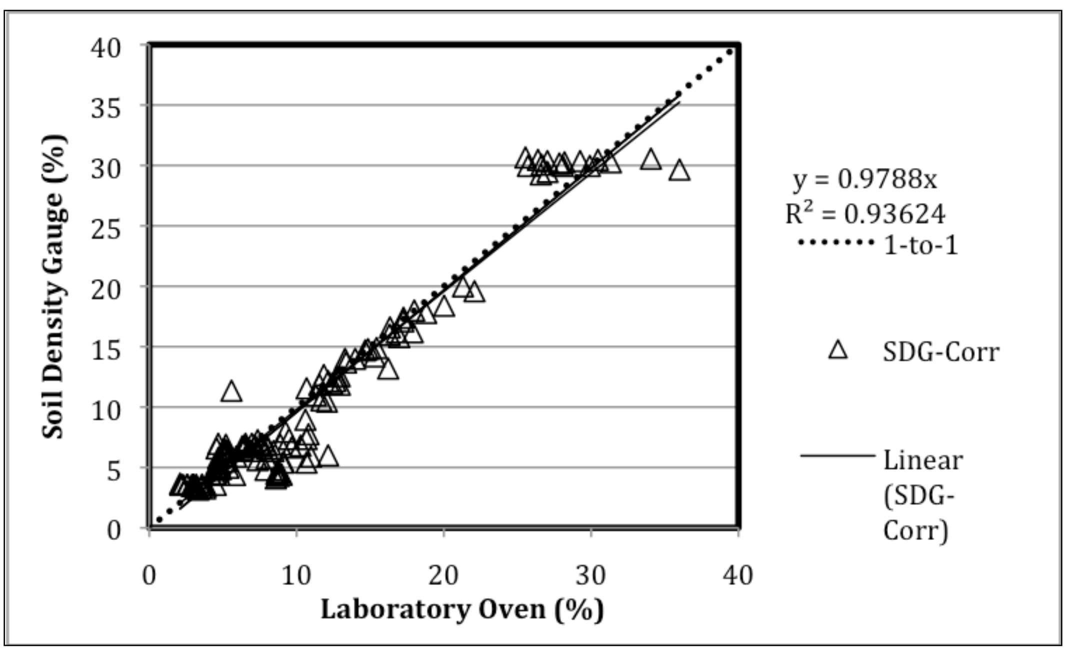

Figure 20. Comparison of corrected moisture contents for soil density gauge (SDG) to the laboratory oven.

4 Data Analysis

Summary of data reduction for each instrument

Reduction of data from the experiment occurred in two phases. The first indicator of a device's performance was its ability to capture the moisture content value compared to the laboratory oven method. This is defined as the accuracy of each device. To determine this metric, an average value of moisture from the laboratory oven for each soil was determined (Appendix A). Next, the device moisture content values were plotted against the average moisture content for each soil. For the electronic field devices tested, the individual moisture content for each device was plotted against the individual lab oven moisture content, as lab oven moisture samples were collected at each location for every device tested. The overall slope of the device versus moisture content was determined for each device. The device's performance was then based on the absolute slope differential between the device's measured slope and unity, which was the slope of plotted results from the laboratory oven. This comparison can be seen in Figure 21. Figure 22 shows a ratio of all average moisture content values by device and soil to the laboratory average, where the ideal measurement would be 1.0. Soils are ranked in order of increasing average grain size.

The second indicator of a device's performance was the deviation of measured values from the average moisture content. This indicates the precision of the instrument. To determine this metric, the ratio of device moisture content to the average lab oven moisture content was taken. The standard deviation for these ratios was then found for each soil as shown in Figure 23 and as an overall standard deviation for the device as shown in Figure 24. Again, soils shown are ranked in order of increasing grain size.

To combine the accuracy and precision of each device, the metric of Total Analytical Error (TAE) was employed. The calculation for TAE is shown in Equations 4 and 5. Figure 25 shows the final metric for each device, and Table 3 shows the values used in computing the TAE.

$$Bias = \left| \frac{1 - slope}{1} \right| \qquad (4)$$

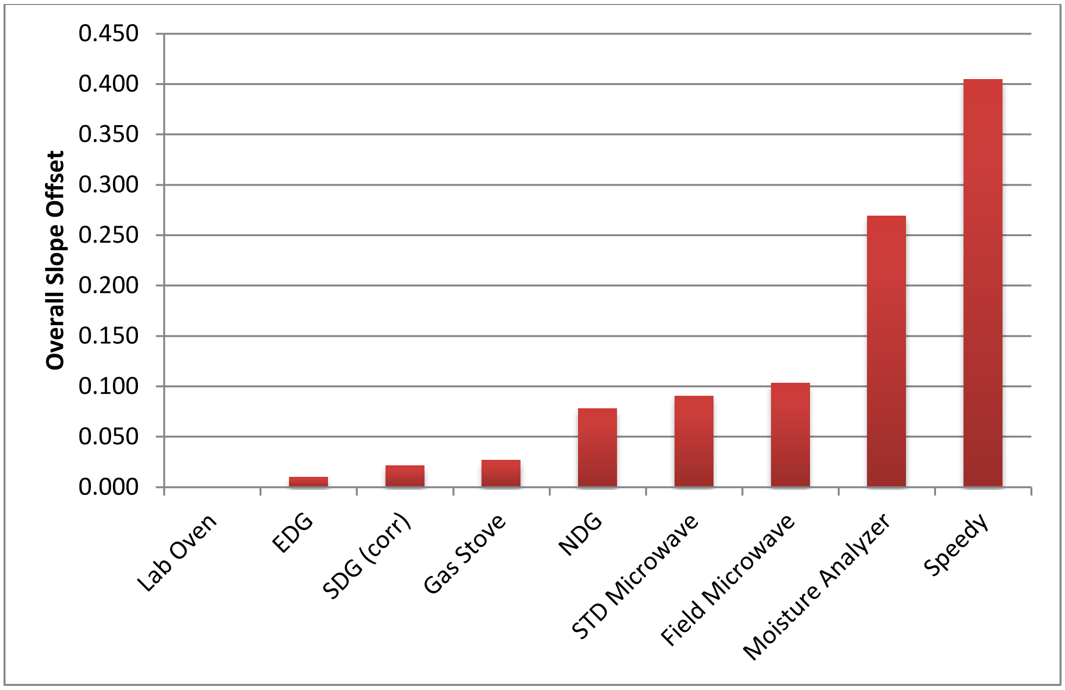

Figure 21. Average slope offset to laboratory oven correlation for each tested device.

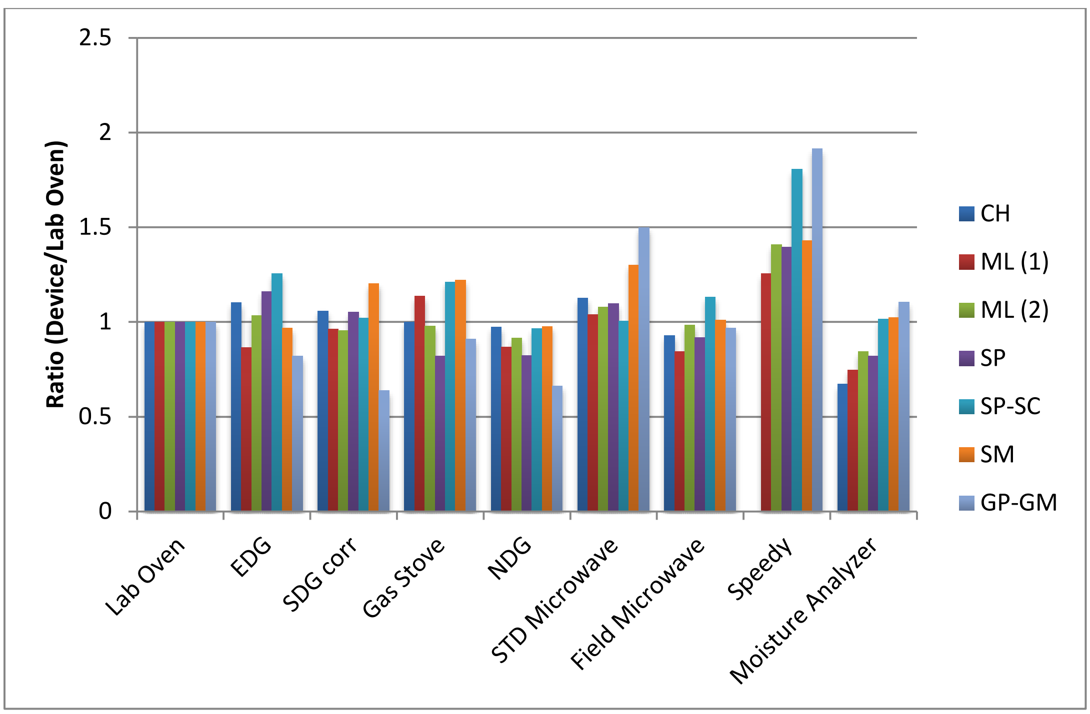

Figure 22. Ratio of average device to laboratory oven moisture content for each soil tested.

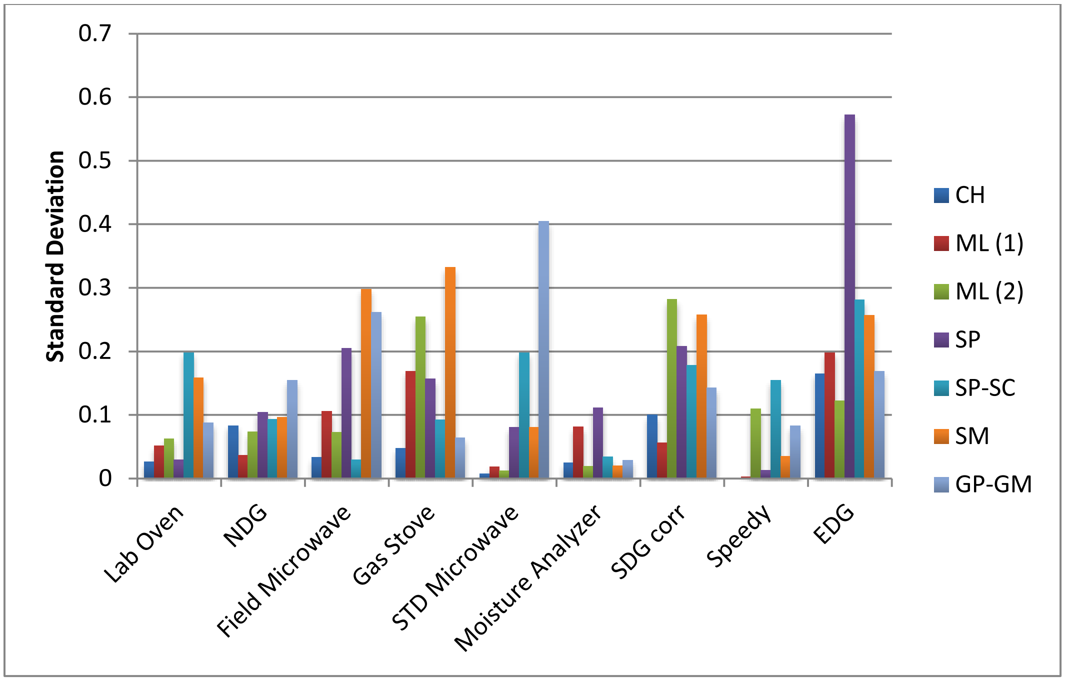

Figure 23. Standard deviation for each tested device for each soil type tested.

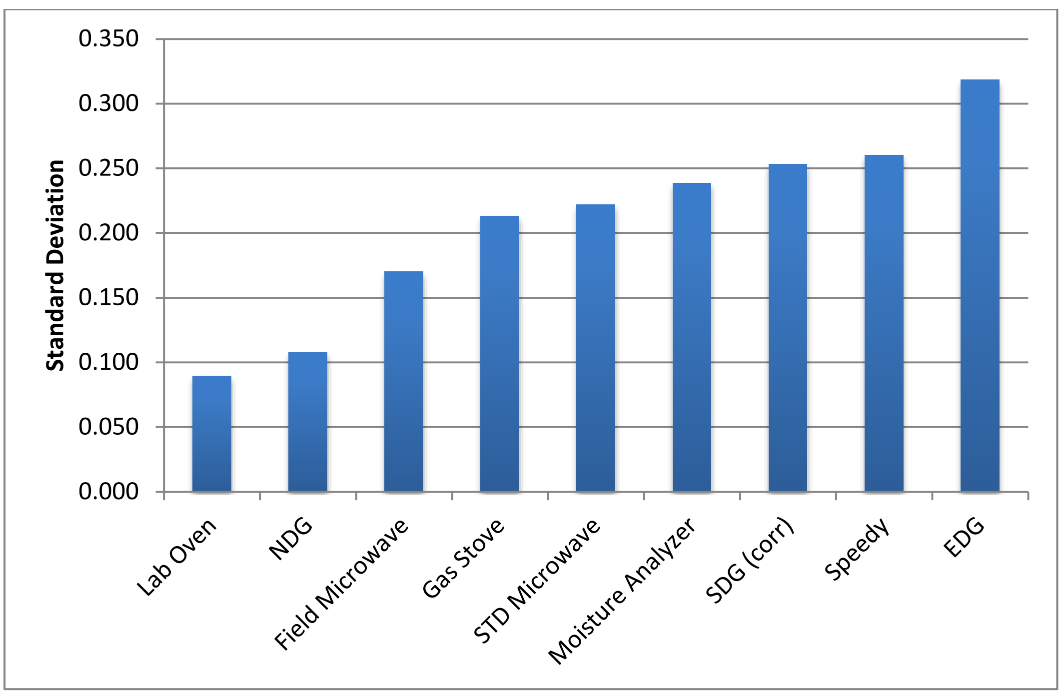

Figure 24. Overall standard deviation over all soils for each tested device.

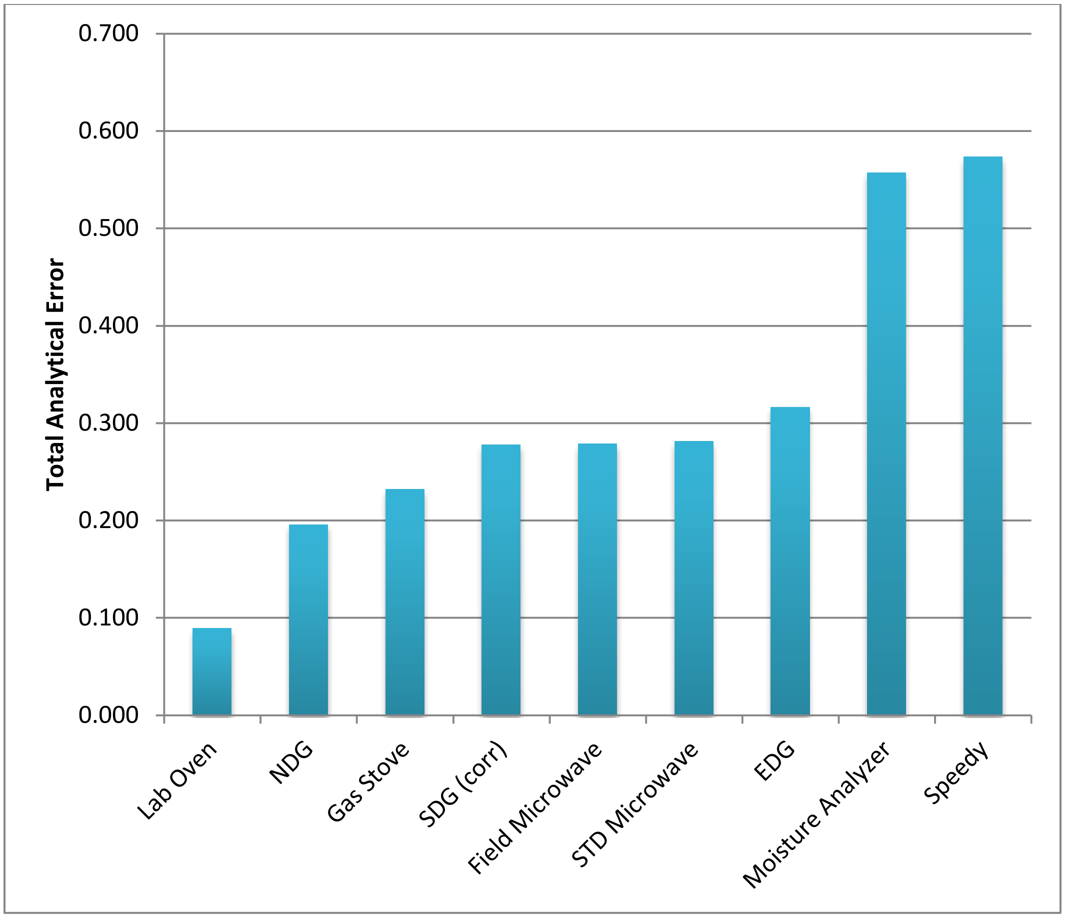

Figure 25. Rating statistic as the product of the slope offset and standard deviation for all tested devices.

Table 3. Summary of accuracy and standard deviation for each device.

	Slope	Slope Offset (Slope-1)	Ratio Standard Deviation	Ratio Average	Total Analytical Error
Lab Oven	1.000	0.000	0.089	1.000	0.089
NDG	0.922	-0.078	0.108	0.916	0.196
Gas Stove	1.027	0.027	0.213	1.039	0.232
SDG (corr)	0.979	-0.021	0.253	0.987	0.278
Field Microwave	0.897	-0.103	0.170	0.969	0.279
STD Microwave	1.091	0.091	0.222	1.163	0.282
EDG	1.010	0.010	0.318	1.040	0.316
Moisture Analyzer	0.731	-0.269	0.238	0.827	0.557
Speedy	1.405	0.405	0.260	1.542	0.574

$$TAE = Bias + \frac{\sigma}{\overline{X}} \quad (5)$$

where:

$Bias$ = Absolute value of the slope offset from desired slope, normalized to the desired slope.
TAE = combination of the accuracy and precision of the measurements
σ = Overall standard deviation of the device to lab oven ratio
$\overline{X}$ = Average of all device to lab oven ratios

Based on the findings, when calibration against laboratory oven results is possible, the electronic gauges provide some of the better field results. When that means of calibration is not available, the gas stove and frying pan or microwave ovens represent the best field devices tested. These devices could be considered as alternatives for use in calibration of the recommended electronic gauges. The moisture analyzer and Speedy are not to be considered reliable field devices over the full spectrum of soils encountered in construction. Devices that did not perform well usually failed when the moisture content in fine-grained soils was high. Coarse grained soils such as sands and gravels tended to yield accurate measurement by more devices. The uniform heating of the gas stove, as opposed to the variable microwave heating, created a much more reliable set of moisture measurements.

Summary of device performance

The following listing explains the findings and the reservations about the use of each device based on both the analytical evaluation and the practical use of each device in the field.

Electrical/nuclear devices

Soil density gauge – This device returned a very accurate measure of moisture content over all soil types when properly calibrated, in this case by the laboratory oven. Without calibration, the device returned values that were far from the true water contents. Thus, one of the heating devices should be considered as a backup for field use to enable the proper implementation of the SDG. The functionality of the SDG was the best of any of the tested devices, making its implementation the most desirable of any of the candidate testing devices.

Electrical density gauge – This device returned very accurate measures of moisture content, but its precision was the worst of all devices tested. The tapered design of the probes allowed penetration into even the coarsest soils yet still allowed adequate soil surface contact to obtain a moisture reading. However, to calibrate the EDG, an alternate method of measuring moisture content was required and was necessary at multiple points. In contrast, the SDG required only one field calibration point to achieve its level of accuracy. Thus, an alternate drying method should be employed on site or the device should be calibrated in the laboratory prior to field use.

Nuclear density gauge – This device was considered the field standard for reference and performed better than all of the competing moisture testing devices or methods, with the exception of the laboratory oven. Additionally, the nuclear gauge does not require calibration to the soil of interest to obtain reliable data. The only calibration required is to a reference platform that is shipped with each device. The NDG is a self-contained apparatus that is simple to use in the field, but comes with onerous safety and bureaucratic requirements related to owning, operating, and transporting the device.

Gravimetric devices

Gas stove – The Gas Stove was overall the best drying candidate of any tested. The open flame has the ability to provide a constant thermal energy source, similar to that of an oven, which allows consistent drying of the soil and prevents over-drying of the soil which can occur when using the microwave. This is why the gas stove, unlike the microwaves, did not show wide variations in moisture content from over or under-drying of the high moisture soils (CH and ML(1)). The gas stove is small and portable requiring only unleaded fuel, a heating pan, and a balance which are relatively simple to transport to the field. When used in a manner similar to the ASTM D4643 (ASTM 2008a) standard, weighing the soil after each minute of cooking, a reliable measure of moisture content can be obtained. The only drawback is that a proper fuel supply must be available, as JP8 and other kerosene/diesel products commonly used in military and construction vehicles are not suitable for use with the tested device. However, there are several commercial manufacturers that produce multi-fuel stoves that can replace the tested device and can accommodate diesel, JP8, and kerosene dependent on the mission specifications.

Field microwave oven – The field microwave provided a fairly reliable estimate of moisture content however its accuracy deviated for high moisture content silts and clays. This was due to the constantly increasing energy source supplied by the microwave, which allows drying of the bound-mineral water in the soil, a water barrier that is not evaporated under constant thermal energy found in a laboratory oven. The field microwave is dependent on a constant battery source. If not kept fully charged, the wattage of the microwave will decrease as the battery loses charge, resulting in soils not drying out fully before test completion. This could cause considerable error in the measurement and is the primary concern which keeps it from being recommended as a replacement to the laboratory microwave.

Laboratory microwave oven – The laboratory microwave has been used in research for decades, and provides reasonable estimates of soil moisture. Its accuracy tends to increase with the grain size of the specimen. The microwave provides an ever-increasing energy supply, which means that over-drying of silt and clay soils can occur, resulting in excessive reported moisture contents. As a field tool, either type of microwave provides accurate enough data for quality control. The laboratory model is powered by a constant AC electrical input, which prevents decay in heating capacity observed in the battery powered field microwave. This suggests that the laboratory microwave would be a better candidate for field-testing if a constant power source is available.

Moisture analyzer –The heat source is hot enough to dry the surface moisture on coarse soil grains such as gravels and sands, but is not able to provide sufficient energy to dry out the bound moisture within pockets of silt and clay as evidenced by the fading trend line shown in Figure 14. The recorded moisture contents for the ML(2), ML(1) and CH soils were all lower than the laboratory and significantly lower as the plasticity of the soil increased. Therefore, this device should only be used for coarse grained soils.

Speed moisture tester – The Speedy was the most precise instrument, but the least accurate. The Speedy overestimated the moisture content for all soil types for varying reasons. For coarse-grained soils, the Speedy overestimated moisture because of the small sample size used (only 20 g) which only allows for the fine grained material of the sample to be tested, the fraction which best retains any available moisture. For fine-grained soils where moisture content is large, the Speedy technique requires a multiplier to be applied to the charted conversion values, which creates an overall error in estimation of moisture content. Therefore, the Speedy should only be used as a last resort if no other technique is available.

5 Conclusions and Recommendations

General recommendations

Based on the findings of the statistic shown in Figure 25 one electronic device (SDG) and one heating device (gas stove) appear to be the best suited devices to replace the NDG in field operation.

Heating devices

First recommended – Gas stove (ASTM 4959-2000)

This device is the most compact and provides a combined best precision and accuracy of all the heating devices. The tested device uses Coleman fuel or unleaded gasoline, a fuel source not as common within military applications as diesel, JP8 or possibly even an electrical source. Other commercial gas stoves that can run thicker fuels are available and should be considered.

Second recommended – Microwave (field or standard) (ASTM 4643-2008a)

The microwave method is next most reliable heating device and is based on current ASTM methods. It is fairly compact, and a commercial 700 Watt microwave is available virtually everywhere in the world. The battery powered field microwave provides an attractive option to the electric microwave in that no generator is required on-site. However, if battery power is not kept fully charged, significant drying errors can occur with the field microwave. This is not an issue with the laboratory microwave. Care must be taken with moisture susceptible soils that over-drying does not occur and therefore ASTM procedures should be followed as close as possible.

Electronic devices

First recommended – Soil density gauge

The SDG is the best field device based on precision and accuracy for measuring the moisture content of soils. However, the accuracy of the device is highly dependent upon calibration with an adjacent field sample tested for microwave/oven moisture content, whereas grain size and Atterberg limit properties are not as critical. Grain size and Atterberg limit calibration parameters can be quickly obtained using rapid field classification techniques allowing a non-laboratory calibration process with no significant error when coupled with a field offset. This device does not work without calibration and currently device calibration without a field sample results in poor accuracy of the device. Continued improvement of the devices internal database should result in improved accuracy.

Second recommended – Electronic density gauge (ASTM 7698)(ASTM 2000)

The EDG is the next best device for measuring soil moisture content. However, like the SDG, the accuracy and precision of the device is highly dependent upon proper calibration points stored in its memory taken from field or laboratory data points. This process is much more involved than the SDG device, and its resulting overall measurement variability is still greater than the SDG. Field calibration of the EDG is still under study, but this process is more time intensive and complex than the SDG calibration, making it slightly less desirable than the SDG.

All other devices tested produce sub-standard accuracy and precision over a broad range of soils, but still could be of value in specific scenarios where a soil type to be tested matches the soils most-suited for a particular device.

Future research

As the development of electronic moisture-density gauges continues, this experiment should be revisited to evaluate improvements in the technology. As the demand to replace the nuclear density gauge within the military grows, the investment in improving these alternative technologies grows producing more innovative and accurate techniques. As for the devices tested, continued research into the SDG and EDG may provide for more consistent field results and a reduction in calibration needs for the user. For heating devices, multi-fuel stoves should be studied and considered as standard military hardware for purposes beyond just the measurement of soil moisture. Current research at ERDC is underway to develop self-weighing microwaves that will automate the measurement process and correct for the over-drying problem consistently seen with the manual technique. It is suggested that when these devices are available, that their capability be assessed and reported in conjunction with the conclusions presented here.

Moisture content is only half of the quality control data usually required in field construction. Density is the other component which is necessary to identify successful construction. The reader is referred to the companion study undertaken at the same time as this one in Berney et al. (in preparation), which documents the use of the electronic devices to measure soil density along with moisture content. The ability to capture both moisture and density with a single device rather than a heating device and a field density apparatus increases the value of these devices as a single solution for construction quality control.

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Appendix A: Collected Field Data

Table A1. Moisture content measurement.

	Moistue Content Measurement							
ML (1)	1	2	3	4	Average	ST Dev	Min	Max
Lab Oven	19.76	18.04	19.72		19.17	0.98	18.04	19.76
Gas Oven	25.5	20	19.8		21.77	3.23	19.8	25.5
Mois Anal	12.81	14	13.89	16.49	14.30	1.56	12.81	14
Std Micro	19.5	20.2	20		19.90	0.36	19.5	20.2
Field Micro	18	14	16.5		16.17	2.02	14	18
Speedy	24	24.1	24.1		24.07	0.06	24	24.1
SP					Average	ST Dev		
Lab Oven	4.44	4.61	4.35		4.47	0.13	4.35	4.61
Gas Oven	4.4	3	3.6		3.67	0.70	3	4.4
Mois Anal	3.68	3	4.21	3.74	3.66	0.50	3	4.21
Std Micro	5.2	5	4.5		4.90	0.36	4.5	5.2
Field Micro	3.1	4.3	4.9		4.10	0.92	3.1	4.9
Speedy	6.2	6.2	6.3		6.23	0.06	6.2	6.3
ML (2)					Average	ST Dev		
Lab Oven	12.64	11.38	12.76		12.26	0.76	11.38	12.76
Gas Oven	13.8	8.4	13.8		12.00	3.12	8.4	13.8
Mois Anal	10.5	10	10.34	10.49	10.33	0.23	10	10.5
Std Micro	13.1	13.4	13.2		13.23	0.15	13.1	13.4
Field Micro	11.5	11.6	13.1		12.07	0.90	11.5	13.1
Speedy		18.2	16.3		17.25	1.34	16.3	18.2
SP-SC					Average	ST Dev		
Lab Oven	7.47	5.56	8.3		7.11	1.41	5.56	8.3
Gas Oven	8.5	9.3	8		8.60	0.66	8	9.3
Mois Anal	7.55	7	7.24	7.09	7.22	0.24	7	7.55
Std Micro	5.8	8.6	7		7.13	1.40	5.8	8.6
Field Micro	7.8	8.1	8.2		8.03	0.21	7.8	8.2
Speedy	12.1	14.1	12.3		12.83	1.10	12.1	14.1
SM					Average	ST Dev		
Lab Oven	8.51	7.42	8.79		8.24	0.72	7.42	8.79
Gas Oven	8.1	7.1	7.3		7.50	0.53	7.1	8.1
Mois Anal	9.43	9	9.06	8.89	9.10	0.23	9	9.43
Std Micro	9.3	15.9	11.8		12.33	3.33	9.3	15.9
Field Micro	5.9	7.8	10.2		7.97	2.15	5.9	10.2
Speedy	15	16	16.3		15.77	0.68	15	16.3
GP-GM					Average	ST Dev		
Lab Oven	2.88	2.41	3.32		2.87	0.46	2.41	3.32
Gas Oven	3.4	4.5	2.6		3.50	0.95	2.6	4.5
Mois Anal	2.9	3	2.97	2.88	2.94	0.06	2.9	3
Std Micro	4	3.6	3.6		3.73	0.23	3.6	4
Field Micro	2	3.7	3		2.90	0.85	2	3.7
Speedy	4.1	4	4.2		4.10	0.10	4	4.2
CH					Average	ST Dev		
Lab Oven	33.05	34.15	32.45		33.22	0.86	32.45	34.15
Gas Oven	33.7	31.4	34.4		33.17	1.57	31.4	34.4
Mois Anal	23.42	22	22.28	21.45	22.29	0.83	22	23.42
Std Micro	37.1	37.6	37.4		37.37	0.25	37.1	37.6
Field Micro	31.6	29.6	31.4		30.87	1.10	29.6	31.6
Speedy	Invalid	Invalid	Invalid	Invalid				

Table A2. Soil density gauge (SDG) moisture content (%).

CH			ML (1)			ML (2)			SP		
SDG	SCG Corr	Lab	SDG	SCG Corr	Lab	SDG	SCG Corr	Lab	SDG	SCG Corr	Lab
22.3	30.46	30.46	10	17.99	17.99	3.7	12.15	12.15	0.2	3.58	3.58
21.8	29.96	29.91	8	15.99	16.31	3.7	12.15	12.63	1.5	4.88	4.87
22.3	30.46	26.39	6.9	14.89	15.43	2.9	11.35	5.58	0.1	3.48	3.85
22.4	30.56	34.06	6	13.99	13.98	-1.1	7.35	9.49	1.1	4.48	8.63
22	30.16	27.84	9.8	17.79	18.8	3.5	11.95	12.42	3.2	6.58	4.57
21.3	29.46	27.04	9.1	17.09	17.25	2.1	10.55	11.68	2.4	5.78	4.68
21.9	30.06	26.64	8.6	16.59	16.34	3.4	11.85	11.55	1.9	5.28	4.56
21.5	29.66	36	6.2	14.19	15.3	2	10.45	12.06	1.1	4.48	4.44
21.8	29.96	28.07	6.8	14.79	14.85	-0.5	7.95	9.25	-0.1	3.28	3.53
22.1	30.26	28.19	12	19.99	21.3	4.2	12.65	11.85	2.6	5.98	5.04
21.1	29.26	26.58	9.4	17.39	17.26	2.5	10.95	11.32	2.6	5.98	5.22
22.1	30.26	31.34	7.8	15.79	16.97	3.1	11.55	10.68	3.1	6.48	5.02
22.2	30.36	29.25	6	13.99	13.29	-0.7	7.75	10.81	1.7	5.08	4.74
21.8	29.96	25.71	6.7	14.69	14.66	-1.8	6.65	9.66	1.4	4.78	4.72
22.5	30.66	25.54	10.4	18.39	20.02	4.1	12.55	12.93	3.5	6.88	5.2
22.2	30.36	27.03	8.2	16.19	17.89	4.1	12.55	12.72	1.6	4.98	5.37
			8.2	16.19	16.8	0.5	8.95	10.6	2.1	5.48	4.68
			5.2	13.19	16.22	-1.1	7.35	10.68	2.1	5.48	5.22
			5.7	13.69	13.36	-2.1	6.35	8.43	1	4.38	4.77
			11.6	19.59	22.08	3.4	11.85	12.94	1	4.38	5.82

SP-SC			SM			GP-GM		
SDG	SCG Corr	Lab	SDG	SCG Corr	Lab	SDG	SCG Corr	Lab
19.9	6.96	6.96	19	3.26	3.26	1.5	5.9	5.9
19.6	6.66	6.52	19.1	3.36	3.15	1	5.4	10.67
19.3	6.36	6.99	19.3	3.56	2.9	-0.1	4.3	8.78
19.3	6.36	5.36	19.3	3.56	2.58	0	4.4	8.99
19.5	6.56	8.02	19.3	3.56	3.57	1.2	5.6	7.35
19.9	6.96	7.62	19	3.26	3.8	0.4	4.8	7.89
19.7	6.76	6.32	19.3	3.56	2.6	0.2	4.6	8.8
19.3	6.36	5.24	19.3	3.56	2.98	-0.3	4.1	8.59
19.4	6.46	6.32	19.4	3.66	2.09	2.5	6.9	8.89
19.8	6.86	7.17	19.3	3.56	3.19	1.5	5.9	10.98
19.9	6.96	6.53	19.3	3.56	2.11	1	5.4	9.14
18.7	5.76	7.96	19.2	3.46	3.08	0.4	4.8	8.75
19.3	6.36	6.93	19.2	3.46	3.19	2.4	6.8	10.27
19.2	6.26	5.14	19.3	3.56	2.28	1.6	6	12.14
19.8	6.86	7.97	19.3	3.56	4.51	1	5.4	9.07
19.9	6.96	4.68	18.9	3.16	3.33	-0.1	4.3	8.75
19.7	6.76	7.66	19.2	3.46	2.89			
19.3	6.36	6.88	19.3	3.56	3.02			
19.4	6.46	5.17	19.3	3.56	2.55			
20.2	7.26	7.36	19.2	3.46	3.17			

Table A3. Nuclear density gauge (NDG) moisture content (%).

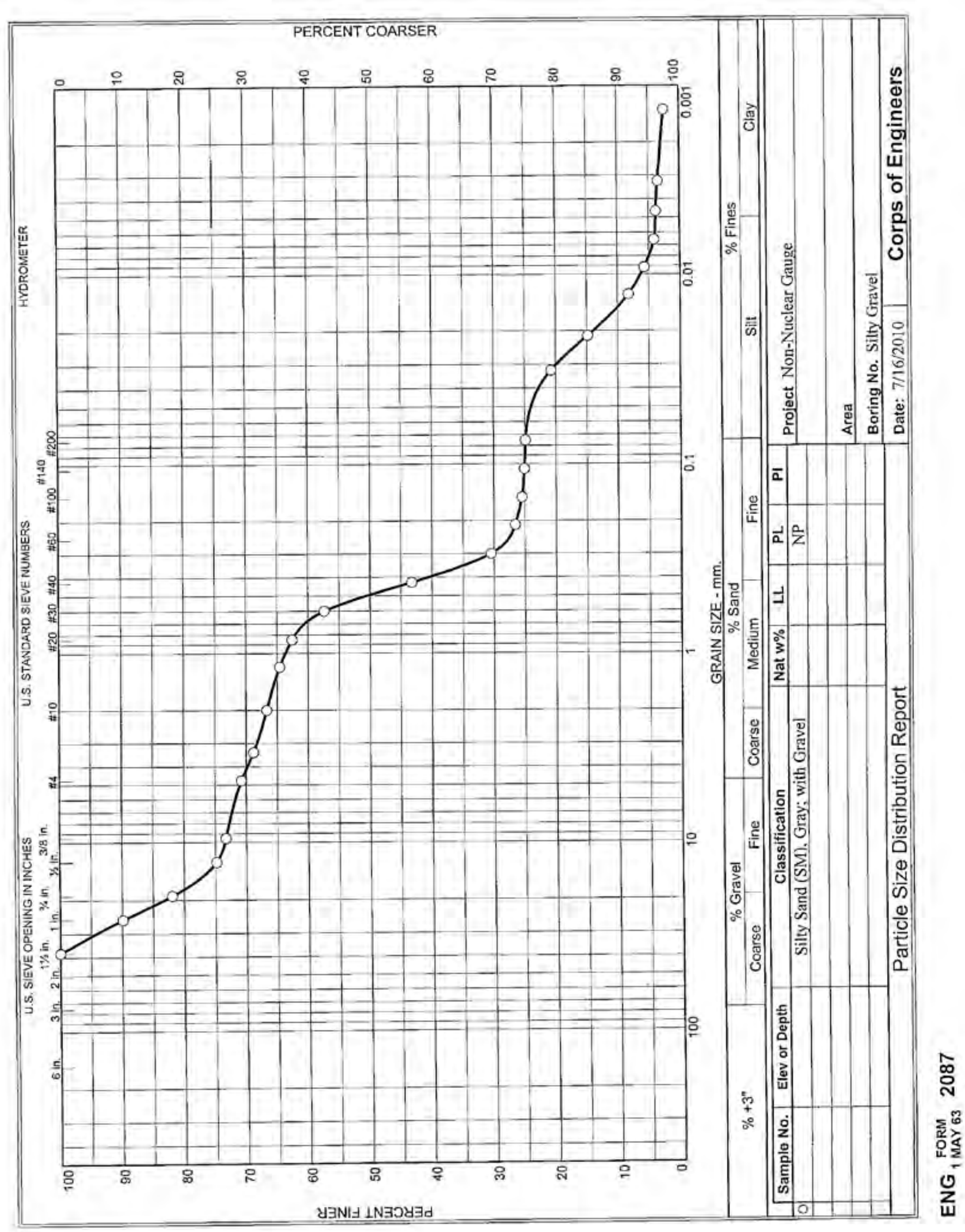
CH		ML(1)		ML(2)		SP		SP-SC		SM		GP-GM	
NG	Lab	NG	Lab	NG	Lab	NG	Lab	NG	Lab	NG	Lab	NG	Lab
27.55	26.95	15.45	18.49	10.2	11.56	3.8	4.26	6.35	5.38	2.8	2.97	7.05	6.67
26.4	26.69	15.3	18.15	11.05	10.88	3.8	3.78	6.75	7.07	3.3	3.16	7.15	10.37
26.5	26.24	14.9	16.31	9.65	10.23	3.55	5.25	6.4	6.48	2.55	2.55	6.8	7.28
27.1	26.77	13.6	15.19	8.5	9.79	3.6	4.68	5.55	4.89	3.3	2.72	6.25	7.11
28.55	26.79	16.9	19.93	10.5	12.24	5.05	5.50	8.2	8.93	3.2	3.4	6.75	7.47
27.25	27.65	15.35	17.08	10.45	14.19	3.4	4.83	6.3	7.74	3.15	3.06	6.75	10.39
25.7	25.98	13.95	15.85	10.4	11.02	3.55	4.32	6.45	6.55	2.45	2.24	6.5	8.16
26.8	27.56	13.4	16.2	10.4	12.17	3.95	4.71	5.8	5.77	2.8	2.89	6.25	7.77
27.1	27.01	13.45	15.91	9.45	9.73	3.45	4.84	6	5.94	2.95	3.31	8.95	8.38
26.4	34.61	19.05	21.25	11.15	13.48	4.95	4.72	8	8.45	3.35	3.49	9.05	9.42
25.15	27.34	14.3	17.05	10.85	12.08	4.05	5.23	6.65	6.91	3.1	3.12	8.05	8.3
25.95	32.59	14.4	16.33	10.45	10.53	3.65	4.7	5.8	6.76	2.7	2.4	7.75	8.93
27.75	26.94	13	16.25	10.5	10.42	3.95	5.17	5.3	5.84	2.75	3.13	8.1	8.96
26.9	25.88	13.45	14.81	9.45	10.9	3.9	5.25	6.05	6.16	3.15	3.16	8.85	7.15
26.15	27.33	17.75	19.6	11.2	12.23	5.1	5.43	7.9	7.85	2.95	3.13	7.25	10.59
25.5	25.1	14.8	17.04	11.6	12.81	3.95	4.92	6.25	7.13	2.35	2.68	7.6	7.77
		14.2	15.33	10.5	11.02	3.75	4.94	5.85	5.53	2.45	2.8		
		13.15	16.29	10.4	12.15	5.4	6.19	6.25	7.34	2.5	2.6		
		13.65	15.99	10.1	10.22			7.7	8.53	2.9	3.55		
		18.15	21.15	11.65	11.51								

Table A4. Electronic density gauge (EDG) moisture content (%).

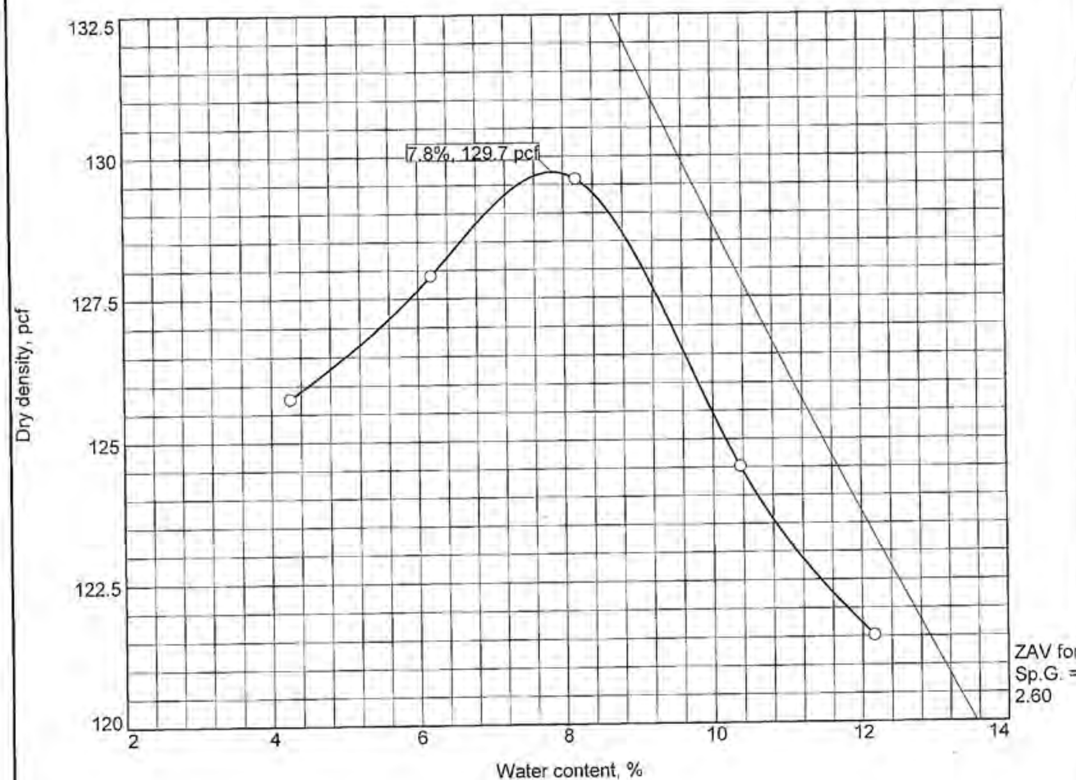
CH		ML		SM		SP		SC		GW		GM	
EDG	Lab	EDG	Lab	EDG	Lab	EDG	Lab	EDG	Lab	EDG	Lab	EDG	Lab
28.7	27.69	13.4	17.95	9.9	12.5	4.3	3.62	8.5	7.88	2.9	3.79	7.6	10.06
25.7	28.22	14.7	18.24	12.6	11.59	4.4	4.11	7.7	7.1	2.9	3.54	7.4	8.5
26.1	26.1	17	17.18	12.6	11.21	4.4	3.95	9	6.01	2.9	3.51	7.6	5.73
36.3	25.47	13.1	17.7	12.2	10.34	1.3	4.54	8.5	4.57	3.2	3.35	7.5	8.5
25.5	26.59	15	18.78	13.1	13.1	10.4	5.74	8.1	9.07	4.9	2.97	7.3	10.33
23.1	26.34	11.2	17.25	9.9	11.77	9.1	5.17	8.6	6.86	3.1	3.73	7.2	8.73
34	27.17	15.1	15.77	12.6	11.41	5.1	4.9	7.8	7.38	2.5	3.04	7.4	6.86
31.7	23.56	18.3	16.82	11.6	10.91	3.6	4.89	8.5	5.53	3	3.68	7.5	7.77
28.7	25.77	12.2	16.8	12	10.85	5.3	4.81	8.6	5.2	2.9	2.92	8.5	10.99
26.7	27.74	14.8	19.73	12.3	13.67	8.9	5.75	8.1	8.97	3.7	3.32	7.3	11.13
25.6	25.86	12	17.79	9.5	9.63	3.6	5.06	7.9	7.01	2.7	3.79	7.4	6.9
34.1	26.46	19.7	17.08	11.9	10.68	5.1	5.44	8	7.1	2.7	3.3	7.6	9.46
32.4	27.04	19.8	17.74	11.8	10.65	5.7	4.85	8.1	5.49	2.6	3.36	8.5	10.78
31.8	27.3	13.2	16.37	11.3	10.68	6.7	5.15	8.5	5.67	3.9	3.26	8.4	11.25
33	28.58	14.2	18.79	13	12.47	14.1	6.06	7.8	9.21	3.4	2.89	7.7	8.58
25.5	26.19	11.6	17.85	9.7	12.95	4.3	5.23	7.7	6.57	2.2	2.99	7.7	9.36
		16.8	16.61	12.6	12.19	3.8	5.21	8	6.16	2.4	3.06		
		23.6	17.23	12.1	10.49	6.1	5.03	7.7	5.65	2.7	3.12		
		12.5	16.02	12.1	10.47	0.4	4.77	8.5	5.87	3.4	2.64		
		15.9	22.45	12.7	11.96	10.5	4.64	8	8.84	4.8	3.39		

Appendix B: Soil Data

Silty-Gravel (SM)



COMPACTION TEST REPORT



Test specification: ASTM D 698-00a Method C Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/4 in.	% < No.200
	USCS	AASHTO						
			0.7	2.60 est.	NP		18.1	24.9

TEST RESULTS

Maximum dry density = 129.7 pcf

Optimum moisture = 7.8 %

MATERIAL DESCRIPTION

Silty Sand (SM), Gray; with Gravel

Project No. MD2210 **Client:** Earnest Barney

Project: Non-nuclear

○ **Source of Sample:** Silty Gravel

Remarks:

Specific Gravity was estimated.

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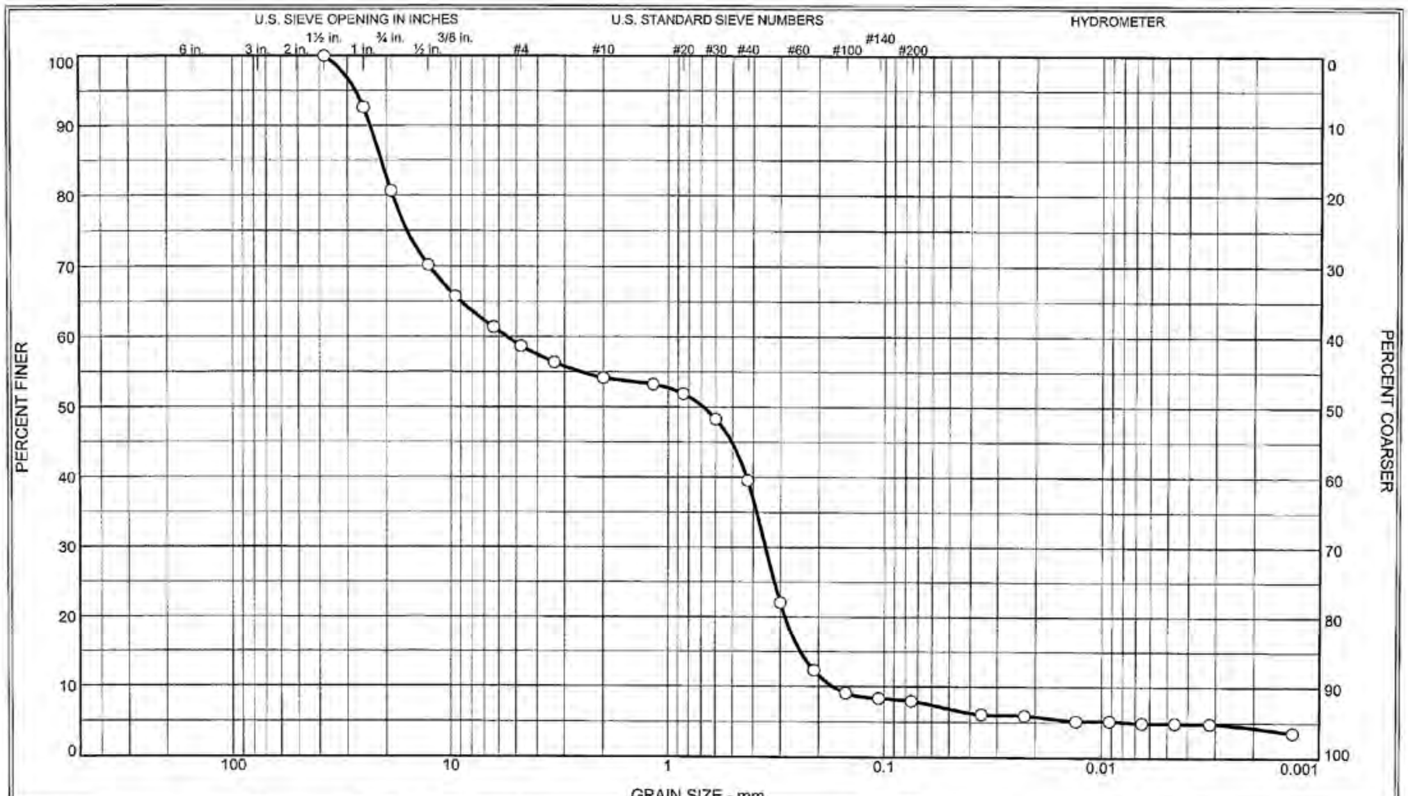
Figure

Tested By: CEC

Clay-Gravel (SP-SC)



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

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
O			Sand (SP-SC), Reddish Brown; with Clay and Gravel		23	13	10

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Area

Boring No. Clay Gravel

Date: 5/17/2010

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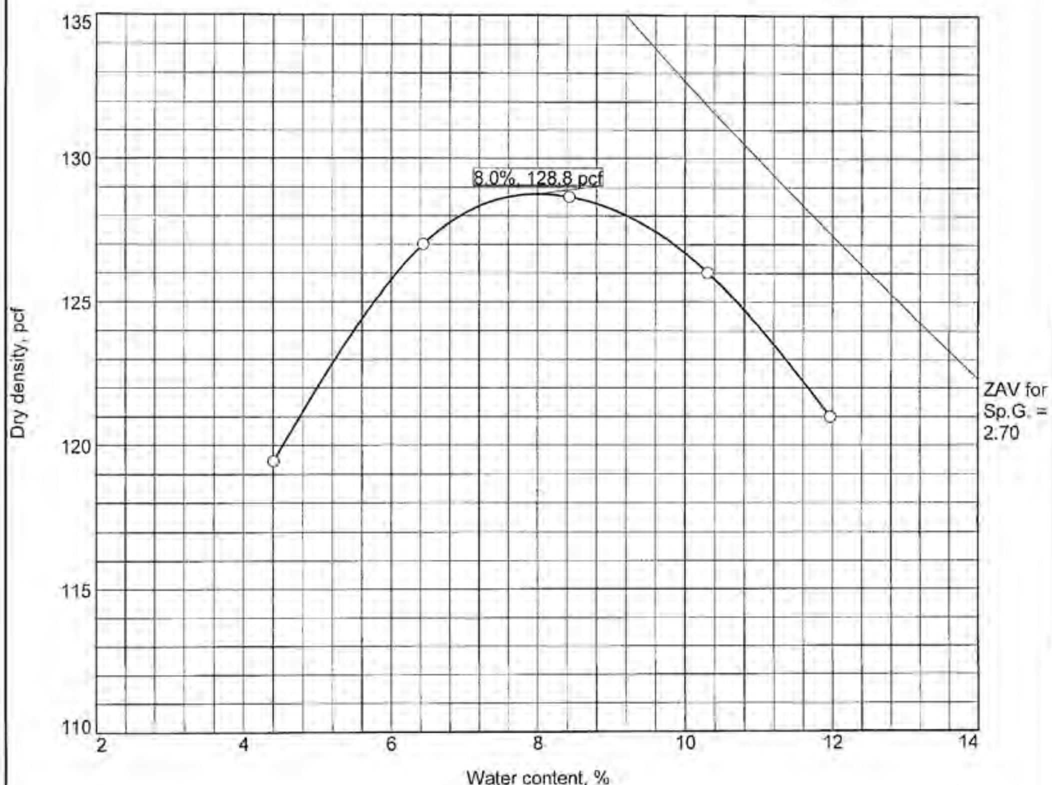


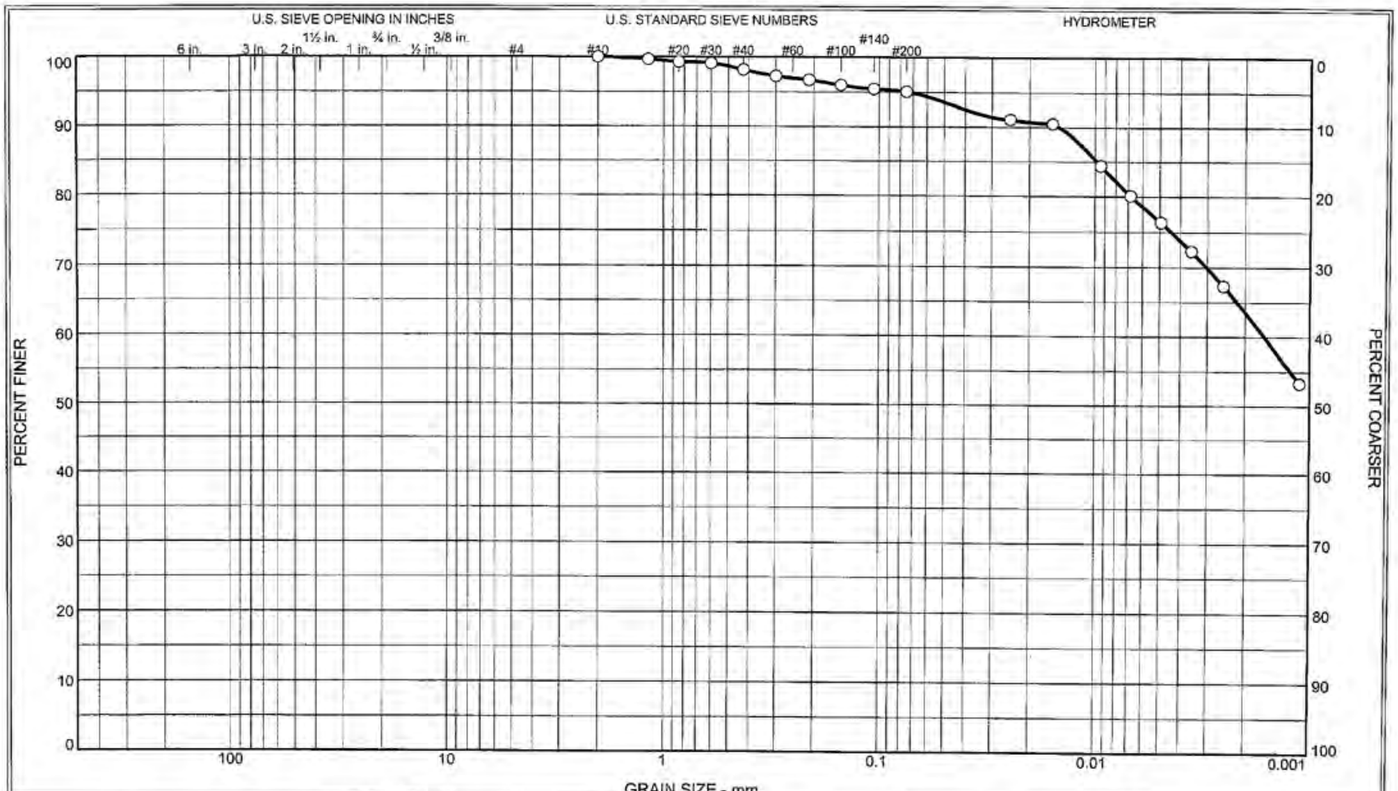
Test specification: ASTM D 698-00a Method B Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > 3/8 in.	% < No.200
	USCS	AASHTO						
			0.4	2.70 EST.	23	13	41.3	8.0

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 128.8 pcf Optimum moisture = 8.0 %	SAND (SP-SC), REDISH BROWN WITH CLAY AND SAND
Project No. MD1910 **Client:** EARNEST BARNEY **Project:** NON-NUCLEAR GAGE STUDY ○ **Source of Sample:** Clay Gravel	**Remarks:**
Corps of Engineers **Engineer Research Development Center**	**Figure**

Tested By: CEC

Buckshot Clay (CH)



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

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

Project Non-Nuclear Gauge Study

Area

Boring No. Buckshot

Date: 5/17/2010

Particle Size Distribution Report

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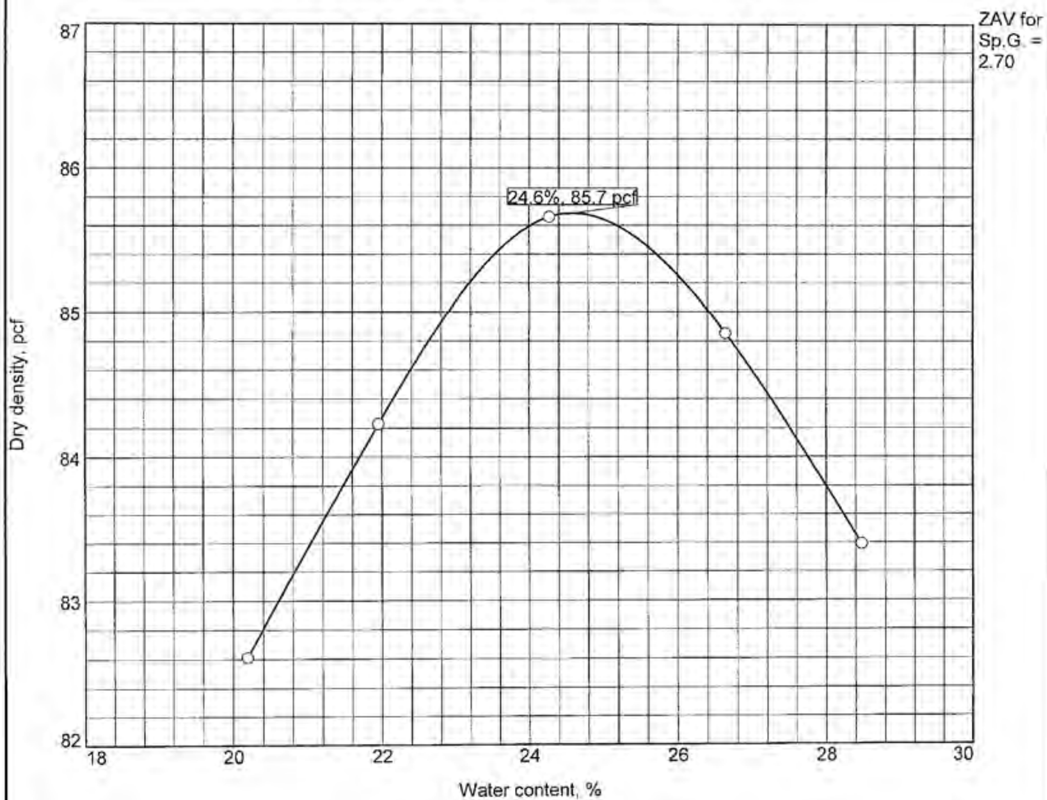
COMPACTION TEST REPORT



Test specification: ASTM D 698-07 Method A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
			2.7	2.70 EST.	73	24	0.0	95.1

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 85.7 pcf Optimum moisture = 24.6 %	CLAY (CH), GRAY

Project No. MD1910 **Client:** EARNEST BARNEY
Project: NON-NUCLEAR GAGE STUDY

○ **Source of Sample:** CLAY

Remarks:

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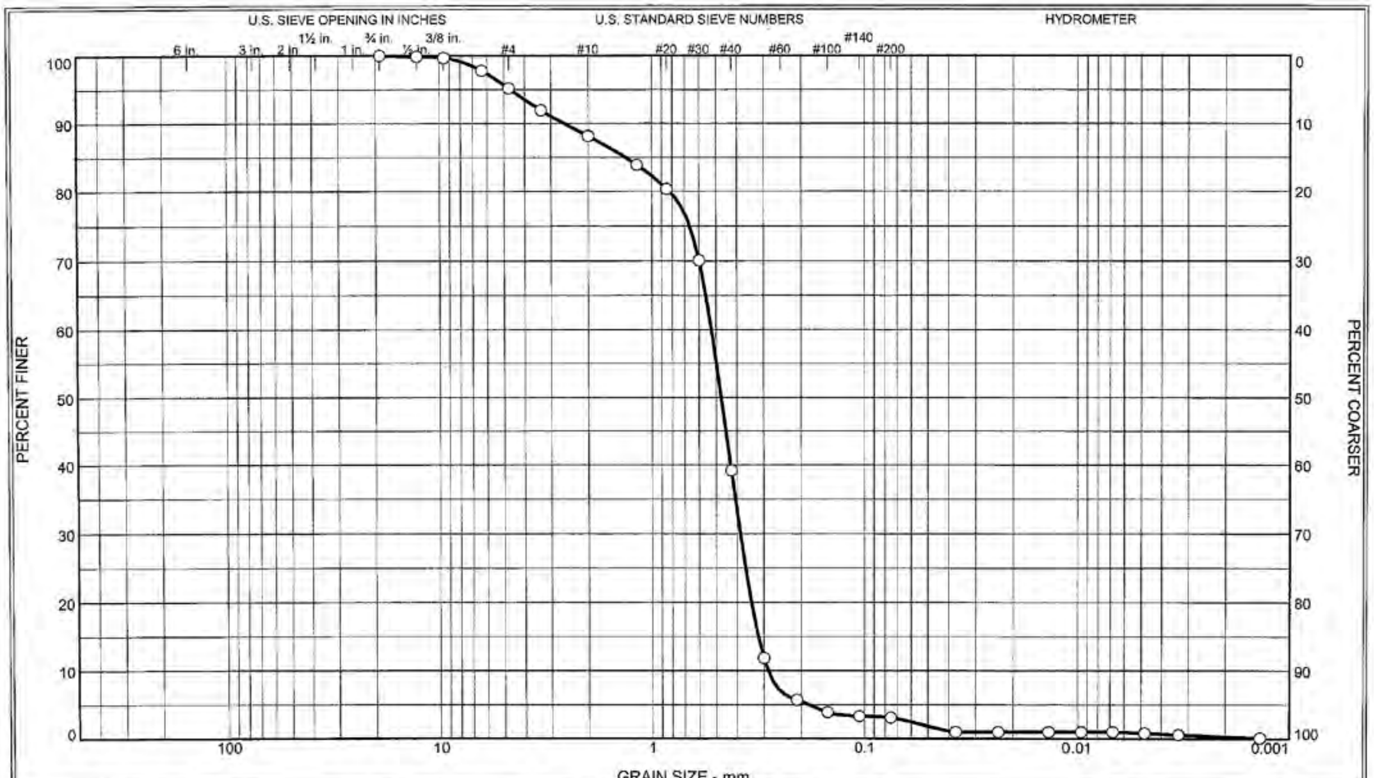
Figure

Tested By: CEC

Concrete Sand (SP)



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

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○			Sand (SP), Brown				

Project Non-Nuclear Gauge Study

Area

Boring No. Sand

Date: 5/17/2010

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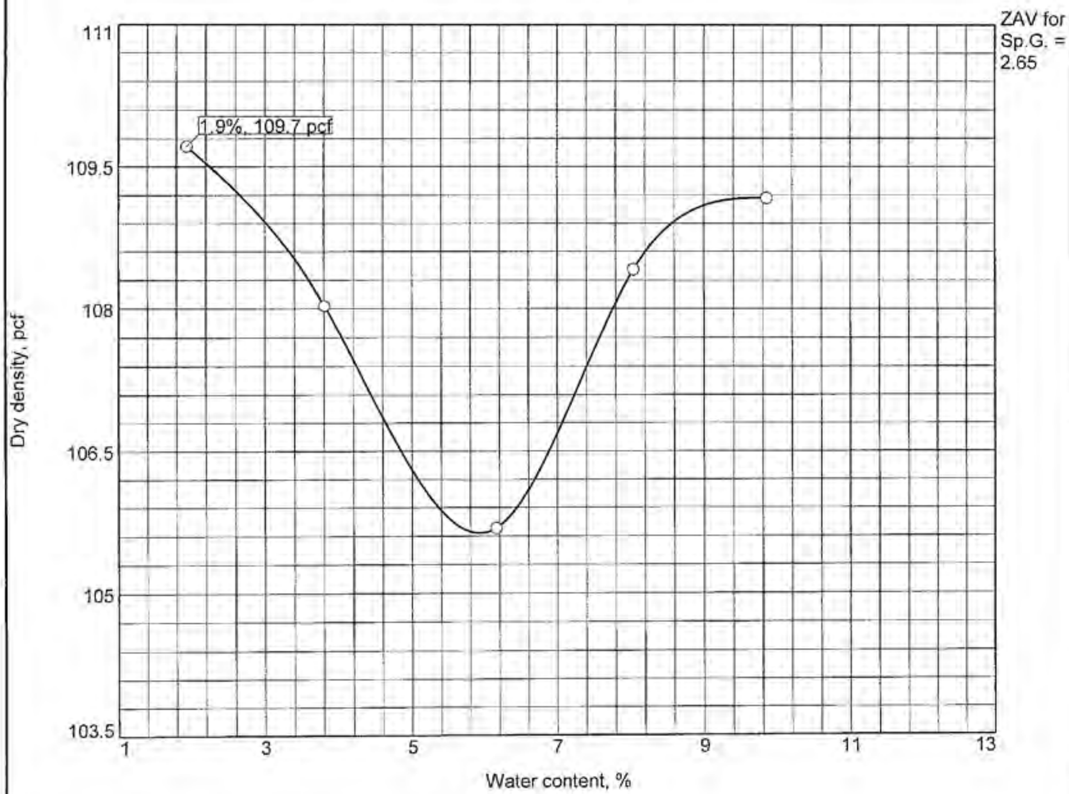
COMPACTION TEST REPORT



Test specification: ASTM D 698-00a Method A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
	SP		0.4	2.65	NP		4.9	3.1

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 109.7 pcf Optimum moisture = 1.9 %	SAND (SP), BROWN

Project No. MD1910 **Client:** EARNEST BARNEY
Project: NON-NUCLEAR GAGE STUDY

○ **Source of Sample:** SAND

Remarks:
SOIL SHIFTED DURING COMPACTION
GRAVITY EST.

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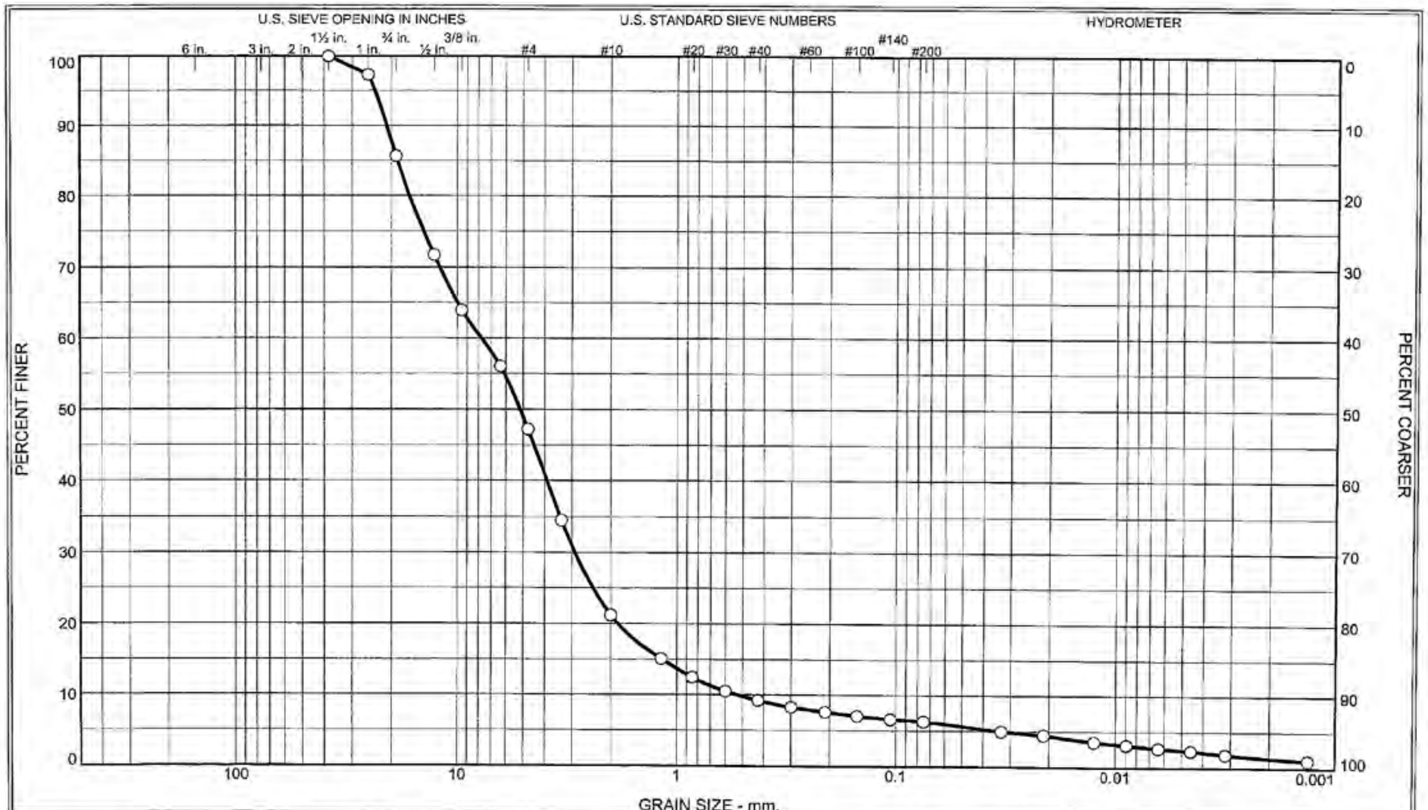
Figure

Tested By: CEC

Crushed Limestone (GP-GM)



% +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), Gray; with Silt and Sand		15	12	3

Particle Size Distribution Report

Project Non-Nuclear Gauge Study

Area

Boring No. Limestone

Date: 5/18/2010

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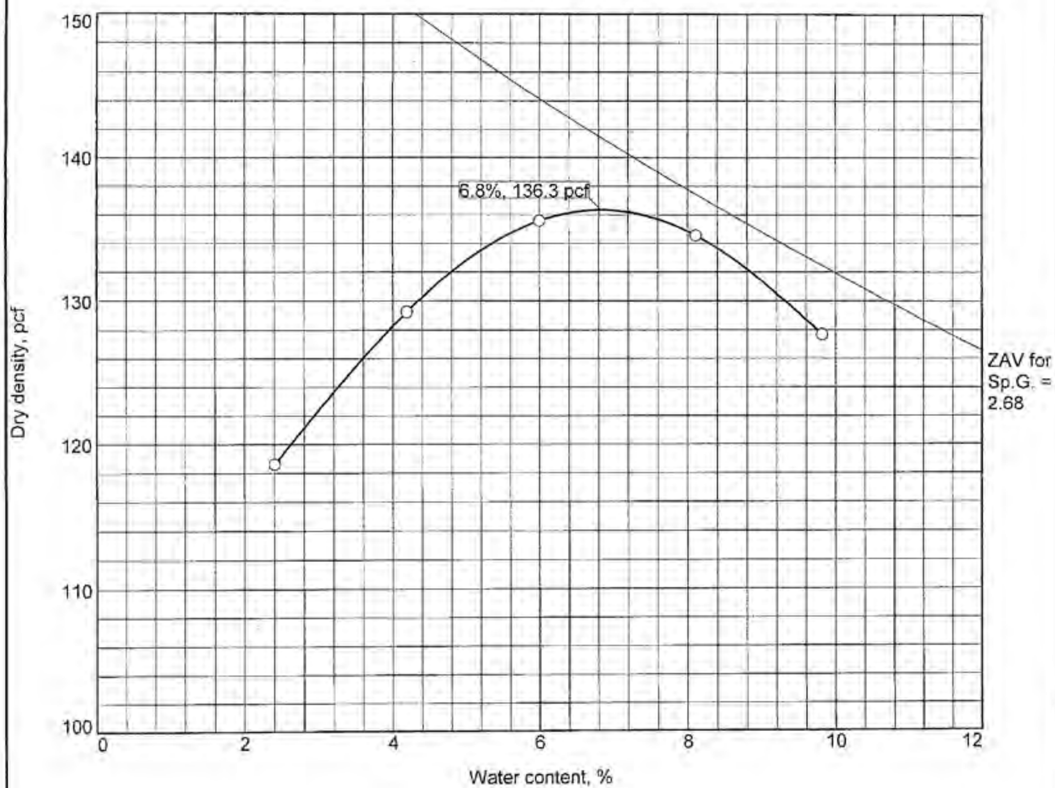
COMPACTION TEST REPORT



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						
			0.2	2.68 EST.	15	12	52.8	6.3

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 136.3 pcf Optimum moisture = 6.8 %	GRAVEL (GW), GRAY WITH SAND

Project No. MD1910 **Client:** EARNEST BARNEY

Project: NON-NUCLEAR GAGE STUDY

○ **Source of Sample:** CRUSH LIMESTONE

Remarks:

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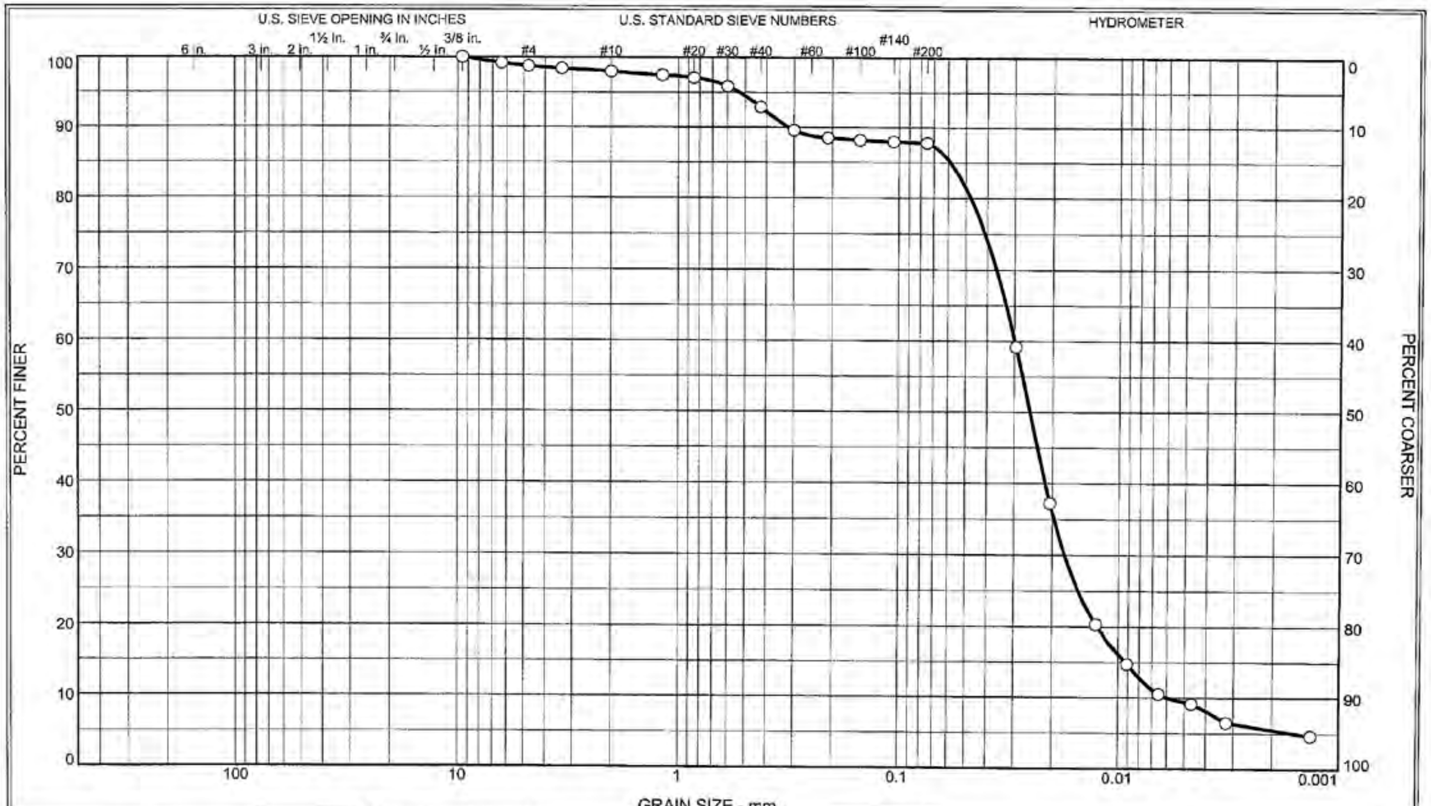
Figure

Tested By: CEC

Vicksburg Loess (ML (1))



% +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			NP	

Project Non-Nuclear Gauge Study

Area

Boring No. Silt

Particle Size Distribution Report

Date: 5/17/2010

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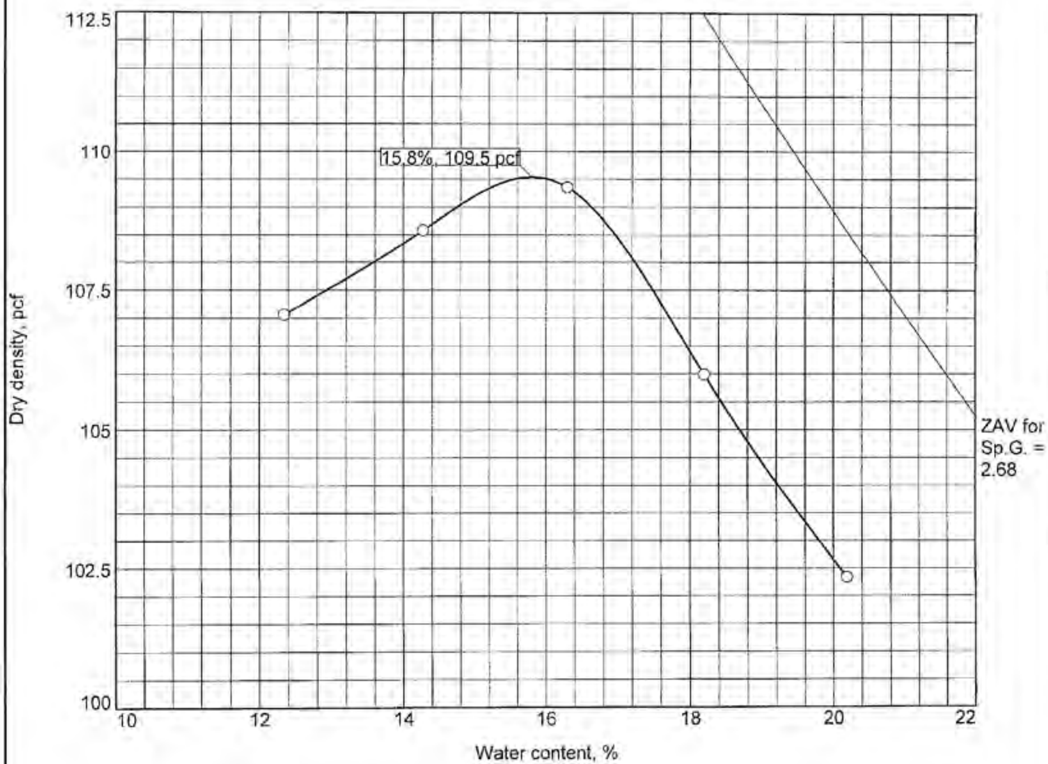
COMPACTION TEST REPORT



Test specification: ASTM D 698-00a Method A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
			1.0	2.68 EST.	NP		1.2	87.7

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 109.5 pcf Optimum moisture = 15.8 %	SILT (ML), BROWN

Project No. MD1910 **Client:** EARNEST BARNEY

Project: NON-NUCLEAR GAGE STUDY

○ **Source of Sample:** SILT

Remarks:

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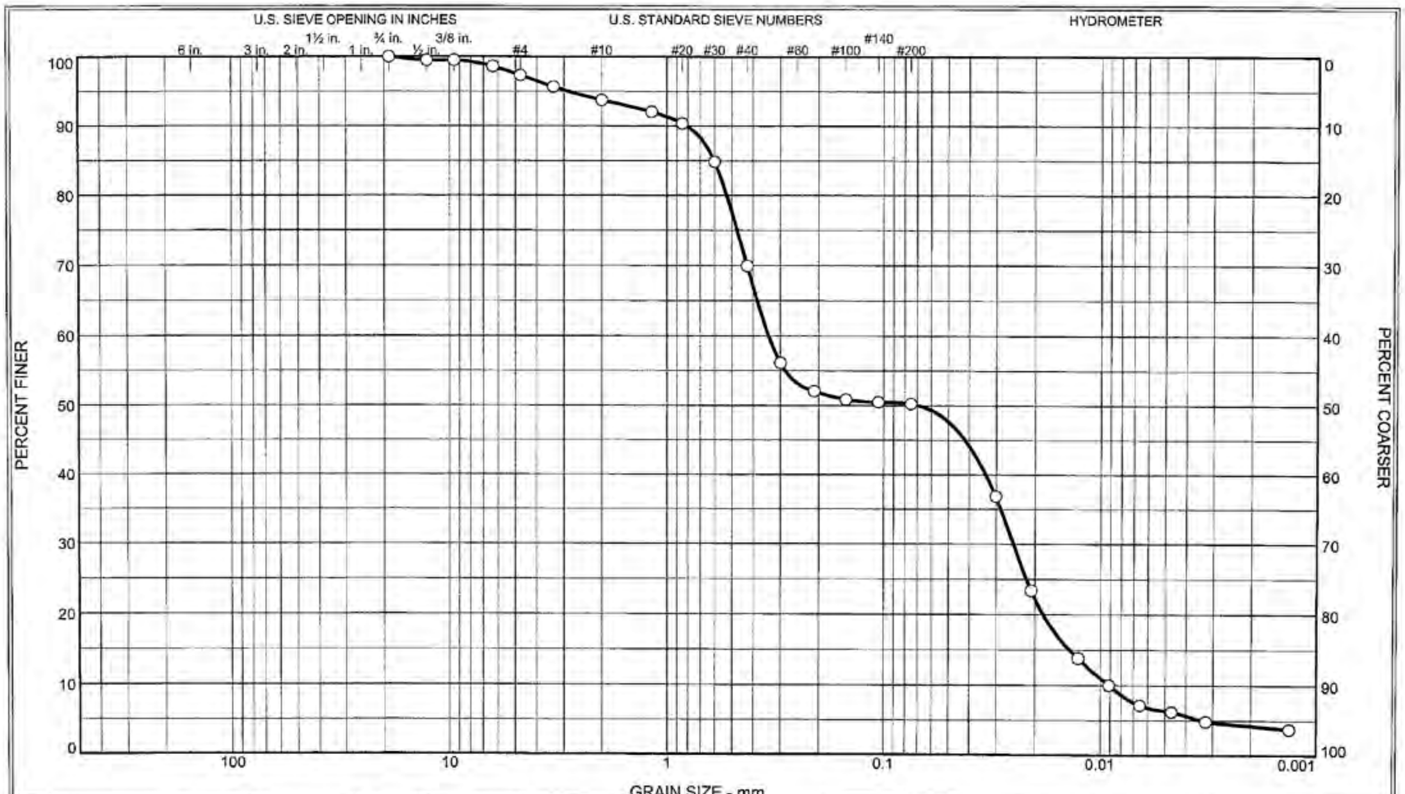
Figure

Tested By: CEC

Silty-Sand (ML (2))



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

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

Project Non-Nuclear Gauge Study

Area

Boring No. Silty Sand

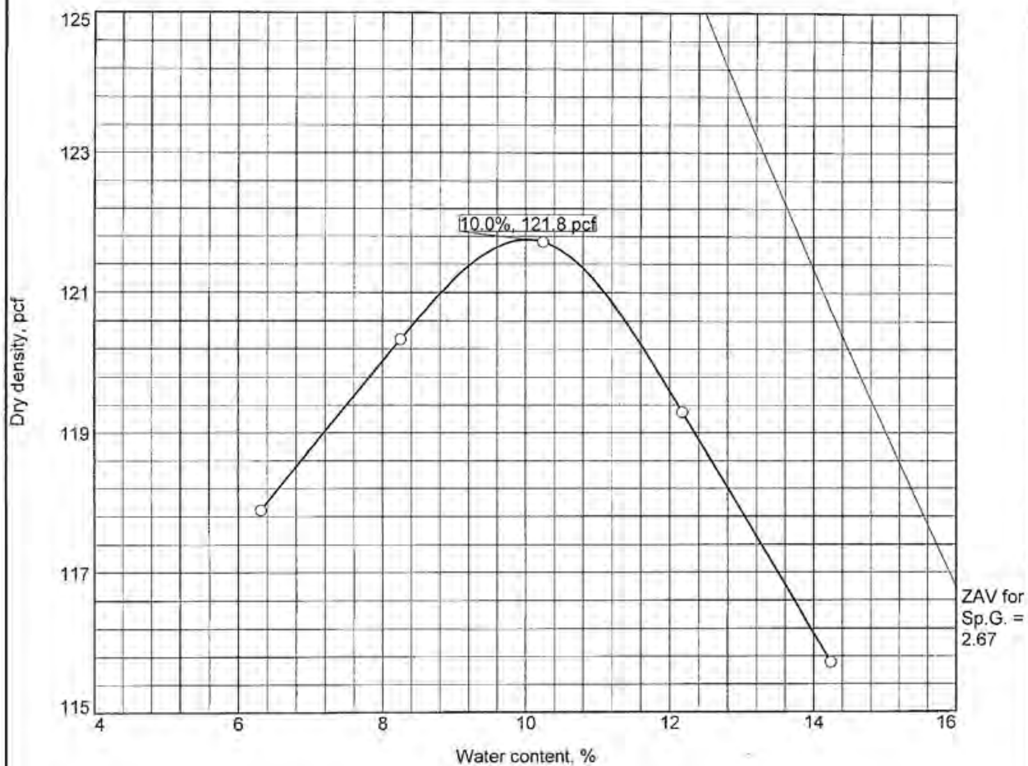
Date: 5/17/2010

Particle Size Distribution Report

Corps of Engineers

ENG FORM 1 MAY 63 2087

COMPACTION TEST REPORT



Test specification: ASTM D 698-00a Method A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > #4	% < No.200
	USCS	AASHTO						
			0.4	2.67 EST.	NP		2.7	50.3

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 121.8 pcf Optimum moisture = 10.0 %	SANDY SILT (ML), BROWN
Project No. MD1910 **Client:** EARNEST BARNEY **Project:** NON-NUCLEAR GAGE STUDY ○ **Source of Sample:** SILTY SAND	**Remarks:**
Corps of Engineers **Engineer Research Development Center**	Figure

Tested By: CEC

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14. ABSTRACT
During the period May 2010-August 2010, researchers of the U.S. Army Engineer Research and Development Center in Vicksburg, MS tested the effectiveness of various devices in determining the moisture content of soil for horizontal construction. These tests were conducted to determine a usable alternative to the nuclear soil density gauge. The accuracy and precision of the different testing devices was compared to the standard laboratory oven soil moisture determination. The devices and techniques tested are grouped into four broad families: gravimetric, electrical, chemical, and nuclear. Gravimetric devices and techniques tested were the laboratory oven, gas stove and fry pan, standard microwave oven, battery-powered field microwave oven, and moisture analyzer. Electrical devices tested were the electrical density gauge, and the soil density gauge. The chemical device tested was the Speedy Calcium Carbide soil moisture test. The nuclear device tested was the nuclear density gauge, included for comparison purposes. This investigation consisted of full-scale construction of seven soils representing a range of materials encountered in operational construction activities. Soils ranged from fine-grained silts and clays to coarse-grained gravels and crushed limestone. This testing showed that the devices showing the optimal combination of precision and accuracy compared to the laboratory oven are the soil density gauge and the gas stove with fry pan technique. Results of the moisture content tests are presented and include (a) comparison of the individual moisture contents to the results obtained using the standard laboratory oven, and (b) ranking of devices versus laboratory oven. Results will be used to provide further guidance for selection of appropriate devices for field determination of soil moisture content.

15. SUBJECT TERMS

	microwave
Soil moisture content	oven
non-nuclear	electrical

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UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		62	