EVALUATION OF NON-NUCLEAR SOIL MOISTURE AND DENSITY DEVICES FOR FIELD QUALITY CONTROL

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Abstract

When constructing new transportation infrastructure or maintaining current infrastructure systems, achieving sufficient soil strength is critical to a successful construction effort. Currently, soil design specifications are given in terms of a minimum soil density and a specified range of soil moisture content. Quality control is achieved by monitoring the soil density and moisture content throughout the construction process. The Nuclear Density Gauge (NDG) is the most commonly employed device to determine soil density and moisture content due to its ease of use, speed of readings, and reliability of results. However, due to potential safety hazards and rigorous user certification requirements, many agencies are seeking to replace the NDG. This paper focuses on a portion of a much larger study that compares a wide range of compaction control devices, looking at the performance of devices measuring only density and moisture content. Several new, commercially available alternatives for measuring soil density were tested on a variety of soil types and conditions to determine the most consistent, well-performing device. For the same soil types and conditions, several devices and techniques for determining soil moisture content were also tested. The combination of the TransTech Soil Density Gauge and the heated fry-pan/open flame field moisture content techniques represented the best alternative to the NDG.

Background

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 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 density gauge (NDG) (1), with accepted alternatives being the sand cone for density and a laboratory oven for moisture content determination. Because of the regulatory and safety burdens required for using the NDG, various agencies tasked with QC for horizontal construction including the Federal Highway Administration, and several state departments of transportation (DOTs), have investigated available alternatives to the NDG. Recently, several large scale investigations were performed, comparing volume replacement (2, 3) and electrical methods based on new technologies including Time Domain Reflectometery (TDR) and Dielectrics (DI) (4-6). These devices are able to provide a measured density and moisture content in the field without the regulatory burden imposed by use of the nuclear gauge. Many other investigations have been performed to develop modulus-based devices for QC applications (3, 7-10). Often these investigations are funded by an individual state DOT, with data collection focused on the native soils of the sponsoring state. Many of these devices are able to provide reasonable correlations for the soil of interest (3). Even after this research, there remains a demand for a device that can measure soil density and moisture content comparable to the NDG over a broad range of soil types.

Development of soil moisture content devices has been episodic with new techniques developed followed by a long lull in product development. One of the first techniques developed was the oven drying method (11). This method is still viewed as the reference standard for determining moisture content of soils however the main drawback to using the laboratory oven is the long time required to return results. Chemical methods were then developed, such as the calcium carbide method, to provide expedient field moisture determination. The next progression in measurement of moisture content were the developments of the NDG (1) followed by the microwave oven moisture content test (12). While producing results faster than the standard oven, the microwave oven test still requires removal of the soil from the field and a power supply for the microwave, capabilities often unavailable in field applications. The most recent developments, TDR- and DI-based devices mentioned previously, can correlate soil moisture content with the electrical properties of the soil (4,6).

Methodology

To provide a broad evaluation of the most successful commercially available equipment, eleven compaction measurement devices and eight moisture-determining devices were identified. For compaction determination, three were based on electrical methods, three on volume replacement methods, and five on stiffness/impact methods. For moisture content determination, four were based on direct heat (gravimetric), three on electronic, and one chemical. All compaction devices were referenced to the wet density obtained using the NDG, that being the desired replacement device; moisture content, and subsequent dry density, were referenced to the laboratory oven. Tables 1 and 2 list the selected density and moisture content devices, respectively, and their associated categories. This exercise investigated their effectiveness on seven soil types to approximate typical soils encountered during horizontal construction efforts for which the NDG serves an important role in QC. Table 3 presents a summary of the soils selected for testing and their associated engineering properties.

The research involved constructing a series of outdoor test sections to approximate real-world test conditions, each 50-ft (15.2m) long by 12-ft (3.7m) wide, consisting of three 6-in.(15.2cm)-thick compacted lifts such that the final test section was 18-in.(45.7cm)- thick (Figures 1, 2). The construction procedure provided a suitable thickness of uniform soil above the natural subgrade to ensure that this layer did not adversely influence the results of the various instruments tested. The first lift placed was approximately two roller widths across, about 12 ft (3.7m), to provide a wide enough base to create a top layer at least 6-ft (1.8m) across. Eight coverages of a CAT CS-443 roller were applied to the first, or bottom, lift and the second, or intermediate, lift. On the third, or top lift, a single proof roll was performed across the entire width of the section tested as coverage number 1, with subsequent coverages being applied as noted below.

For data collection, each soil test section was divided into four test regions, as shown in Figure 2. These regions were contained within the central 40-ft (12.2m) of the test item (Figure 3). Each test region was 10-ft (3m) long and 4-ft(1.2m) wide. Each device was used in each of the four regions to generate four replicate readings to accommodate inherent variability in the soil and compaction process. Oven-dried moisture contents were taken at each location where a density/modulus test was performed to allow normalization of response to changing environmental conditions. Tests were conducted at coverages 1, 2, 4, and 8 to provide varying density conditions in each of the four regions. Following these tests, the test sections were soaked with a portable water sprayer and retested in a more moist condition for different field moisture content (Figure 2).

Calibration and Use of Devices

Density/Modulus Devices and Techniques

Electrical Moisture-Density Devices

The EDG and M+DI measure electrical resistance between a series of probes embedded in a soil (4). The resultant resistance is compared to a set of calibrated readings covering the range of field moisture contents and wet densities expected in the field. The SDG is a plate that rests above the soil surface and computes the impedance of the soil based on statistical factors from the frequency sweep generated during testing (6). To function in the field, each device must be calibrated to some known soil physical data. The EDG requires internal correlations to be developed between the expected field range of moisture-density conditions measured with the NDG (or some other density standard) and the resultant soil resistance. For this study, the correlation was achieved by comparing three data points in the field: at the first and the last pass of the second lift (low and high density) and on loose soil dried to the side of the test section (low moisture). The M+DI was calibrated using built-in data sets that approximated the moisture-density response in the field. A proper ASTM laboratory calibration was planned; however during field testing, the M+DI often provided null readings, especially in granular soils. Due to this, the M+DI was not further calibrated or evaluated for moisture content and since this study was undertaken, has been removed from the marketplace. The SDG was calibrated using soil index properties based on laboratory testing to provide an initial reading of the device. A corrected SDG reading (SDG-Corr) was later obtained by including a linear offset factor derived from the dry density and moisture content readings obtained from the first sand cone test and the laboratory oven test conducted on each soil type. All of these electrical devices provided the user the wet density, dry density, and moisture content of the soil, resulting in a comparative data set to the NDG.

Volume Replacement Devices

Volume replacement techniques for density determination are useful due to the lack of calibration required for use. However, these techniques are especially sensitive to the hole dug to determine the volume of removed soil. The sand cone (SC) and water balloon (WB) have been identified as the most common volume replacement devices, with the steel shot replacement (SS) being a recent military development (13). Each technique measures a weight of wet soil excavated from a hole and uses a known volume of material to fill the hole. Dividing the wet soil weight by the excavated volume provides a wet density for the soil. A sample of the wet soil is dried in an oven to obtain the moisture content. Finally, the wet density and water content are used to obtain the dry density of the soil, resulting in a comparative data set to the NDG.

Stiffness/Modulus Devices

Each of the instruments in this category returns varying responses. The DCP provides a number of hammer drops per depth of penetration (14,15). For the analysis, a summary total of hammer drops over a nominal 6-in. depth of penetration is used as the comparative value to the density. The CH returns a Clegg Index value (CIV) that corresponds to the acceleration response at the point of impact of the hammer (8). This is the value used as the comparison to density. The Zorn and Dynatest LWD devices return a deflection measurement of the plate and a back-calculated soil modulus based on an assumed Poisson's ratio. However, only the deflection was used as a comparative measure to density in this research, as the back-calculated modulus is a derived data output from the devices. The GG returns a modulus (force/area) and a stiffness (force/length), only one of which was chosen as the representative output for the device (16). After considerable analytical effort during this project, it was confirmed that no clear correlations existed between modulus/stiffness values of soil and the Proctor density-moisture relationship. This is an issue that is well documented in the literature (3,17) and is an area for continued research. Therefore, only the electrical and volume replacement devices are offered for side-by-side comparison to the NDG. Details of the modulus/stiffness observations and response data can be found in the full technical report (18).

Moisture Content Devices and Techniques

Electrical Devices

The EDG and the SDG, previously described, are the two electrical devices fully evaluated in this study.

Gravimetric Devices

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These devices consist of drying technologies including convection (laboratory oven), radiation (standard and field microwaves), and conduction from a ceramic heating element (moisture analyzer) or a gas flame burner (gas stove). The microwaves and gas burner require a series of manual measurements to be made during the drying process to determine the final constant dry mass of the soil. This technique is assisted by the use of software developed specifically for these types of drying used in the U.S. Army Engineer Research and Development Center's Rapid Soils Analysis Kit (19). The software prompts the user for mass of the soil at one minute drying increments and internally calculates the mass differential between drying times until a prescribed minimum difference is obtained. For field use, the threshold is considered as less than 1% of the total wet mass. For the associated microwave ASTM specification, the threshold is nearer to 0.1% of the total wet mass. The 1% value is used for military consideration based on an outdoor scenario in which wind and environmental conditions prevent measurement accuracy consistent enough to measure a 0.1% differential, especially with small soil specimens.

Chemical Devices

The Speedy moisture tester indirectly measures the moisture content of soil by determining the amount of acetylene gas produced by a reactant material and the free moisture in the soil. The Speedy moisture uses calcium carbide as the reactant material. The device measures the amount of acetylene gas produced by recording the pressure change in a steel vessel during the water-chemical reaction. This pressure change is then related to the mass of water and ultimately the gravimetric moisture content, assuming all free water in the soil has reacted with the calcium carbide.

Collection of Data

For all density devices tested, a soil sample was taken from the top 2 to 4 in. (5 to 10cm) of the ground surface at the point of each device measurement to normalize any data response with laboratory oven moisture content. For the electrical devices, the field moisture content allowed a comparison to be made directly to the laboratory oven. For the NDG, the wet density is assumed to be the most accurate measurement, and so the oven moisture content represented a check against this device's measured moisture and was used to calculate the dry density at each test location. The moisture content from the laboratory oven was used to calculate the dry density of all the volume replacement techniques, as this was a required part of their testing procedure.

To conduct the moisture content study, a bulk sample was taken from the stockpile of each soil used during construction. The samples were placed in one-gallon metal paint cans and sealed until moisture measurements were conducted. Each paint can held about 4-5 kg (9-11 lbs) of soil, which was enough to provide at least three replicate experiments using 200-250 g (7-9oz) of material for each of six test devices. 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 of the remaining samples were treated similarly, with three random samples of soil drawn from the can and tested. The NDG, EDG, and SDG were all tested based on their responses during the large-scale density study. All collected data and analyses can be viewed in greater detail in a complementary technical report (20).

Experimental Results and Analysis

Density Devices

Though the overall testing lasted over a period of two months, all seven test sections were constructed and tested concurrently with construction. For each soil type and density/modulus device, 20 data points were collected: four replicates at each of four coverage levels and the final soaked condition. The evaluation of the compaction monitoring devices involved comparing the dry densities obtained by each device to the dry density obtained by the NDG as this was the device sought for replacement. In all cases, the dry density was determined by converting all reported wet densities, γ_w , to dry density, γ_d , as shown in Equation 1 using the laboratory oven moisture content (MC_{lab}) as the reference standard.

$$\gamma_D = \gamma_W \div \left(1 + MC_{lab}\right) \tag{1}$$

The initial analysis identified the maximum percentage of outliers for each device to define performance based on reliability. It was found that the WB and M+DI both exhibited greater than 25% null readings (or outliers) and

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therefore were considered inadequate replacements for the NDG and removed from further consideration. The next step in the comparison process was to determine the percent device density deviation from the NDG for the remaining density devices, SC, SS, EDG, SDG, and SDG-Corr. The percent deviation was used because it would return a dimensionless performance indicator. Due to the variable nature of QC in soils and testing over increasing levels of compaction, spreads in deviation readings are more indicative of the ability of a device to present reliable data than are the absolute readings themselves. The spreads in deviation were calculated as shown in the flowchart in Figure 4. This approach was taken because each device was tested randomly within a 40-ft^2 test region, but not at the same location as the NDG. Therefore a one-to-one comparison of device to NDG is not representative of device response as there is variability of density and moisture within the test section leading to variability between NDG readings for a single coverage level and device variability.

The spreads for the density devices for a particular soil (average and max-min) were ranked in increasing order from 1 to 5 with 1 being the best and 5 the worst. The rankings for each device for all soil types were then added to yield a composite rank for comparative analysis as shown in Figures 5 and 6 for the average high-low and max-min values, respectively. The figures show the individual rankings for each soil type, with the lowest scoring devices performing significantly better than the highest scoring devices.

Moisture Devices

Processing of data from the moisture content 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 (accuracy). To determine this metric, the slope of the device's moisture content plotted against the laboratory oven's moisture content (unity) was determined for all soil types. The Bias of a device's performance (Equation 2) was based on the absolute slope differential between the device's measured slope and unity. This comparison can be seen in Figure 7. 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. Table 4 shows device data as compared to that of the laboratory oven including the slope, slope offset from laboratory oven, and the standard deviation of the device/lab oven ratio. The second indicator of a device's performance was the deviation of measured values from the average moisture content (precision). 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 8. Soils are ranked in order of increasing average grain size.

To combine the accuracy and precision of each device for moisture content, the metric of Total Analytical Error (TAE) was employed. The calculation for TAE is shown in Equations 2 and 3. Figure 9 shows the final metric for each device. Devices with a lower TAE have a better combination of accuracy and precision than devices with a higher TAE.

$$Bias = \left| \frac{1 - slope}{1} \right| \tag{2}$$

$$TAE = Bias + \frac{\sigma}{\overline{X}} \tag{3}$$

Where:

Bias= Absolute value of the slope offset from the 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 devices to lab oven ratios

Conclusions

Moisture Content

When calibration against the laboratory oven is possible, the SDG and NDG both provide devices that can return accurate and reliable density and moisture content values. When calibration is not available, the gas stove or microwave ovens represent the best field devices. These devices can also be considered as alternatives for use in calibration of the recommended electronic gauges. The moisture analyzer and Speedy are not considered reliable field devices over the full spectrum of soils encountered in construction. Devices that did not perform well usually

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failed when the physical structure of the soils allowed for greater variation in moisture content, such as with the coarse-grained soils. Fine- grained soils and non-plastic soils, such as the silts, tended to yield accurate measurements by more devices. The uniform heating of the gas stove, as opposed to the interrupted microwave heating, created a much more reliable set of moisture measurements.

Density

Considering that if a device is to replace the NDG, it should have performance approaching or exceeding that of the NDG and therefore all devices were compared to the performance of the NDG. Based on Figures 5 and 6, the corrected SDG-Corr proved to have the least variability in both the average value for each soil and the least amount of high-low scatter from the average value and was deemed the best electronic substitute for the NDG. The sand cone was the next best device overall and deemed the best volumetric replacement device compared to the NDG. The EDG performed well but required a more complex calibration routine to establish its accuracy. The steel shot test proved to have the greatest variability in the soils tested, although this device is intended primarily for contingency measurements allowing for a larger amount of scatter in return for a more expedient test procedure. It should be noted that the uncorrected SDG experienced considerably more variability than the EDG or sand cone, indicating a lack of sufficient internal calibration for the soils tested.

Overall, the ability to capture both moisture and density with a single device rather than with both a heating device and a field density apparatus increases the value of the electronic devices as a single solution for replacing the NDG for construction QC.

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List of Tables and Figures

TABLE 1 Density/Modulus Devices and Techniques

Wet Density & Moisture Content	Wet Density only	Modulus or Stiffness
Moisture Density Indicator (MDI) Electrical Density Gauge (EDG) Soil Density Gauge (SDG) Nuclear Density Gauge (NDG)	Water Balloon (WB) Sand Cone (SC) Steel Shot (SS)	Clegg Hammer (CH) GeoGauge (GG) Dynatest Lightweight Deflectometer (D-LWD) Zorn Lightweight Deflectometer (Z-LWD) Dynamic Cone Penetrometer (DCP)

TABLE 2 Moisture Content Devices and Techniques

Electronic	Direct Heat (Gravimetric)	Chemical
Electrical Density Gauge (EDG) Soil Density Gauge (SDG) Nuclear Density Gauge (NDG)	Laboratory Oven Lab Microwave Field Microwave Gas Stove Moisture Analyzer	Speedy Moisture

TABLE 3 Soil Types Tested

		Grain Size Percentage by Weight				**Atterberg Limits**		**Standard Proctor**	
Descriptor	**USCS Class.**	**Gravel**	**Sand**	**Silt**	**Clay**	**LL**	**PL**	**OMC (%)**	**MDD (pcf)/(gm/cm^3)**
Crushed Limestone	GP-GM	52.8	40.9	3.9	2.4	15	12	6.8	136.3/(2.183)
Silty Gravel	SM	29.2	45.9	21.1	3.8	NP	NP	7.8	129.7/(2.076)
Clay Gravel	SP-SC	41.3	50.7	3.1	4.9	23	13	8	128.8/(2.063)
Silty Sand	ML-2	2.7	47	43.9	6.4	NP	NP	10	121.8/(1.951)
Concrete Sand	SP	4.9	36.1	2.3	0.8	NP	NP	9.5	109/(1.746)
Vicksburg Loess	ML-1	1.2	11	78.4	9.4	NP	NP	15.8	109.5/(1.754)
Buckshot Clay	CH	0	4.9	18.6	76.5	73	24	24.6	85.7/(1.373)

TABLE 4 Device Moisture Content vs Laboratory Oven

Device	Slope	Slope Offset (Slope-1)	Standard Deviation of Device to Laboratory Oven Ratio
Lab Oven	1.000	0.000	0.089
NDG	0.922	-0.078	0.108
Gas Stove	1.027	0.027	0.213
SDG (corr)	0.979	-0.021	0.253
Field Microwave	0.897	-0.103	0.170
STD Microwave	1.091	0.091	0.222
EDG	1.010	0.010	0.318
Moisture Analyzer	0.731	-0.269	0.238
Speedy	1.405	0.405	0.260

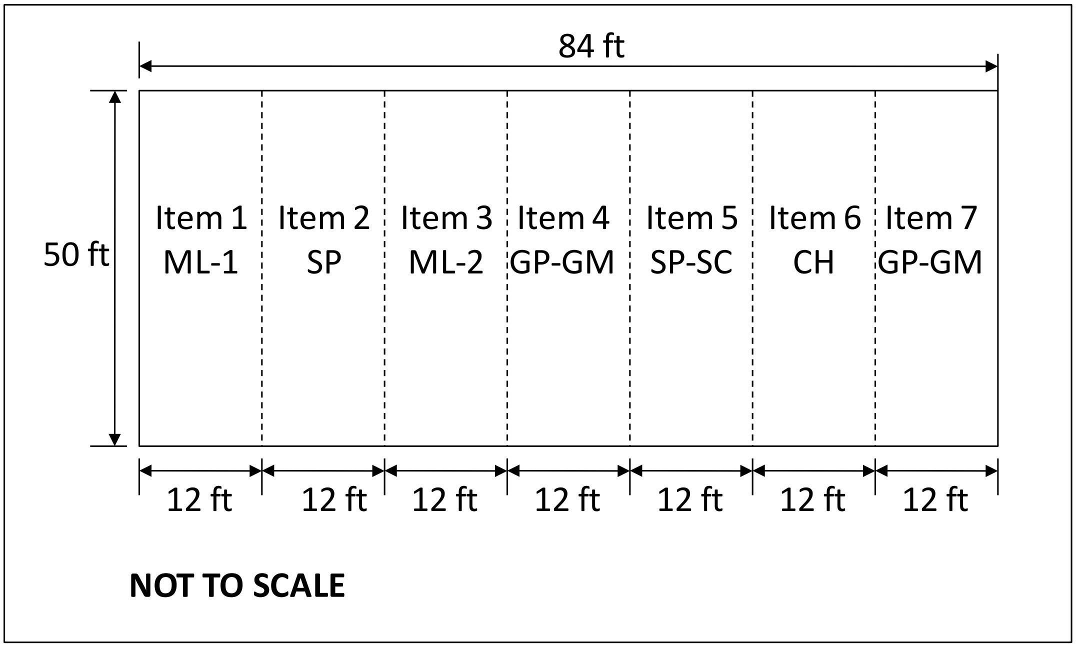

FIGURE 1 Test layout for all soils.

FIGURE 2 Test Execution. Top left: Device testing on ML-1. Top right: Construction of SP-SC layer (final lift). Bottom left: Construction of GP-GM with test regions marked. Bottom right: Soaking of ML-1 test section following testing of 8th coverage.

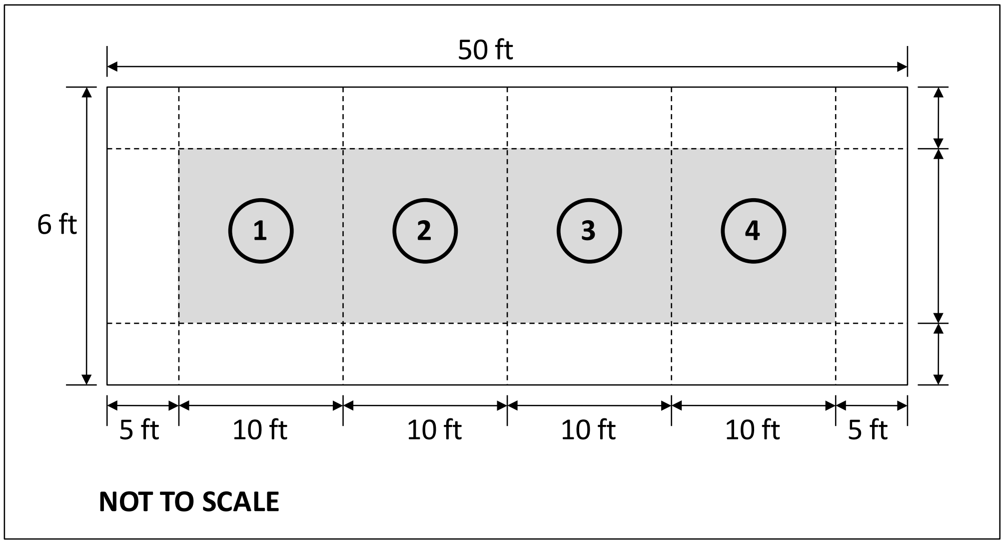

FIGURE 3 Individual soil showing four testing regions.

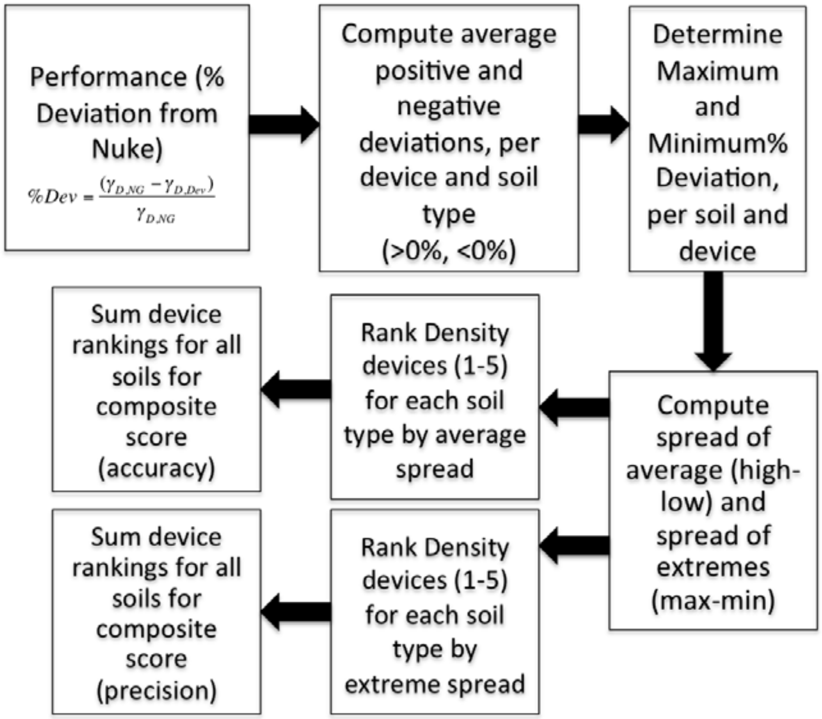

FIGURE 4 Flow chart indicating approach to measuring device performance.

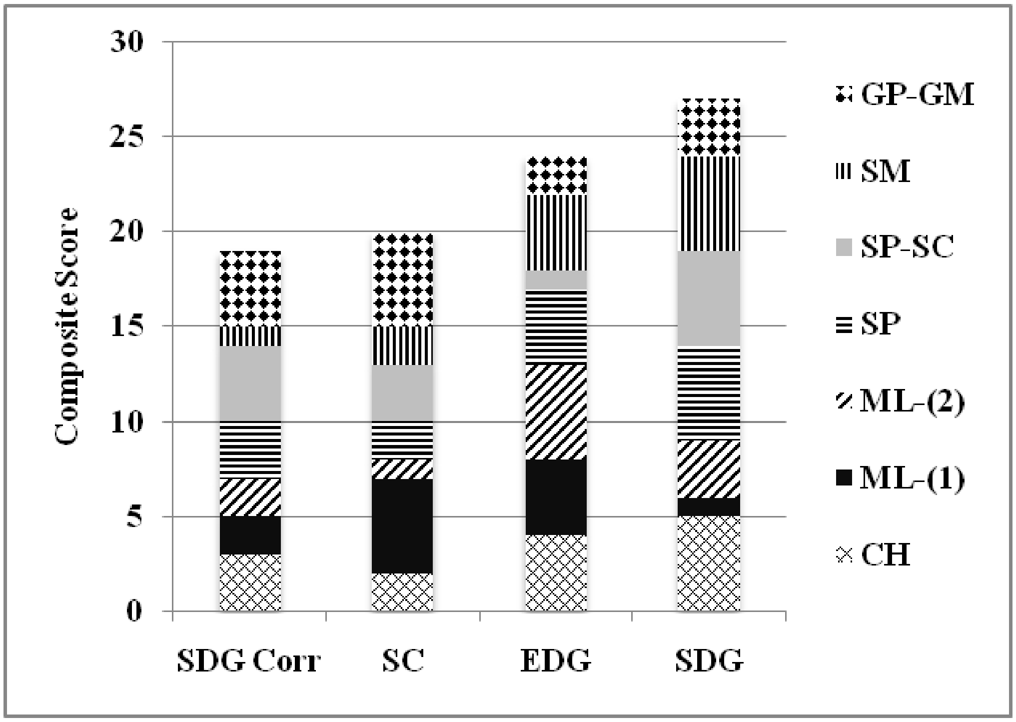

FIGURE 5 Average Dry Density Spread Value Overall Ranking.

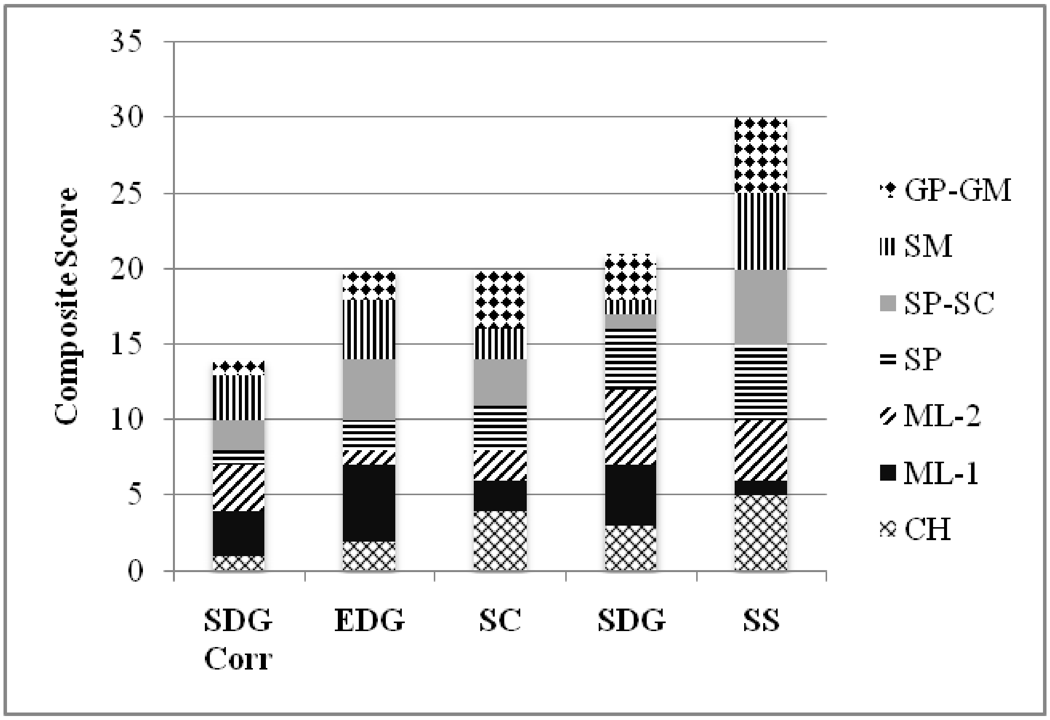

FIGURE 6 Maximum-Minimum Dry Density Spread Value Overall Ranking.

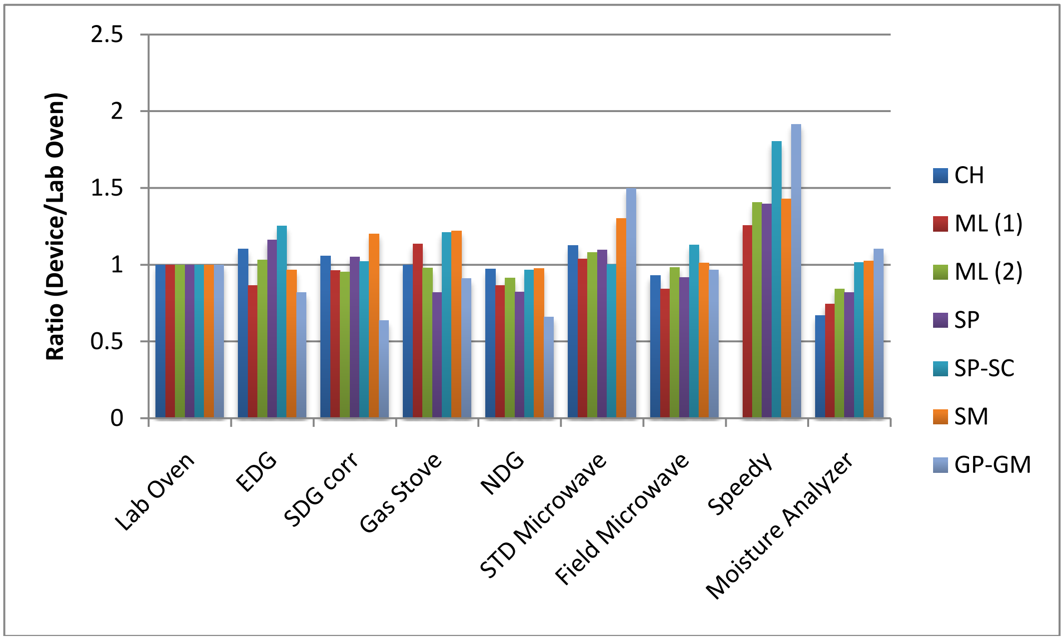

FIGURE 7 Ratio of average device to laboratory oven moisture content for each soil tested.

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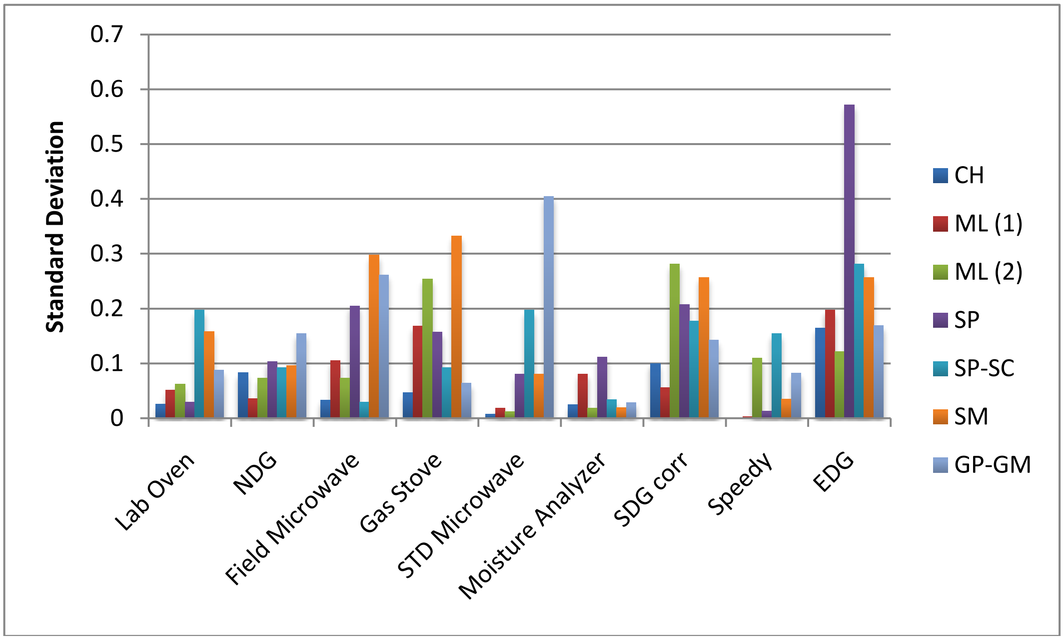

FIGURE 8 Standard deviation of moisture content for each tested device for each soil type tested.

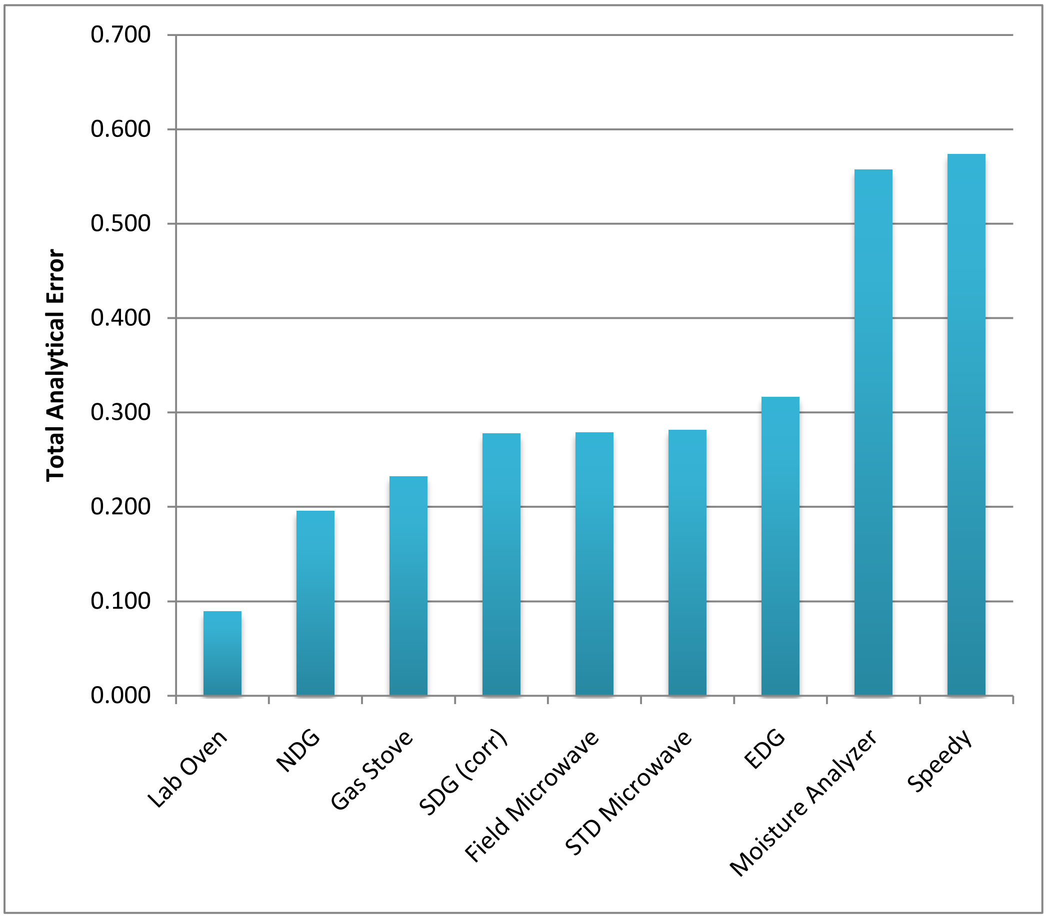

FIGURE 7 Rating statistic for moisture content as the product of the slope offset and standard deviation for all tested devices.