

Designation: D7830/D7830M - 14

Standard Test Method for In-Place Density (Unit Weight) and Water Content of Soil Using an Electromagnetic Soil Density Gauge¹

This standard is issued under the fixed designation D7830/D7830M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers the procedures for determining in-place properties of non-frozen, unbound soil and soil aggregate mixtures such as total density, gravimetric water content and relative compaction by measuring the intrinsic impedance of the compacted soil.

1.1.1 The method and device described in this test method are intended for in-process quality control of earthwork projects. Site or material characterization is not an intended result.

1.2 Units—The values stated in either SI units or inchpound units [given in brackets] are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.2.1 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight) while the unit for mass is slugs. The rationalized slug unit is not given in this standard.

1.2.2 In the engineering profession, it is customary practice to use, interchangeably, units representing both mass and force, unless dynamic calculations are involved. This implicitly combines two separate systems of units, that is, the absolute system and the gravimetric system. It is undesirable to combine the use of two separate systems within a single standard. The use of balances or scales recording pounds of mass (lbm), or the recording of density in lbm/ft³ should not be regarded as nonconformance with this standard.

1.3 All observed and calculated values shall conform to the Guide for Significant Digits and Rounding established in Practice D6026.

1.3.1 The procedures used to specify how data is collected, recorded, and calculated in this standard are regarded as industry standard. In addition, they are representative of the significant digits that should generally be retained. The proce-

dures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or decrease the number of significant digits of reported data commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in the analysis methods for engineering design.

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

NOTE 1—ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

2. Referenced Documents

- 2.1 ASTM Standards:²
- D422 Test Method for Particle-Size Analysis of Soils
- D653 Terminology Relating to Soil, Rock, and Contained Fluids
- D698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³))
- D1556 Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method
- D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³))
- D2167 Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method
- D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
- D2937 Test Method for Density of Soil in Place by the Drive-Cylinder Method

¹ This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.08 on Special and Construction Control Tests.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
- D4253 Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table
- D4254 Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density
- D4318 Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
- D4643 Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating
- D4718 Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles
- D7382 Test Methods for Determination of Maximum Dry Unit Weight and Water Content Range for Effective Compaction of Granular Soils Using a Vibrating Hammer
- D4944 Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester
- D4959 Test Method for Determination of Water (Moisture) Content of Soil By Direct Heating
- D6026 Practice for Using Significant Digits in Geotechnical Data
- D6938 Test Method for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)
- E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
- 2.2 Other Referenced Documents:
- "Development of a Non-Nuclear Soil Density Gauge to Eliminate the Need for Nuclear Density Gauges"³

3. Terminology

- 3.1 Definitions:
- 3.1.1 See Terminology D653 for general definitions.
- 3.2 Definitions of Terms Specific to This Standard:
- 3.2.1 *impedance*, *n*—a measure of opposition to alternating current (AC).

3.2.2 *impedance spectroscopy, n*—a method that measures the electromagnetic properties of a medium as a function of frequency.

4. Summary of Test Method

4.1 The total or wet density and gravimetric water content of soil and soil-aggregate are correlated to empirical data using an electromagnetic impedance spectroscopy device. Electromagnetic properties of the soil are determined at specific frequencies by measuring the changes in the electromagnetic field. A function is generated that describes the relationship between electrical properties over a range of frequencies. That function is compared to an empirical model and other calibration checks to determine water content and density.

4.2 This method employs electromagnetic impedance spectroscopy to determine the volumetric water content and wet density. The measurement spectrum is made up of frequencies ranging from 30 kHz to 50 MHz.

4.3 Properties such as dry density, gravimetric water content and relative compaction are calculated from the total density and the volumetric water content.

5. Significance and Use

5.1 The method described determines wet density and gravimetric water content by correlating complex impedance measurement data to an empirically developed model. The empirical model is generated by comparing the electrical properties of typical soils encountered in civil construction projects to their wet densities and gravimetric water contents determined by other accepted methods.

5.2 The test method described is useful as a rapid, nondestructive technique for determining the in-place total density and gravimetric water content of soil and soil-aggregate mixtures and the determination of dry density.

5.3 This method may be used for quality control and acceptance of compacted soil and soil-aggregate mixtures as used in construction and also for research and development. The non-destructive nature allows for repetitive measurements at a single test location and statistical analysis of the results.

Note 2—The quality of the result produced by this standard test method is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the requirements of Practice D3740 are generally considered capable of competent and objective sampling/testing/inspection, and the like. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluation some of those factors.

6. Interferences

6.1 Anomalies in the test material with electrical impedance properties significantly different from construction soils and aggregate evaluated during soil model development, such as metal objects or organic material, may affect the accuracy of the test method.

6.2 Chemical and mineralogical composition may affect the results of a test. Examples of materials that may impact the results include but are not limited to, quarried materials containing higher concentrations of iron, volcanic rock, and materials that have significant fractions of cemented particles, organic soils, recycled materials or materials containing asphalt, portland cement, lime, fly ash, or other stabilizing modifiers. In most cases the effect may be satisfactorily addressed by following the Calibration Procedure in Section 7.

6.3 A significant increase in the conductivity of the pore water such as from ground water that may contain significant salt deposits or contaminants. In most cases the effect may be satisfactorily addressed by following the Calibration Procedure in Section 7.

6.4 This test method applies only to non-frozen soil. The electrical properties of soil change with temperature. Generally, testing should be limited to soil temperatures above 10°C [50°F] and below 40°C [104°F]. Effects of temperature on electrical properties of soils also depend on soil type.

³ Prepared for The Department of Homeland Security under contract No. HSHQDC-07-C-00080. Dated October 31, 2008. Available from the U.S. Department of Homeland Security, Washington, D.C. 20528, http://www.dhs.gov.



Clayey soils are more temperature sensitive than sandy soils. Accuracy of measurements improves when the temperature of soil is close to the temperature used in the model calibration. Calibration for temperature effects should be done when soil temperatures differ by more than 10° C [18°F] from model calibration temperatures. Calibration Procedures are given in Section 7.

6.5 The accuracy of the results obtained by this test method may be influenced by poor or incorrect placement of the device on the soil being tested. Non-homogeneous soils, non-uniform surface texture, large air voids that may be present may decrease the precision of the results. Correct placement of the soil gauge is important to the quality of the electrical measurements collected by the device.

6.6 Oversized particles in the measurement volume may cause an error in water content and/or density results. Where lack of uniformity in the soil is suspected due to layering, aggregates, or voids, the test site should be excavated and visually examined to determine if the material is representative of the in-situ material in general and if an oversize correction is required in accordance with Practice D4718.

6.7 Variation from actual values may increase for soil material that is significantly drier or wetter than optimum water content as determined using Test Methods D698 or D1557. Variation from actual values may increase for soil material that is compacted to less than 80 % of the maximum dry density as determined using Test Methods D698 or D1557.

6.8 Attempts to measure unknown in-place soils with a soil model that was generated from a limited range of density or water content values, or both, may result in density and water content errors.

6.9 Strong electromagnetic fields such as those generated by high tension power lines may interfere with the device operation.

6.10 For a circular sensor 280 mm [11 in.] in diameter, the typical maximum measured volume is approximately 0.0034 m^3 [0.12 ft³]. The actual measured volume is indeterminate and varies with the plate diameter, sensor configuration, and

material being tested. Results are typically influenced more by the density and water content of the material near the surface.

7. Apparatus^{4,5}

7.1 *Electromagnetic Soil Density Gauge*—A device capable of generating an electromagnetic field and measuring the differential voltage change between two electrodes. An example of the device is shown in Fig. 1 and a sensor schematic section and approximate electrical fields that sense the soil is shown in Fig. 2. While the exact details of construction of the apparatus may vary, the system shall consist of:

7.1.1 Electronic circuitry to provide power and signal conditioning to the sensor and to provide the data acquisition and display functions. The circuitry shall be designed to perform a calibration of the unit over a range of conditions and materials expected in the field.

7.1.2 Internal circuitry suitable for displaying individual measurements to allow operators to record the results.

7.1.3 A rugged housing designed for taking in-situ density and water content measurements of soil and soil-aggregate mixtures during routine earthwork operations.

7.1.4 Infrared Temperature Measuring Device, shall be capable of measuring the surface temperature of the material being tested to $\pm 0.5^{\circ}$ C [$\pm 1^{\circ}$ F] throughout a range of 0° to 50°C [30° to 120°F].

7.2 *Soil Calibration Container*—Containers for calibration of the gauge as described in section 8.5.1, Container Calibration.

⁵ The Electromagnetic Soil Density Gauge is covered by a patent (patent no.: US 7,219,024 B2). Interested parties are invited to submit information regarding the identification of an alternative(s) to this patented item to the ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend.



FIG. 1 Electromagnetic Soil Density Gauge

⁴ The sole source of supply of the TransTech Soil Density Gauge (SDG) apparatus known to the committee at this time is TransTech Systems, Inc. 1594 State Street, Schenectady, NY. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend.



FIG. 2 Sensor Section and Schematic

8. Calibration

8.1 For Factory Calibration information and requirements please refer to Annex A1.

8.2 The *soil density gauge* has been designed to determine the moisture and density in a compacted soil sample without the need for special field generated soil models. The ability to measure moisture and density is based on multiple soil models that were developed by studying various soil types. As the soil density gauge's measurement performance is based on these models, there will be occasions where the soil being measured is so different from one that has been studied previously that an adjustment may be required to enable the soil density gauge to produce acceptable results.⁶

8.3 Determine the test parameters that will be used to calibrate the device. For example, selection of a pre-existing soil model or manual entry of soil model parameters for calibration.

8.3.1 Obtain a representative sample of soil from the site where in-place testing is conducted or from the borrow source.

8.3.2 Determine the laboratory compaction characteristics of the material to be tested. Test Methods D698 or D1557 for fine grained soils and soil rock mixtures that exhibit a clear maximum dry density or Test Methods D4253 or Test Methods D7382 for predominately granular material.

8.3.3 Information required by the device to associate the soil to the correct predetermined soil model may include but not be limited to: maximum dry density; optimum water content as determined by Test Methods D698 or D1557; percent of sample larger than 75 mm [3 in.]; percentage of sample between 75 mm [3 in.] and 19 mm [0.75 in.]; percent gravel; percent sand; percent fines; coefficient of uniformity; and coefficient of curvature in accordance with Test Method D422, Plastic Limit, and Test Methods D4318, Liquid Limit.

8.4 Prior to using the gauge derived water content on any new material, the value for water content should be verified by comparison to another accepted test method such as Test Methods D2216, D4643, D4944, or D4959. Prior to using the gauge derived density on any new material, the value should be verified by comparison to another accepted test method such as Test Methods D1556, D2167, D2937, or D6938. As part of a user developed procedure, occasional tests should be taken beneath the gauge and from samples taken beneath the gauge

⁶ A comparison to other accepted test methods is recommended on a regular frequency to verify the validity and appropriateness of the calibration.



and comparison test be done to confirm the gauge derived water content values. Following the manufacturer procedures for correcting the gauge derived water content and density values.

8.5 The calibration should be checked prior to performing tests on materials that are distinctly different from material types previously used in obtaining or adjusting the calibration. If a field calibration is necessary follow the procedures below.

8.5.1 *Container Calibration*—Prepare containers of compacted material with a known water content as determined by Test Methods D2216, D4643, D4944, or D4959 and a wet density calculated by dividing the mass of the material by the inside volume of the container.

8.5.1.1 Containers used for preparing compacted samples shall have minimum dimensions of 0.66 m [2 ft] wide, 0.66 m [2 ft] long, and 0.33 m [1 ft] deep and be constructed of a non-conductive material capable of retaining its shape during the compaction process.

8.5.1.2 Material used for calibration shall be representative of the material to be tested and should be compacted at optimum moisture content ± 2 % and should be compacted to 95 % ± 2 %.

8.5.1.3 Calibration shall be performed on soil at or near temperatures expected in the field during routine testing.

8.5.2 Onsite Calibration—Where prepared containers of compacted samples are not available, the gauge may be correlated by using a minimum of three sets of test results taken in an area of a compaction project where material has been placed at different water contents. The test sites shall represent the range of water contents and densities, over which the correlation is to be used. At least three gauge readings shall be made at each test site. The density at each site shall be verified by tests performed in accordance with Test Methods D1556, D2167, D2937, or D6938. The water content at each site shall be determined in accordance with Test Methods D2216, D4643, D4944, or D4959. Use the mean value of the replicate readings as the correlation point value for each test site.

8.5.2.1 Calibration shall be performed on material that is at or near material temperatures expected during routine testing.

8.5.3 The mean value of the difference between the water content as determined in 8.5.2 and the values measured with the gauge shall be used as a correction to those measurements made in the field.

8.5.3.1 The water content correction can be applied manually, or can be entered into the device if the device is equipped with an offset or correction feature.

8.5.4 The mean value of the difference between the wet density as determined in 8.5.2 and the values measured with the gauge shall be used as a correction to those measurements made in the field.

8.5.4.1 The wet density correction can be applied manually, or can be entered into the device if the device is equipped with an offset or correction feature.

8.6 The method and test procedures used to obtain the electrical measurements must be the same as those used during routine testing.

9. Procedure

9.1 Preparation of Test Site:

9.1.1 Select a test location in accordance with the contract documents, located to be representative of the total material being placed and to minimize potential interferences.

9.1.2 Remove all loose and disturbed material, or overlying material, as necessary to expose the true surface of the material to be tested.

9.2 Place the device on the surface of the material to be tested.

9.3 Secure and record one or more density and water content measurements.

9.4 Measure the soil temperature to the nearest $1^{\circ}C$ [0.5°F]. (The temperature of the material during testing should be representative of the material temperature during calibration.)

9.5 For proper use of the gauge and accurate values of both water content and density corrections to density (8.5.4), to water content (8.5.3) and for oversize particles (Practice D4718) should be applied when applicable.

9.5.1 When there is any uncertainty as to the presence of oversize particles, it is advisable to sample the material beneath the gauge to verify the presence and relative proportion of the oversize particles. A rock correction can then be made for both the water content and the density by the method in Practice D4718.

10. Calculation of Results

10.1 Determine the Wet Density, ρ_t :

10.1.1 Read the value directly in kg/m³ [lbm/ft³].

10.1.2 Record the density to the nearest 1 kg/m³ [0.1 lbm/ft^3].

10.1.2.1 If desired, calculate the wet unit weight, γ_t , as follows:

$$\gamma_t = 9.8066 \times \rho_t, \text{ N/m}^3 \tag{1}$$

or

$$\gamma_t = 62.428 \times \rho_t, \ \text{lbf/ft}^3 \tag{2}$$

10.2 Determine the Water Content, w:

10.2.1 Read the value directly in percent.

10.2.2 If the gauge determines water mass per unit volume, M_w in kg/m³ [lbm /ft³], calculate w using the equation:

$$w = \frac{M_w \times 100}{\rho_t - M_w} \tag{3}$$

or, if the gauge determines water weight per unit volume, W_w in N/m³ [lbf /ft³], calculate w using the formula:

$$w = \frac{W_w \times 100}{\gamma_t - W_w} \tag{4}$$

10.2.3 Record water content to the nearest 0.1 %.

10.3 Determine the Dry Density by One of the Following Methods:

10.3.1 If the water content is obtained by electromagnetic methods, use the gauge readings directly for dry density in kg/m^3 [lbm/ft³]. The value can also be calculated from:

$$\rho_d = \rho_t - M_w = \text{dry density, } \text{kg/m}^3 \left[1 \text{ b m / ft}^3 \right]$$
 (5)

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$$\gamma_d = \gamma_t - W_w = dry \text{ unit weight, N/m}^3 \left[1 \text{ b f / ft}^3 \right]$$
 (6)

10.3.2 If the water content is to be determined manually from a sample of soil, follow the procedures and perform the calculations of the chosen test method (Test Methods D2216, D4643, D4944, or D4959).

10.3.3 With a water content value from 10.3.2 calculate the dry density from:

$$\rho_d = \frac{\rho_t}{1 + \frac{w}{100}} \tag{7}$$

10.3.4 Report the dry density to the nearest 1 kg/m³ [0.1 lbm/ft^3].

10.3.4.1 If desired, calculate the dry unit weight, γ_d , as follows:

$$\gamma_d (k N / m^3) = 0.0098066 \times \rho_d (k g / m^3)$$
 (8)

or

$$\gamma_d \left(l \ b \ f / f t^3 \right) = 0.062428 \times \rho_d \left(k \ g / m^3 \right)$$
(9)

10.4 Determine the Percent Compaction:

10.4.1 It may be desired to express the in-place dry density as a percentage of a laboratory density such as Test Methods D698, D1557, D4253, or D4254. This relationship can be calculated by dividing the *in-place dry density* by the *laboratory maximum dry density* and multiplying by 100. Procedures for calculating relative density are provided in Test Method D4254 which requires that Test Method D4253 also be performed. Corrections for oversize material, if required, shall be performed in accordance with Practice D4718.

11. Report: Test Data Sheet(s)/Form(s)/Final Report(s)

11.1 The Field Data Records Shall Include, as a Minimum, the Following:

11.1.1 Test number or test identification.

11.1.2 Location of test (for example, station number or global positioning system (GPS) number or coordinates or other identifiable information).

11.1.3 Visual description of material tested.

11.1.4 Lift number or elevation or depth.

11.1.5 Name of the operator(s).

11.1.6 Make, model, and serial number of the test gauge.

11.1.7 Standardization and adjustment data for the date of the tests.

11.1.8 Any corrections made in the reported values and reasons for these corrections (that is, over-sized particles, water content).

11.1.9 Maximum laboratory density value in kg/m 3 [lbm/ ft 3].

11.1.10 Dry density in kg/m³ [lbm/ft³].

11.1.11 Wet density in kg/m³ [lbm/ft³].

11.1.12 Gravimetric water content in percent.

11.1.13 Percent compaction.

11.1.14 Soil temperature.

11.1.15 Observation made during testing including but not limited to: site conditions, weather, material being tested, equipment used to achieve compaction.

11.2 Final Report (Minimum Required Information):

11.2.1 Test number.

11.2.2 Gauge serial number.

11.2.3 Location of test (for example, station number or GPS number or coordinates or other identifiable information).

11.2.4 Lift number or elevation or depth.

11.2.5 Water content as a percent.

11.2.6 Maximum laboratory density value in kg/m³ [lbm/ ft³].

11.2.7 Dry density result in kg/m³ [lbm/ft³].

11.2.8 Percent compaction.

11.2.9 Name of operator(s).

12. Precision and Bias

12.1 *Precision*—Complete test data on precision in accordance with Practice E691 is not presented due to the nature of this test method. It is either not feasible or too costly at this time to have ten or more agencies participate in an in-situ testing program at a given site. The Subcommittee (D18.08) is seeking any data from the users of this test method that might be used to make a limited statement on precision. Task group D18.08.03 is looking into an ASTM sponsored interlaboratory study (ILS) to generate data on a variety of soils for a precision statement.

12.1.1 In lieu of a Practice E691 precision study, the following information from "Development of a Non-Nuclear Soil Density Gauge to Eliminate the Need for Nuclear Density Gauges" is provided in Tables 1 and 2. A description of the materials tested is given in Table 3.

TABLE 1 Single Operator Precision

NOTE 1-One instrument with one operator, each at one location.

USCS	SP	GP-GM	CL	GP-GM	GW-GM	CL-ML
Wet Density kg/m ³	2077 ± 0.9	2228 ± 17	2040 ± 4.6	2246 ± 12	1868 ± 21.2	1920 ± 15.8
[lbm/ft ³]	$[129.7 \pm 1.9]$	139.1 ± 1.1]	$[127.4 \pm 0.3]$	$[140.2 \pm 0.8]$	$[116.6 \pm 1.3]$	$[119.8 \pm 1.0]$
Vol Water kg/m ³	133 ± 8.0	167 ± 3.2	373 ± 1.6	151 ± 4.8	86 ± 4.8	181 ± 3.2
[lbm/ft ³]	[8.3 ± 0.5]	$[10.4 \pm 0.2]$	[23.3 ± 0.1]	$[9.4 \pm 0.3]$	$[5.4 \pm 0.3]$	[11.3 ± 0.2]
Dry Density kg/m ³	1945 ± 23.2	2061 ± 13.6	1667 ± 3.3	2096 ± 6.9	1781 ± 16.4	1723 ± 12.3
[lbm/ft ³]	$[121.4 \pm 1.4]$	[128.7 ± 0.8]	[104.1 ± 0.2]	[130.8 ± 0.4]	[111.2 ± 1.0]	[107.6 ± 0.8]
Water (%)	6.8 ± 0.3	8.0 ± 0.1	22.4 ± 0.03	7.2 ± 0.2	4.9 ± 0.2	11.4 ± 0.1

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TABLE 2 Multi-Operator Precision

NOTE 1—Four instruments with four operators at six locations.						
USCS	SP	GP-GM	CL	GP-GM	GW-GM	CL-ML
Wet Density kg/m ³	2052 ± 84.9	2185 ± 104.1	2041 ± 9.6	2235 ± 14.4	1863 ± 30.4	1869 ± 64.1
[lbm/ft ³]	[128.1 ± 5.3]	[136.4 ± 6.5]	[127.4 ± 0.6]	[139.5 ± 0.9]	[116.3 ± 1.9]	[116.7 ± 4.0]
Vol. Water kg/m ³	127 ± 22.4	159 ± 24	373 ± 3.2	146 ± 8	86 ± 6.4	184 ± 16
[lbm/ft ³]	[7.9 ± 1.4]	[9.9 ± 1.5]	[23.3 ± 0.2]	[9.1 ± 0.5]	[5.4 ± 0.4]	[11.5 ± 1.0]
Dry Density kg/m ³	1925 ± 62.5	2026 ± 80.1	1669 ± 6.4	2089 ± 8.0	1776 ± 24.0	1685 ± 48.1
[lbm/ft ³]	[120.2 ± 3.9]	[126.5 ± 5.0]	[104.2 ± 0.4]	[130.4 ± 0.5]	[110.9 ± 1.5]	[105.2 ± 3.0]
Water (%)	6.6 ± 1.0	7.8 ± 0.9	22.4 ± 0.1	7.0 ± 0.3	4.8 ± 0.3	10.9 ± 0.7

TABLE 3 Description of Materials Tested

	USCS	Common Name
1	SP (Poorly graded sand with gravel)	100 mm [4 in.] Gravel Borrow
2	GP-GM (Poorly graded gravel with silt and sand)	31.5 mm [11/4 in.] Crushed Base Course
3	CL (Lean clay)	Red Silty Clay
4	GP-GM (Poorly graded gravel with silt and sand)	Graded Aggregate Base
5	GW-GM (Well graded gravel with silt and sand)	Red Sand with Rock
6	CL-ML (Silty clay)	Red Sandy Clay

12.2 *Density Bias*—Due to the variability in materials and construction practices, there is no consensus as to the most accurate test method for measurement of density against which this test can be compared. Accordingly, a statement of method bias cannot be made.

12.3 *Water Content Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined. Deviations from Test Method D2216 can be determined from comparison results.

13. Keywords

13.1 acceptance testing; compaction test; construction control; dry density; electromagnetic density gauge; field density; impedance spectroscopy; in-place density; nondestructive testing; non-nuclear test method; quality control; soil density; wet density

ANNEXES

(Mandatory Information)

A1. FACTORY CALIBRATION

A1.1 *Calibration*—Gauges shall be calibrated initially, after any repairs and at intervals not exceeding 12 months.

A1.1.1 Gauge calibration response shall be within ± 16 kg/m³ [± 1.0 lbm/ft³] on blocks on which the gauge was calibrated. This calibration shall be performed by the manufacturer, or a manufacturer certified repair and calibration facility. Impedance is influenced by chemical and mineralogical composition of measured materials. This response must be considered when establishing the calibration block density. The materials used for calibration shall represent densities and water contents common in earthwork projects. The density of the blocks shall be determined in such a manner that the estimated standard deviation of the blocks shall not exceed 1.0 % of the measured block density.

A1.1.2 Re-establish or verify the density of the block(s) used to calibrate or verify calibrations at a period not to exceed five years.

A1.1.3 Sufficient data shall be taken on each calibration block to ensure a gauge precision of at least one-half the gauge precision required for field use. The data may be presented in the form of a graph, table, equation or coefficients or stored in the gauge to allow for corrected measurements.

A1.1.4 The method and test procedures used in estimating the calibration data shall be the same as those used for obtaining the field data.

A1.1.5 The material type, actual density or established density of each calibration block used to establish or verify calibrations shall be stated as part of the calibration data.

A1.1.6 The calibration blocks should be sufficient in size so that the electrical measurements will not change if the block is enlarged in any dimension.



A2. GAUGE PRECISION

A2.1 Gauge precision is defined as the change in density or water mass per unit volume that occurs corresponding to a one standard deviation change in the measured electrical signal. The density and water content of the material must be stated.

A2.1.1 Calculate using the repetitive method described in A2.1.2 for wet density, use a material having a density of 1920 \pm 80 kg/m³ (120.0 \pm 5 lbm/ft³). Typical values for *P* are <16 kg/m³ [1.0 lbm/ft³].

A2.1.2 *Gauge Precision–Repetitive Method*—Obtain a minimum of 20 repetitive measurements while picking up the gauge and placing in the same location between readings. Calculate the standard deviation of the resulting readings. This is the gauge precision.

APPENDIXES

(Nonmandatory Information)

X1. SOIL DENSITY AND MOISTURE FROM ELECTROMAGNETIC IMPEDANCE SPECTROSCOPY

X1.1 Variations in an electromagnetic field due to the properties of soils have been used as the basis of inferring soil properties for many years. The work of Schlumberger and Wenner $(1-3)^7$ was directed at using electro-resistive sensing to determine a multidimensional image of in-situ soil. Later, various penetrating probe designs were developed to determine soil moisture and soil wet density (Drnevich (4) and Anderson (5)). All of these methods required that probes be driven into the ground. An alternative approach has been developed using a non-invasive, circular plate and a coplanar ring.

X1.2 The described device, TransTech SDG, determines wet density and moisture content by correlating impedance measurement data to an empirically developed model. The device produces an electric field in the soil at a prescribed depth and measures the impedance of the material under test. Electromagnetic impedance spectroscopy is then used to determine the volumetric moisture content and wet density. The measurement spectrum is made up of frequencies ranging from 30 kHz to 50 MHz. The empirical model was generated by comparing a spectral impedance property of typical soils encountered in civil construction projects to their wet densities and moisture contents which were determined by other accepted methods.

X1.2.1 The impedance is written as:

$$Z = R + jX \tag{X1.1}$$

where:

Z = the impedance, measured in ohms,

- R = the resistance, measured in ohms,
- X = the reactance, measured in ohms, and

j = the imaginary unit.

X1.2.2 An alternate formulation is written as:

$$Y = 1/Z = G + jB \tag{X1.2}$$

where:

Y = the admittance, measured in siemens (also known as *mho*, the inverse of ohm),

G = the conductance, measured in siemens, and

B = the susceptance, measured in siemens.

X1.2.3 The susceptance may be written as:

$$B = \frac{-X}{X^2 + R^2}$$
(X1.3)

X1.3 We analytically identified the impedance components which best represented the control parameters (wet density and gravimetric moisture). Next, the control parameters of soils were statistically compared to spectrographic representations of the impedance components in order to verify the analytical predictions. These representations were then used to compute the predicted value of the control parameters. The results were that for wet density the spectrographic slope of the susceptance provided the best statistical correlation and the spectrographic slope of the resistance provided the best correlation with moisture.

X1.3.1 The wet density is determined by the electromagnetic impedance spectroscopy measurement representing the average value of the volume measured by the device. Based upon an analytical and statistical evaluation of the various spectrographic impedance properties, it was determined that a spectrographic evaluation of the susceptance, *B*, over a range of frequencies, provides the best empirical correlation between the measurements and the wet density as determined by other accepted methods.

X1.3.2 The term used is *density function*, *D*, which is a spectrographic function of the susceptance over a range of frequencies and the soil being measured. In the following example, the soil is classified as *GP-GM*.

$$D_{GP-GM} = \Delta B_{GP-GM} / \Delta f_{(fi-fn)}$$
(X1.4)

⁷ The boldface numbers in parentheses refer to the list of references at the end of this standard.

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where:

- D_{GP-GM} = the density function for soil type *GP-GM* based on the slope of B_{GP-GM} ,
- B_{GP-GM} = the susceptance measured on soil type GP-GM, and
- $f_i f_n$ = the frequency range over which the slope of B_{GPGM} is determined.

X1.3.3 This function is then empirically related to the wet density as determined by other accepted methods with a linear least squares fit in the form:

$$\rho_t = m_d^* D + b_d \tag{X1.5}$$

where:

- p_t = the wet density in appropriate units,
- m_d = the slope as determined from the empirical linear curve fit, and
- b_d = the offset as determined from the empirical linear curve fit.

X1.4 A controlled laboratory compaction test was conducted with a silty gravel, *GP-GM* classified soil. Proctor and gradation data for the material were obtained. The soil was mixed with water to obtain five gravimetric water levels at 4.58 %, 5.37 %, 6.64 %, 7.60 %, and 9.42 %, as determined by oven dry tests. Four were below the proctor optimum of 8.5 %. At each moisture level, measurements were taken at four compaction levels. At each compaction level, there were four test locations and at each test location four readings were taken with a TransTech SDG and a nuclear density gauge (NDG). This yields 64 data points for each moisture level and a total of 320 data points over all moisture levels. This test is referred to as the "Large Box" test.

X1.4.1 For the case of the controlled compaction study of GP-GM soil with variations of moisture and compaction, the relation is:

$$\rho_w = -0.43698 * D_{GP-GM} + 185.23 \tag{X1.6}$$

X1.5 The volumetric water content, determined by the electromagnetic impedance spectroscopy measurement, represents the average value of the volume measured by the device. Based upon an analytical and statistical evaluation of the various spectrographic impedance properties, it was determined that a spectrographic evaluation of the resistance, R, over a range of frequencies provides the best empirical correlation between the measurements and the volumetric water content as determined by other accepted methods.

X1.5.1 The term used is *moisture function*, M, which is a spectrographic function of the resistance and the soil being measured:

$$M_{GPGM} = (R_{GP-GM f2} - R_{GP-GM f1})/(f_2 - f_1)$$
(X1.7)

where:

 M_{GPGM} = the density function for soil type *GP-GM* based on the slope of R_{GP-GM} ,

 R_{GPGM} = the resistance measured on soil type *GP-GM*, and $f_2 - f_1$ = the frequency range over which the slope of R_{GP-GM} is determined.

X1.5.2 This function (that is, SDG coefficient) is then empirically related to the volumetric water content, which was determined by utilizing the gravimetric oven dry method and the independent wet density or other accepted methods with a linear least squares fit in the form:

$$w_v = m_w * M_{GP-GM} + b_w$$
 (X1.8)

where:

- w_v = the volumetric moisture (%),
- m_w = the slope as determined from the empirical linear curve fit, and
- b_w = the offset as determined from the empirical linear curve fit.

X1.5.3 For the case of the controlled compaction study of GP-GM soil with variations of moisture and compaction, the relation is:



FIG. X1.1 Independent Wet Density versus Density Function

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FIG. X1.2 Volumetric Water Content versus Moisture Function

 $w_v = 6.7916^* M_{GP-GM} + 45.4 \tag{X1.9}$

X2. COMPARISON OF ELECTROMAGNETIC SOIL DENSITY GAUGE DENSITY AND MOISTURE RESULTS WITH NUCLEAR DENSITY GAUGE RESULTS

X2.1 A controlled laboratory compaction test was conducted with a *GP-GM* classified soil. Proctor and gradation data for the material were obtained. The soil was mixed with water to obtain five gravimetric water levels at 4.58 %, 5.37 %, 6.64 %, 7.60 %, and 9.42 %, as determined by oven dry tests. Four were below the proctor optimum of 8.5 %. At each moisture level, measurements were taken at four compaction levels. At each compaction level, there were four test locations and at each test location four readings were taken with a TransTech SDG and a NDG. This yields 64 data points for each moisture level and a total of 320 data points over all moisture levels. This test is referred to as the "Large Box" test.

X2.2 Using the "Large Box" data, the wet density and water content algorithms were developed. The raw SDG frequency spectra were processed with an electronic model, that is, equivalent circuit model of the unit's measurement board, which allowed for the generation of the soil's measured resistance and susceptance versus frequency. A correlation study was completed in which the measured resistance was mapped to the samples' known volumetric water. The control volumetric water was determined from soil samples that were oven dried to obtain the gravimetric water and the control wet density. Also, a correlation study was completed in which the measured susceptance was mapped to the sample's known wet density. The control wet density was determined from the NDG. Using these relationships, two linear equations were developed, one for volumetric water and the second for wet density as described in Appendix X1. While the SDG displays the water content, the unit measures volumetric water.

NOTE X2.1—The reliability of the SDG improved when multiple frequencies, a spectrographic approach, were used. Therefore, the spec-

trographic approach was used such that the slopes of the resistance and susceptance over the corresponding frequency region were calculated and used for the correlations and subsequent algorithms.

X2.3 Wet Density Results

X2.3.1 Using Matlab, an unpaired *t*-test was completed using the NDG wet density and the SDG wet density measurements. (Each NDG reading was an average of three measurements and each SDG reading was an average of five.) The test accepted the null hypothesis that the mean difference is due to chance, using an alpha of 0.05. Therefore, there is no statistically significant difference between the two sets of results. The standard deviation from the unpaired *t*-test was 6.45 lbm/ft³. **Fig. X2.1** is a plot of the NDG wet density (x-axis) and the SDG wet density (y-axis). The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.3.2 Using MATLAB, the Pearson R^2 correlation value between the SDG's wet unit weight and the NDG's wet unit weight was determined to be 0.83, thus the correlation is statistically significant.

X2.3.3 Figs. X2.2 and X2.3 show a comparison of the absolute values of wet unit weight and the standard deviation of the readings of wet unit weight for the SDG and NDG at each of the four compaction levels for the five moisture levels in the "Large Box" testing. The absolute value of wet unit weight is the average of the 16 measurements taken at each compaction level.

X2.4 Water Content Results

X2.4.1 Control Water Content:

X2.4.1.1 The control water content was determined from soil samples that were oven dried to obtain the gravimetric

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FIG. X2.1 NDG Wet Unit Weight versus SDG Wet Unit Weight



FIG. X2.2 The SDG and NDG Wet Unit Weight Averaged at Each Compaction Level (4) for Each Water Content Level (5)

water content. On each of the five test days, different gravimetric water content was desired. The average water content that is reported was determined by eight soil samples. Four soil samples were taken from the compaction area before the day's testing began and four soil samples were taken from the compaction area after the day's testing finished. The average water contents and their standard deviations are reported in the Table X2.1.

X2.4.2 Water Content Results for SDG:

X2.4.2.1 Using MATLAB, an unpaired *t*-test was completed using the control water content, that is, oven dry results, and the calculated SDG water content. The standard deviation from

TABLE X2.1 Average Water Content (Control) and Standard Deviation

Test Day	Average Water Content (%)	Standard Deviation (%)
1	4.58	0.21
2	5.37	0.20
3	6.64	0.22
4	7.60	0.44
5	9.42	0.86

the unpaired *t*-test was 1.67 %. Fig. X2.4 is a plot of the control water content (Table X2.1) (X-axis) and the SDG water content

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FIG. X2.3 The Standard Deviation of the SDG and NDG Wet Unit Weight at Each Compaction Level (4) for Each Water Content Level (5)



FIG. X2.4 SDG Water Content (%) versus Control Water Content (%) Using Each Day's Average

(Y-axis). The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.4.2.2 Using MATLAB, the Pearson R^2 correlation value between the SDG's water content and the Control water content was determined to be 0.54, thus the correlation is statistically significant.

X2.4.3 Water Content Results for NDG:

X2.4.3.1 Using MATLAB, an unpaired test was completed using the control water content, that is, oven dry results, and the measured NDG water content. The standard deviation from the unpaired *t*-test was 1.86%. Fig. X2.5 is a plot of the control water content (X-axis) and the NDG water content (Y-axis). The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.4.3.2 Using MATLAB, the Pearson's R^2 correlation value between the NDG's water content and the Control water

content was determined to be 0.89, thus the correlation is statistically significant.

X2.5 Dry Unit Weight Results

X2.5.1 Control Dry Unit Weight:

X2.5.1.1 In making a comparison of the dry densities of the SDG and NDG, a control dry unit weight is developed based on the measurements of the two gauges and the oven dry water content (Table X2.1). The use of the average of the gauges wet unit weight measurement is an attempt to accommodate the measurement variations in the gauges as noted above. The control dry unit weight is used for comparison to both the SDG dry unit weight and the NDG dry unit weight. The calculation for the control dry unit weight is given by the following relation:

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FIG. X2.5 NDG Water Content versus Oven Dry Water Content Results Using Each Day's Average

$$Control_{DD} = \frac{0.5(NDG_{WD} + SDG_{WD})}{\left(1 + \frac{OvenDry_{WC}}{100}\right)}$$
(X2.1)

X2.5.2 SDG versus Control:

X2.5.2.1 Using MATLAB, an unpaired *t*-test was completed using the SDG dry unit weight and the control dry unit weight, that is, above equation. The standard deviation from the unpaired *t*-test was 4.84 lbf/ft³. Fig. X2.6 is a plot of the control dry unit weight (X-axis) and the SDG dry unit weight (Y-axis).

The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.5.2.2 Using MATLAB, the Pearson's R^2 correlation value between the SDG's dry unit weight and the control dry unit weight was determined to be 0.87, thus the correlation is statistically significant.

X2.5.3 NDG versus Control:

X2.5.3.1 Using MATLAB, an unpaired *t*-test was completed using the NDG dry unit weight and the control dry unit weight,



FIG. X2.6 SDG Dry Unit Weight versus Control Dry Unit Weight

that is, above equation. The standard deviation from the unpaired *t*-test was 4.88 lbf/ft^3 . Fig. X2.7 is a plot of the control dry unit weight (X-axis) and the NDG dry unit weight (Y-axis). The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.5.3.2 Using MATLAB, the Pearson's R^2 correlation value between the NDG's dry unit weight and the control dry unit weight was determined to be 0.91, thus the correlation is statistically significant.

X2.5.4 SDG versus NDG Dry Unit Weight:

X2.5.4.1 Using MATLAB, an unpaired *t*-test was completed using the NDG dry unit weight and the SDG dry unit weight measurements. The test accepted the null hypothesis that the mean difference is due to chance, using an alpha of 0.05. Therefore, there is no statistically significant difference between the two sets of results. The standard deviation from the unpaired *t*-test was 5.12 lbf/ft³. Fig. X2.8 is a plot of the NDG dry unit weight (X-axis) and the SDG dry unit weight (Y-axis). The standard deviation from the 1-to-1 line of equality is shown with the dashed lines.

X2.5.4.2 Using MATLAB, the Pearson's R^2 correlation value between the SDG's dry unit weight and the NDG's dry unit weight was determined to be 0.69, thus the correlation is statistically significant.

X2.6 Dry Unit Weight versus Water Content

X2.6.1 Figs. X2.9-X2.11 are the dry unit weight versus water content for the control, NDG and SDG. The control dry unit weight (y-axis) was calculated using the average of the SDG and NDG wet densities and control water content (Table X2.1). The R^2 values of the second order fits for the dry unit weight versus water content data were 0.22 for the control, 0.24 for the NDG, and 0.04 for the SDG. This indicates a lack of statistically significant correlation.

X2.6.2 The proctor test results: max dry unit weight = 137.27 lbf/ft^3 , optimum water content = 8.5 %.

X2.6.3 Using the three curve fits of each data set, the approximate peaks of each fit are:

Control: maximum dry unit weight = 130.41 lbf/ft³, optimum water content = 8.8 %

NDG: maximum dry unit weight = 130.48 lbf/ft³, optimum water content = 10.9 %

SDG: maximum dry unit weight = 128.14 lbf/ft³, optimum water content = 8.0 %

X2.6.4 The control, NDG and SDG all have lower max dry densities than the proctor test max dry unit weight due to the fact that the electric plate compactor that was used was limited in its ability to provide sufficient compaction. The dry unit weight standard deviation between the SDG and NDG was calculated to be 5.12 lbf/ft³, based on the unpaired *t*-test comparison between the NDG and SDG dry unit weight. Applying this standard deviation to the max dry densities above, the SDG (128.14 lbf/ft³) and NDG (130.41 lbf/ft³) are statistically the same.

X2.7 Conclusion

X2.7.1 SDG versus Standard:

X2.7.1.1 The SDG and NDG wet unit weight unpaired *t*-test resulted in the acceptance of the null hypothesis that the mean difference is due to chance, using an alpha of 0.05. Therefore, there is no statistically significant difference between the SDG and NDG wet unit weight results. The Pearson's R^2 correlation value between the two units was determined to be 0.83. Therefore, the correlation is statistically significant.

X2.7.1.2 The Pearson's R^2 correlation value between the SDG and the oven dry was determined to be 0.54. Therefore, the correlation is statistically significant. Additional work is needed to improve the accuracy of the SDG's water content calculation.



FIG. X2.7 NDG Dry Unit Weight versus Control Dry Unit Weight

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FIG. X2.8 SDG Dry Unit Weight versus NDG Dry Unit Weight



FIG. X2.9 Control Dry Unit Weight versus Control Moisture (Table X2.1)

X2.7.1.3 The Pearson's R^2 correlation value between the SDG and the control dry unit weight was determined to be 0.87. Therefore, the correlation is statistically significant.

X2.7.1.4 The SDG and NDG dry unit weight unpaired *t*-test resulted in the acceptance of the null hypothesis that the mean difference is due to chance, using an alpha of 0.05. Therefore, there is no statistically significant difference between the SDG and NDG dry unit weight results. The Pearson's R^2 correlation value between the two units was determined to be 0.69. Therefore, the correlation is statistically significant.

X2.7.2 NDG versus Standard:

X2.7.2.1 The Pearson's R^2 correlation value between the NDG water content and the oven dry water content was determined to be 0.89. Therefore, the correlation is statistically significant. The error of the NDG water content appears to be an offset, which may explain why the result of the unpaired *t*-test says the two measurements (NDG and oven dry) are not the same, yet the result of the correlation is high.

X2.7.2.2 The Pearson's R^2 correlation value between the NDG dry unit weight and the control dry unit weight was determined to be 0.91. Therefore, the correlation is statistically significant. Since the dominating factor of the dry unit weight



FIG. X2.10 NDG Dry Unit Weight versus NDG Moisture



FIG. X2.11 SDG Dry Unit Weight versus SDG Moisture

calculation for low water contents is wet unit weight, the high correlation is expected.

X2.7.3 General:

X2.7.3.1 In order to give a quick snapshot of the data presented, we can compare the average standard deviation versus the average value of the results for each area tested with both the SDG and the NDG. The average wet unit weight value for the SDG was 136.48 lbf/ft³ with a standard deviation of 2.74 lbf/ft³. For the NDG, the average wet unit weight value was 136.42 lbf/ft³ with a standard deviation of 2.00 lbf/ft³. The

average water content value for the SDG was 7.3 % with a standard deviation of 1.02 % and the NDG had an average water content value of 7.7 % with a standard deviation of 0.52 %. The oven dry results had an average water content value of 6.7 % with a standard deviation of 0.4 %. The standard deviation can be interpreted as a tolerance or uncertainty. Thus we can say that, on the average, the wet unit weight results obtained by the SDG are accurate to within 2.0 %, where the NDG results have a tolerance of about 1.5 %. The percentage of uncertainty was calculated using the average standard



deviation divided by the average wet unit weight result. Clearly, they are both very close, which is reflected in the unpaired *t*-test that was performed. The water content comparison of percentage of uncertainty is not as good but are easily within an order of magnitude of each other. The water content results obtained by the SDG and NDG are accurate to within 14.2 % and 6.1 %, respectively, relative to the average of the oven dry results have a tolerance of

about 5.3 %. However, a water content device should be properly compared to an oven dry test for accuracy. In this case, (and using the same methodology for uncertainty) the SDG result is within 17.6 % of the oven dry result, while the NDG result was within 15.2 % of the oven dry result. This illustrates that for actual water content assessment, they perform about the same.

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(3) Added "intrinsic" before "Impedance" where appropriate.

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D7830/D7830M - 13) that may impact the use of this standard. (November 1, 2014)

(1) Revised Annexes to provide clearer information on calibration and verification.

(2) Replaced photographs of devices in Fig. 1 with a line drawing.

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