Designation: D7698 – 11a

Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method[1]

This standard is issued under the fixed designation D7698; 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 *Purpose and Application*

1.1.1 This test method describes the procedure, equipment, and interpretation methods for estimating in-place soil dry density and water content using a Complex-Impedance Measuring Instrument (CIMI).

1.1.2 CIMI measurements as described in this Standard Test Method are applicable to measurements of compacted soils intended for roads and foundations.

1.1.3 This test method describes the procedure for estimating in-place density and water content of soils and soil-aggregates by use of a CIMI. The electrical properties of soil are measured using a radio frequency voltage applied to soil electrical probes driven into the soils and soil-aggregates to be tested, in a prescribed pattern and depth. Certain algorithms of these properties are related to wet density and water content. This correlation between electrical measurements, and density and water content is accomplished using a calibration methodology. In the calibration methodology, density and water content are determined by other ASTM Test Standards that measure soil density and water content, thereafter correlating the corresponding measured electrical properties to the soil physical properties.

1.1.4 The values stated in SI units are to be regarded as standard. The inch-pound units given in parentheses are mathematical conversions which are provided for information purposes only and are not considered standard.

1.1.5 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026 unless superseded by this standard.

1.2 *Generalized Theory*

1.2.1 Two key electrical properties of soil are conductivity and relative dielectric permittivity which are manifested as a value of complex-impedance that can be determined.

1.2.2 The soil conductivity contributes primarily to the real component of the complex-impedance, and the soil relative dielectric permittivity contributes primarily to the imaginary component of the complex-impedance.

1.2.3 The complex-impedance of soil can be determined by placing two electrodes in the soil to be tested at a known distance apart and a known depth. The application of a known frequency of alternating current to the electrodes enables a measurement of current through the soil, voltage across the electrodes, and the electrical phase difference between the voltage and current waves. Complex-impedance is calculated from these known and measured parameters.

1.2.4 From the determined complex-impedance, an electrical network consisting of a resistor (R) and capacitor (C) connected in parallel are used to represent a model of the soil being tested.

1.2.5 Relationships can be made between the soil wet density and the magnitude of the complex-impedance, and also between the soil water mass per unit measured, and the quotient of the values of C and R using a Soil Model process.

1.2.6 The Soil Model process results in mathematical relationships between the physical and electrical characteristics of the soil which are used for soil-specific calibration of the CIMI.

1.2.7 Refer to Appendix X1 for a more detailed explanation of complex-impedance measurement of in-place soil, and its use in field measurements for the estimation of dry density and water content.

1.3 *Precautions*

1.3.1 The radio frequencies and output power levels of the CIMI method are such that they are harmless according to the Federal Communications Commission (FCC).

[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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1.3.2 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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/ft^3 (600 kN-m/m^3))

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/ft^3 (2,700 kN-m/m^3))

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

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

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

D4944 Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester

D6026 Practice for Using Significant Digits in Geotechnical Data

D7382 Test Methods for Determination of Maximum Dry Unit Weight and Water Content Range for Effective Compaction of Granular Soils Using a Vibrating Hammer

3. Terminology

3.1 Definitions shall be in accordance with the terms and symbols given in Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *complex impedance, n*—the ratio of the phasor equivalent of a steady-state sine-wave or voltage like quantity (driving force) to the phasor equivalent of a steady-state sine-wave current of current like quantity (response) **(1)** . In practice, CIMI uses the magnitude of the impedance ratio (|Z|) in its calculations.

3.2.2 *dielectric properties, n*—see *relative dielectric permittivity* and *dielectric phase angle*.

3.2.2.1 *dielectric phase angle, n*—the angular difference in phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting alternating current having the same period as the voltage.

3.2.2.2 *relative dielectric permittivity, n*—the property that determines the electrostatic energy stored per unit volume for unit potential gradient multiplied by the permittivity of free space **(2)**.

3.2.3 *phase relationship, n*—the electrical phase difference between the applied probe-to-probe radio frequency voltage, and the resulting soil current.

3.2.4 *probe-to-probe voltage, n*—the peak value of radio frequency voltage measured across two probes that are conducting soil current.

3.2.5 *radio frequency, n*—a frequency useful for radio transmission **(1)**.[3]

3.2.6 *soil capacitance, n*—the value of the capacitor in an equivalent parallel resistor-capacitor circuit that results from the probe-to-probe voltage, soil current, and resulting phase relationship due to the application of a radio frequency alternating voltage source applied to the probes.

3.2.7 *soil current , n*—the peak value of the radio frequency current passing through the soil from one probe electrode to another.

3.2.8 *Soil Model, n*—the result of a calibration procedure that establishes a correlating linear function between measured electrical soil properties and measured physical soil properties.

3.2.9 *Soil Model linear correlation function, n*—one of the two mathematical expressions that are derived from performing linear regressions on two sets of soil test data; measured physical soil characteristics, and a corresponding set of electrical measurements made on the soil samples.

3.2.10 *soil resistance, n*—the value of the resistor in an equivalent parallel resistor-capacitor circuit that results from the probe-to-probe voltage, soil current, and resulting phase relationship due to the application of a radio frequency alternating voltage source applied to the probes.

3.2.11 *water mass per unit volume, n*—the mass of water contained in a volume of soil being measured, and is expressed dimensionally as kg/m^3.

4. Summary of the Test Method

4.1 The test method is a two step process.

4.1.1 A Soil Model that relates impedance measurement to the density and water content of the soil is developed. In this step the electrical measurements are collected at locations that have various water contents and densities typical of the range to be expected. Concurrent with collecting the electrical data, determination of density and water content are performed at the same locations using one or more of the traditional test methods, such as Test Methods D1556 and D2216. The process is repeated over the site sufficiently that a range of water contents and densities are obtained. The combined data (impedance and density/water content) will generate the correlating linear regression functions of the Soil Model.

[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.

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

4.1.2 Once the Soil Model has been developed the CIMI device is used to make electrical measurements of the soil at locations of unknown density and water content. Using the Soil Model linear correlation functions, the procedure then estimates the values of soil density and water content based on the measured electrical properties.

5. Significance and Use

5.1 The test method is a procedure for estimating in-place values of density and water content of soils and soil-aggregates based on electrical measurements.

5.2 The test method may be used for quality control and acceptance testing of compacted soil and soil aggregate mixtures as used in construction and also for research and development. The minimal disturbance nature of the methodology allows repetitive measurements in a single test location and statistical analysis of the results.[4]

5.3 *Limitations:*

5.3.1 This test method provides an overview of the CIMI measurement procedure using a controlling console connected to a soil sensor unit which applies 3.0 MHz radio frequency to an in-place soil via metallic probes are driven at a prescribed distance apart. This test method does not discuss the details of the CIMI electronics, computer, or software that utilize on-board algorithms for estimating the soil density and water content

5.3.2 It is difficult to address an infinite variety of soils in this standard. This test method does not address the various types of soils on which the CIMI method may or may not be applicable. However, data presented in X3.1 provides a list of soil types that are applicable for the CIMI use.

5.3.3 The procedures used to specify how data are collected, recorded, or calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures prescribed in this standard do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analytical methods for engineering design.

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 The accuracy of the results obtained by this test method may be influenced by poor contact between the soil electrical probes and the soil being tested. Large air voids, relative to the volume of material being tested, that may be present between soil probes and the surface of the material being tested may cause incorrect density measurements. The shape of the soil electrical probe is important to the quality of the electrical measurements collected by the CIMI.

6.3 When driving the measuring electrical probes, it is critical to the accuracy of the measurement that they make a complete and tight contact with the soil over the entire conical part of the probe.

6.4 If the volume of soil material being tested as defined in X2.10 has oversize particles or large voids in the electrical field, this may cause errors in measurements of electrical properties. Where lack of uniformity in the soil due to layering, aggregate or voids is suspected, the test site should be excavated and visually examined to determine if the test material is representative of the in-situ material in general and if an oversize correction is required in accordance with Practice D4718. Soils must be homogeneous and practically free of rocks that are in excess of five centimeters in diameter and construction debris for the most accurate results.

6.5 Statistical variance may increase for soil material that is significantly drier or wetter than optimum water content (2.5 % over optimum or 6.0 % below optimum) as determined using Test Methods D698 or D1557. Statistical variance may increase for soil material that is compacted to less than 88 % of the maximum dry density as determined using Test Methods D698 or D1557. The CIMI is generally more accurate when the Soil Model range is broader than the range of soil density and water content being tested in the field.

6.6 If temperature measurements are not used, an error may be introduced in the results depending on the value of the difference between the temperature of the soil used for the Soil Model and the unknown in-place soil being measured. All electrical values are equilibrated to 15.55 °C. The equilibration is necessary because the soil temperature affects the electrical signals that are measured.

6.7 This test method applies only to non-frozen soil. The electrical properties of soil change considerably as soil temperature approaches the freezing point of the entrained water.

6.8 The use of electrical probes with different length than those used to make the soil mode will introduce an error in the interpretation of the data and the estimation of the density of water content of the tested soils.

6.9 The use of a Soil Model that was generated from a different soil than that selected for unknown in-place measurements will result in errors in the estimation of the density and water content of the tested soils.

6.10 Attempts to measure unknown in-place soils with a Soil Model that was generated from a limited range of wet density or water content values, or both, may result in density and water content estimation errors.

6.11 Variation in pore water salinity, soil chemistry, soil mineralogy or other anomalies that causes field-test electronic

[4] Notwithstanding the statements on precision and bias contained in this test method, the precision of this 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 criteria of Practice D3740 are generally considered capable of competent and objective testing. Users of this test method are cautioned that compliance with Practice D3740 does not in itself ensure reliable results. Reliable testing depends on many factors; Practice D3740 provides a means of evaluating some of those factors.

measurements to be outside the soil model operational range will cause the CIMI to report a warning message. X2.1 contains additional information regarding variation in electrical measurements and CIMI management techniques.

7. Apparatus

7.1 *Complex-Impedance Measuring Instrument (See Fig. 1)*—While exact details of construction of the apparatus and the electric circuits therein may vary, the system shall consist of the following:

7.1.1 *Soil Sensor Unit*—The "Soil Sensor" is a component of the CIMI which electronically combines the Frequency source and the three measurement devices. Cables are used to connect the Soil Sensor to the electrical probes.

7.1.1.1 *Radio Frequency Source*—Typically a 3 MHz frequency source is applied to the soil under test by probe type electrodes driven into the in-place soil at a prescribed depth and spacing. The radio frequency current that passes through the soil electrical probes into the soil and the voltage that appears across the soil electrical probes are measured. Additionally the electrical phase relationship between the soil current and the probe-to-probe voltage is determined.

7.1.1.2 *Ammeter*—Means for measuring the soil current.

7.1.1.3 *Voltmeter*—Means for measuring the probe-to-probe voltage.

7.1.1.4 *Phase Difference Meter*—Means for measuring the phase difference between the probe-to-probe voltage and soil current.

7.1.1.5 *Connecting Cables*—For connecting the electrical sensors (that is, ammeter, voltmeter, and phase difference meter) to the soil electrical probes and to the display console.

7.1.2 *Display Console Unit*

7.2 *Soil Electrical Probes (Four Required, Equally Dimensioned)*—Of electrical conducting material suitable for driving into compacted material, typically constructed of common or stainless steel.

7.2.1 The length of soil electrical probes can vary typically having embedment lengths between 101.6 mm [4 in.] and 304.8 mm [12 in.] and diameters between 6.35 mm [¼ in.] and 12.7 mm [½ in.]. Since a portion of the probe must be above the surface to facilitate electrical clip connector, the desired embedment depth must be clearly indicated with a scribed mark or change in geometry.

7.3 A *template* should be used to place the electrodes as they are driven into the soil. The four probes are driven into the soil at the 0°, 90°, 180°, and 270° in clockwise positions around the periphery of the template.

7.4 *Thermistor* temperature probe that connects to the CIMI for soil temperature measurement, and resulting compensation of calculated electrical soil parameters.

7.5 *Hand Tools*—Hand tools for driving and retrieving the soil electrical probes. A 6- to 10-lb dead blow or brass-faced hammer is used to avoid damaging the steel probes.

7.6 Other components of the system are:

7.6.1 *Safety goggles*, and

7.6.2 *Software* with which to download and process the data.

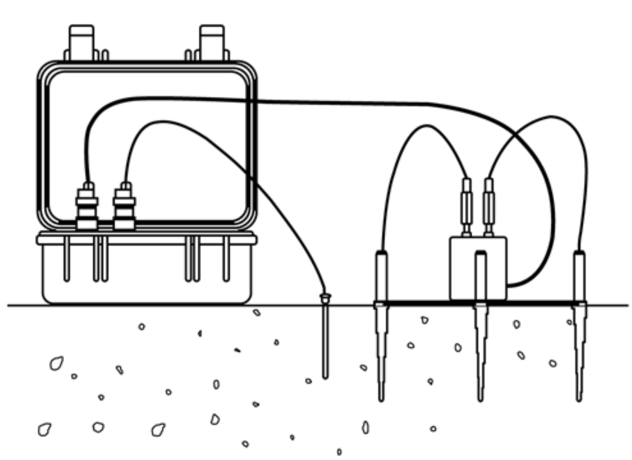
8. Calibration and Standardization

8.1 For a soil type that has not yet been modeled, a Soil Model must be generated. Refer to Section 9 for details on how the testing is performed.

8.2 Determine the test method(s) that will be used in conjunction with developing the Soil Model through calibration. For example, one or more of the test methods cited in 2.1. Assemble the equipment required for each test method.

8.3 Obtain a representative sample of soil from the site where in-place testing is conducted or from the borrow area planned as a source of material. The sample should be of sufficient amount of soil for at least five compaction specimens, typically about 20 Kg (44 lb). For materials with maximum particle size less than 5 cm (No. 4) sieve with a 5-cm screen. More material may be required if ancillary testing is planned, such as Atterberg limits, particle size analysis, etc.

8.4 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



NOTE 1—The wires crossing in the diagram are not touching each other during use to prevent parasitic capacitance.

FIG. 1 Diagram of a CIMI in Use

maximum dry density or Test Methods D4253 or D7382 for predominately granular material.

8.5 Determine the depth of investigation required for the job and select the electrical probes with length equal to the depth of investigation. These same length probes must be used for both creating the Soil Model and for testing at the Job Site.

8.6 Select areas on the Job Site where the type of soil is consistent from place to place, and where there are differences in water content and compaction. Special preparation of spots of different densities or water contents should be done the day before, so as to allow stabilization of the soil water content.

8.7 A matrix of six (6) spots should be used during the calibration procedure, consisting of two different soil density conditions and three (3) water content conditions that cover the range that is expected to be measured. The three calibration tests that evaluate high density soil will use test locations that ideally will have soil conditions that are close to the maximum density as determined by Test Methods D1557 or an equivalent method. The range in water content should include low water content, middle range water content, and high water content that is near the optimum water content as determined by Test Methods D1557 and D2216 or equivalent test methods.

8.7.1 A four spot Soil Model matrix will result in the development of a Soil Model with an accuracy that will typically be less than the six-spot matrixes, and a nine-spot soil matrix will only slightly increase the accuracy of the Soil Model over that of the six-spot Soil Model matrixes. The four-spot Soil Model matrixes should have variation of two density conditions and two water content conditions, wherein the high density and high water content should be performed in soil that is near the maximum density and optimum water content as determined by Test Methods D1557 or an equivalent test method. The nine-spot Soil Model should have variation of three density conditions and three water contents, wherein the high density-high water content should be performed in soil that is near the maximum density and optimum water content as determined by Test Methods D1557 or an equivalent test method.

8.8 Be sure the spot does not contain large rocks or construction debris, and level the surface before testing.

8.9 Drive a large nail or small screwdriver into the soil near the test spot and insert the temperature probe at least 2 in.

8.10 Perform electrical tests with the CIMI on the selected Soil Model spots as prescribed in 9.4 – 9.7. Determine in-place wet density with physical means, such as Test Methods D1556, or an equivalent test method. Remove soil samples from the spot tested and perform an oven-dry moisture test as specified in Test Method D4643, Test Method D4944, or an equivalent test, to determine the water content.

8.11 Enter these physical data into the CIMI Console to associate them with the earlier electrical readings. The console will have the capability to perform an error analysis on the resulting Soil Model.

9. Procedure

9.1 Before testing a Job Site, the Soil Model for the soil type to be tested must be associated with that site, using the appropriate menu on the console display.

9.2 Prepare the test spots by leveling the surface, and checking for foreign debris, such as metal scraps or asphalt.

9.3 Drive a large nail or small screwdriver into the soil near the test spot and insert the temperature probe at least half the length of the probe into the ground.

9.4 Using the template, drive the 4 electrical probes into the spot so they are solid in place and driven to the proper depth. Soil probes must enter the soil in nearly perpendicular direction (not more than 20° from perpendicular) to the surface of the soil under test. The soil probes should be driven to the full depth of the conical section of each probe. If rocks are encountered during the process of driving the probes into the ground that result in refusal or deviation of greater than 20°, then the operator should abandon the test site and move to another location that is close by.

9.5 Place the Soil Sensor (pins up) in the center of the template and connect the cables to two of the probes that are diametrically opposite. The cables must be away from each other and run straight to the probes. If a probe is loosened when attaching the cable, tap it with the hammer to seat it solidly.

9.6 Turn on the Console and create or select the Job Site to be tested.

9.7 Perform the test for the collection of the electrical data with the four electrical probes as outlined in the procedural instructions for the CIMI. The test will include measurement from both sets of electrical probes, wherein a set of the probes are across from each other.

9.8 The Console will calculate dry density, water content, and percent compaction automatically for display.

9.9 Observe and record dry density, water content, and percent compaction.

9.10 Record latitude and longitude of the testing site, if required.

9.11 Download to the data analysis software as required.

10.

10.1 Using the electrical measurements made at the Soil Model test spots, the electrical **impedance** is computed by the quotient of the value of the voltage applied to the soil, and the resulting current through the soil without regard to the phase difference.

$$Z = \frac{V}{I} \quad (1)$$

where:

Z = impedance
V = Voltage, and
I = Current.

10.2 The **impedance** is temperature compensated using an empirically determined procedure.

10.3 A Linear Regression Analysis is performed with the physically determined wet density obtained in the Soil Model process, and the calculated and temperature-compensated **impedance**. Fig. 2 shows a graphical representation of the linear regression that relates the soil impedance to the estimated soil wet density.

10.4 A parallel-circuit combination of a resistor (**R**) and capacitor (**C**) can be used to express the equivalent electrical characteristics of soil. These values are calculated by solving simultaneous electrical equations using voltage, current, and phase.

10.5 The ratio **C/R** is temperature compensated using an empirically determined procedure.

10.6 A Linear Regression Analysis is performed using the physically determined water mass per unit volume obtained in the Soil Model Process, and the temperature compensated ratio **C/R**. Fig. 3 shows a graphical representation of the linear regression that relates the ratio of the capacitance over the resistance to the calculated water content.

10.7 When testing an unknown in-place soil type, the electrical measurements are used first to calculate impedance, then to calculate **C/R** as was done in the Soil Model procedure. These factors are then temperature compensated.

10.8 The wet density is calculated using the temperature-compensated impedance of the unknown in-place soil using the appropriate regression equation that was determined in the Soil Model process.

10.9 The water mass per unit volume [kg/m^3] in the unknown in-place soil is also calculated with the temperature compensated **C/R**, using the appropriate regression equation developed in the Soil Model.

10.10 The dry density of the unknown in-place soil is determined by taking the difference of the wet density and the water mass per unit volume as determined from the Soil Model regression equations.

$$\rho_{dry} = \frac{\rho_{wet}}{1 + \frac{W}{100}} \quad (2)$$

where:

ρ_{dry} = dry density,
ρ_{wet} = wet density, and
W = water content.

10.11 The water content is calculated by obtaining the quotient of the water mass per unit volume and the dry density, expressed as a percentage.

$$W\% = \frac{100 \times water\ mass\ per\ unit\ volume}{\rho_{dry}} \quad (3)$$

where:

$W\%$ = percent water content.

10.12 The percent compaction is calculated by obtaining the quotient of the measured dry density and the maximum dry density, expressed as a percentage as determined by Test Methods D698 or D1557.

$$\%\ compaction = 100\ \frac{\rho_{dry}}{max\ \rho_{dry}} \quad (4)$$

where:

% compaction = soil relative compaction as related to the maximum dry density of the soil as determined by Test Methods D698 or D1557.

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 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 Soil Model used.
11.1.8 Length of electrical probes used during testing.
11.1.9 Weather conditions.
11.1.10 Any corrections made in the reported values and reasons for these corrections (that is, over-sized particles, Water Content).
11.1.11 Maximum laboratory density.
11.1.12 Dry density.
11.1.13 Wet density.
11.1.14 Water content in percent.
11.1.15 Percent 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, 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.
11.2.7 Dry density.
11.2.8 Percent compaction.
11.2.9 Name of Operator(s).

12. Precision and Bias

12.1 *Precision*—Test data on precision are not presented due to the nature of this standard 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. ASTM 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.

12.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

13. Keywords

13.1 capacitor; compaction; complex-impedance; current; dielectric permittivity; dry density; impedance magnitude; percent compaction; phase; radio frequency; resistor; water content; water mass per unit volume; wet density; voltage

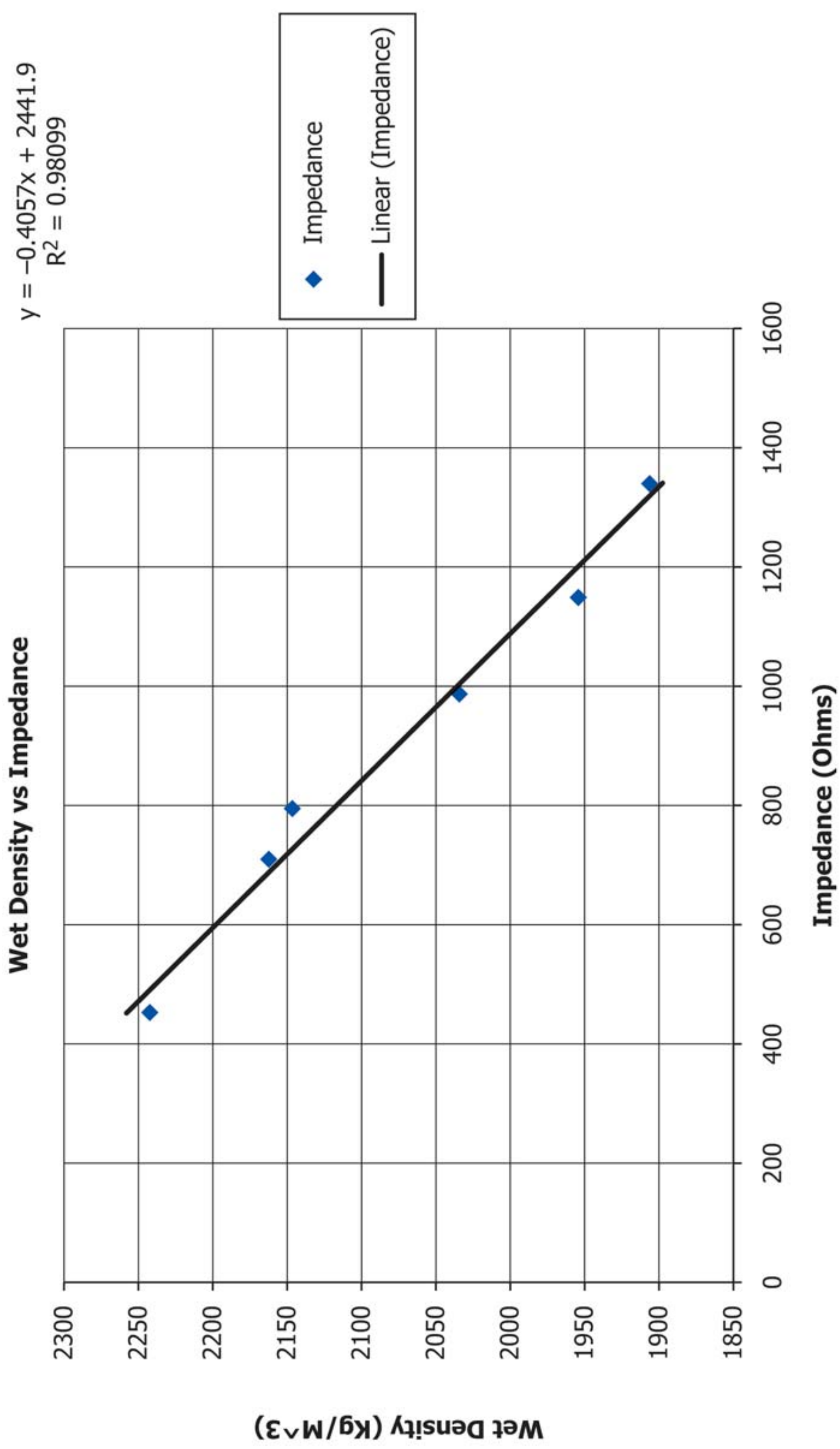


FIG. 2 Typical Values of Wet Density Vs. Impedance (Regression Equation Upper Right)

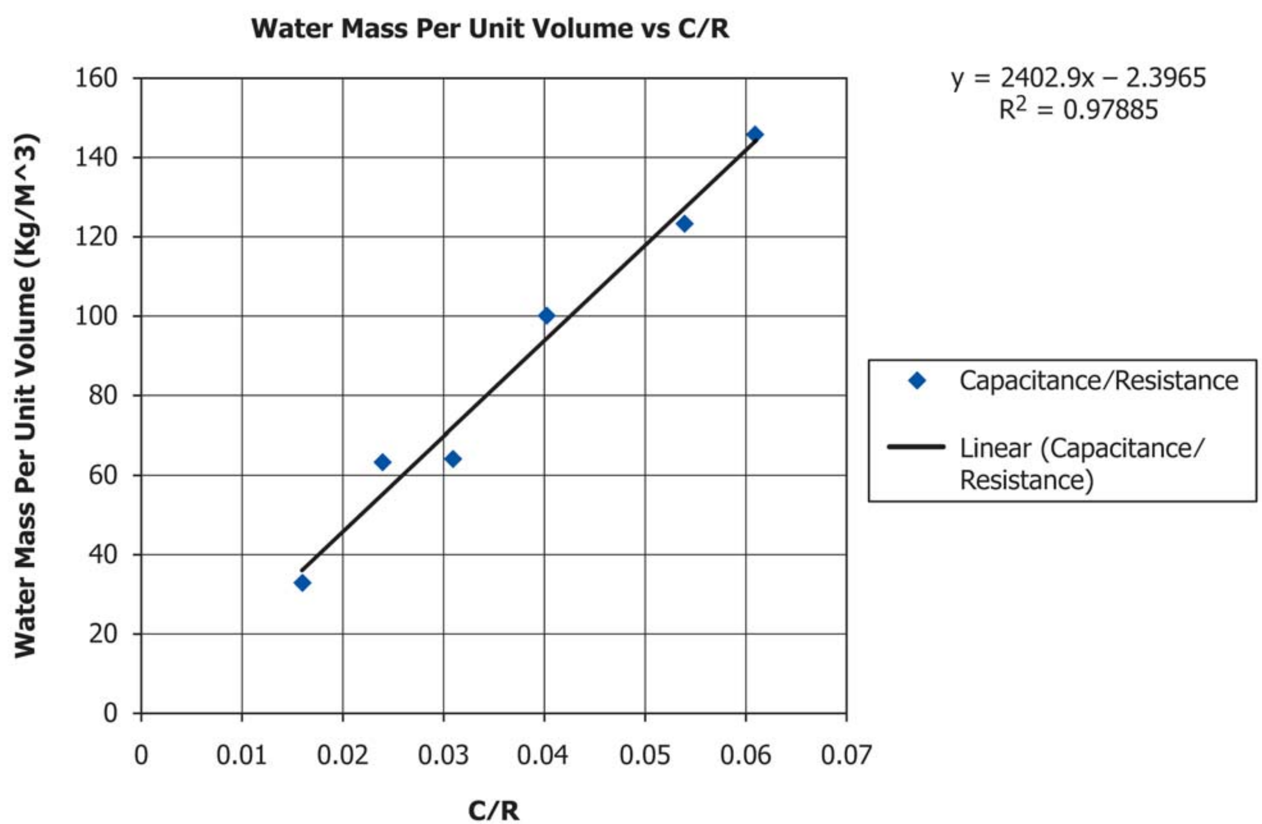


FIG. 3 Typical Values of Water Mass Per Unit Volume Vs. C/R (Regression Equation Upper Right)

APPENDIXES

(Nonmandatory Information)

X1. COMPLEX IMPEDANCE MEASURING INSTRUMENT DETAILED THEORY

X1.1 Soil, as measured, can be electrically characterized by a circuit consisting of a parallel Resistor and Capacitor combination (R-C). The value of the complex-impedance of the R-C network can be measured, and is dependent upon the soil properties, the sensing electrode array, and the measurement frequency. The characteristic R and C values are thus determined from the measured impedance.

X1.1.1 Using metallic probes of specified length and spacing driven into the soil, CIMI applies a 3.0 MHz radio frequency voltage to the soil under test, and measures the voltage across the probes, the current through the soil, and the phase difference between the current and voltage waves. The 3.0 MHz frequency has been shown to work well. Other frequencies could also be used effectively to derive similar accurate results.

X1.1.2 Impedance magnitude (|Z|) is determined by calculating the quotient of the voltage across the probes in the soil and the current passing through the soil.

X1.1.3 The values of equivalent soil R and C are calculated from the three measured parameters, phase difference, voltage across the soil, and current through the soil.

X1.2 As soil density and water content are changed, the equivalent soil values for R, C, and |Z| will be affected.

X1.2.1 The equivalent soil resistance will decrease as water content increases and as soil is compacted. (Assumes the soil is below its water saturation point).

X1.2.2 The equivalent soil capacitance will increase as water content increases and as the soil is compacted. (Assumes the soil is below its water saturation point).

X1.2.3 The impedance magnitude will decrease as soil is compacted and as water content increases. (Assumes the soil is below its water saturation point).

X1.3 CIMI employs two relationships between the physical and electrical properties that permit the calculation of dry density and water content.

X1.3.1 The wet density of soil is inversely proportional to the impedance magnitude (|Z|). During the soil calibration process, a regression analysis on the Soil Model data is performed resulting in an equation that describes this relationship.

X1.3.2 The water mass per unit volume measured is directly proportional to the quotient of equivalent soil capacitance and equivalent soil resistance (**C/R**). During the soil calibration process, a regression analysis on the Soil Model data is performed resulting in an equation that describes this relationship.

X1.3.3 When testing calibrated soil in the field, water mass per unit volume measured is determined using the appropriate regression equation for the **C/R** quotient.

X1.3.4 When testing calibrated soil in the field, wet density is determined using the appropriate regression equation for the measured |Z|.

X1.3.5 Dry density is determined by subtracting the water mass per unit volume measured from the soil wet density.

X1.3.6 Soil water content is the ratio of water mass per volume measured and dry density, expressed as a percentage.

X2. COMPLEX IMPEDANCE MEASURING TECHNOLOGY CONCEPTS

X2.1 The Soil Model process is used to gather data about the relationship of soil electrical properties as correlated to the soil physical properties for the soil type that is the subject of the field testing. The soil's physical properties, pore water salinity, mineralogy, chemistry, or combinations thereof, all affect the electrical measurements as the Soil Model procedure is conducted, and the measured variation of electrical properties are used to establish the limits for the operational range of the Soil Model. The salinity of the construction water that is used as the wetting agent during compaction of a soil foundation is an important factor in the electrical properties of the soil. The field Soil Model development and the subsequent field test rely on having consistency in the physical and electrical properties and therefore the construction water used at project site for moisture conditioning and compaction should be of equivalent chemistry and salinity as that used while creating the Soil Model, preferably from a single source. A Complex Impedance Measuring Instrument (CIMI) user may evaluate the chemistry of the Soil Model sites and the field test sites for consistency. When a set of soil locations with differing wet densities and water contents are physically and electrically measured in-place and the impedance calculated, a regression analysis is performed on the wet density data versus the corresponding electrical values of impedance. This analysis results in one of the two equations that are used to determine the dry density and water content of unknown in-place subject soil. During field testing of the subject soil, the electrical measurements are compared with electrical properties of the Soil Model. If the measured electrical properties of the subject soil are greater than or less than the operational range of the Soil Model, then the CIMI displays an error message when values exceed ± 10 % of the model parameters reporting the field test measurements are outside the operational range of the Soil Model. Research shows that this method works well, although other criteria could be used to limit the effective range of a Soil Model.

X2.2 From a large Soil Model data base, it has been found empirically, that there is an effective correlation between the water mass per unit volume and the quotient of the equivalent electrical capacitance and equivalent electrical resistance (**C/R**) of a soil sample.

X2.3 A regression analysis is performed using the Soil Model data points for water mass per unit volume versus the respective electrical **C/R** values. The resulting equation enables calculation of the water mass per unit volume, which is the other half of the data necessary to determine dry density and water content for unknown in-place soils of the Soil Model type.

X2.4 Since the soil impedance parameters are temperature sensitive, soil temperature is measured with a thermistor type temperature probe.

X2.5 When an in-place soil is tested, a radio-frequency field is applied to the soil by the measuring probes. The radio-frequency current through and the radio-frequency voltage across the soil are measured. Impedance is calculated from the ratio of the voltage and current. The soil wet density is calculated from the temperature-compensated impedance using the first regression equation.

X2.6 The phase difference between voltage and current is measured. Using voltage, current, and phase difference, values are calculated for the equivalent parallel resistor-capacitor combination. The water mass per unit volume is calculated from the temperature compensated value of the **C/R** ratio using the second regression equation.

X2.7 Dry density is calculated by taking the difference between the wet density and water mass per unit volume.

X2.8 Water content is the ratio, expressed as a percentage, of the water mass per unit volume to the dry density.

X2.9 Percent compaction results from the ratio of the calculated dry density and the derived maximum dry density using Test Methods D698 or an equivalent test method.

X2.10 Measurement depth is determined by the length of the probes used when measuring the unknown in-place soil. The volume of soil or aggregate material being tested by a CIMI is approximately equivalent to the solid geometry of a cylinder, where the diameter is equal to the spacing of the electronic probes and the height is equal to the length of the electronic probes. Use of four probes ensures that an average of the entire volume is obtained.

X3. COMPLEX IMPEDANCE MEASURING INSTRUMENT TEST DATA

X3.1 The CIMI was compared to a nuclear density gauge in various construction soil materials. The data was collected over a three-year period primarily in Nevada and eastern California. 230 tests were compiled in the data set that included 34 test sites where the soil was tested. A Unified Soil Classification list of the soils that were tested is presented below. Soil types varied from aggregate road base to fine grain soils with moderate clay content. The CIMI was field calibrated for each of the soil using a nuclear density gauge to generate the in-place soil density and water content. The CIMI was then compared to the field results of the tests performed on the soil again using the nuclear density gauge. Using a one sigma standard deviation, comparing CIMI density readings with Nuclear gauge density readings results in 68 % of the CIMI readings being between ± 2.65 % of the Nuclear gauge readings. 14 tests were greater than ± 5 % difference in estimated densities between the CIMI and the nuclear density gauge results. The one sigma standard deviation, comparing CIMI water content readings with Nuclear gauge water content readings results in 68 % of the CIMI readings being between ± 1.55 % of the Nuclear gauge readings. Five tests were greater than plus or minus five percent difference in water content between the CIMI and the nuclear density gauge results. These data are available on file with the ASTM[5] and are depicted graphically in Fig. X3.1 and Fig. X3.2.

[5] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D18-1019.

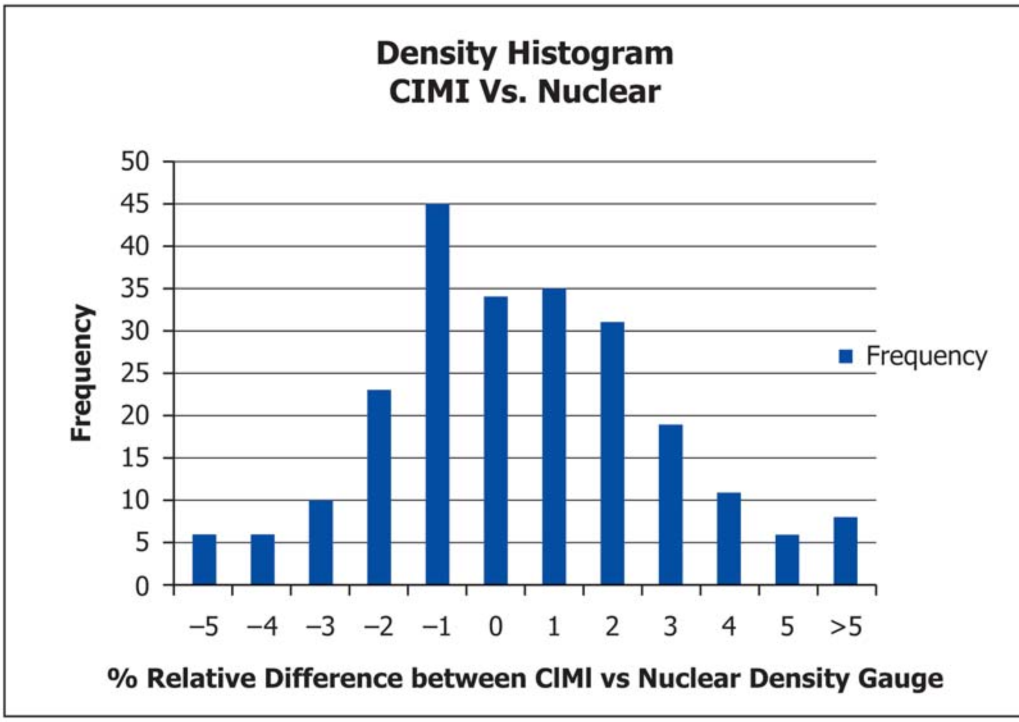


FIG. X3.1 Density Histogram

X4. COMPLEX IMPEDANCE MEASURING INSTRUMENT INDEPENDENT RESEARCH DATA

X4.1 In 2007 the Vermont Agency of Transportation tested the CIMI on several materials ranging between borrow sand and 3.8 cm [1.5 in.] diameter coarse aggregate to evaluate the relative differences. This study showed good correlation between the CIMI and the nuclear density gauge. The data and graphical interpretations of the data are available from the Vermont Agency of Transportation.[6]

[6] *Non-Nuclear Compaction Gauge Comparison Study (Final Report—2008)*: http://www.aot.state.vt.us/matres/RandDProjectsReports.htm. Available from the Vermont Agency of Transportation, One National Life Drive, Montpelier, VT 05633-5001.

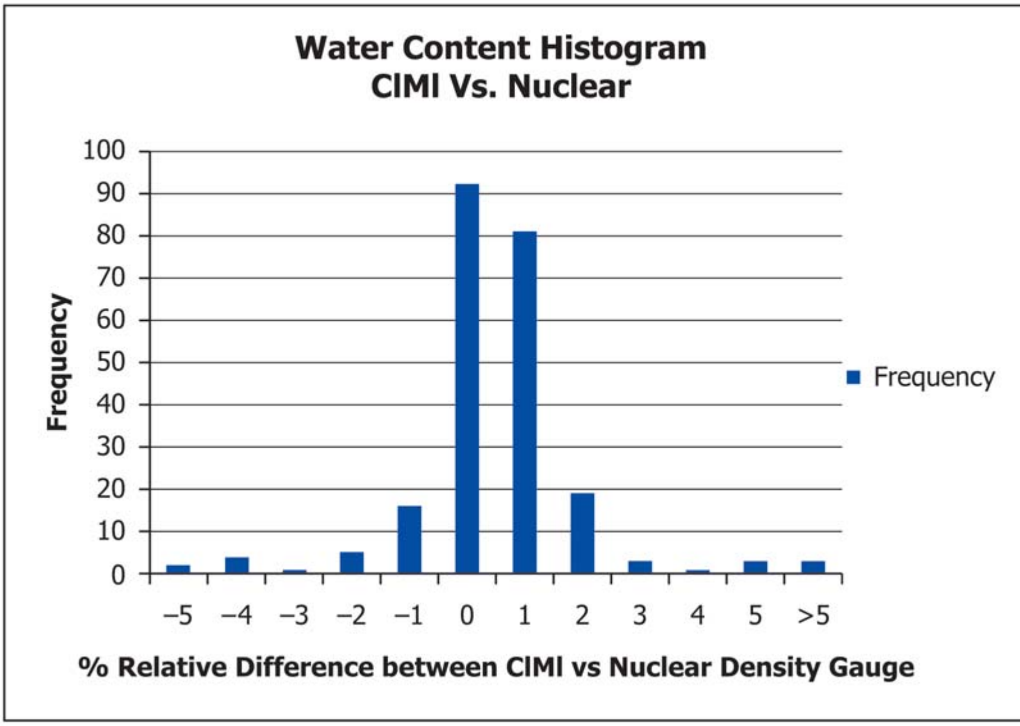


FIG. X3.2 Water Content Histogram

34		Total Soil Testing Sites: 230 field tests
2	Soil ″GM-SP″	6 %
7	Soil ″GW-GM″	21 %
7	Soil ″GC-CL″	21 %
3	Soil ″GM″	9 %
3	Soil ″SW-SM″	9 %
3	Soil ″SC-SM″	9 %
7	Soil ″GM-GW″	21 %
1	Soil ″OL-OH″	3 %
1	Soil ″SW-SM″	3 %
		100 %

REFERENCES

(1) Institute of Electrical and Electronics Engineers Standards 100, 1972

(2) Sears & Zemansky, *University Physics*, 10th Edition