Designation: D6780/D6780M – 12

Standard Test Method for Water Content and Density of Soil In situ by Time Domain Reflectometry (TDR)[1]

This standard is issued under the fixed designation D6780/D6780M; 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 may be used to determine the water content of soils and the in situ density of soils using a TDR apparatus.

1.2 This test method applies to soils that have 30 % or less by weight of their particles retained on the 19.0-mm [¾-in.] sieve.

1.3 This test method is suitable for use as a means of acceptance for compacted fill or embankments.

1.4 This test method may not be suitable for organic and highly plastic soils.

1.5 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.5.1 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

1.6 Two alternative procedures are provided.

1.6.1 *Procedure A* involves two tests in the field, an in situ test and a test in a mold containing material excavated from the in situ test location. The apparent dielectric constant is determined in both tests.

1.6.2 *Procedure B* involves only an in situ test by incorporating the first voltage drop and long term voltage (V_1 and V_f) in addition to the apparent dielectric constant. While the bulk electrical conductivity can be determined from these measurements, it is not needed for the determination of water content and density.

1.7 The values stated in either SI units or inch-pound units 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. For additional information consult SI10.

1.8 *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))

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

D4753 Guide for Evaluating, Selecting, and Specifying Balances and Standard Masses for Use in Soil, Rock, and Construction Materials Testing

D6026 Practice for Using Significant Digits in Geotechnical Data

D6565 Test Method for Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method (Withdrawn 2014)[3]

E1 Specification for ASTM Liquid-in-Glass Thermometers

SI10 Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions*—Refer to Terminology D653 for standard definitions of terms.

[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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *apparent dielectric constant, $K_{in\ situ}$, K_{mold}*—the squared ratio of the velocity of light in air to the apparent velocity of electromagnetic wave propagation in the soil measured by a TDR apparatus in situ and in the cylindrical mold, respectively.

3.2.2 *apparent length, l_a*—on a plot of electromagnetic wave signal versus scaled distance measured by a TDR apparatus as shown in Fig. 1, it is the horizontal distance between the point on the waveform due to the reflection from the surface of the soil where the probe is inserted into the soil to the point on the waveform due to the reflection from the end of the probe.

3.2.3 *bulk electrical conductivity, EC_b*—electrical conductivity is a measure of how well a material accommodates the transport of electric charge. Its SI derived unit is Siemens per meter (S/m). As an electromagnetic wave propagates along TDR probed buried in soil, the signal energy is attenuated in proportion to the electrical conductivity along the travel path. Determination of bulk electrical conductivity is illustrated in Fig. 1.

3.2.4 *coaxial head, CH*[4]—a device that forms a transition from the coaxial cable connected to the TDR apparatus to the Multiple Rod Probe or to a Cylindrical Mold Probe.

3.2.5 *cylindrical mold probe, CMP*[4]—a probe formed by a cylindrical metal mold as the outer conductor having a non-metallic end plate, filled with compacted soil, and with an inner conductor consisting of a rod driven into the soil along the axis of the mold.

3.2.6 *first voltage drop, V_1*—it is the vertical distance (voltage) between the point on the waveform due to the reflection from the surface of the soil where the probe is inserted into the soil to the point on the waveform due to the reflection from the end of the probe, as illustrated in Fig. 1.

3.2.7 *long term voltage, V_f*—the long term voltage as illustrated in Fig. 1.

3.2.8 *multiple rod probe, MRP*[4]—a probe formed by driving four rods of equal length into the soil in a pattern where three of the rods define the outer conductor of a "coaxial cable" and one of the rods is the inner conductor.

3.2.9 *probe length, L*—the length of the TDR probe that is below the surface of the soil.

3.2.10 *scaled distance, l*—the product of the velocity of light in air and electromagnetic wave travel time in the soil divided by two.

3.2.11 *source voltage, V_s*—the source voltage and equal to twice the step voltage generated by the TDR.

3.2.12 *TDR internal resistance, R_s*—the internal resistance of the TDR's pulse generator (generally 50 ohms).

[4] The apparatus is covered by patents. Interested parties are invited to submit information regarding the identification of alternative(s) to this patented item to the ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

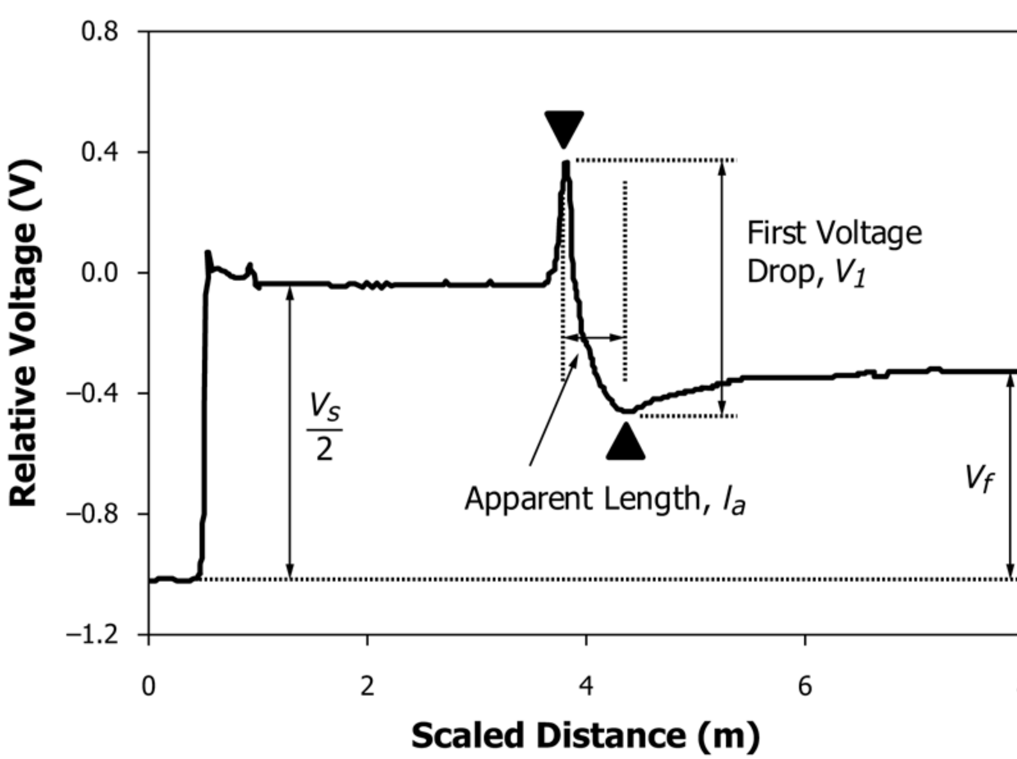


FIG. 1 Typical TDR Waveform for Soil Showing Measurements to Obtain Apparent Dielectric Constant, K_a, Bulk D.C. Electrical Conductivity, EC_b, First Voltage Drop, V_1, and Long Term Voltage, V_f .

4. Summary of Test Method

4.1 *Procedure A*[5]—The dielectric constant of the soil in situ is determined using a multiple rod probe (*MRP*), a coaxial head (*CH*), and TDR apparatus. The soil at the location of the in situ measurement is then excavated and compacted in a mold. By measurement of the mass of the mold and soil and with the mass and volume of the mold known, the wet density of the soil in the mold is determined. A rod driven into the soil along the axis of the mold creates a cylindrical mold probe (*CMP*). Using the same coaxial head (*CH*), an adapter ring, and the TDR apparatus the dielectric constant of the soil in the mold is measured. The water content of the soil in the mold is determined using a correlation between the dielectric constant, moisture content and soil density. The correlation requires two constants that are somewhat soil specific. It is assumed that the water content of the soil in situ is the same as the water content in the mold. The density of the soil in situ is determined from the density of the soil in the mold and the dielectric constants measured in the mold and in situ.

4.2 *Procedure B*[5]—The apparent dielectric constant of the soil in situ, first voltage drop and long term voltage (V_1 and V_f) are determined using a multiple rod probe (*MRP*), a coaxial head (*CH*), and TDR apparatus. The water content and density of the soil in situ are determined from the measured apparent dielectric constant, V_1, V_f and five constants. The five soil constants are soil and in situ pore fluid dependent. The five soil constants are determined in conjunction with laboratory compaction procedures using specified compaction procedures, for example, Test Method D698, and by taking measurements of the apparent dielectric constant, V_1 and V_f for each compaction point.

5. Significance and Use

5.1 This test method can be used to determine the density and water content of naturally occurring soils and of soils placed during the construction of earth embankments, road fills, and structural backfills.

5.2 Time domain reflectometry (TDR) measures the apparent dielectric constant (Procedure A) and the apparent dielectric constant, first voltage drop and long term voltage (V_1 and V_f) (Procedure B) of soil. The apparent dielectric constant is affected significantly by the water content and density of soil, and to a lesser extent by the chemical composition of soil and pore water, and by temperature. The first voltage drop and long term voltage (V_1 and V_f) are affected significantly by the water content, density, and the chemical composition of the in situ pore water, and to a lesser extent the chemical composition of the soil solids. This test method measures the gravimetric water content and makes use of a different relationship between the electrical properties and water content from Test Method D6565 which measures the volumetric water content.

5.3 Soil and pore water characteristics are accounted for in Procedure A with two calibration constants and for Procedure B with five calibration constants. The two soil constants for Procedure A are determined for a given soil by performing compaction tests in a special mold as described in Annex A2. The five soil constants for Procedure B are determined in conjunction with compaction testing in accordance with specified compaction procedures, for example, Test Method D698 as described in Annex A3. Both Procedures A and B use Test Method D2216 to determine the water contents.

5.4 When following Procedure A, the water content is the average value over the length of the cylindrical mold and the density is the average value over the length of the multiple-rod probe embedded in the soil. When following Procedure B, the water content and density is the average values over the length of the multiple-rod embedded in the soil.

NOTE 1—The quality of the result produced by this standard 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/sampling/inspection/etc. 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 evaluating some of those factors.

6. Interferences

6.1 Quality and accuracy of the test results significantly depend on soil having contact with the inner conductor of the probes. To assist this, when installing the rods of the *MRP*, the rod that forms the inner conductor must be the last rod installed. If in the installation process, the rod hits upon a large particle that causes it to drift from vertical alignment, all rods should be removed and the test conducted in a new location at least 0.2-m [8-in.] from the previous test location.

6.2 The quality of the signal read by the TDR apparatus depends on having clean contacts between the *CH* and the *MRP* and the *CMP*. The contacting surfaces should be wiped with a clean cloth prior to placing the *CH* on the *MRP* and the *CMP*. Once placed, observe the signal on the TDR apparatus. If the characteristic signal is not present, the *CH* may have to be slightly rotated about its axis to make better contact.

6.3 This test method only applies to non-frozen soil. The apparent dielectric constant is slightly temperature dependent for soils and depends on soil type. For soil temperatures between 15°C and 25°C [59°F and 77°F], no temperature corrections are needed for most soils. A simple temperature adjustment for water content determination is part of the test method.

7. Apparatus

7.1 *TDR Apparatus,* a Metallic Time Domain Reflectometer with a scaled length resolution of at least 2.4-mm [0.10-in.] (this corresponds approximately to a time between data points less than or equal to sixteen picoseconds (16×10^{-12} s). A portable computer with a communication port to the TDR is suggested for controlling the apparatus, acquiring and saving the data, and for making the calculations as the test proceeds.

7.2 *Multiple Rod Probe (MRP)*[4] with Coaxial Head (CH)[3]

[5] The apparatus and procedures are covered by patents and pending patents. Interested parties are invited to submit information regarding the identification of alternative(s) to these patented items to the ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

7.2.1 The *MRP* consists of four common steel spikes, typically 250-mm [10-in.] in length and uniform diameters of 9.5-mm [3⁄8-in.]. (Other length spikes, but with the same diameter, may be used but in no case should they have lengths less than 150-mm [6-in.]. For lengths longer than 250-mm [10-in.], drift in the alignment of the spikes and loss of reflected signal from the end of the *MRP* may occur.)

7.2.2 A *MRP* guide template (see Fig. 2) is used to guide the spikes as they are driven into the soil. The template must allow for its removal after the spikes are driven and before a TDR measurement is made. (The radius from the central spike to the outer spikes must be within the range of 5 to 7.5 times the diameter of the central spike.)

7.2.3 The Coaxial Head (*CH*)[4] (see Fig. 3) forms a transition from the coaxial cable coming from the TDR apparatus to the *MRP*.

7.3 *Cylindrical Mold Probe (CMP)*[4], the *CMP* consists of a cylindrical mold, a guide template, a central rod, and a ring collar. Details for these items are shown in Fig. 4.

7.3.1 The central rod is a stainless steel rod with a diameter of 8.0-mm [5⁄16-in.] and a length of 264-mm [10.4-in.] in length.

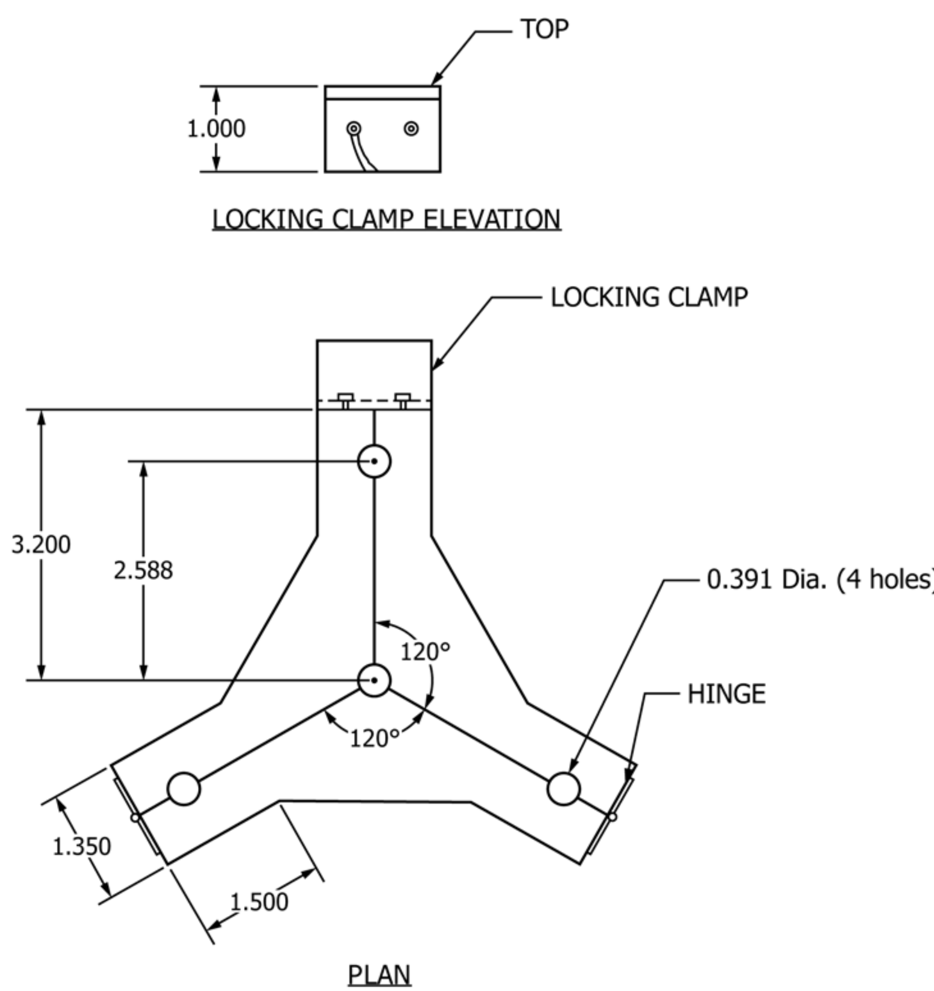
TABLE 1 Metric Equivalents for Dimensions in Fig. 2

[in.]	Tol. [in.]	mm	Tol. mm
0.391	± 0.002	10.00	± 0.05
1.000	± 0.005	25.00	± 0.15
1.350	± 0.015	34.30	± 0.40
1.500	± 0.015	38.00	± 0.40
2.588	± 0.005	65.70	± 0.13
3.200	± 0.020	80.00	± 0.50

7.4 *Balances or Scales,* meeting Specification GP10 of Specification D4753 to determine the mass of the soil and the cylindrical mold. A battery-operated balance or scale having a minimum capacity of 10 kg is suitable when an apparatus with the dimension given in Fig. 3 is used.

7.5 *Driving Tools,* a brass-headed hammer for driving spikes for the *MRP* and the central rod into the cylindrical mold. A resin-headed hammer also may be used for driving the central rod into the cylindrical mold. (Use of these hammers prevents peening of the driving end of the steel rods from repeated use.)

7.6 *Tamping Rod,* an aluminum rod with flat ends, a diameter of 37-mm [1.5-in.], and a length of 380-mm [15-in.].



Note 1—All dimensions are in inches. See Table 1 for tolerances and metric equivalents.

FIG. 2 *MRP* Guide Template

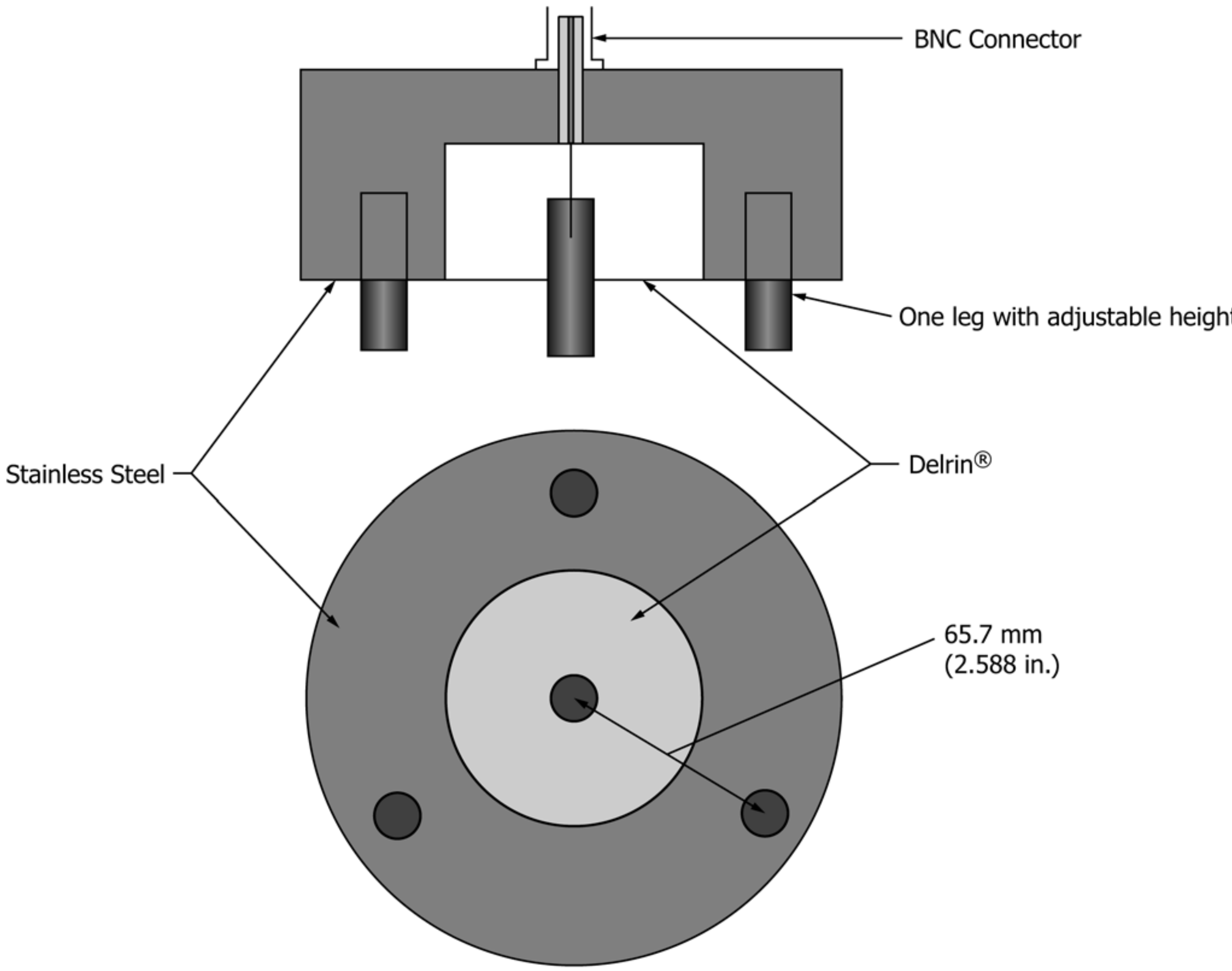


FIG. 3 Coaxial Head (*CH*)

Other tamping devices which provide a relatively uniformly compacted specimen also may be used.

7.7 *Thermometric Device,* 0 to 50 °C range, 0.5 °C graduations, conforming to requirements of Specification E1 or a temperature measuring device with equal or better accuracy.

7.8 *Vernier or Dial Caliper,* having a measuring range of at least 0 to 250-mm [0 to 10-in.] and readable to at least 0.02-mm [0.001-in.].

7.9 *Miscellaneous Tools,* a battery-powered hand drill with a spare battery and charger and with a 25-mm [1-in.] diameter auger bit (alternatively, a small pick will work), straight edge for smoothing the surface of the soil for the in situ test and for smoothing the surface of the soil in the cylindrical mold, pliers for removing the spikes and central rod, small scoop or spoon for removal of the loosened soil and for placement in the cylindrical mold, and a brush for removing excess soil from around the base of the cylindrical mold prior to determining its mass.

8. Preparation of Apparatus

8.1 Charge or replace, as appropriate batteries in the TDR apparatus, the hand drill, and the balance.

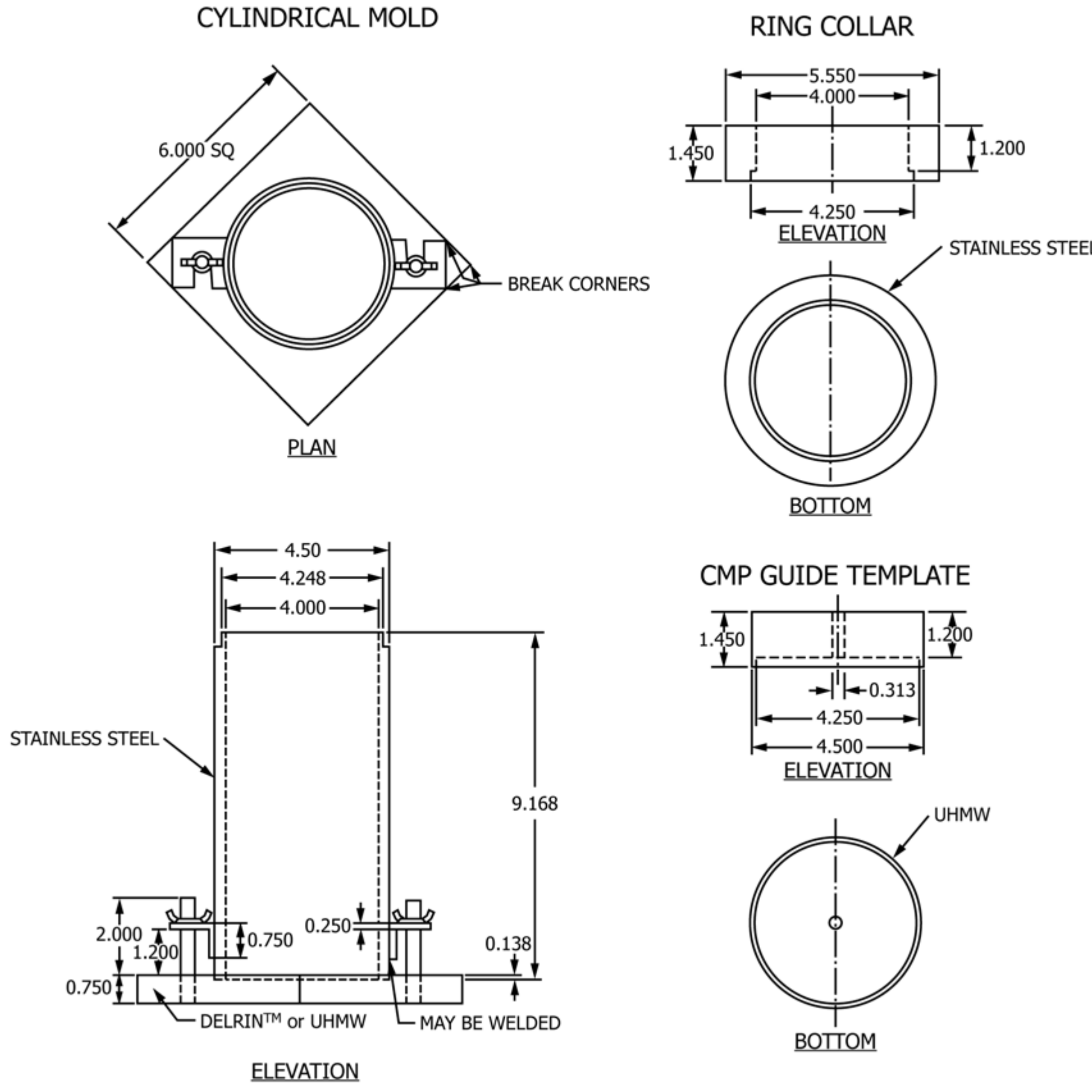
9. Calibration and Standardization

9.1 Determine the average length of the spikes that will penetrate into the soil surface in the in situ test, $L_{in\ situ}$, m [in.], by inserting each spike into the *MRP* guide template and measuring the length that each spike protrudes from the template when fully inserted. All measured lengths should be equal within 0.5-mm [0.020-in.].

9.2 Determine the volume of the cylindrical mold, V_{mold}, m^3 [in. ^{3}], in accordance with Annex A1.

9.3 Determine the mass of the empty and clean cylindrical mold including the base, but without the ring collar, M_2, kg [lbf], by placing on a calibrated balance.

9.4 Determine the length of the central rod for insertion into the compaction mold, $L_{central\ rod}$, m [in.].



NOTE 1—All dimensions are in inches. See Table 2 for tolerances and metric equivalents.

FIG. 4 Cylindrical Mold, Ring Collar, and Guide Template

TABLE 2 Metric Equivalents for Dimensions in Fig. 4

[in.]	Tol. [in.]	mm	Tol. mm
0.138	± 0.005	3.50	± 0.13
0.250	± 0.005	6.30	± 0.13
0.313	+ 0.002, – 0.000	7.88	+ 0.05, – 0.00
0.750	± 0.010	18.90	± 0.25
1.000	± 0.010	25.00	± 0.25
1.200	± 0.002	30.24	± 0.05
1.450	± 0.005	36.54	± 0.13
2.000	± 0.020	50.00	± 0.50
4.000	± 0.016	100.00	± 0.40
4.248	+ 0.000, – 0.003	107.90	+ 0.00, – 0.08
4.250	+ 0.003, – 0.000	107.95	+ 0.08, –0.00
4.500	± 0.020	115.00	± 0.50
5.500	± 0.020	140.00	± 0.50
6.000	± 0.020	150.00	± 0.50
9.168	± 0.020	231.00	± 0.50

9.5 *Calibration Constants:*

9.5.1 *Procedure A*—Determine the values of *a* and *b* for the soils to be tested in the field by procedures in Annex A2.

9.5.2 *Procedure B*—Determine the values *a*, *b*, *c*, *d*, and *f* for the soils to be tested in the field by procedures in Annex A3.

10. Procedure for In situ Testing

10.1 The following is applicable for Procedures A and B:

10.1.1 Prepare the surface at the test location so that it is plane and level.

10.1.2 Seat the *MRP* guide template on the plane surface.

10.1.3 Drive the outer spikes through the guide holes so that the bottom surfaces of the spike heads touch the template. Drive the central spike last. (See Fig. 5.)

10.1.4 Remove the template as shown in Fig. 6. Check that all spikes are driven properly without any air gap around the spikes where they penetrate the soil.

10.1.5 Connect the coaxial cable to the *CH* and the TDR device. Turn on the device.

10.1.6 Wipe the top surfaces of the spike heads and ends of the studs on the *CH* and place the *CH* on the spikes, centering the *CH* on the heads of all the spikes as shown in Fig. 7.

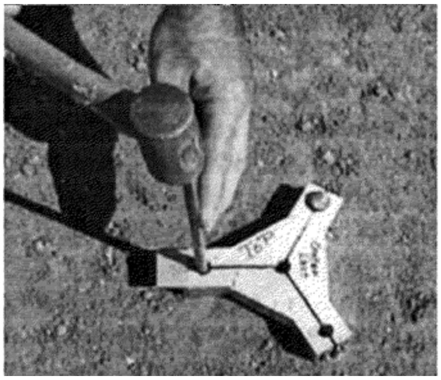


FIG. 5 Driving Spikes through Template

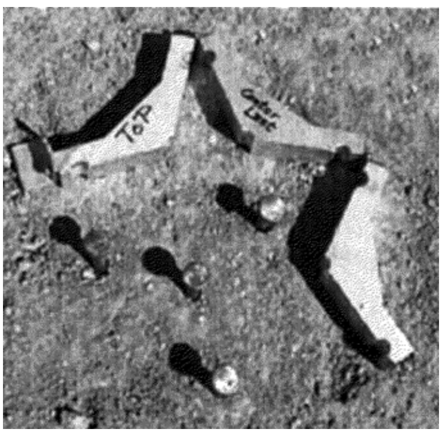


FIG. 6 Removal of Template after Driving Spikes

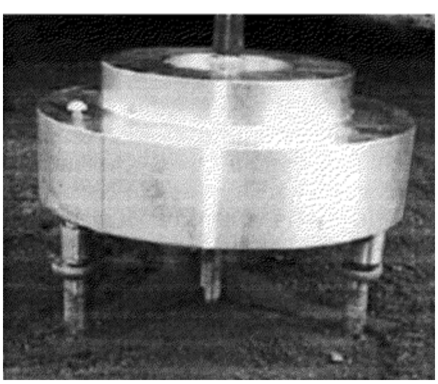


FIG. 7 Placement of Coaxial Head on Spikes

10.1.7 Determine and record the apparent length, $l_{in\ situ}$, m [in.] with the TDR equipment.[6,7]

10.1.8 When following Procedure B, determine and record the source voltage, V_s, the first voltage drop, V_1, and the long term voltage, V_f, from the TDR waveform[8] as illustrated in Fig. 1.

10.1.9 Remove the spikes.

10.2 For Procedure A, do the following:

10.2.1 Measure the apparent length in the cylindrical mold.

10.2.2 Assemble and secure the cylindrical mold to the base plate and attach the ring collar.

10.2.3 With the use of the power drill or other suitable digging implement, excavate the soil from the between the holes left by the outer rods of the *MRP* and to a depth corresponding to the rod penetration and place the soil into the cylindrical mold in 6 uniform lifts applying 10 blows per lift using the aluminum-tamping rod or other suitable tamping device. Soil should be taken uniformly over the entire depth of in situ measurement and placed directly and quickly into the cylindrical mold to minimize moisture loss. Remove the ring collar and strike the surface level with the straight edge after compaction. Remove any spilled soil from around the exterior of the base plate with the brush.

10.2.4 Make sure the balance is leveled, measure and record the mass of the soil-filled cylindrical mold including the base plate, M_1, kg [lb].

10.2.5 Clean the shoulder at the top of the mold and mount the cylindrical mold guide template on to the cylindrical mold.

10.2.6 Using the brass-headed or resin-headed hammer, drive the central rod through the guide hole into the soil until the top of rod is flush with the template.

10.2.7 Remove the guide template from the cylindrical mold.

10.2.8 Determine and record the length of the central rod above the soil surface, $L_{rod\ exposed}$, m [in.].

10.2.9 Clean the shoulder at the top of the mold and place the ring collar on the cylindrical mold. Rotate the ring back and forth on the mold to facilitate good electrical contact.

10.2.10 Wipe the top surface of the ring collar, the central rod and the ends of studs of the *CH* and then place the *CH* on the ring collar, centering the central stud on the central rod as shown in Fig. 8.

10.2.11 Determine and record the apparent length, l_{mold}, m, with the TDR device.[6]

10.2.12 Remove the central rod from the mold.

10.2.13 If the soil is a cohesive soil and if the temperature of the soil is estimated to be outside the range of 15 to 25°C [59

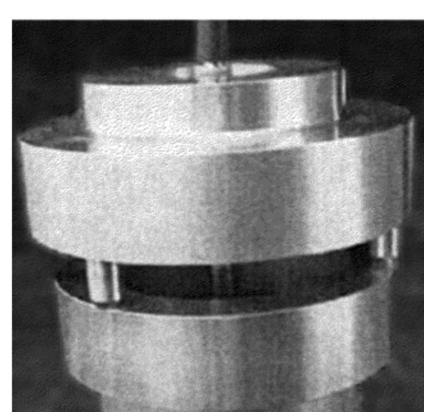


FIG. 8 Coaxial Head on Ring Collar

[6] Automated procedures for doing this are usually contained in a program on the portable computer. Algorithms for various procedures are discussed by Baker and Allmaras (1990) (**1**[7]), Feng et al. (1998) (**2**), Heimovaara and Bouten (1990) (**3**), and Wraith and Or (1999) (**4**).

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

[8] Background for making these measurements is provided by Yu and Drnevich (2004) (**5**) and Jung (2011) (**6**).

to 77°F], insert a metal thermometer into the hole created by the central rod, wait until the temperature stabilizes, and record the temperature, °C.

10.2.14 Remove the soil from the cylindrical mold.

11. Calculation or Interpretation of Results

11.1 Calculate the apparent dielectric constant of the soil in place as follows:

$$K_{in\ situ} = \left[\frac{(l_a)_{in\ situ}}{L_{in\ situ}}\right]^2 \quad (1)$$

where:

$K_{in\ situ}$ = apparent dielectric constant of the soil in situ,
$(l_a)_{in\ situ}$ = measured apparent length in situ, m [in.], and
$L_{in\ situ}$ = length of the spikes inserted into the soil, m [in.].

11.2 *Procedure A:*

11.2.1 Calculate the dielectric constant of the soil in the mold as follows:

$$K_{mold} = \left[\frac{(l_a)_{mold}}{L_{mold}}\right]^2 \quad (2)$$

where:

K_{mold} = apparent dielectric constant of soil in the mold,
$(l_a)_{mold}$ = measured apparent length in the mold, m [in.], and
L_{mold} = length of the rod inserted into the soil in the mold, m [in.]
= $L_{central\ rod} - L_{rod\ exposed}$

11.2.2 Calculate the wet density of the soil in mold as follows:

$$\rho_{t,mold} = \frac{M_1 - M_2}{V_{mold}} \quad (3)$$

where:

$\rho_{t,mold}$ = wet density of the soil in the mold, kg/m³ [lbf/ft³],
M_1 = mass of the soil-filled mold, and base plate, kg [lbf],
M_2 = mass of the empty mold and base plate, kg [lbf],
V_{mold} = volume of the mold, m³ [ft³].

11.2.3 Calculate the apparent dielectric constant of the soil in the mold at 20 °C from:

$$K_{mold,20\,^\circ C} = K_{mold,T\,^\circ C} \times TCF_K \quad (4)$$

where:

TCF_K = Temperature Correction Factor,[9]
= 0.97 + 0.0015T °C for cohesionless soils, 4 °C ≤T °C ≤ 40 °C, and
= 1.04 – 0.0019 T °C for cohesive soils, 4 °C ≤ T °C ≤ 40 °C.

11.2.4 Calculate the water content of the soil in the mold and in place as follows:

$$w_{in\ situ} = w_{mold} = \frac{\sqrt{K_{mold,20\,^\circ C}} - \dfrac{a\rho_{t,mold}}{\rho_w}}{\dfrac{b\rho_{t,mold}}{\rho_w} - \sqrt{K_{mold,20\,^\circ C}}} \times 100 \quad (5)$$

where:

w_{mold} = water content of the soil in the mold, %,
$w_{in\ situ}$ = water content of the soil in situ, %,
ρ_w = density of water = 1000 kg/m³ [62.4 lbf/ft³],
a = calibration constant, (see Annex A2), and
b = calibration constant, (see Annex A2).

11.2.5 Correct the apparent dielectric constant calculated in 11.1 to $K_{in\ situ,\ 20°C}$ from:

$$K_{in\ situ,\ 20\,^\circ C} = K_{in\ situ,\ T^\circ} \times TCF_K \quad (6)$$

11.2.6 Calculate the in situ dry density of the soil as follows:

$$\rho_{d,in\ situ} = \frac{\sqrt{K_{in\ situ,\ 20^\circ C}}}{\sqrt{K_{mold,\ 20\,^\circ C}}} \times \frac{\rho_{t,mold}}{1 + \dfrac{w_{mold}}{100}} \quad (7)$$

where:

$\rho_{d,\ in\ situ}$ = dry density of the soil in situ, kg/m³ [lbf/ft³].

11.3 *Procedure B:*

11.3.1 Obtain the first voltage drop and long term voltages (V_1 and V_f) from the in situ TDR waveform obtained in 10.1.8.

11.3.2 Correct the ratio of $\frac{V_{1,\ in\ situ}}{V_{f,\ in\ situ}}$ to $\left(\frac{V_{1,\ in\ situ}}{V_{f,\ in\ situ}}\right)_{20°C}$ by use of:

$$\left(\frac{V_{1,\ in\ situ}}{V_{f,\ in\ situ}}\right)_{20\,^\circ C} = \frac{V_{1,\ in\ situ}}{V_{f,\ in\ situ}} \times TCF_{VR} \quad (8)$$

where:

TCF_{VR} = Temperature Correction Factor.

$$TCF_{VR} = \frac{80 + \dfrac{V_{f,\ in\ situ}}{0.5\ V_s}(T\ ^\circ C - 20)}{(1.08 - 0.004\ T\ ^\circ C)(40 + 2.0\ T\ ^\circ C)}$$

for cohesionless soils, 4 °C ≤ T °C ≤ 40 °C

$$TCF_{VR} = \frac{80 + \dfrac{V_{f,\ in\ situ}}{0.5\ V_s}(T\ ^\circ C - 20)}{(0.94 + 0.003\ T\ ^\circ C)(40 + 2.0\ T\ ^\circ C)}$$

for cohesive soils, 4 °C ≤ T °C ≤ 40 °C

Calculate the dry density and water content of the soil in situ as follows:

$$\rho_{d,\ in\ situ} = \frac{\left(\dfrac{V_{1,\ in\ situ}}{V_{f,\ in\ situ}}\right)_{20\,^\circ C}\rho_w}{c + d(K_{in\ situ,\ 20\,^\circ C} - 1) - c\cdot\exp[-f\cdot(K_{in\ situ,\ 20\,^\circ C} - 1)]} \quad (9)$$

$$w_{in\ situ} = \frac{1}{b}\left(\sqrt{K_{in\ situ,\ 20\,^\circ C}}\frac{\rho_w}{\rho_{d,\ in\ situ}} - a\right) \quad (10)$$

where:

$\rho_{d,\ in\ situ}$ = dry density of the soil in situ, kg/m³ [lb/ft³]
$V_{1,\ in\ situ}$ = first voltage drop of the soil in situ, V
$V_{f,\ in\ situ}$ = long term voltage of the soil in situ, V, and
$w_{in\ situ}$ = water content of the soil in situ, %.

a, b, c, d, and f = calibration constants, (see Annex A3)

12. Report

12.1 The report shall include the following:

12.1.1 Procedure used (A or B).

[9] See Dallinger (2006) (7) for discussion of these values.

12.1.2 Test site identification.
12.1.3 Date and time of test.
12.1.4 Name of the operator(s).
12.1.5 Visual description of the material tested.
12.1.6 Make, model and serial number of the TDR apparatus.
12.1.7 Average length of the spikes that penetrated into the soil surface in the in situ test, $L_{in\ situ}$, m [in.],

12.2 The report shall include the following for Procedure A:
12.2.1 Volume of the cylindrical mold, V_{mold}, m^3 [ft^3].
12.2.2 Length of the central rod, $L_{central\ rod}$, m [in.], the length of the central rod exposed, $L_{rod\ exposed}$, m [in.], and inserted length of the central rod in the mold, L_{mold}, m [in.].
12.2.3 Temperature of the soil in the mold, $T_{mold,\ T°C}$.
12.2.4 Values of apparent dielectric constant for the in situ test, $K_{in\ situ}$, and the test in the mold, K_{mold}.
12.2.5 Water content in percent, $w_{in\ situ}$, from Eq 5.
12.2.6 Dry density of the soil in situ, $\rho_{d,in\ situ}$, kg/m^3 [lbf/ft^3] from Eq 7.
12.2.7 Calibration constants *a* and *b*.
12.2.8 Other comments as appropriate.

12.3 The report shall include the following for Procedure B:
12.3.1 Temperature of the soil in situ, $T_{in\ situ,T°C}$.
12.3.2 Value of the apparent dielectric constant of the soil in situ, $K_{in\ situ}$.
12.3.3 Value of the source voltage, V_s.
12.3.4 Value of the first voltage drop of the soil in situ, $V_{1,in\ situ}$.
12.3.5 Value of the long term voltage, $V_{f,in\ situ}$.
12.3.6 Dry density of the soil in situ, $\rho_{d,in\ situ}$ from Eq 10.
12.3.7 Water content of the soil in situ, $w_{in\ situ}$, from Eq 11
12.3.8 Calibration constants *a*, *b*, *c*, *d*, and *f*.
12.3.9 Other comments as appropriate.

13. Precision and Bias

13.1 *Precision*—Test data on precision 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.

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

NOTE 2—Guidance is available in Lin, C. P., Drnevich, Feng, and Deschamps, (**8**) for determining test variability for a given soil from laboratory tests simulating field tests.

14. Keywords

14.1 compaction test; construction control; density; dielectric constant; electrical permittivity; electromagnetic waves; field control; field tests; inspection; moisture content; quality control; soil compaction; soil density; time domain reflectometry; water content

ANNEXES

(Mandatory Information)

A1. VOLUME OF CYLINDRICAL MOLD

A1.1 Scope

A1.1.1 This annex describes the procedure for determining the volume of a compaction mold.

A1.1.2 The volume is determined by a water-filled method and checked by a linear-measurement method.

A1.2 Apparatus

A1.2.1 In addition to the apparatus listed in Section 7 the following items are required:
A1.2.1.1 *Vernier or Dial Caliper,* having a measuring range of at least 0 to 250-mm [0 to 10-in.] and readable to at least 0.02-mm [0.001-in.].
A1.2.1.2 *Inside Micrometer,* having a measuring range of at least 100 to 150-mm [4 to 5-in.] and readable to at least 0.02-mm [0.001-in.].
A1.2.1.3 *Plastic or Glass Plates,* two plastic or glass plates approximately 200 by 200 by 6-mm thick [8 by 8 by ¼-in. thick].
A1.2.1.4 *Thermometric Device,* 0 to 50°C range, 0.5°C graduations, conforming to requirements of Specification E1 or a temperature measuring device with equal or better accuracy.
A1.2.1.5 *Stopcock Grease,* or similar sealant.
A1.2.1.6 *Miscellaneous Equipment,* bulb syringe, towels, etc.

A1.3 Precautions

A1.3.1 Perform this method in an area isolated from drafts or extreme temperature fluctuations.

A1.4 Procedure

A1.4.1 *Water-Filling Method:*
A1.4.1.1 Lightly grease the bottom of the compaction mold and place it on one of the plastic or glass plates. Lightly grease the top of the mold. Be careful not to get grease on the inside of the mold. If it is necessary to use the base plate, place the greased mold onto the base plate and secure with the locking studs.
A1.4.1.2 Determine the mass of the greased mold and either plastic or glass plates to the nearest 1-g [0.01-lbm] and record. When the base plate is being used in lieu of the bottom plastic or glass plate determine the mass of the mold, base plate and a single plastic or glass plate to be used on top of the mold to the nearest 1-g [0.01-lbm] and record.

A1.4.1.3 Place the mold and the bottom plastic or glass plate on a firm, level surface and fill the mold with water to slightly above its rim.

A1.4.1.4 Slide the second plate over the top surface of the mold so that the mold remains completely filled with water and air bubbles are not entrapped. Add or remove water as necessary with a bulb syringe.

A1.4.1.5 Completely dry any excess water from the outside of the mold and plates.

A1.4.1.6 Determine the mass of the mold, plates and water and record to the nearest 1-g [0.01-lbm].

A1.4.1.7 Determine the temperature of the water in the mold to the nearest 1°C and record. Determine and record the absolute density of water from Table A1.1.

A1.4.1.8 Calculate the mass of water in the mold by subtracting the mass determined in A1.4.1.2 from the mass determined in A1.4.1.6.

A1.4.1.9 Calculate the volume of water by dividing the mass of water by the density of water and record to the nearest 1 cm^3 [0.0001 ft^3].

A1.4.1.10 When the base plate is used for the calibration of the mold volume repeat A1.4.1.3 – A1.4.1.9.

A1.4.2 *Linear Measurement Method:*

A1.4.2.1 Using either the vernier caliper or the inside micrometer, measure the diameter of the mold 6 times at the top of the mold and 6 times at the bottom of the mold, spacing each of the six top and bottom measurements equally around the circumference of the mold. Record the values to the nearest 0.02-mm [0.001-in.].

A1.4.2.2 Using the vernier caliper, measure the inside height of the mold by making three measurements equally spaced around the circumference of the mold. Record values to the nearest 0.02-mm [0.001-in.].

A1.4.2.3 Calculate the average top diameter, average bottom diameter and average height.

A1.4.2.4 Calculate the volume of the mold and record to the nearest 1 cm^3 [0.0001 ft^3] as follows:

$$V = \frac{\pi(d_t + d_b)^2 h}{16} \times \left(\frac{1 \text{ ft}^3}{1728 \text{ in.}^3}\right) \text{(inch − pound system)} \quad (A1.1)$$

$$V = \frac{\pi(d_t + d_b)^2 h}{16} \times \left(\frac{1 \text{ m}^3}{10^9 \text{ mm}^3}\right) \text{(SI system)} \quad (A1.2)$$

where:

V = volume of mold, m^3 [ft^3],
H = average height, mm [in.],
d_t = average top diameter, mm [in.], and
d_b = average bottom diameter, mm [in.].

TABLE A1.1 Density of Water[A]

Temperature, °C [°F]	Density of Water, g/ml
18 [64.4]	0.99862
19 [66.2]	0.99843
20 [68.0]	0.99823
21 [69.8]	0.99802
22 [71.6]	0.99779
23 [73.4]	0.99756
24 [75.2]	0.99733
25 [77.0]	0.99707
26 [78.8]	0.99681

[A] Values other than shown may be obtained by referring to the *Handbook of Chemistry and Physics* (**9**).

A1.5 Comparison of Results

A1.5.1 The volume obtained by either method should be within the volume tolerance requirements of 6.1.1 and 6.1.2.

A1.5.2 The difference between the two methods should not exceed 0.5 % of the nominal volume of the mold.

A1.5.3 Repeat the determination of volume if these criteria are not met.

A1.5.4 Failure to obtain satisfactory agreement between the two methods, even after several trials, is an indication that the mold is badly deformed and should be replaced.

A1.5.5 Use the volume of the mold determined using the water-filling method as the assigned volume value for calculating the wet density (see 11.3).

A2. DETERMINATION OF PARAMETERS *a* AND *b*

A2.1 Scope

A2.1.1 This annex describes the procedure for determining the soil specific parameters *a* and *b* for use in Eq 5 of Section 11.

A2.1.2 The determination requires that four or more tests at different water contents be performed using the cylindrical mold probe.

A2.2 Apparatus

A2.2.1 See items 7.1, 7.2.3, 7.5, and 7.8.

A2.2.2 *Guide Template,* similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A2.2.3 *Ring Collar,* similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A2.2.4 *Mold, 4-in.*—See 6.1 of Test Method D698.

NOTE A2.1—Molds from most manufacturers are made from mild steel and zinc plated to resist rust. With age and corrosion these plated steel molds may interfere with the TDR's electrical signal. The user may wish to consider using mold bodies constructed of series 303 stainless steel.

A2.2.5 *Non-conductive Base Plate,* a non-conductive base plate made of UHMW or Delrin™ similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A2.2.6 *Central Rod,* a stainless steel central rod with a diameter of 8-mm [5⁄16-in.] and a length of 147-mm [5.791-in.].

A2.2.7 See 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, and 6.8 of Test Method D698.

A2.3 Precautions

A2.3.1 Perform this method in an area where the ambient temperatures and the temperature of the soil are within the range of 15 to 25°C [59 to 77°F].

A2.4 Procedure

A2.4.1 Obtain a representative sample of soil from the site where in situ testing has been conducted or from the borrow area planned as a source of material. The sample should be of sufficient mass for at least five compaction specimens, typically about 20-kg [44-lb]. More material may be required if ancillary testing is planned such as particle size analysis.

A2.4.2 Air-dry the soil sample.

A2.4.3 Thoroughly break up the soil clumps in such a manner as to avoid breaking individual particles. Pass the material through a No. 4 [4.75-mm] sieve.

A2.4.4 Prepare the specimens having water contents such that they bracket the estimated field water content and vary by about 2 %. Preparation procedure should be as specified in section 10.2 or 10.3 of Test Methods D698.

A2.4.5 Determine the volume of the cylindrical mold in accordance with Annex A1.

A2.4.6 Determine and record the mass of the cylindrical mold and base plate, and the length of the central rod.

A2.4.7 Assemble and secure the cylindrical mold and ring collar to the base plate.

A2.4.8 *Compaction*—After curing, if required, each specimen shall be compacted in accordance 10.4.1 through 10.4.7 of Test Method D698.

A2.4.9 Remove the ring collar and strike the surface level with the straight edge after compaction. Remove any soil from around the exterior of the base plate with the brush.

A2.4.10 Do procedures 10.2.4 – 10.2.13.

A2.4.11 Remove the soil from the cylindrical mold. Obtain a portion of the sample for water content determination by slicing the compacted specimen axially through the center and removing at least 0.500 kg [1 lb] of soil from the cut faces. Obtain the water content in accordance with Test Method D2216.

A2.4.12 Repeat A2.4.6 to A2.4.9 for each soil specimen.

A2.5 Calculation

A2.5.1 For each of the soil specimens, calculate the dielectric constant of soil in the cylindrical mold (K_{mold}) using Eq 2.

A2.5.2 Calculate water content, $w_{oven\ dry}$, in accordance with Test Method D2216.

A2.5.3 Calculate the wet density of the soil in the cylindrical mold using Eq 3.

A2.5.4 Calculate the dry density of the soil in the cylindrical mold as follows:

$$\rho_d = \frac{\rho_t}{1 + \frac{w_{oven\ dry}}{100}} \tag{A2.1}$$

where:

ρ_d = dry density of the soil in the cylindrical mold, kg/m^3 [lbf/ft^3],
ρ_t = wet density of the soil in the cylindrical mold, kg/m^3 [lbf/ft^3], and
$w_{oven\ dry}$ = oven dry water content from step A2.5.2, %.

A2.5.5 Plot $\sqrt{K_{mold}}\frac{\rho_w}{\rho_d}$ versus $w_{oven\ dry}$ for determining calibration coefficients a and b.

where:

K_{mold} = dielectric constant of soil in the cylindrical mold,
ρ_d = dry density of the soil in the cylindrical mold, kg/m^3 [lbf/ft^3], from Eq A2.1,
ρ_w = density of water = 1000 kg/m^3 [62.4 lbf/ft^3], and
$w_{oven\ dry}$ = oven dry water content, decimal, from step A2.5.2.

A2.5.6 Determine calibration coefficients a and b from plot in A2.5.5 where:

a = zero intercept of the best-fit straight line, and
b = slope of the best-fit straight line.

NOTE A2.2—Values of a typically are between 0.7 and 1.8 and values of b are typically between 7.5 and 11 for commonly encountered natural soils. An example plot for determining calibration coefficients a and b is shown in Fig. A2.1.

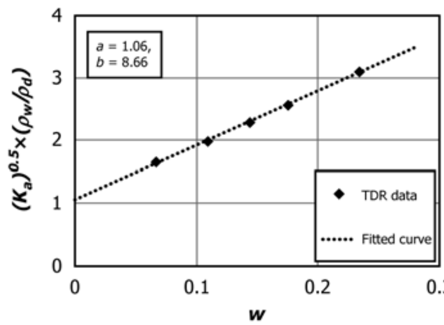


FIG. A2.1 Example Plot for Determining Calibration Coefficients *a* and *b*

A3. DETERMINATION OF PARAMETERS *a*, *b*, *c*, *d*, AND *f*

A3.1 Scope

A3.1.1 This annex describes the procedure for determining the soil specific parameters *a*, *b*, *c*, *d*, and *f* for use in Eq 11 and 12 of Section 11.

A3.1.2 The determination requires that four or more tests at different water content be performed using a 4-in. diameter mold similar that described in Test Method D698, Procedure A or B.

A3.2 Apparatus

A3.2.1 See items 7.1, 7.2.3, 7.5, and 7.8.

A3.2.2 *Guide Template,* similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A3.2.3 *Ring Collar,* similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A3.2.4 *Mold, 4-in.*—See 6.1 of Test Method D698.

NOTE A3.1—Molds from most manufacturers are made from mild steel and zinc plated to resist rust. With age and corrosion these plated steel molds may interfere with the TDR's electrical signal. The user may wish to consider using mold bodies constructed of series 303 stainless steel.

A3.2.5 *Non-conductive Base Plate,* a non-conductive base plate made of UHMW or Delrin™ similar to that shown on Fig. 4, but modified to conform to user's 4-in. compaction mold.

A3.2.6 *Central Rod,* a stainless steel central rod with a diameter of 8-mm [5⁄16-in.] and a length of 147-mm [5.791-in.].

A3.2.7 See 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, and 6.8 Test Method D698.

A3.3 Precautions

A3.3.1 Perform this method in an area where the ambient temperatures and the temperature of the test soil are within the range of 15 to 25°C [59 to 77°F].

A3.4 Procedure

A3.4.1 Obtain a representative sample of soil from the site where in situ testing has been conducted or from the borrow area planned as a source of material. The sample should be of sufficient mass for at least five compaction specimens, typically about 20-kg [44-lb]. More material may be required if ancillary testing is planned such as particle size analysis.

A3.4.2 Air-dry the soil sample.

A3.4.3 Thoroughly break up the soil clumps in such a manner as to avoid breaking individual particles. Pass the material through a No. 4 (4.75-mm) sieve.

A3.4.4 Prepare five specimens having water contents such that they bracket the estimated field water content and the optimum water content. Incrementally increase the water content from driest compaction point by about 2 %. Preparation procedures should be as specified in section 10.2 or 10.3 of Test Method D698.

A3.4.5 Determine the volume of the 4-in. cylindrical mold in accordance with Annex A1.

A3.4.6 Determine and record the mass of the cylindrical mold and base plate, and the length of the central rod.

A3.4.7 Assemble and secure the cylindrical mold and collar to the base plate.

A3.4.8 *Compaction*—After curing, if required, each specimen shall be compacted in accordance 10.4.1 through 10.4.7 of Test Method D698.

A3.4.9 Determine and record the mass of the specimen and mold to the nearest gram. When the base plate is left attached, determine and record the mass of the specimen, mold and base plate to the nearest gram.

A3.4.10 Do procedure 10.2.4 – 10.2.13.

A3.4.11 Remove the soil from the cylindrical mold. Obtain a portion of the sample for water content determination by slicing the compacted specimen axially through the center and removing at least 0.5 kg [1 lb] of foil from the cut faces. Obtain the water content in accordance with Test Method D2216.

A3.4.12 Repeat A3.4.6 to A3.4.11 for each soil specimen.

A3.5 Calculations

A3.5.1 For each of the soil specimens, calculate the dielectric constant of soil in the cylindrical mold (K_{mold}) using Eq 2 and obtain the first voltage drop, V_1, and long term voltage, V_f, of soil in the cylindrical mold.

A3.5.2 Do calculations A2.5.2 – A2.5.6.

A3.5.3 Plot for obtaining calibration coefficients c, d, and f:

$$\frac{V_{1,\ mold}}{V_{f,\ mold}} \frac{\rho_w}{\rho_d} \text{ vs. } K_{mold} \tag{A3.1}$$

where:

$V_{1,\ mold}$ = first voltage drop of soil in the cylindrical mold, V, and
$V_{f,\ mold}$ = long term voltage of soil in the cylindrical mold, V.

A3.5.4 Determine calibration coefficients c, d, and f using least-squared method of minimizing differences between y-value and x-value from plot in A3.5.3 where:

$$\min \sum_{i=1}^{n} \left[\left(\frac{V_{1,\ mold}(i)}{V_{f,\ mold}(i)} \frac{\rho_w}{\rho_d} \right) - (c + d\,(K_{mold}(i) - 1) - c \cdot \exp(- f \cdot (K_{mold}(i) - 1))) \right]^2 \tag{A3.2}$$

where:

i = ith number of measurements in A3.4, and
n = total number of measurements in A3.4.

NOTE A3.2—Values of c typically are between 0.002 and 0.150, values of d are typically between 0.005 and 0.040, and values of f are typically between 0.10 and 1.00 for commonly encountered natural soils. An example plot for determining calibration coefficients c, d, and f is shown in Fig. A3.1.

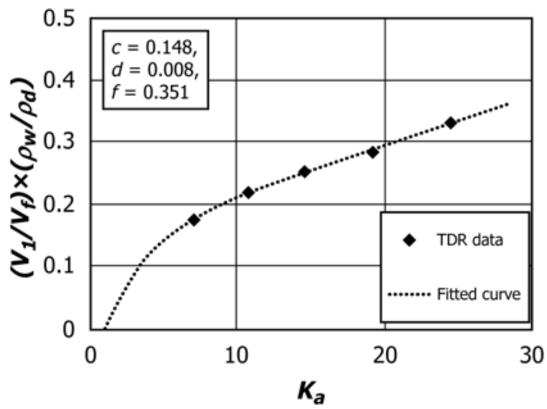


FIG. A3.1 Example Plot for Determining Calibration Coefficients *c*, *d*, and *f*

APPENDIX

(Nonmandatory Information)

X1. BULK ELECTRICAL CONDUCTIVITY

X1.1 If the user is interested in the bulk electrical conductivity, it may be calculated using voltages from the in situ TDR waveform obtained in 10 from:

$$EC_b = \frac{1}{C}\left(\frac{V_s}{V_f} - 1\right) \tag{X1.1}$$

where:

EC_b = bulk electrical conductivity, S/m,
V_s = source voltage and equal to twice the step voltage (see Fig. 1),
V_f = long term voltage level (see Fig. 1), and
C = Constant related to probe configuration, and for the coaxial probe with a central rod having a diameter of 8.0-mm [5/16-in.] and with a mold diameter of 100 mm [4.0-in.] is calculated from:[10]

$$C = 2.46 L_{in\ situ} R_s \tag{X1.2}$$

C = Constant related to probe configuration, and for the field probe with four spikes having diameters of 9.5 mm [3/8-in.] and at a spacing of 65.7 mm [2.59-in.] the value of C is calculated from:[10]

$$C = 2.02 L_{in\ situ} R_s \tag{X1.3}$$

where:

$L_{in\ situ}$ = length of the TDR probe that is below the surface of the soil,
R_s = internal resistance of the TDR's pulse generator

X1.2 Values of EC_b for soils are not affected by temperature if they are dry. For soils with water contents in the vicinity of the optimum water content, values of EC_b to 20 °C by use of the following equation:[10]

$$EC_{b,\ 20\ °C} = \frac{EC_b}{(0.025\ T\ \ °C + 0.5)} \tag{X1.4}$$

[10] Background for these calculations is provided by Dallinger (2006) (7)

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SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D6780 – 05) that may impact the use of this standard. (Approved May 15, 2012.)

(1) The term "in-place" has been replaced with "in situ" in the title and throughout the standard.
(2) New TDR parameter, V_1, has been introduced and included in the Section 3 Terminolgy and in Fig. 1.
(3) Calculation of electrical conductivity, EC_b has been moved from the body of the Standard to a non-mandatory Appendix because it is no longer needed to determine water content and dry density, but may be of interest to the user. It includes corrections for test temperature and for mold and field probe geometries.
(4) Procedure B has been modified with utilizing V_1.
(5) The number of calibration equations for determining dry density and water content of the soil in situ for Procedure B have been reduced from three to two and the number of calibration constants have been reduced from six to five.
(6) Reporting requirements have been changed to include V_s and the new parameter, V_1.
(7) The number of compaction tests required for determination of calibration constants has been changed from "five" to "four or more."
(8) Annex A3 has been modified for guidance in determining calibration constants *c*, *d*, and *f* that are associated with Procedure B.
(9) A set of example graphs have been added to show how the calibration constants are determined for a typical soil.
(10) Added two references and footnotes to reference them.