Designation: D5334 – 22a

Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure[1]

This standard is issued under the fixed designation D5334; 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 presents a procedure for determining the thermal conductivity (λ) of soil and rock using a transient heat method. This test method is applicable for both intact specimens of soil and rock and reconstituted soil specimens, and is effective in the lab and in the field. This test method is most suitable for homogeneous materials, but can also give a representative average value for non-homogeneous materials.

1.2 This test method is applicable to dry, unsaturated or saturated materials that can sustain a hole for the sensor. It is valid over temperatures ranging from <0 to >100°C, depending on the suitability of the thermal needle probe construction to temperature extremes. However, care must be taken to prevent significant error from: *(1)* redistribution of water due to thermal gradients resulting from heating of the needle probe; *(2)* redistribution of water due to hydraulic gradients (gravity drainage for high degrees of saturation or surface evaporation); *(3)* phase change of water in specimens with temperatures near 0°C or 100°C.

1.3 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurements are included in this standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this standard.

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

1.4.1 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 used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or 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.

NOTE 1—This test method is also applicable and commonly used for determining thermal conductivity of a variety of engineered porous materials of geologic origin including concrete, Fluidized Thermal Backfill (FTB), and thermal grout.

1.5 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

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 and Data Records in Geotechnical Data

3. Terminology

3.1 *Definitions*—For definitions of common technical terms used in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

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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.

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

3.2.1 *heat input, n*—power consumption of heater wire in watts per unit length that is assumed to be the equivalent of heat output per unit length of wire.

3.2.2 *thermal epoxy, n*—heat conductive resin material having a value of $\lambda > 0.5$ W/(m·K).

3.2.3 *thermal grease, n*—heat conductive lubricating material having a value of $\lambda > 1.5$ W/(m·K).

4. Summary of Test Method

4.1 Thermal conductivity is determined by a variation of the line source test method using a needle probe having a large length to diameter ratio to simulate conditions for an infinitely long, infinitely thin heating source. The probe consists of a heating element and a temperature measuring element and is inserted into the specimen. A known current and voltage are applied to the probe heating element over a period of time and the temperature rise is recorded. The temperature decay with time after the cessation of heating can also be included in the analysis. Thermal conductivity is obtained from an analysis of the temperature time series data during the heating cycle and (optionally) the cooling cycle, by comparing it to a theoretical curve using non-linear least-squares inversion technique.

5. Significance and Use

5.1 The thermal conductivity of intact soil specimens, reconstituted soil specimens, and rock specimens is used to analyze and design systems involving underground transmission lines, oil and gas pipelines, radioactive waste disposal, geothermal applications, and solar thermal storage facilities, among others. Measurements can be made on site (in situ), or samples can be tested in a lab environment.

NOTE 2—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. Users of this standard are cautioned that compliance with Practice D3740 does not in itself ensure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Thermal Needle Probe*—A device that creates a linear heat source and incorporates a thermocouple or thermistor to measure the variation of temperature at a point along the line. The construction of a suitable device is described in Appendix X1.

6.2 *Constant Current Source*—A device to produce a constant current.

6.3 *Temperature Readout Unit or Recorder*—A device to record the temperature from the thermocouple or thermistor with a readability of 0.01 K or better.

6.4 *Digital Multimeter (DMM)*—A device to read voltage and current to the nearest 0.01 V and 0.001 A.

6.5 *Timer*—A clock, stopwatch, digital timer, or integrated electronic timer capable of measuring to the nearest 0.1 s or better for the duration of the measurement.

6.6 *Drilling Device*—(*for rock specimens*) A drill capable of making a straight axial hole having a diameter equivalent to that of the needle and to a depth equivalent to the length of the needle.

6.7 *Balance*—A balance that meets the requirements of Guide D4753 and has a readability of 0.01 g for specimens having a mass of up to 200 g and a readability of 0.1 g for specimens with a mass over 200 g. However, the balance used may be controlled by the number of significant digits needed.

7. Specimen Preparation

7.1 *General Specimen Preparation Guidelines:*

7.1.1 The main factors affecting the accuracy of a thermal conductivity reading include the density and water content of the sample, the size of the specimen, the sensitivity and accuracy of temperature measurements, the amount of heat applied, and the relative conductivities of the needle and the sample. Annex A1 contains more information for configuring the test.

7.1.2 Because the density and water content of the sample are major factors in its thermal conductivity, take care to make the specimen the same density and water content as the material it represents, whether that is the undisturbed soil or the installed state of a backfill. As a general reference, a density of more than 2000 kg/m^3 is necessary for resistivity to be under 50 °C·cm/W.

7.1.3 The specimen radius needs to be large enough that a heat pulse is not reflected off the outside boundary, and so that the surroundings do not factor into the reading. The diffusivity of the sample determines how fast heat can travel through it, independent of its conductivity or the temperature difference at the source. By assuming that a 99 % heat reduction at distance r is sufficiently small to have a negligible effect on the reading, curves delineating the minimum size of the specimen (that is, the radius, and also the approximate length beyond the end of the needle) can be derived empirically from Eq 3 parameterized by the diffusivity (D) of the specimen, time duration (t) of the reading including heating and cooling if included, and the radius of the needle. Fig. 1 plots three such curves generated for probe sizes selected to span common needle radii. Given the product of the sample diffusivity (D) and reading time duration (t) on the x-axis, the minimum specimen radius can be read off the y-axis. In addition, a power law equation approximates the results for each of the curves. For other needle radii, interpolation or generating a new curve may be appropriate.

$$r = 3.971(D_t)^{0.4382} \quad a = 2mm \tag{1}$$

$$r = 3.5453(D_t)^{0.4526} \quad a = 1.2mm$$

$$r = 3.2392(D_t)^{0.4623} \quad a = 0.64mm$$

where:

r = distance from the heated needle (mm) (minimum radius of the specimen),
D = thermal diffusivity of the specimen (mm^2/s),
t = time from the beginning of heating to the end of the test (s), and
a = radius of the needle.

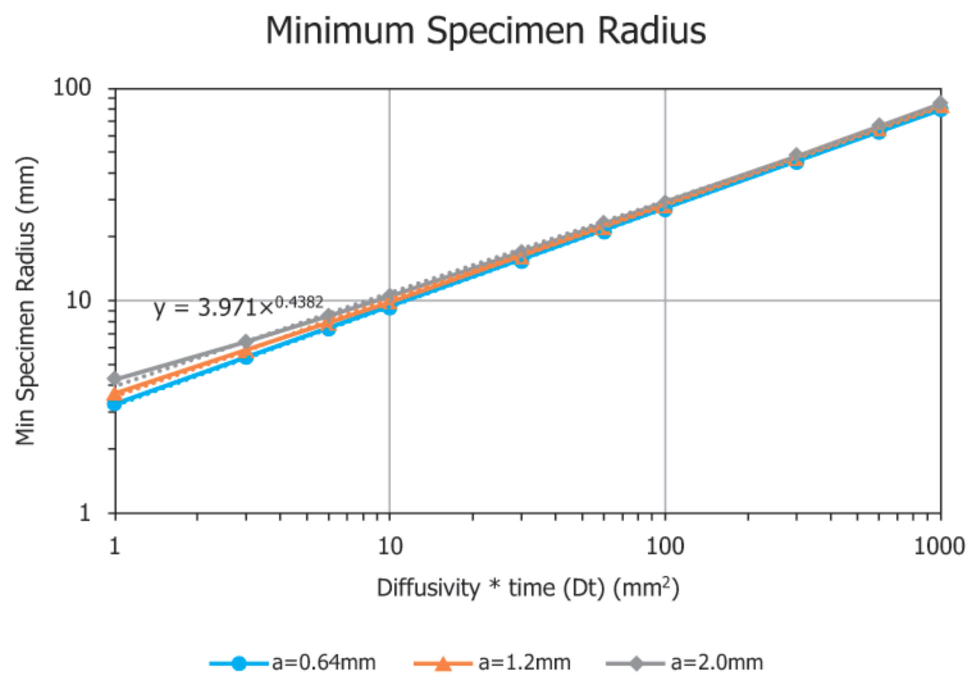

FIG. 1 Minimum Radius of a Specimen

7.1.4 There are many ways to get an estimate of the specimen's diffusivity. It can be measured directly with an instrument designed for that purpose. Alternately, it can be calculated from a previous measurement of the thermal Conductivity and the specimen's volumetric heat capacity ($\rho_s c_s$) in MJ/(m^3·K) according to the equation:

$$D = \frac{\lambda}{\rho_s c_s} \tag{2}$$

where:

D = diffusivity (m^2/s),
λ = conductivity (W/(m·K)),
ρ_s = density (kg/m^3), and
c_s = specific heat (J/(kg·K)).

Another option is to estimate it from a graph of diffusivity values, such as the one in Fig. 2(**1**).[3]

7.1.5 The specimen length needs to be greater than or equal to that of the sensor needle. If the specimen and needle are close to the same length, then the nature of the material contacting the end of the specimen may adversely affect the reading; highly conductive materials affect the reading more than insulating materials. An addition to the sample length equal to its minimum radius would provide a sufficient security measure.

NOTE 3—The specimen dimensions are specified as if the specimen was in the shape of a cylinder, with the needle to be inserted (and a hole to be drilled if necessary) along the axis of the cylinder. In actuality, as long as the specimen can circumscribe a cylinder of the specified radius and length, the shape of the specimen is immaterial.

7.2 *Intact Soil Specimens (Thin-Walled Tube or Drive Specimens):*

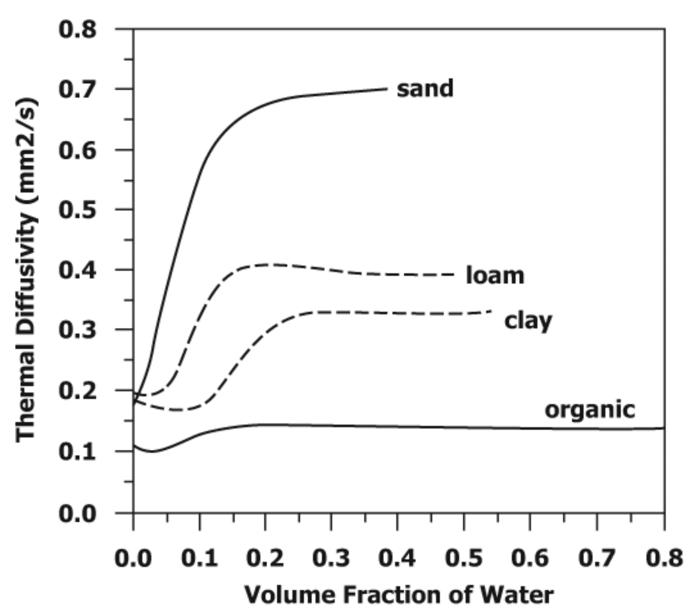

FIG. 2 Diffusivity Values for Select Soil Types

7.2.1 Cut a section of a sampling tube containing an intact soil specimen diameter compliant to 7.1. Consider cutting the section in a way that facilitates determining the volume of the specimen and preserves the integrity of the sample.

7.2.2 Seal the specimen to prevent water loss and redistribution during storage or measurement.

7.3 *Reconstituted Soil Specimens:*

7.3.1 Compact the specimen to the desired dry density and gravimetric water content in a thin-walled metal or plastic tube that complies with the size guidelines in 7.1 using an appropriate compaction technique (compaction and water content both affect the thermal conductivity). For further guidance on

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