~~Designation:D5334–05~~ Designation: D 5334 – 08

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

This standard is issued under the fixed designation D 5334; 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 of soil and soft rock using a transient heat method. This test method is applicable for both undisturbed and remolded soil specimens and soft rock specimens. This test method is suitable only for isotropic materials.

~~1.2This test method is applicable to dry materials over the temperature range from 20 to 100°C. It may be used over a limited range around ambient room temperatures for specimens containing moisture.~~

1.2 This test method is applicable to dry materials over a wide temperature range from <0 to >100°C, depending on the suitability of the thermal needle probe construction to temperature extremes. This method may also be used for specimens containing moisture. 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, and *(2)* phase change (melting) of ice in specimens with temperatures <0°C. Both of these errors can be minimized by adding less total heat to the specimen either through minimizing power applied to the needle probe and/or minimizing the heating duration of the measurement.

1.3 For satisfactory results in conformance with this test method, the principles governing the size, construction, and use of the apparatus described in this test method should be followed. If the results are to be reported as having been obtained by this test method, then all pertinent requirements prescribed in this test method shall be met.

1.4 It is not practicable in a test method of this type to aim to establish details of construction and procedure to cover all contingencies that might offer difficulties to a person without technical knowledge concerning the theory of heat flow, temperature measurement, and general testing practices. Standardization of this test method does not reduce the need for such technical knowledge. It is recognized also that it would be unwise, because of the standardization of this test method, to resist in any way the further development of improved or new methods or procedures by research workers.

1.5 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

~~1.6All~~1.6 All measured and calculated values shall conform to the guidelines for significant digits and rounding established In Practice D 6026.

1.7 *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]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids
D 2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D 3740 Practice for Minimum Requirements for Agencies Engaged in ~~The testing~~Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D 4439~~Terminology for Geotextiles~~ Terminology for Geosynthetics
D 6026 Practice for Using Significant Digits in Geotechnical Data

3. ~~Terminology~~

~~3.1Terminology used within this test method is in accordance with Terminologies D653~~ Terminology

---

[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.
Current edition approved ~~Nov.~~July 1, ~~2005.~~2008. Published ~~November 2005.~~July 2008. Originally approved in 1992. Last previous edition approved in ~~2004~~2005 as ~~D5334–00(2004).~~ D 5334 – 05.

[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.**

3.1 For terminology used in this test method, refer to Terminologies D 653 and D 4439~~with the addition of the following:~~
~~3.1.1.~~

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *heat input*—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.

~~3.1.2~~
3.2.2 *thermal epoxy*—any thermally conductive filled epoxy material having a value of λ > 4 W/(m·k).

~~3.1.3~~
3.2.3 *thermal grease*—any thermally conductivity grease having a value of λ > 4 W/(m·k).

4. ~~Summary of Test Method~~

~~4.1The 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 stimulate conditions for an infinitely long specimen. The probe consists of a heating element and a temperature measuring element and is inserted into the specimen. A known current and voltage is applied to the probe and the temperature rise with time noted over a period of time. The thermal conductivity is obtained from an analysis of the approximately linear portion of the quasi-steady-state temperature-time response.~~ Summary of Test Method

4.1 The 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 and the temperature rise with time is recorded over a period of time. The temperature decay with time after the cessation of heating can also be included in the analysis to minimize effects of temperature drift during measurement. The thermal conductivity is obtained from an analysis of the time series temperature data during the heating cycle and cooling cycle if applicable.

5. Significance and Use

~~5.1The~~5.1 The thermal conductivity of both undisturbed and remolded soil specimens as well as soft rock specimens is used to analyze and design systems used, for example, in underground transmission lines, oil and gas pipelines, radioactive waste disposal, and solar thermal storage facilities.

NOTE 1—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 D 3740 are generally considered capable of competent and objective testing. Users of this test method are cautioned that compliance with Practice D 3740 does not in itself assure reliable testing. Reliable testing depends on many factors; Practice D 3740 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 temperature measuring element (thermocouple or thermistor) to measure the variation of temperature at a point along the line. The construction of a suitable device is described in Annex A1.

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

6.3 ~~*Thermal Readout Unit*—A device to produce a digital readout of temperature in degrees Celsius to the nearest 0.1K~~ Temperature Readout Unit or Recorder—A device to record or produce a digital readout of temperature in degrees Celsius with enough resolution to resolve changes in temperature induced by heating of the needle (typically 0.1 to 0.01 K).

6.4 *Voltage-Ohm-Meter (VOM)*—A device to read voltage and current to the nearest 0.01 V and ampere.

6.5 *Timer*~~, stopwatch or similar time measuring instrument capable of measuring to the nearest 0.1 s for a minimum of 15 min.~~
~~6.6~~*, stopwatch or integrated electronic timer capable of measuring to the nearest 0.1 s for the duration of the measurement.*

6.6 *Equipment*, capable of drilling a straight vertical hole having a diameter as close as possible to that of the needle and to a depth at least equal to the length of the needle.

7. Specimen Preparation

7.1 *Undisturbed Soil Specimens* :

7.1.1 *Thin-Walled Tube or Drive Specimens* —Cut a 200 ± 30-mm (8.0 ± 1-in.) long section of a sampling tube containing an undisturbed soil specimen. The tube section should have a minimum diameter of 51 mm (2 in.).

7.1.2 Weigh the specimen in a sampling tube or brass rings.

7.1.3 Insert the thermal needle probe down the axis of the specimen by either pushing the probe into a predrilled hole (dense specimen) to a depth equal to the length of the probe or pushing the probe into the specimen (loose specimen). Care should be taken to ensure that the thermal probe shaft is fully embedded in the specimen and not left partially exposed. (See Note 2.)

NOTE 2—To provide better thermal contact between the specimen and the probe, the probe may be coated with a thin layer of thermal grease. If a hole is predrilled for the needle probe, the diameter of the hole should be equal to the diameter of the needle probe to ensure a tight fit. A device, such as a drill press, may be used to insert the probe to ensure that the probe is inserted vertically and that no void spaces are formed between the specimen and the probe.

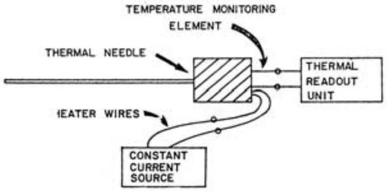


FIG. 1 Thermal Probe Experimental Setup

7.2 *Remolded Soil Specimens*:

7.2.1 Compact the specimen to the desired density and water content (in a thin-walled metal or plastic tube) using an appropriate compaction technique. For further guidance on the effect of the various compaction techniques on thermal conductivity, refer to Mitchell et ~~al.~~al (**1**).[3] The tube should have a minimum diameter of 51 mm (2 in.) and a length of 200 ± 30 mm (8.0 ± 1 in.).

7.2.2 Perform 7.1.2 and 7.1.3.

7.3 *Soft Rock Specimens*:

7.3.1 Specimen dimensions shall be no less than those of the calibration standard (8.3).

~~7.3.2Insert~~7.3.2 Insert the thermal needle probe into the specimen by predrilling a hole to a depth equal to the length of the probe. Care should be taken to ensure that the thermal probe shaft is fully embedded in the specimen and not left partially exposed. (See Note 2.)

8. ~~Calibration~~

~~8.1The thermal needle probe apparatus should be calibrated before its use. Perform calibration by comparing the experimental determination of the thermal conductivity of a standard material to its known value.~~ Calibration

8.1 The thermal needle probe apparatus should be calibrated before its use. Perform calibration by comparing the experimental determination of the thermal conductivity of a standard material to its known value. A calibration factor, *C*, should be calculated where:

$$C = \frac{\lambda_{material}}{\lambda_{measured}} \tag{1}$$

where:

$\lambda_{material}$ = the known thermal conductivity of the calibration material, and
$\lambda_{measured}$ = the thermal conductivity of that material measured with the thermal needle probe apparatus.

8.1.1 All subsequent measurements with the thermal needle probe apparatus should be multiplied by *C* before being reported. This is especially important with large diameter needle probes (that is, $d > 2.5$ mm) where departures from the assumption of an infinitely thin probe cause potentially significant differences in estimation of the thermal conductivity due to non-negligible heat storage and transmission in the needle probe itself.

8.1.2 The calibration factor, *C*, has been shown to be a function of thermal conductivity when using a large diameter needle probe (see Hanson et al, 2004) (**2**). For users of large diameter probes, it may be necessary to determine *C* at several thermal conductivities in the range of measurement and construct a calibration function which is then applied to subsequent data collected with the thermal needle probe.

8.2 Conduct the test specified in Section 9 using a calibration standard as specified in 8.3.

8.3 *Calibration Standard*—One or more materials with known values of thermal conductivity in the range of the materials being measured (typically $0.2 < \lambda < 5$ W/m·K). Suitable materials include dry Ottawa sand, Pyrex 7740, Fused ~~Silica and~~ Silica, Pryoceram 9606 (**~~2~~4**)~~. The calibration standard shall be in the shape of a cylinder. The diameter of the cylinder shall be at least 40 mm and the length shall be at least 10 cm longer than the needle probe. A hole shall be drilled along the axis of the cylinder to a depth equal to the length of the probe. The diameter of the hole shall be equal to the diameter of the probe so that the probe fits tightly into the hole.~~ , glycerine (glycerol) with a known thermal conductivity of 0.292 W m^{-1} K^{-1} at 25°C (**4**), or water stabilized with 5 g agar per liter (to prevent free convection) with a known thermal conductivity of 0.607 W m^{-1} K^{-1} at 25°C (**4**). (See Annex A2 for details on preparation of calibration standards.) The calibration standard shall be in the shape of a cylinder. The diameter of the cylinder shall be at least 40 mm or 10 times the diameter of the thermal needle probe (whichever is larger) and the length shall be at least 20 % longer than the needle probe. On solid specimens, a hole is drilled along the axis of the cylinder to a depth equal to the length of the probe. The diameter of the hole shall be equal to the diameter of the probe so that the probe fits tightly into the hole. For drilled specimens the probe should be coated with thermal grease to minimize contact resistance.

---

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

8.4 The measured thermal conductivity of the calibration specimen must agree within one standard deviation of the published value of thermal conductivity, or with the value of thermal conductivity determined by an independent method.

~~8.5For~~8.5 For purposes of comparing a measured value with specified limits, the measured value shall be rounded to the nearest decimal given in the specification limits in accordance with the provisions of Practice D 6026.

9. Procedure

~~9.1Allow the specimen to come to equilibrium with room temperature.~~

9.1 Allow the specimen to come to equilibrium at the selected testing temperature. This is especially important if only the heating data are to be analyzed as temperature drift will cause a significant error in the thermal conductivity measurement. Errors from small temperature drifts are minimized if both heating and cooling data are used in the analysis.

9.2 Connect the heater wire of the thermal probe to the constant current source. (See Fig. 1.)

9.3 Connect the temperature measuring element leads to the readout unit.

9.4 Apply a known constant current (for example, equal to 1.0 A) to the heater wire such that the temperature change is less than 10 K in 1000 s.

9.5 ~~Record the temperature readings at 0, 5, 10, 15, 30, 45, and 60 s, then take readings at 30-s time intervals for a minimum of 1000 s. (See Fig. 2.)~~ Record time and temperature readings for at least 20–30 steps throughout the heating period. The total heating time should be appropriate to the thermal needle probe size. For a small diameter needle (that is, $d < 2.5$ mm), a 30 to 60 second heating duration is sufficient to accurately measure thermal conductivity. With a larger diameter needle, a longer heating duration may be necessary. However, this method is only valid if the thermal pulse does not encounter the boundaries of the specimen, so care must be taken not to choose too long a heating duration. Also note that potential errors from redistribution of water in moist specimens increase with heating time as discussed in 1.2.

9.6 Turn off the constant current source.

~~9.7Plot the temperature data as a function of time on a semilog graph. (See Fig. 3.)~~

~~9.8Select linear portion of curve (quasi steady state portion) and draw a straight line through the points. (See Fig. 4.)~~

~~9.9Select times t_1 and t_2 at appropriate points on the line and read the corresponding temperatures T_1 and T_2~~

9.7 If cooling data are to be included in the analysis, record the time and temperature readings for at least 20–30 steps throughout a cooling period equal in duration to the heating cycle.

9.8 Use a suitable inverse method (graphical or statistical) to determine thermal conductivity. (See Section 10, Data Analysis.)

9.9 Perform an initial moisture content test method (see Test Method D 2216) and a dry density test method (see Test Method D 4439) on a representative sample of the specimen.

10. Data Analysis

10.1 *Theory*:

10.1.1 If a constant amount of heat is applied to a zero mass heater over a period of time, the temperature response is:

$$\Delta T = -\frac{Q}{4\pi\lambda} Ei\left(\frac{-r^2}{4Dt}\right) \quad 0 < t \le t_1 \tag{2}$$

where:

t = time from the beginning of heating (s),
ΔT = temperature rise from time zero (K),
Q = heat input per unit length of heater (W/m),
r = distance from the heated needle (m),
D = thermal diffusivity (m^2/s),
λ = thermal conductivity (W m^{-1} K^{-1}),
Ei = exponential integral, and
t_1 = heating time.

10.1.2 The temperature rise after the heat is turned off is given by:

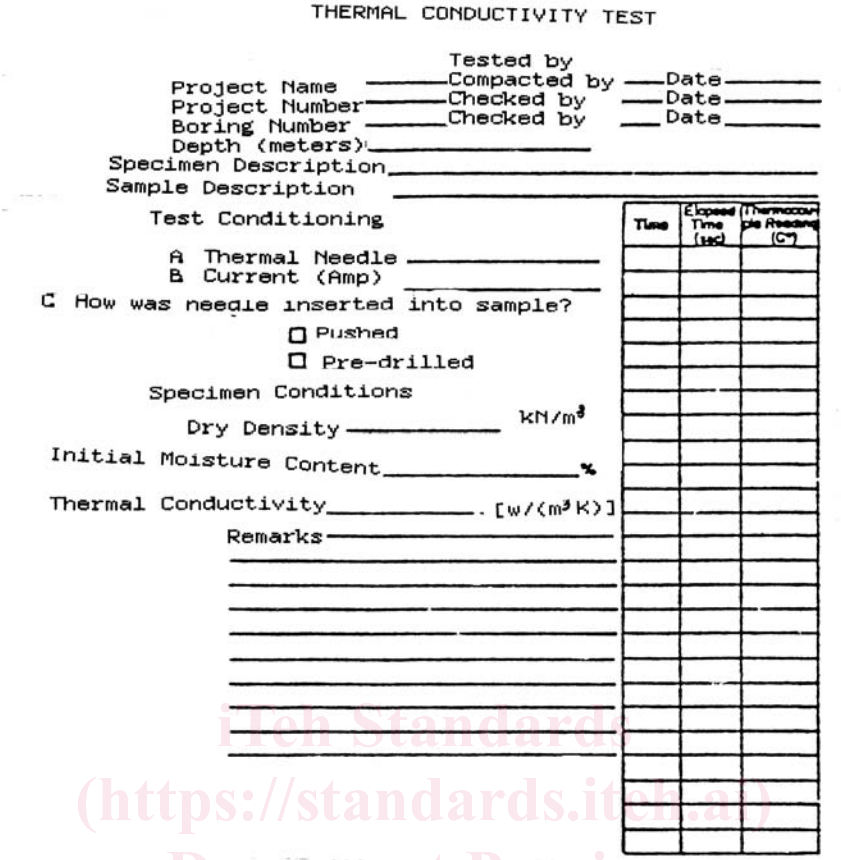
$$\Delta T = -\frac{Q}{4\pi\lambda}\left[-Ei\left(\frac{-r^2}{4Dt}\right) + Ei\left(\frac{-r^2}{4D(t-t_1)}\right)\right] \quad t > t_1 \tag{3}$$

10.1.3 The behavior of finite diameter and finite length probes can be approximated using these same equations, but D and λ will not represent the actual diffusivity and conductivity, so calibration factors must be obtained for these probes as outlined in Section 8.

~~9.10Perform an initial moisture content test method (see Test Method D2216) and a dry density test method (see Test Method D4439) on a representative specimen of the sample.~~

~~10.Calculation~~

~~10.1Compute the thermal conductivity (λ) of the specimen from the linear portion of the experimental curve shown in Fig. 4 using the following relationship:~~



THERMAL CONDUCTIVITY TEST

Project Name ________ Tested by
Compacted by ____ Date ________
Project Number ________ Checked by ____ Date ________
Boring Number ________ Checked by ____ Date ________
Depth (meters) ________________
Specimen Description ________________________
Sample Description ________________________
Test Conditioning
A Thermal Needle ______________
B Current (Amp) ______________
C How was needle inserted into sample?
☐ Pushed
☐ Pre-drilled
Specimen Conditions
Dry Density ____________ kN/m³
Initial Moisture Content ______________ %
Thermal Conductivity __________ . [w/(m³K)]
Remarks ________________________

Time	Elapsed Time (sec)	Thermocouple Reading (C°)

THERMAL CONDUCTIVITY TEST

	Tested by	
Project Name	Compacted by	Date
Project Number	Checked by	Date
Boring Number	Checked by	Date

Depth (meters)

Specimen Description

Sample Description

Test Conditioning:

A. Thermal needle ID

B. Current (Amp)

C. Method of needle insertion into sample
☐ Pushed
☐ Pre-drilled

D. Total time of data included in analysis s

E. Calibration coefficient applied to measured thermal conductivity value

Specimen Conditions:

A. Dry Density kg/m^3

B. Initial moisture content (% mass basis)

Results:

A. Thermal conductivity ($Wm^{-1}K^{-1}$)

$$\lambda = \frac{2.30Q}{\cancel{4\pi(T_2 - T_1)}}\,\mathrm{Log}_{10}(t_2/t_1) = ln(t) \quad 0 < t \le t_1 \qquad (1)$$

(1) $\lambda = 2.30Q4\pi(T2 - T1)$

10.1.4 The most direct and precise method to calculate thermal conductivity is to use Eq 2 and 3 directly with the time series data collected as described in Section 9. Unfortunately, Eq 2 and 3 cannot be solved for λ and *D* explicitly, so a non-linear least-squares inversion technique must be used. A simplified analysis, which gives adequate results, approximates the exponential integral in Eq 2 and 3 by the most significant term of its series expansion:

$$\Delta T \cong \frac{Q}{4\pi\lambda} \ln(t) \quad 0 < t \le t_1 \qquad (4)$$

$$\Delta T \cong \frac{Q}{\cancel{4\pi(T_2 - T_1)}} ln(t_2/t_1) \qquad (5)$$

$4\pi\lambda \;\; \ln tt - t1 \quad t > t1$

10.2 *Simplified Method*:

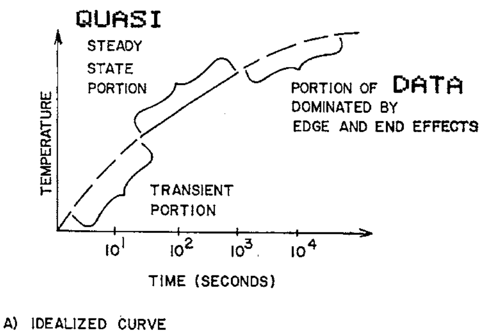
10.2.1 For thermal needle probes with diameter of 2.5 mm or less, exclude from the analysis the first 10 to 30 seconds of data from both the heating and, if used, cooling data. For larger diameter thermal needle probes it will be necessary to plot the data on a semi-log plot as described in 10.2.2 and identify the duration of the non-linear portion of initial data that should be excluded. These data are most strongly affected by terms ignored in Eq 4 and 5, and will result in decreased accuracy if they are included in the subsequent analysis. The total time duration of the data included in the analysis, and duration of initial values excluded from the analysis, should be fixed for any thermal needle probe configuration and used during calibration and all subsequent thermal conductivity measurements with that probe type to avoid biasing results due to subjective selection of the time range for analysis.

10.2.2 Using the remaining data, determine the slope, S_h of a straight line representing temperature versus ln *t* for the heating phase, and, if used, the slope, S_c of a straight line representing temperature versus $\ln[t/(t - t_1)]$ for the cooling phase (see Fig. 4). The early and late portions of the test (representing transient conditions and boundary effects, respectively) should not be used for the curve fitting. These slopes can be determined using linear regression with any standard spreadsheet or data analysis software, or manually, by plotting the data and fitting a straight line to the data by eye. If manual methods are used to determine the slope, it may be convenient to use semi-log graph paper with $\log_{10}$ time. If the slope of temperature versus $\log_{10} t$ is used in the analysis, the slopes of the plots should be termed (S_{h10}) for the heating phase, and (S_{c10}) for the cooling phase.

10.2.3 The data included in the analysis should be evenly spaced with the logarithm of time (*X*-axis). If data are collected in even time increments and subsequently plotted on a log time scale, then the distribution becomes uneven biasing the analysis too heavily toward the long-term of the testing period. Fig. 4 shows a data set that has been properly filtered to provide an even data distribution along the log time axis.

10.2.4 Compute thermal conductivity using Eq 6, where *S* is the average of S_h and S_c and S_{10} is the average of S_{h10} and S_{c10} if both heating and cooling data are used for the analysis or just S_h (or S_{h10}) if only heating data are used. Typically S_h and S_c differ because of specimen temperature drift during the measurement. Averaging the two values minimizes the effects of the drift, which can cause large errors in determination of λ. Note that *C* is the calibration coefficient determined in Section 8.

$$\lambda = \frac{CQ}{4\pi S} = \frac{2.3CQ}{4\pi S_{10}} \qquad (6)$$



A) IDEALIZED CURVE

FIG. 3 Typical Record of Data (Idealized Curve)