Designation: D 5334 – 00

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 as well as in situ and laboratory soft rock specimens. This test method is suitable only for isotropic materials.

1.2 This 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.

1.3 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.

1.6 *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:*

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[2]

D 4439 Terminology for Geotextiles[3]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *thermal epoxy*—any thermally conductive filled epoxy material having a value of $\lambda > 4$ W/(m·k).

3.1.2 *thermal grease*—any thermally conductivity grease having a value of $\lambda > 4$ W/(m·k).

3.2 *Symbols:*

3.2.1 E—measured voltage (V).

3.2.2 I—current flowing through heater wire (A).

3.2.3 L—length of heater wire (m).

3.2.4 λ—thermal conductivity [W/(m·k)].

3.2.5 Q—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.

3.2.6 R—total resistance of heater wire (Ω).

3.2.7 T_1—initial temperature (k).

3.2.8 t_1—initial time (s).

3.2.9 T_2—final temperature (k).

3.2.10 t_2—final time (s).

3.2.11 p_d—dry density (kg/m^3).

4. 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 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.

5. Significance and Use

5.1 The thermal conductivity of both undisturbed and remolded soil specimens as well as in situ and laboratory soft

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[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] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

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.

6. Apparatus

6.1 The apparatus shall consist of the following:

6.1.1 *Thermal Needle Probe*—A device that creates a linear heat source and incorporates a temperature measuring element (thermocouple or thermister) to measure the variation of temperature at a point along the line. The construction of a suitable device is described in Annex A1.

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

6.1.3 *Thermal Readout Unit*—A device to produce a digital readout of temperature in degrees Celsius to the nearest 0.1K.

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

6.1.5 *Timer*, stopwatch or similar time measuring instrument capable of measuring to the nearest 0.1 s for a minimum of 15 min.

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

7. Specimen Preparation

7.1 *Undisturbed 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 (2.0 in.).

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

7.1.3 Insert the thermal needle probe into 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 enbedded in the specimen and not left partially exposed. (See Note 1.)

NOTE 1—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 or slightly less than 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.

7.2 *Remolded 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. **(1)**.[4] The tube should have a minimum diameter of 51 mm (2.0 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).

7.3.2 Insert the thermal needle probe into the specimen by predrilling a hole to a depth equal to the length of the probe. (See Note 1.)

8. 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.

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 Pryoceram 9606 **(2)**. 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.

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.

9. Procedure

9.1 For tests conducted in the laboratory, allow the specimen to come to equilibrium with room temperature.

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.

9.6 Turn off the constant current source.

9.7 Plot the temperature data as a function of time on a semilog graph. (See Fig. 2)

9.8 Select linear portion of curve (pseudo steady state

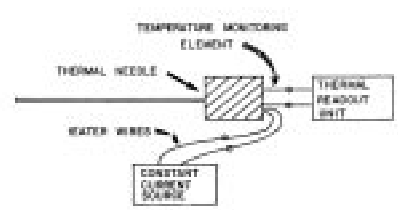
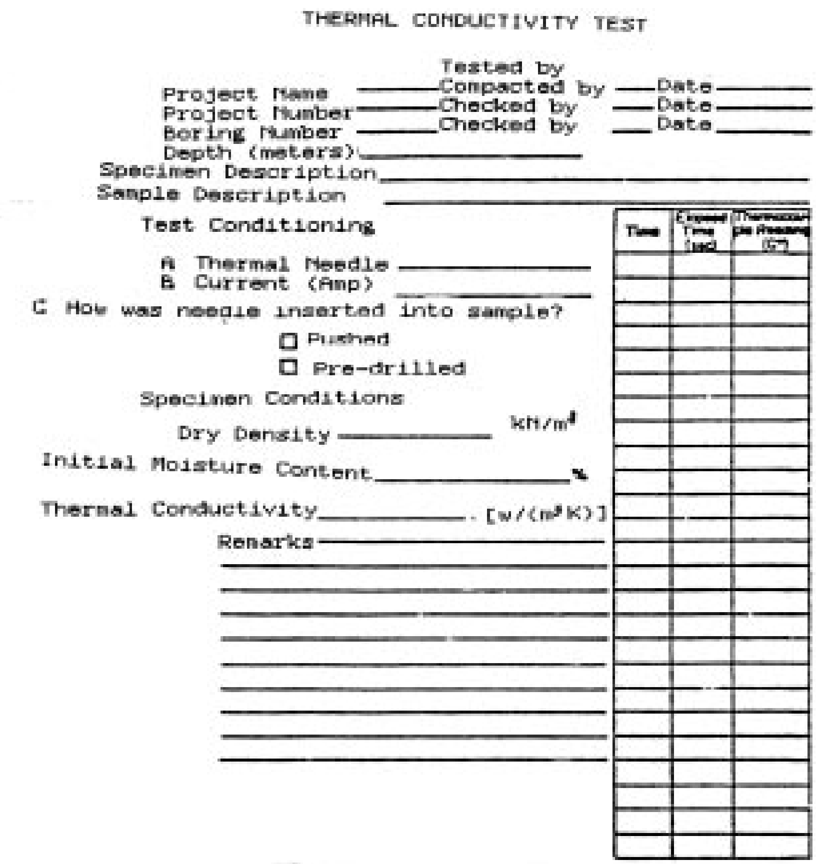


FIG. 1 Thermal Probe Experimental Setup

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


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/(m°K)]
Remarks ______

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

FIG. 2 Typical Experimental Test Results Plotted on Semilog Graph

portion) and draw a straight line through the points. (See Fig. 3.)

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

9.10 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 specimen of the sample.

10. Calculation

10.1 Compute the thermal conductivity (λ) of the specimen from the linear portion of the experimental curve shown in Fig. 3 using the following relationship:

$$\lambda = \frac{2.30\,Q}{4\pi(T_2 - T_1)}\,\text{Log}_{10}(t_2/t_1) = \frac{Q}{4\pi(T_2 - T_1)}\,ln\,(t_2/t_1) \qquad (1)$$

where:

Q = heat input = $\frac{I^2R}{L} = \frac{EI}{L}$

10.2 Derivation of Eq 1 is presented by Carslaw and Jaeger **(3)**, and adapted to soils by VanRooyen and Winterkorn **(4)**; VanHerzen and Maxwell **(5)**; and Winterkorn **(6)**.

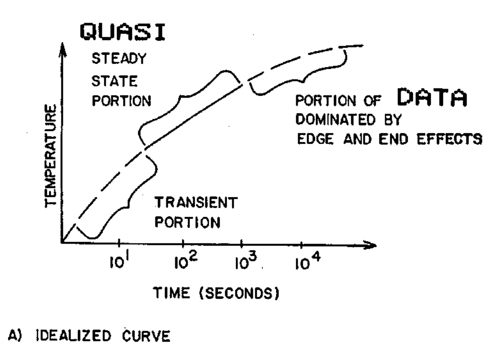


FIG. 3 Typical Experimental Test Results Plotted on Semilog Graph

11. Report

11.1 For each thermal conductivity test, fill out a data sheet similar to that shown in Fig. 4, reporting the following:

11.1.1 Date of the test and project name or number,

11.1.2 Boring number, sample or tube number, sample depth, and data recorded in 9.5.

11.1.3 Initial moisture content and dry density,

11.1.4 Time versus temperature plot (see Fig. 3),

11.1.5 Thermal conductivity, and

11.1.6 Physical description of sample including soil or rock type. If rock, describe location and orientation of apparent weakness planes, bedding planes, and any large inclusions or inhomogeneities.

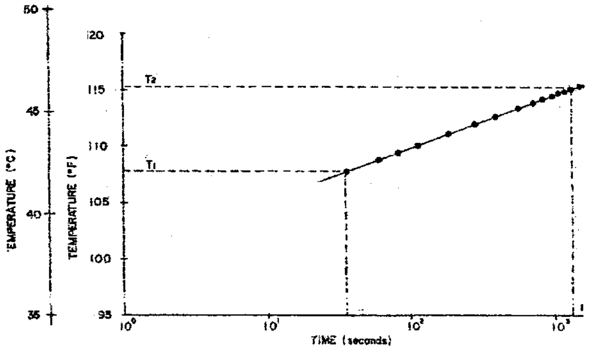


FIG. 4 Typical Data Sheet

12. Precision and Bias

12.1 An interlaboratory study involving line-source methods, including needle probes used for rock and soils, was undertaken by ASTM Committee C-16 **(7)**. The materials of known thermal conductivity that were evaluated included Ottawa sand and paraffin wax (having a thermal conductivity similar to certain soil and soft rock types). The results indicated a measurement precision of between ±10 and ±15 % with a tendency to a positive bias (higher value) over the known values for the materials studied. Subcommittee D18.12 welcomes proposals that would allow for a more comprehensive precision and bias statement covering the full range of soil and rock materials.

13. Keywords

13.1 heat flow; temperature; thermal conductivity; thermal probe; thermal properties

ANNEX

(Mandatory Information)

A1. COMPONENTS AND ASSEMBLY OF THERMAL NEEDLE

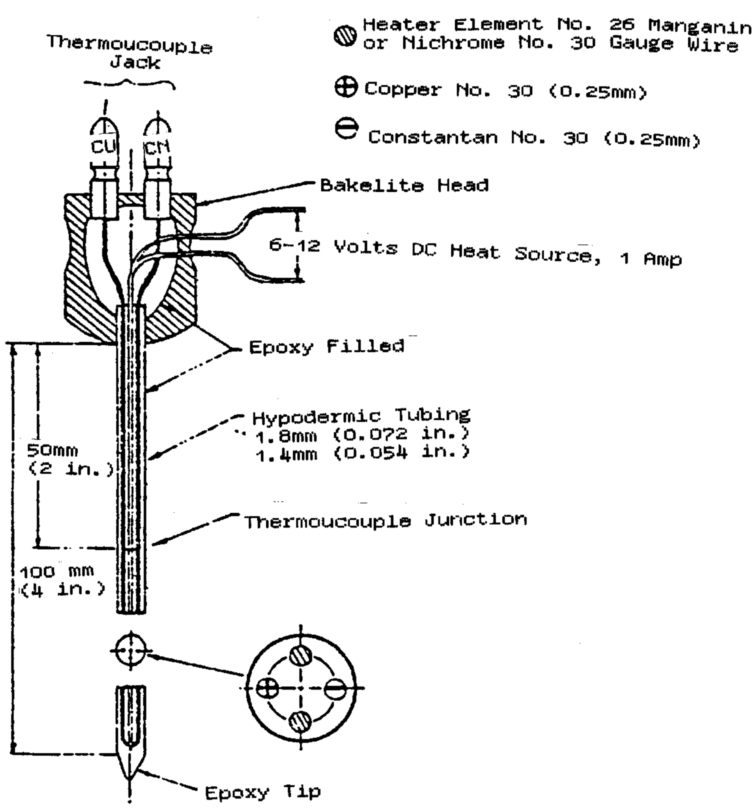


FIG. A1.1 Typical Probe Components

A1.1 The thermal needle consists of a stainless steel hypodermic tubing containing a heater element and a thermocouple as shown in Fig. A1.1. Its components and assembly are similar to the one described by Mitchell et al **(1)** and Footnote 5.[5] To construct a thermal needle, hypodermic tubing is cut to 115 mm (4½ in.) in length. The end to be inserted into the bakelite head of a thermocouple jack is roughened for a length of 15 mm (0.5 in.). A copper-constantan thermocouple wire junction previously coated with an insulating varnish is threaded into the hypodermic needle with the junction 50 mm (2 in.) from the end of the needle (see Note A1.1). At the same time, a manganin heater element is inserted with approximately 75-mm (3-in.) pigtails extending from the top of the needle as shown in Fig. A1.2. The uncut end of the needle is then inserted into an evacuating flask through a rubber stopper and the other end is placed in a reservoir of thermal epoxy primer as shown in Fig. A1.2. A vacuum pump connected to the evacuating flask is used to draw the thermal epoxy up through the needle. The needle is removed from the reservoir and flask, and a blob of putty is placed at the end of the needle to hold the thermal epoxy in place for hardening. After the thermal epoxy hardens, the thermocouple wires are soldered to the pins of a polarized thermocouple jack and the roughened end of the needle is placed in the bakelite head of the jack. The heater leads are brought out through two holes in the back of the bakelite head (see Fig. A1.1).

NOTE A1.1—For soft rock specimens it may not be possible to drill a hole to accommodate a 115-mm (4.50-in.) long thermal needle. In this case a shorter needle may be used. The length of the needle should not be less than 25.4 mm (1.0 in.) to avoid boundary effects.

[5] Mitchell, J. K., (Personal Communication), 1978 b.

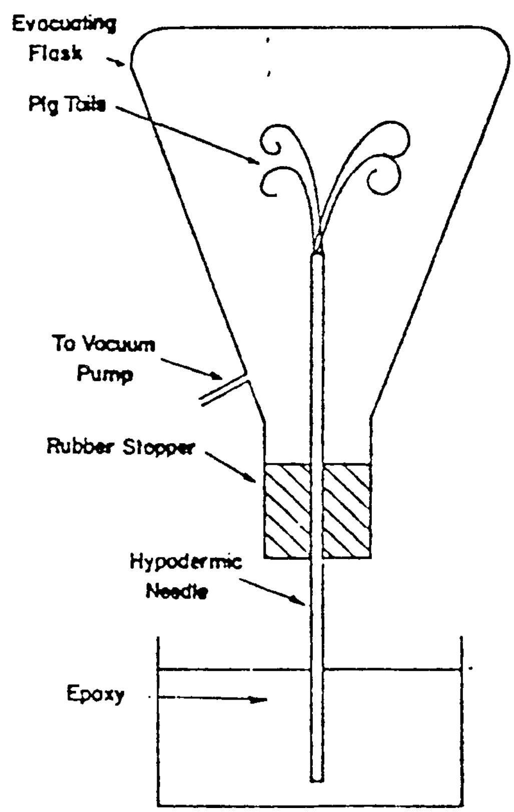


FIG. A1.2 Drawing Thermal Epoxy Into Hypodermic Tubing

REFERENCES

(**1**) Mitchell, J. K., Kao, T. C., and Abdel-Hadi, O. N., "Backfill Materials for Underground Power Cables," Department of Civil Engineering, University of California at Berkeley, EPRI EL-506, June 1977.

(**2**) Powell, R.W., Ho, C.Y., and Liley, P.E., "Thermal Conductivity of Selected Materials," *Special Publication, NSRDS-NBS 8*, National Bureau of Standards, Washington, DC, 1996. (See also Ref 7).

(**3**) Carslaw, H. S., and Jaeger, J. C., *Conduction of Heat in Solids*, Oxford Press, 2nd ed., 1946.

(**4**) Van Rooyen, M., and Winterkorn, H. F., "Theoretical and Practical Concepts of the Thermal Conductivity of Soils and Similar Granular Systems," *Highway Research Board*, *Bulletin 168—Fundamental and Practical Concepts of Soil Freezing*, 1957, pp. 143–205.

(**5**) Von Herzen, R., and Maxwell, A. E., "The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method," *Journal of Geophysical Research*, Vol 64, No. 10, October 1959, pp. 1557–1563.

(**6**) Winterkorn, H. K., "Suggested Method of Test for Thermal Resistivity of Soil by the Thermal Probe," *Special Procedures for Testing Soil and Rock for Engineering Purposes, ASTM STP 479*, ASTM, 1970, pp. 264–270.

(**7**) Hust, J.G., and Smith, D.R., "Interlaboratory Comparison of Two Types of Line-Source Thermal Conductivity Apparatus Measuring Five Insulating Materials," NISTIR, 89-3908, 1989.