AMERICAN SOCIETY FOR TESTING AND MATERIALS
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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 laboratory 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 samples as well as in situ and laboratory soft rock samples. This test method is suitable only for isotropic materials.

1.2 This test method is applicable over the temperature range from 20 to 100°C (68 to 212°F).

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 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 problems, 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]

3. Terminology

3.1 *Symbols:Symbols:*

3.1.1 *E*—measured voltage (volts).

3.1.2 *I*—current flowing through heater wire (amps).

3.1.3 *L*—length of heater wire (m).

3.1.4 λ—thermal conductivity (watts/m-°K).

3.1.5 *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.

3.1.6 *R*—total resistance of heater wire (ohms).

3.1.7 ρ—thermal resistivity (°K-m/watt).

3.1.8 T_1—initial temperature (°K).

3.1.9 t_1—initial time (seconds).

3.1.10 T_2—final temperature (°K).

3.1.11 t_2—final time (seconds).

4. Summary of Test Method

4.1 The rate at which heat flows through a material is a measure of its thermal conductivity. In this test method the thermal conductivity is determined by inserting a relatively long needle of small diameter into the material. The needle consists of both heating and temperature measuring elements. To perform the test a known amount of current is passed through the heater element and the resulting variation of temperature is monitored as a function of time.

5. Significance and Use

5.1 The test method presented here is used to determine the thermal conductivity (λ) of both undisturbed and remolded soil samples as well as in situ and laboratory soft rock samples. This parameter is used in the thermal analysis of underground electrical transmission lines, oil 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 the device is described in the annex.

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

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[1] This test method is under the jurisdiction of ASTM Committee D-18 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.

readout of temperature in degrees Celsius to the nearest 0.1°K.

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 2.3 mm (0.09 in.) diameter hole to a depth equal to the length of the needle.

6.1.7 *Thermal Grease*—Any thermally conductive grease with $\lambda > 50$ W/m-°K.

6.1.8 *Thermal Epoxy*—Any thermally conductive epoxy with $\lambda > 50$ W/m-°K.

6.1.9 *Calibration Standard*—A material with known thermal conductivity (typically fused silica, $\epsilon\ \lambda = 1.34$ W/m-°K at 20°C is used). 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.

7. Sample Preparation

7.1 *Undisturbed Samples*:

7.1.1 *Thin Wall Tube or Drive Samples*—Cut a 200 ± 30 mm (8.0 ± 1 in.) long section of a sampling tube containing an undisturbed soil sample. The tube section should have a minimum diameter of 51 mm (2.0 in.).

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

7.1.3 Insert the thermal needle probe into the sample by either pushing the probe into a predrilled hole (dense sample) to a depth equal to the length of the probe or pushing the probe into the sample (loose sample). Care should be taken to ensure that the thermal probe shaft is fully enbedded in the sample and not left partially exposed. (See Note 1.)

NOTE 1—To provide better thermal contact between the sample 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 slightly less than the diameter of the needle probe to ensure a tight fit. A device, such as a drill press, shall 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 Samples*:

7.2.1 Compact sample to 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 the reader is referred to Mitchell et al. **(1)**.[3] 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 Samples*—Insert the thermal needle probe into the sample 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 7 using a calibration standard as specified in 6.1.9.

8.3 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 Allow sample 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 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. A typical data sheet and a typical record of data are shown in Fig. 2 and Fig. 3 respectively.

9.6 Turn off constant current source.

9.7 Select linear portion of curve (pseudo steady state portion) and draw a straight line through the points.

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

9.9 Remove soil from the thin wall tube or sampling rings.

9.10 Perform a moisture content test (see Test Method D 2216) on a representative specimen of the sample.

9.11 Clean the thin wall tube or sampling rings and weigh.

10. Calculation

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

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

where:

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

10.2 Derivation of (Eq 1) is presented by Carslaw and Jaeger **(2)**; and adapted to soils by VanRooyen and Winterkorn **(3)**; VanHerzen and Maxwell **(4)**; and Winterkorn **(5)**.

11. Report

11.1 For each thermal conductivity test record, report the

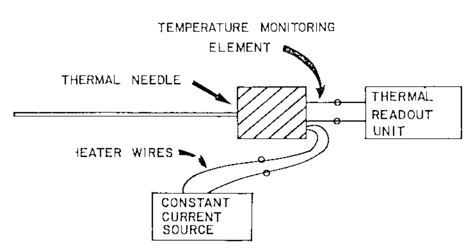
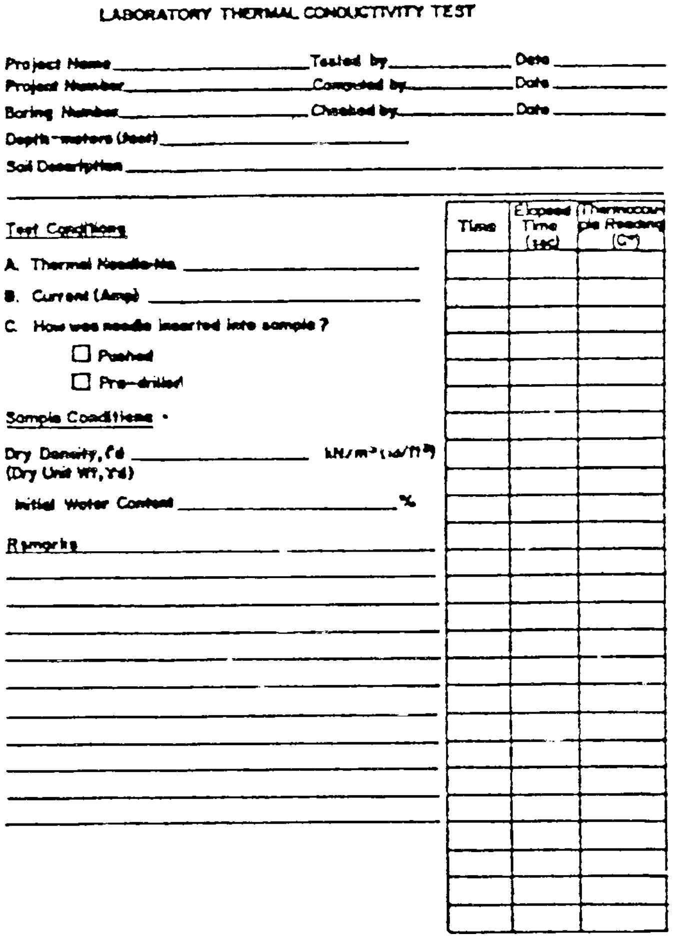


FIG. 1 Thermal Probe Experimental Setup (Idealized Setup)

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


LABORATORY THERMAL CONDUCTIVITY TEST

Project Name ____ Tested by ____ Date ____
Project Number ____ Computed by ____ Date ____
Boring Number ____ Checked by ____ Date ____
Depth—meters (feet) ____
Soil Description ____

Test Conditions
A. Thermal Needle No. ____
B. Current (Amp) ____
C. How was needle inserted into sample ?
☐ Pushed
☐ Pre-drilled

Sample Conditions •
Dry Density, ρd ____ kN/m³ (lb/ft³)
(Dry Unit Wt, γd)
Initial Water Content ____ %

Remarks ____

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

FIG. 2 Typical Laboratory Data Sheet

following observations:

11.1.1 Date of the test,

11.1.2 Boring number, sample or tube number, sample depth,

11.1.3 Initial moisture content and dry density,

11.1.4 Time versus temperature plot,

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.

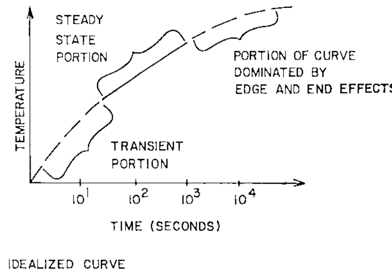


FIG. 3 Typical Experimental Test Results (Idealized Curve)

12. Precision and Bias

12.1 Due to the nature of the soil or rock materials tested by this test method it is either not feasible or too costly at this time to produce multiple specimens that have uniform physical properties. Any variation observed on the data is just as likely to be due to specimen variation as to operator or laboratory testing variation. Data obtained from tests on materials with known thermal conductivity indicate that precision of 5 to 10 % can be achieved. Subcommittee D18.12 welcomes proposals that would allow for development of a valid precision statement. There is no accepted reference value of soil or rock for this test method, therefore, bias cannot be determined.

13. Keywords

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

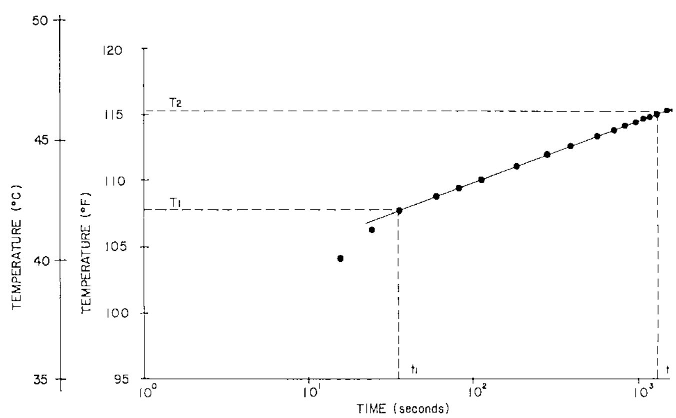


FIG. 4 Typical Experimental Test Results

ANNEX

(Mandatory Information)

A1. COMPONENTS AND ASSEMBLY OF THERMAL NEEDLE

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 4.[4] 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. A1.2).

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

NOTE A1.1—For soft rock samples 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.

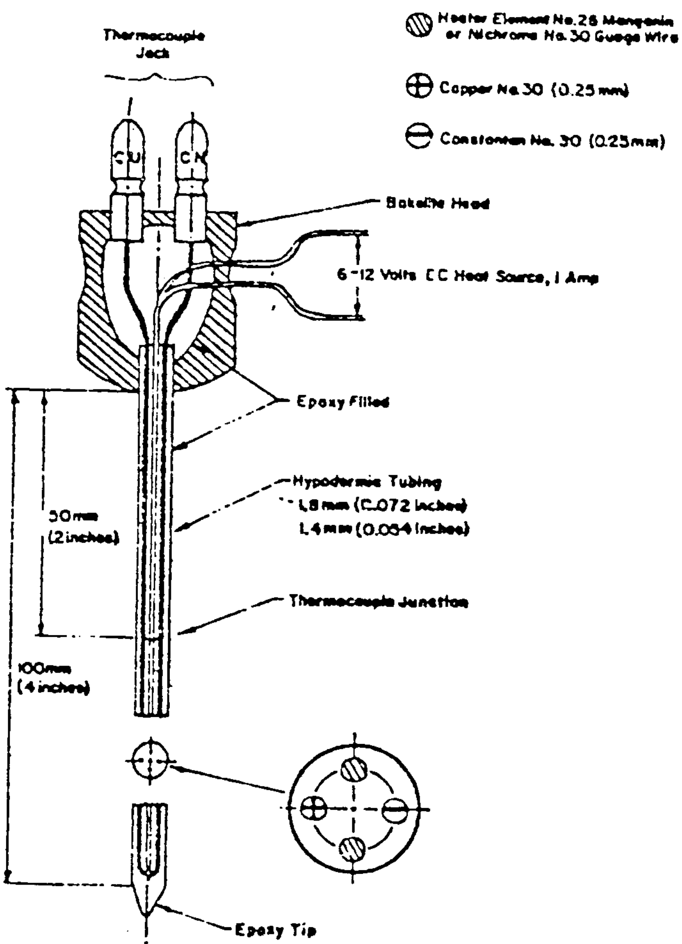


FIG. A1.1 Typical Probe Components

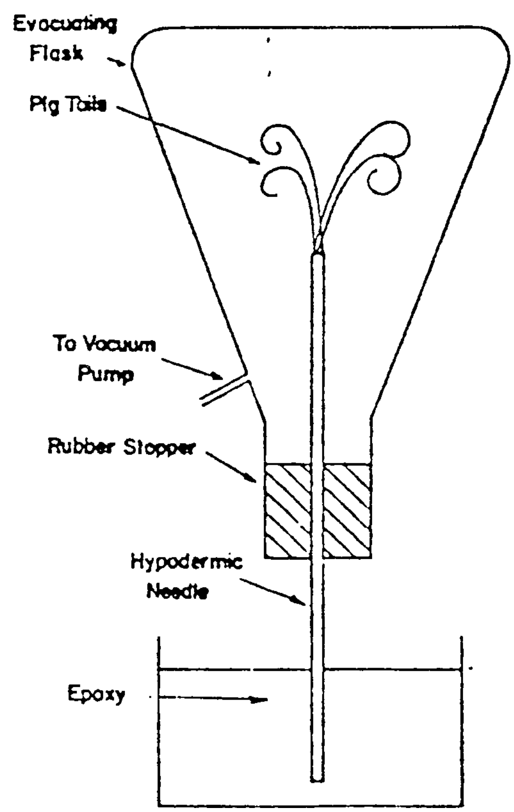


FIG. A1.2 Drawing Thermal Epoxy Into Hypodermic Tubing

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

(**3**) Van Rooyen, M., and Winterkown, 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.

(**4**) 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.

(**5**) Winterkown, 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.