Designation: D4612 – 16

Standard Test Method for Calculating Thermal Diffusivity of Rock and Soil[1]

This standard is issued under the fixed designation D4612; 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 involves calculation of the thermal diffusivity from measured values of the mass density, thermal conductivity, and specific heat at constant pressure. It is applicable for any materials where these data can be determined. The temperature range covered by this test method is 293 to 573 K. This test method is closely linked to the overall test procedure used in obtaining the primary data on density, specific heat, and thermal conductivity. It cannot be used as a "stand alone" test method because the thermal diffusivity values calculated by this test method are dependent on the nature of the primary data base. The test method furnishes general guidelines to calculate the thermal diffusivity but cannot be considered to be all-inclusive to capture issues related to the density, specific heat, and thermal conductivity

NOTE 1—The diffusivity, as determined by this test method, is intended to be a volume average value, with the averaging volume being $\geq 2 \times 10^{-5}$ m^3 (20 cm^3). This requirement necessitates the use of specimens with volumes greater than the minimum averaging volume and precludes use of flash methods of measuring thermal diffusivity, such as the laser pulse technique.

1.2 The values stated in SI units are to be regarded as the standard. No other units of measurements are included in this standard.

1.3 This test method is intended to apply to isotropic samples; that is, samples in which the thermal transport properties do not depend on the direction of heat flow. If the thermal conductivity depends on the direction of heat flow, then the diffusivity derived by this test method must be associated with the same direction as that utilized in the conductivity measurement.

1.4 The thermal conductivity, specific heat, and mass density measurements must be made with specimens that are as near identical in composition and water content as possible.

1.5 The generally inhomogeneous nature of geologic formations precludes the unique specification of a thermal diffusivity characterizing an entire rock formation or soil layer. Geologic media are highly variable in character, and it is impossible to specify a test method for diffusivity determination that will be suitable for all possible cases. Some of the most important limitations arise from the following factors:

1.5.1 *Variable Mineralogy*—If the mineralogy of the formation under study is highly variable over distances on the same order as the size of the sample from which the conductivity, specific heat, and density specimens are cut, then the calculated diffusivity for a given set of specimens will be dependent on the precise locations from which these specimens were obtained.

1.5.2 *Variable Porosity*—The thermal properties of porous rock or soil are highly dependent on the amount and nature of the porosity. A spatially varying porosity introduces problems of a nature similar to those encountered with a spatially varying composition. In addition, the character of the porosity may preclude complete dehydration by oven drying.

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

1.6.1 The procedure 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.

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.*

[1] This test metis 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 May 1, 2016. Published May 2016. Originally approved in 1986. Last previous edition approved in 2008 as D4612 – 08. DOI: 10.1520/D4612-16.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C642 Test Method for Density, Absorption, and Voids in Hardened Concrete

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

D4611 Test Method for Specific Heat of Rock and Soil

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

D5334 Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure

D6026 Practice for Using Significant Digits in Geotechnical Data

E145 Specification for Gravity-Convection and Forced-Ventilation Ovens

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.2 *Symbols:*

3.2.1 *mass density*—ρ (kg/m^3).

3.2.2 *instantaneous specific heat*—c_p (J/kgK).

3.2.3 *thermal conductivity*—k (W/mK).

3.2.4 *thermal diffusivity*—α (m^2/s).

3.2.5 *enthalpy*—h.

4. Summary of Test Method

4.1 The thermal diffusivity is determined from the equation in 9.3. The data for k and c_p must be available over the temperature range of interest. For density, ρ, a single measurement at room temperature may be used because the density is approximately constant over the 293 to 573 K temperature range covered by this test method.

4.2 The measurements of k, ρ, and c_p are to be performed using the test methods in Section 8.

[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.

5. Significance and Use

5.1 The thermal diffusivity is a parameter that arises in the solution of transient heat conduction problems. It generally characterizes the rate at which a heat pulse will diffuse through a solid material.

5.2 The number of parameters required for solution of a transient heat conduction problem depends on both the geometry and imposed boundary conditions. In a few special cases, only the thermal diffusivity of the material is required. In most cases, separate values of k, ρ, and c_p are required in addition to α. This test method provides a consistent set of parameters for numerical or analytical heat conduction calculations related to heat transport through rocks.

5.3 In order to use this test method for determination of the thermal diffusivity, the parameters (k, ρ, c_p) must be determined under as near identical specimen conditions as possible.

5.4 The diffusivity determined by this test method can only be used to analyze heat transport in rock under thermal conditions identical to those existing for the k, ρ, and c_p measurements.

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/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. Apparatus

6.1 *Analytical Balance*—A class GP5 balance meeting the requirements of Specification D4753 for a balance of 1-g readability.

6.2 *Drying Oven*—Vented, thermostatically-controlled, preferably of the forced-draft type, meeting the requirements of Specification E145 and capable of maintaining a uniform temperature of 110 ± 5°C throughout the drying chamber.

6.3 *Vernier caliper,* with an accuracy of ±0.025 mm.

6.4 *Waterproof Flexible Container*—A waterproof, flexible container suitable for encapsulating soil specimens for determining dimensions by immersion.

6.5 *Container,* suitable for immersing the specimen and suitable wire for suspending the specimen in water.

7. Specimen

7.1 *Intact Soil Specimens:*

7.1.1 *Thin-Walled Tube or Drive Specimens*—Cut a 200 ± 30 mm long section of a sampling tube containing an intact soil specimen. The tube section shall have a minimum diameter of 50 mm.

7.1.2 Determine and record the mass of the specimen in a sampling tube or brass ring to the nearest 0.1 g.

7.1.3 Measure and record the length and diameter of the specimen to 0.025 mm. Take a minimum of three length measurements 120° apart and at least three diameter measurements at the quarter points of the height. Determine the average length and diameter of the specimen.

7.2 *Reconstituted Soil Specimens:*

7.2.1 Compact the specimen to the desired dry density and gravimetric water content in a thin-walled metal or plastic tube using an appropriate compaction technique.

7.3 *Rock Specimens:*

7.3.1 Determine and record the mass of the specimen to the nearest 0.1 g and follow the procedure given in 7.1.3 to determine the specimen diameter and length.

8. Procedure

8.1 *General:*

8.1.1 Obtain the data for k, ρ, and c_p as a function of temperature using the appropriate ASTM standard test methods with the required levels of accuracy associated with the given test methods for each parameter, as qualified below. If possible, make measurements using specimens obtained from the same general location in the sample in order to ensure that the specimens are as near identical in composition and morphology as possible.

8.1.2 To minimize water content variation among specimens, dry specimens at 378 K following the procedures in Test Method D2216, until the percent mass loss is constant to ±0.5 %.

8.2 *Qualifications to Other Test Methods:*

8.2.1 Calculate the specimen total density in one of the two following ways:

8.2.1.1 Using the mass of the specimen, m_s, measured on an analytical balance to the nearest 0.1 g and the volume of the specimens, V_s to the nearest 0.000001 m^3 by measurement of sample dimensions using a Vernier caliper or by water displacement (immersion). If the volume is measured by immersion, the specimen must be encapsulated in a waterproof flexible container of negligible volume compared to the specimen volume. The diameter and height of the test specimen for determination of total density shall be at least ten times the diameter of the largest mineral grain. The minimum specimen diameter and height of approximately 47 mm satisfy this criterion in the majority of cases. When cores of diameter and height smaller than the specified minimum must be tested because of the unavailability of larger samples, suitable notation of this fact shall be made in the report. Calculate the specimen total density ρ (kg/m^3), as follows,

$$\rho = m_s / V_s \tag{1}$$

where:

m_s = specimen mass (kg), and
V_s = specimen volume (m^3).

Also estimate the accuracy of the ρ determination from the accuracies associated with the m_s and V_s measurements.

8.2.1.2 Measure the specimen bulk specific gravity using Test Method C642 to the accuracy prescribed in the standard. In situations where the measurement is to be made at temperatures near or above the boiling point of water, a suitable oil working fluid may be substituted for water in this procedure. Calculate the total density, ρ, by multiplying the bulk specific gravity by the density of the working fluid at the immersion temperature. Estimate the accuracy of the ρ determination from the accuracies associated with the bulk specific gravity and the working fluid measurements.

8.2.2 Measure the specimen specific heat using Test Method D4611 to the prescribed accuracy.

8.2.3 Measure the specimen thermal conductivity using Test Method D5334, Test Method C518, or Test Method C177 to the prescribed accuracy.

9. Calculations

9.1 *General*—The following method of calculation is recommended for deriving the temperature dependent diffusivity, $\alpha(T)$, from data from k, ρ, and c_p.

NOTE 3—The recommended data analysis technique is not intended to preclude the use of other methods of data analysis which may be more suitable in certain cases. It does provide a method by which a consistent set of temperature dependent parameters may be derived from the primary data base, and also a method by which the uncertainties in each parameter may be estimated. The results of the calculations for the temperature dependent parameters will be in a form which is useful for most thermal analysis computer programs.

9.2 *Description of the Method*—The parameter data for an associated set of specimens will usually be in the form of tables giving the measured parameter value versus the measurement temperature. Each parameter shall be fit to an equation of the following form:

$$\gamma(T) = \sum_{n=o}^{N} c_n \left(T - T_o\right)^n \tag{2}$$

where:

γ = parameter (k, ρ, or, c_p),
T_o = 293 K,
T = temperature (K), and
N = maximum power used in the fit.

9.2.1 The fit shall be performed using ordinary least squares techniques.[3] The value of N shall be as small as possible, consistent with obtaining a reasonable fit to the data. The result of this fit will be a set of coefficients, (c_n), and the estimated standard error in the parameter, given by the following equation:

$$s_\gamma \left\{ \sum_{i=1}^{M} \left[_\gamma(T_i) - _{\gamma i}(T_i)\right]^2 \right\}^{1/2} \tag{3}$$

where:

M = number of temperatures at whichγ is measured, and
γ_i = measured value of the parameter at temperature T_i.

NOTE 4—In the case of density, a measurement is usually available only at room temperature, T_o. In this situation, take $\rho(T) = \rho(T_o)$, corresponding to $c_o = \rho(T_o)$, $c_n = 0$ for $n > 0$. The associated error, s_ρ, is the estimated error for the single measurement.

9.3 Calculate the diffusivity from the curve fit relation determined in 9.2 as follows:

$$\alpha(T) = k(T)/\left[\rho(T) c_p(T)\right]$$
$$\text{or } \alpha(T) = k(T)/\left[\rho(T_o) c_p(T)\right]$$

9.4 Fit $\alpha(T)$ to an equation of the form of Eq 2, and calculate s_α from (Eq 3).

[3] Beck, J. V., and Arnold, K. J. *Parameter Estimation in Engineering and Science*, John Wiley, NY, 1977, pp. 234–237.

9.5 Estimate the error in α, δα, caused by measurement errors in k, ρ, and c_p from the equation,

$$(\delta\alpha/\alpha)^2 = (\delta k/k)^2 + (\delta\rho/\rho)^2 + (\delta c_p/c_p)^2 \quad (4)$$

9.5.1 The relative parameter errors; $\delta k/k$, $\delta\rho/\rho$, and $\delta c_p/c_p$, are determined or estimated, or both, in each of the separate parameter measurements where the appropriate ASTM procedures are used.

10. Report: Test Data Sheet(s)/Form(s)

10.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.6 and Practice D6026.

10.2 Record as a minimum the following general information (data:)

10.2.1 Database used for the diffusivity calculation giving k, ρ, and c_p versus the temperatures at which each parameter was measured, along with the accuracies of each parameter associated with the different testing methods. The values of k should be reported to the nearest 0.01 W/mK, the values of ρ should be reported to the nearest 1 kg/m^3, and the values of c_p should be reported to the nearest 0.01 J/kgK.

10.2.2 The methods used to obtain the data and any deviations from ASTM procedures in these methods. If one or more of the parameters was determined from literature values in place of direct measurement, then a complete reference shall be given and, in addition, the following information shall be quoted directly from the cited references:

10.2.2.1 Raw parameter versus temperature data unless the parameter was determined from a recommended curve.

10.2.2.2 The estimated relative error in the reported value, $\delta\gamma/\gamma$, where $\gamma = k$, ρ, or c_p, and the method of determining this error, if reported.

10.2.3 The method used to derive the diffusivity from the data in 9.2. If the recommended method in 9.2 is not followed, a complete description of the alternate method used shall be given. In the case where the recommended method is employed, the following calculated results shall be reported:

10.2.3.1 The coefficients, c_n; $n = 0, 1, ..., N$ characterizing the fit of each parameter as a function of temperature, Eq 2, and the estimated standard error for each fit, s_γ , from Eq 3.

10.2.3.2 The coefficients characterizing $\alpha(T)$ from 9.2 and the estimated standard error of the fit s_α.

10.2.3.3 The estimated relative error in α, as found in 9.2.

10.2.4 Sample identification and characterization information.

10.2.4.1 Identification of block or core sample from which the specimens were cut, including geographic location and depth from which the sample was obtained.

10.2.4.2 Qualitative description of sample mineralogy, morphology, isotropy.

10.2.4.3 Sample dimensions.

10.2.4.4 Dimensions of specimens used in each parameter measurement and location relative to the sample from which each specimen was taken.

10.2.4.5 Specimen porosity, if measured, and method of determination.

10.2.4.6 Specimen residual saturation, if measured, and method of determination.

10.2.5 Technician name, and time and date of testing run.

11. Precision and Bias

11.1 *Precision*—Test data on precision is not presented due to the nature of the (insert type: soil or rock, or both) materials tested by this test method. It is either not feasible or too costly at this time to have ten or more laboratories participate in a round-robin testing program. (The following two sentences may be omitted if uniform test specimens can be obtained.) Also, it is either not feasible or too costly to produce multiple specimens that have uniform physical properties. Any variation observed in the data is just as likely to be due to specimen variation as to operator or laboratory testing variation.

11.1.1 The Subcommittee D18.12 is seeking any data from the users of this test method that might be used to make a limited statement on precision

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

12. Keywords

12.1 density; heating tests; porosity; rock; specific heat; temperature tests; thermal analysis; thermal diffusivity

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D4612 – 08) that may impact the use of this standard. (May 1, 2016)

(1) Updated 1.2 to clarify that the standard is SI-only.
(2) Inserted 1.6.1.
(3) Updated Note 2.
(4) Changed the standard practice to a standard test method.
(5) Removed the definitions and referenced Terminology D653.
(6) Precision and bias statement added (Section 11).
(7) Specimen section added.
(8) Updated apparatus section.