Designation: D 5335 – 99

Standard Test Method for Linear Coefficient of Thermal Expansion of Rock Using Bonded Electric Resistance Strain Gages[1]

This standard is issued under the fixed designation D 5335; 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 covers the laboratory determination of the linear (one-dimensional) coefficient of thermal expansion of rock using bonded electric resistance strain gages.

1.2 This test method is applicable for unconfined pressure conditions over the temperature range from 20 to 260°C (68 to 500°F).

NOTE 1—Unconfined tests performed at elevated temperatures may alter the mineralogy or grain structure of the test specimen. This alteration may change the physical and thermal properties of the test specimen.

NOTE 2—The strain gages are mounted with epoxy. Most commercially available high temperature epoxies require elevated temperature curing. The elevated temperature required for this curing may alter the physical and thermal properties of the test specimen. Epoxy should be selected based upon the maximum expected test temperature. Room temperature curing epoxy should be used whenever possible.

1.3 The test specimens may be either saturated or dry. If saturated specimens are used, then the test temperature shall be at least 10°C (18°F) less than the boiling point of the saturating fluid in order to minimize the effects of evaporization of the fluid.

NOTE 3—When testing a saturated specimen, the moisture content of the specimen may change unless special precautions are taken to encapsulate the test specimen. Refer to 7.4.

1.4 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.

1.5 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.

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

1.7 *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:*

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

E 83 Practice for Verification and Classification of Extensometers[3]

E 228 Test Method for Linear Thermal Expansion of Solid Materials With a Vitreous Silica Dilatometer[4]

E 289 Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *linear coefficient of thermal expansion*—the change in length of a unit length for a temperature change of 1°. The mathematical expression is:

$$\bar{\alpha} = [(L_2 - L_1)/L_0] \times [(1/(T_2 - T_1)] \quad (1)$$

In terms of thermal strains:

$$\bar{\alpha} = (\epsilon_{T2} - \epsilon_{T1})/(T_2 - T_1) = \Delta\epsilon_T/\Delta T \quad (2)$$

where ϵ_{T1} and ϵ_{T2} are the thermal strains of the specimen as a result of a temperature change from T_0 to T_1 and from T_0 to T_2 respectively, $\bar{\alpha}$ is obtained by dividing the change in thermal strain ($\Delta\epsilon_T$) by the change in temperature (ΔT). The units of $\bar{\alpha}$ are millimetres/millimetre per degree Celsius (inches/inch per degree Fahrenheit).

3.1.2 *thermal strain*—the change in length of a unit length of a sample due to a change in temperature. The mathematical expression is:

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

[3] *Annual Book of ASTM Standards*, Vol 03.01.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

$$\epsilon_T = \frac{L_2 - L_1}{L_0} \quad (3)$$

where L_1 and L_2 are the specimen lengths at temperatures T_1 and T_2, respectively, and L_0 is the specimen length at the reference temperature T_0.

4. Summary of Test Method

4.1 The application of heat to rock causes it to expand. This change in dimension of the rock when divided by the length of rock is the strain developed in the rock. A wire or foil grid suitably bonded to the rock will be strained precisely the same amount as the rock. This straining, or stretching, of the grid results in a change in the electrical resistance of the grid. Measurement of the change in the electrical resistance of the grid is thus a measure of the change in dimension of the rock.

4.2 The application of heat to the grid may cause a change in the electrical resistance of the grid. To eliminate errors due to gage heating, a second grid is attached to a reference specimen and the output of the gage attached to the reference specimen is subtracted from the output of the gage attached to the test specimen.

5. Significance and Use

5.1 Information concerning the thermal expansion characteristics of rocks is important in the design of any underground excavation where the temperature of the surrounding rock may be altered. Thermal strain causes thermal stress that ultimately affects the stability of underground excavations. Examples of applications where rock thermal strain is important include: nuclear waste repositories, underground power stations, compressed air energy storage facilities, and geothermal energy facilities.

5.2 The linear coefficient of thermal expansion, α, of rock is known to vary as the temperature changes. Rock thermal strain is normally not a linear function of temperature. This test method provides a procedure for continuously monitoring thermal strain as a function of temperature. Therefore, information on how α changes with temperature is obtained.

5.3 Other methods of measuring the expansion coefficient of rock by averaging the thermal strain of a large specimen over a temperature range of many degrees may result in failure to determine the variation in α of that rock for one or more of the following reasons:

5.3.1 Alpha is not always linear with temperature,

5.3.2 Some rocks are anisotropic having directional characteristics which can vary by more than a factor of two.

5.3.3 Alpha may have a negative value in one direction and, at the same time, a positive value in the others.

5.4 Strain gages, both wire and foil types, have been successfully employed to measure the thermal expansion coefficients of rock. These coefficients are frequently very small, being on the order of millionths of a millimetre per millimetre for each degree Celsius (millionths of an inch per inch for each degree Fahrenheit). The thermal strain of rocks is about one tenth that of plastics and one half or one quarter that of many metals. Therefore, measurement methods for rocks require greater precision than methods that are routinely used on plastics and metals.

6. Apparatus

6.1 *Bonded Strain Gages*, corresponding to ASTM Class A resistance strain gage extensometer (see Practice E 83). The gage length shall be at least ten times the largest grain in the rock. Care shall be exercised to have the same length and type of connecting wires on all specimens.

6.2 *Strain-Measuring System*, having sensitivity of at least 5 μm/m (5 μin./in.) with an accuracy of at least ±0.1 % of the reading and a linearity of at least ±0.1 % of the interval.

6.3 *Reference Specimen*, having minimum dimensions at least twice the length of the strain gage. The reference specimen shall have a maximum linear coefficient of thermal expansion of 0.5×10^{-6} cm/cm°C (0.9×10^{-6} in./in.°F).

NOTE 4—Suitable reference materials include titanium silicate, Zerodur, and ultra-low expansion glass, all having expansion coefficients of less than 0.5×10^{6}/°C (0.9×10^{6}/°F) over the temperature range from 0 to 200°C (32 to 400°F)

6.4 *Temperature Measurement System*—The system chosen to monitor and record temperature depends primarily on the test apparatus and the maximum test temperature. Special limits of error thermocouples or platinum resistance thermometers (RTDs) are recommended. The temperature sensor (transducer) shall be accurate to better than 0.2°C (0.5°F) with a resolution of better than 0.05°C (0.1°F).

6.5 *Heating System*—The heating unit (furnace) shall be large enough to contain the test calibration, and reference specimens such that the gage length specified in 6.1 can be maintained at a constant temperature over its length to 0.1°C (0.2°F). It shall also incorporate controls so that specimens may be heated or cooled at a rate not greater than 1°C (1.8°F)/min while still maintaining the constant temperature along the gage length. If the heating unit consists of a liquid bath, then the specimens shall be encapsulated to prevent penetration of the fluid into the specimens.

7. Sampling

7.1 *Scope*—The number and types of rock samples needed depends partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermomechanical investigation of a specific rock type may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

7.2 *Statistical Requirements*—The number of specimens tested shall be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types that are highly variable will require more tests than relatively uniform rocks in order to evaluate the results with equal uncertainty.

7.3 *Nonhomogenities*—Discontinuities in the rock mass, such as joints, inclusions, voids, veins, bedding, etc., can influence the thermal expansion of the rock. Microcracks may be produced during sampling or test preparation.

7.4 *Moisture Condition of Samples*—The moisture condition of the rock can influence the measured thermal expansion. It is recommended that specimens be tested in both natural and dry conditions. For natural conditions, preserve the moisture content of the rock between the time of recovery and testing.

7.5 *Anisotropy*—The thermal expansion coefficient of many rocks is dependent on direction. Therefore, thermal expansion should be measured in several directions in order to assess the degree of anisotropy.

7.6 *Documentation*—Since the thermal expansion of most rocks is anisotropic, it is important that the field orientation of each sample is recorded. The orientation of each sample shall be noted on the sample and suitable markings shall be carried through each cutting to the final specimen ready for testing. These markings should indicate compass direction, up/down directions, and orientation with respect to geologic structure.

8. Test Specimens

8.1 *Dimensions*—Test specimens shall be right circular cylinders or right prisms. The minimum dimensions shall be adequate to accommodate the strain gages as specified in 6.1.

8.2 *Preparation*—The areas on the specimen where the strain gages are to be mounted shall be smooth to within 0.025 mm (0.001 in.). Do not degrade the rock during the machining process. Prevent thermal fracturing by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but some materials require special fluids, such as saturated brine for salt or glycerin for expansive shales.

8.3 *Drying*—If the specimen is to be tested dry, dry it at 80°C (176°F) in a heating unit, as described in 6.5, for 24 h. At no time during the drying process shall the specimen be subjected to heating or cooling rates greater than 1°C/min.

9. Calibration and Standardization

9.1 Prepare a calibration specimen whose thermal expansion is known with three pairs of strain gages. Run this cube, at the same time, through the same temperature schedule along with the rock specimens being measured. The calculation of the thermal expansion coefficient of the calibration specimen provides an indication of the performance of the measuring system and procedure.

NOTE 5—Calibration standards are available from the National Institute of Standards and Technology. Standard reference materials include borosilicate glass, stainless steel, and fused silica.

9.2 The strain measuring system should be set up so that it can be switched to the calibration specimen at any time that a question arises regarding the behavior of the system.

10. Procedure

10.1 For specimens tested in the dry condition (see 7.4), perform a water (moisture) content test on the specimen, in accordance with Test Method D 2216, prior to testing. For specimens testing in the natural condition (see 7.4), perform a water (moisture) content test on another, representative, specimen from the sample in accordance with Test Method D 2216.

10.2 Center and bond two strain gages parallel to each other, one on each of two opposite sides of the reference specimen and the test specimen, in the direction for which the thermal strains are to be measured. One, two, or three pairs of gages may be affixed to each test specimen, depending on the number of directions in which information is required. Connect the two strain gages of each pair according to the wiring diagram shown in Fig. 1. Mount the strain gages in accordance with the manufacturer's directions. If the adhesive requires a heat cure, raise and lower the temperature of the sample at a rate no greater than 1°C (1.8°F) per minute.

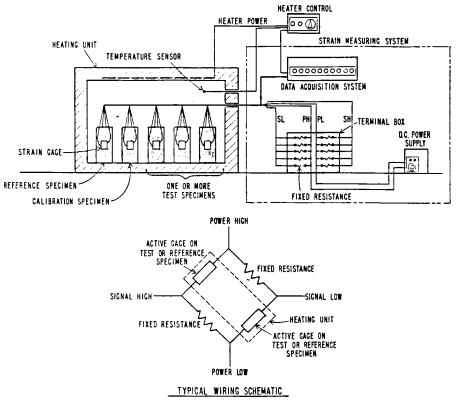

FIG. 1 Schematic of Test Setup

10.3 Place the reference specimen, the test specimen, and the calibration specimen into the heating unit. Initially, the temperature of the heating unit must be within 5°C (9°F) of the temperature of the test specimen to minimize thermal "shock" to the test specimen.

10.4 Heat the specimens according to either Thermal Schedule A or B as described in 10.5 or 10.6, respectively. The heating rate must be less than 1°C (1.8°F) to minimize thermally-induced fractures.

10.5 *Thermal Schedule A; a Series of Constant Temperatures*:

10.5.1 When the heating unit reaches the desired test temperature, monitor all temperature and strain outputs until thermal equilibrium is attained. The sample will be considered to have attained thermal equilibrium when the strain gage reading is constant for at least three readings over a period of not less than 30 min, except for normal fluctuations caused by the limitations of the test system.

10.5.2 Record at least eight data points at equally spaced temperature intervals for each of the heating and cooling cycles. The system shall reach thermal equilibrium for each data point.

10.6 *Thermal Schedule B; Heating and Cooling at Constant Rate*:

10.6.1 Continuously monitor all thermal strains and specimen temperatures as the specimens are heated and cooled at a constant rate.

10.7 Perform at least two complete heating and cooling cycles consecutively on each specimen to check for changes induced by heating.

11. Calculation

11.1 The mean coefficient of linear thermal expansion of the test specimen, $\bar{\alpha}_{ss}$, over the temperature range of T_1 to T_2, is calculated using:

$$\bar{\alpha}_{ss} = [(\epsilon_t - \epsilon_r)/(T_2 - T_1)] + \bar{\alpha}_{rs} \quad (4)$$

where:

ϵ_t = strain of the test specimen over the temperature range of T_1 to T_2,

ϵ_r = strain of the reference specimen over the temperature range of T_1 to T_2,
T_2 and T_1 = stabilized temperatures, and
$\bar{\alpha}_{rs}$ = mean linear coefficient of thermal expansion of the reference specimen over the temperature range of T_1 to T_2.

11.2 The instantaneous coefficient of linear thermal expansion of the test specimen, $\bar{\alpha}_i$, at temperature T, is calculated using:

$$\bar{\alpha}_i = \frac{\partial(\epsilon_t - \epsilon_r)}{\partial T} + \bar{\alpha}_{ri} \quad (5)$$

where:
$\frac{\partial(\epsilon_t - \epsilon_r)}{\partial T}$ = slope of the differential strain vs. temperature curve at temperature T, and
$\bar{\alpha}_{ri}$ = instantaneous coefficient of linear thermal expansion of the reference material at temperature T.

12. Report

12.1 Report the following information:

12.1.1 A discussion of the scope of the testing program that includes the number of specimens tested, rationale for sample selection, and the limitations of the testing program.

12.1.2 Description of the specimens. The rock type, structure and fabric, specimen size, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results.

12.1.3 Include detailed listing of the equipment actually used for the test in the report. List the name, model number, and basic specifications of each major piece.

12.1.4 If the actual equipment or procedure has varied from the requirements contained in this test method, note each variation and the reasons for it. Discuss the effect of the variation upon the test results.

12.1.5 Present a summary table of results including test suite designations, temperature ranges, average coefficients of thermal expansion, ranges, and uncertainties.

12.1.6 Present table of results for individual samples including, as a minimum, individual specimen number, rock type, thermal history during prep temperature range, coefficient of thermal expansion, specimen moisture condition (dry or natural), and moisture content of the specimen (dry) or representative specimen (natural).

12.1.7 For each suite of rock samples, calculate the mean value of thermal expansion, range, standard deviation, and 95 % confidence limits for the mean as a minimum. Compare the uncertainty of the sample suite with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

13. Precision and Bias

13.1 Since this test method determines $\bar{\alpha}$ of rocks with respect to $\bar{\alpha}$ of a reference specimen, the accuracy of this test method is limited by the accuracy to which $\bar{\alpha}$ of the reference specimen is known. The measured $\bar{\alpha}$ of the calibration specimen must agree within one standard deviation of the published value of $\bar{\alpha}$, or with the value of $\bar{\alpha}$ determined by an independent method, such as Test Method E 289 or E 228.

NOTE 6—Values of $\bar{\alpha}$ for reference and calibration can often be obtained from the manufacturers of the materials or from the National Institute of Standards and Technology (NIST). See Note 5 for a listing of several materials available from NIST.

13.2 Subcommittee D18.12 welcomes proposals that would allow for development of valid precision and bias statements.

14. Keywords

14.1 heating tests; strain gages; temperature; thermal expansion; thermal properties

APPENDIX

(Nonmandatory Information)

X1. DERIVATION OF EQUATIONS USED TO CALCULATE THE COEFFICIENT OF THERMAL EXPANSION

X1.1 Using the Wheatstone bridge configuration shown in Fig. 1, strain can be determined by measuring the input and output voltage to the bridge. First, normalize the output voltage to the nominal input voltage using:

$$V_n = \frac{V_o}{V_e} \times V_{\text{nom}} \quad (X1.1)$$

where:
V_{nom} = nominal input voltage, V,
V_n = normalized output voltage, V,
V_o = measured output voltage, V, and
V_e = measured excitation voltage V.

Then correct the gage factor of the strain gages for temperature effects using:

$$F_c = F\left(1 + \frac{\Delta F\%}{100}\right) \quad (X1.2)$$

where:
F_c = corrected gage factor,
F = gage factor at initial temperature, and
$\Delta F\%$ = percent change in gage factor with temperature.

Next compute the apparent strain using the half-bridge configuration equation:

$$\epsilon_a = \frac{2\Delta V_n}{F_c \times 10^{-3}\,(V_{nom} - \Delta V_n \times 10^{-3})} \quad (X1.3)$$

where:
ϵ_a = strain, μm/m (μin./in.),
V_{nom} = nominal excitation voltage, V, and

ΔV_n = change in normalized output voltage, V, from the initial temperature to the test temperature.