Designation: D5335 – 14

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

This standard is issued under the fixed designation D5335; 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 gauges. This test method is intended for evaluation of intact rock cores. Discontinuities in the rock mass, such as joints, inclusions, voids, veins, bedding, and the like can influence the thermal expansion of the rock, and judgment should be used when selecting the specimen to be analyzed in this test method.

1.2 This test method is applicable for unconfined stress states over the temperature range from 20 to 260°C.

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 gauges 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 practical.

1.3 The test specimens may be either saturated, dry or unsaturated. If saturated or unsaturated specimens are used, then the test temperature shall be at least 10°C less than the boiling point of the saturating fluid in order to reduce the effects of evaporation of the fluid.

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

1.4 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

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

1.5.1 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.

1.6 *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 requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Investigation

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

D6026 Practice for Using Significant Digits in Geotechnical Data

E83 Practice for Verification and Classification of Extensometer Systems

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

E228 Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer

E289 Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry

[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 June 1, 2014. Published July 2014. Originally approved in 1992. Last previous edition approved in 2008 as D5335 – 08. DOI: 10.1520/D5335-14.

[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. Terminology

3.1 *Definitions*—For definitions of common technical terms, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *mean coefficient of linear thermal expansion, α_m, [D/T^1], n*—a value, often expressed in parts per million per degree obtained by dividing the linear thermal strain, $((L_2 - L_1)/L_0)$, by the change in temperature $(T_2 - T_1)$.

3.2.1.1 *Discussion*—The sign convention used for αm, is as follows: αm will be a positive value indicating an increase in the length of the rock specimen, $(T_2 > T_1)$ and α_m will be a negative value indicating a decrease or contraction of the rock specimen. The coefficient of linear thermal expansion can also be obtained by dividing the change in thermal strain $(\Delta_{\varepsilon T})$ by the change in temperature (Δ_T). ε_{T_1} and ε_{T_2} are the specimen thermal strains as a result of a temperature change from T_0 to T_1 and from T_0 to T_2, respectively.

3.2.2 *specimen thermal strain, ε_{ts}, [D], n*—the change in length, $(L_2 - L_1)$, divided by the original length, L_0, of the specimen when the specimen is subjected to heat.

3.2.2.1 *Discussion*—L_1 and L_2 are the specimen lengths at temperatures T_1 and T_2, respectively. L_0 is the original specimen length at the reference temperature T_0.

4. Summary of Test Method

4.1 In general, the application of heat to rock causes it to expand. This change in linear expansion divided by the original length of the rock specimen is the thermal strain developed in the rock specimen from which the coefficients of expansion can be calculated. A wire or foil strain gauge suitably bonded to the rock is strained the same amount as the rock specimen. This straining, or stretching, of the gauge results in a change in the electrical resistance of the gauge. Measurement of the change in the electrical resistance of the gauge is thus a measure of the change in linear dimension of the rock specimen.

4.2 The application of heat to the gauge may cause a change in the electrical resistance of the gauge. To eliminate errors due to gauge heating, a second gauge is attached to a reference specimen that is not heated. During heating of the test specimen, the output of the gauge attached to the reference specimen is subtracted from the output of the gauge 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 underground excavation where the temperature of the surrounding rock may be altered. Depending on the restraint conditions, thermal strain may cause thermal stress that may affect the stability of underground excavations. Examples of applications where an understanding of rock thermal strain is important include: nuclear waste repositories, underground power stations, compressed air energy storage facilities, energy foundations, and geothermal energy facilities.

5.2 The coefficient of linear 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 the coefficient of linear thermal expansion changes with temperature is obtained.

5.3 Other methods of measuring the coefficient of linear thermal expansion 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 α 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. If anisotropy is expected, specimen with different orientations should be prepared and tested.

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

5.4 Both wire and foil type strain gauges 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. 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.

NOTE 4—The quality of the results 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 ensure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Bonded Strain Gauges*—The gauges shall be ASTM Class A type resistance strain gauge extensometers as described in Practice E83. The gauge 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*—Any type having sensitivity of at least 5×10^{-6} 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*—The reference specimen shall have a maximum coefficient of linear thermal expansion of 0.5×10^{-6} m/(m · °C) and have minimum dimensions of at least twice the length of the strain gauge.

NOTE 5—Suitable reference materials include titanium silicate, borosilicate glass, stainless steel, fused silica, and ultra-low expansion glass, that have expansion coefficients of less than 0.5×10^{-6}m/(m · °C) over the temperature range from 0 to 200°C.

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 0.2°C or better with a resolution of 0.05°C or better.

6.5 *Heating System*—The heating unit (furnace) shall be large enough to contain the test calibration and reference specimens such that the gauge length specified in 6.1 can be maintained at a constant temperature over its length to 0.1°C. It shall also incorporate controls so that specimens may be heated or cooled at a rate not greater than 1°C/min while still maintaining the constant temperature along the gauge 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.

6.6 *Specimen Size Measurement Devices*—Devices used to measure the length and diameter of the specimen shall be capable of measuring the desired dimension to within 0.1 % of its actual length.

6.7 *Epoxy*—Commercially available high temperature or room temperature epoxy may be used; however the type selected shall be based upon the maximum expected test temperature. See Note 2.

7. Sampling

7.1 Rock samples can be in the form of block or core samples. 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 thermo-mechanical evaluation of a specific rock type or particular location may require many tests from a single formation. The final testing program will depend on the technical judgment and experience of project personnel. Additional information may be found in Practice D2113, which describes rock core drilling and sampling of rock for site investigations.

7.2 *Statistical Requirements*—The number of samples and 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.

7.2.1 The number of samples and specimens required to obtain a specific level of statistically valid results may be determined using test method E122. However, it may not be economically practicable to achieve specific confidence levels and professional judgment may be required.

7.3 Discontinuities in the rock mass, such as joints, inclusions, voids, veins, bedding, and the like shall be avoided if practicable as their presence can influence the thermal expansion of the rock. Micro-cracks 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. The samples shall be preserved to prevent changes in water content. It is recommended that specimens be tested in both natural (saturate or unsaturated) and dry conditions.

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

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 marked on the sample and carry suitable markings through each cutting until the final specimen is ready for testing. These markings on the sample and specimen shall indicate compass direction, up/down directions, and orientation with respect to geologic structure.

8. Preparation of Test Specimens

8.1 Take the samples and machine them into the proper geometry as discussed in 8.2.

8.1.1 Do not degrade the rock during machining. Prevent mechanical and thermal fracture damage to the rock fabric by appropriately slow machining processes and the use of proper coolant. Select coolant fluids based upon chemical compatibility with the rock; for example, tap water may be adequate for granite or other hard rock, whereas saturated brine is adequate for salt, or mineral oil may be best for expansive shales.

8.1.2 Use a segmented diamond saw for cutting core or block samples into right circular cylinders or right prisms. Right circular cylinders are easily produced by cutting a core sample at two locations as required by 8.1, parallel to each other and at right angles to the longitudinal axis. Apply cooling fluid continuously to cool the blade and flush cuttings from the cut. If required, laboratory core drilling of the rock block samples can be done to obtain drill cores.

8.1.3 The areas on the specimen where the strain gauges are to be mounted shall be smooth to within 0.025 mm.

8.2 *Dimensions and Geometry*—In general, the proper geometry of a test specimen shall be right circular cylinder or right prism having a length to diameter ratio of 2 to 1. The minimum dimensions shall be adequate to accommodate the strain gauges as specified in 6.1. The length of the specimen shall be at least ten times the largest grain in the rock. Measure and record the length and diameter of the specimen to 0.001 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.

8.3 *Moisture Condition of Specimens*—Test the specimens in a manner that best simulates the in situ conditions of interest. For natural conditions, the moisture content of the test specimen shall be preserved between the time of recovery and testing. Determine and record the gravimetric water content of representative material contiguous to the test specimen in accordance with Test Methods D2216.

8.3.1 If the specimen is to be tested dry, dry at 80°C 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. Determine and record the water content of this specimen in accordance with Test Methods D2216.

8.3.1.1 An alternative drying schedule may be used in those instances where a heating unit is not available and it is not of interest to know the test specimen response to the first application of heat. In such a case, heat the specimen to 105 ±

2°C at a rate not greater than 1°C/min. Maintain this temperature for at least 24 h. Cool the specimen to ambient temperature at a rate no greater than 1°C/min

9. Verification and Standardization

9.1 *Reference Specimen*—Prepare a reference specimen of known thermal expansion from titanium silicate or other ultra-low expansion glass material of known low (0.5×10^{-6} m/m/°C) thermal expansion with three pairs of strain gauges. The reference specimen shall have the same geometry and dimensions as the test specimen(s) to be tested.

9.2 Test the reference specimen at the same time, through the same temperature schedule along with the test specimen(s) being tested using the same procedure. The calculation of the thermal expansion coefficient of the reference specimen provides an indication of the performance of the measuring system and procedure.

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

10. Preconditioning

10.1 Rock specimens shall not be thermally cycled before the actual testing unless drying is specified, in which case, drying shall be performed in accordance with 8.3.1.

11. Procedure

11.1 Prior to testing, determine the gravimetric water content as described in 8.3.1 for dry condition specimens and 8.3 for natural condition specimens.

11.2 Center and bond two strain gauges 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 gauges may be affixed to each test specimen, depending on the number of directions in which information is required. Connect the two strain gauges of each pair according to the wiring diagram shown in Fig. 1. Mount the strain gauges in accordance with the manufacturer's directions. If the epoxy requires a heat cure, raise the temperature of the sample at a rate no greater than 1°C per minute.

11.3 Place the reference specimen, the test specimen, and the reference specimen into the heating unit. Initially, the temperature of the heating unit must be within 5°C of the temperature of the test specimen to reduce thermal "shock" to the test specimen.

11.4 Heat and cool the specimens according to either Thermal Schedule A or B as described in 11.5 or 11.5.1, respectively. The heating and cooling rates must be less than 1°C/min to reduce thermally-induced fractures.

11.5 *Thermal Schedule A; A Series of Constant Temperatures:*

11.5.1 When the heating unit reaches the first desired test temperature, monitor each of the temperature and strain outputs until thermal equilibrium is attained. The specimen will be considered to have attained thermal equilibrium when the strain gauge 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.

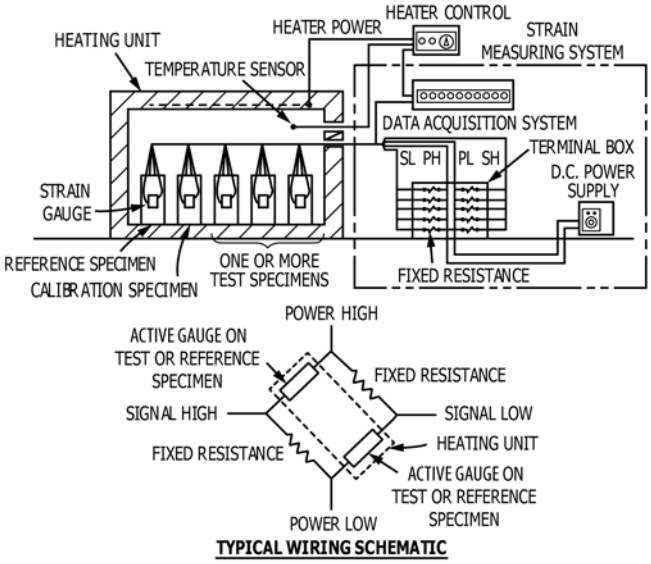

FIG. 1 Schematic of Test Setup

11.5.2 Repeat the heating process described in 11.5.1 to reach thermal equilibrium at seven more equally spaced temperature intervals. The system shall reach thermal equilibrium for each temperature interval.

11.5.3 After this point, let the specimen cool to ambient laboratory temperature under the same temperature intervals. The system shall reach thermal equilibrium for each temperature interval.

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

11.6.1 Continuously monitor and record each of the thermal strains and specimen temperatures as the specimens are heated and cooled at a constant rate to the desired test temperature. After reaching thermal equilibrium as described in 11.5.1, cool the specimen to ambient laboratory temperature under the same rate as the specimen was heated.

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

12. Calculation

12.1 Calculate the thermal strain for the test and reference specimens as follows:

$$\varepsilon_{ts} = \frac{L_2 - L_1}{L_0} \quad (1)$$

$$\varepsilon_{rs} = \frac{L_2 - L_1}{L_0} \quad (2)$$

where:

ε_{ts} = thermal strain of the test specimen over the temperature range of T_1 to T_2,

ε_{rs} = thermal strain of the reference specimen over the temperature range of T_1 to T_2,

L_1 = test or reference specimen length at temperature, T_1, mm,
L_2 = test or reference specimen length at temperature, T_2, mm,
L_0 = original test or reference specimen length at reference temperature T_0, mm, and
T_2, T_1 = stabilized temperatures, °C.

12.2 Calculate the mean coefficient of linear thermal expansion of the reference specimen as follows:

$$\alpha_{rs} = \frac{L_2 - L_1}{L_0(T_2 - T_1)} \quad (3)$$

where:

α_{rs} = mean coefficient of linear thermal expansion of the reference specimen over the temperature range of T_1 to T_2,
L_1 = test or reference specimen length at temperature, T_1, mm,
L_2 = test or reference specimen length at temperature, T_2, mm,
L_0 = original test or reference length at reference temperature, T_0, mm, and
T_2, T_1 = stabilized temperatures, °C.

12.3 Calculate the mean coefficient of linear thermal expansion of the test specimen, α_m as follows:

$$\alpha_m = \left(\frac{\varepsilon_{ts} - \varepsilon_{rs}}{T_2 - T_1}\right) + \alpha_{rs} \quad (4)$$

where:

α_m = mean coefficient of linear thermal expansion of the test specimen over the temperature range of T_1 to T_2

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

$$\alpha_i = \frac{\partial(\varepsilon_{ts} - \varepsilon_{rs})}{\partial T} + \alpha_{ri} \quad (5)$$

where:

α_I = instantaneous coefficient of linear thermal exapansion of the test specimen at temperature, T,
$\frac{\partial(\varepsilon_{ts} - \varepsilon_{rs})}{\partial T}$ = slope of the differential thermal strain versus temperature curve at temperature T, and
α_{ri} = instantaneous coefficient of linear thermal expansion of the reference material at temperature T. This value can be calculated as the tangent of the change in strain versus change in temperature plot at a desired test temperature, T.

12.5 For each suite of rock specimens, calculate the mean value of thermal expansion, the range, the standard deviation, and the 95 % confidence limits for the mean as a minimum.

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

13.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.5 and Practice D6026.

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

13.2.1 Project information, such as project name, number, source of test specimens, including other pertinent data that helps identify the specimen.

13.2.2 Name of person(s) who prepared and tested the samples/specimens, including the date(s) performed.

13.2.3 A discussion of the scope of the testing program that includes the number of samples and specimens tested, rationale for sample selection, source of the samples, any important sampling issues, and the limitations of the testing program, as applicable. If anisotropy is expected, document reason for this expectation and the orientations tested.

13.2.4 Description of the specimens. Include:

13.2.4.1 The specimen identification for each specimen.

13.2.4.2 The rock type.

13.2.4.3 The structure and fabric, include the field orientation of each specimen if applicable.

13.2.4.4 Specimen shape: right circular cylinder or right prism.

13.2.4.5 Grain size.

13.2.4.6 Note any discontinuities or voids and weathering of the sample(s)/specimen(s) as applicable.

13.2.5 Describe special handling procedures, such as those used to maintain water content, to avoid damage during machining, and the like.

13.3 Record as a minimum the following test specimen data:

13.3.1 The thermal schedule used, A or B.

13.3.2 The average, initial length and diameter of the specimen(s) to three significant digits, mm.

13.3.3 The moisture condition of the sample(s)/specimen(s): dry or natural.

13.3.4 The gravimetric water content of the sample(s)/specimen(s), to the nearest 1 %.

13.3.5 The temperatures, T_1, T_2, the reference temperature T_0 to the nearest 0.2°C, and the temperature range.

13.3.6 The specimen lengths, L_0, L_1, L_2, taken at their respective temperatures, to three significant digits, mm.

13.3.7 The specimen thermal strain of the test and reference specimens, ε_{ts}, ε_{rs}, to three significant digits.

13.3.8 The coefficient of linear thermal expansion, α_{rs} and α_m to three significant digits.

13.3.9 The instantaneous coefficient of linear thermal expansion, α_I and α_{ri} to three significant digits.

13.3.10 The value of α for the reference specimen.

13.3.11 The thermal history during preparation.

13.3.12 A listing of the test equipment actually used including the name, model number, if known, and basic specifications of each major piece, as applicable.

13.3.13 List any deviations from the Procedure section or the equipment used. Discuss the effect of the variation upon the test results.

13.3.14 Summary tables may be presented. These may include test suite designations, temperature ranges, average coefficients of linear thermal expansion, ranges, uncertainties, and results for individual samples/specimens.

13.3.15 Plots of the thermal strain versus temperature for each specimen. Include on each plot the sample and specimen designation, rock type, and temperature range.

13.3.15.1 Each plot shall have error bars indicating the magnitude of the estimated 95 % level of uncertainty.

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

14. Precision and Bias

14.1 Since this test method determines α of rocks with respect to α of a reference specimen, the accuracy of this test method is limited by the accuracy to which α of the reference specimen is known. The measured α of the reference specimen must agree within one standard deviation of the published value of α, or with the value of α determined by an independent method, such as Test Method E289 or E228.

NOTE 6—Values of α for reference specimens 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.

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

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

15. Keywords

15.1 heating tests; rock; strain gauges; temperature; thermal expansion/contraction; 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:

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

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 gauge factor of the strain gauges for temperature effects using:

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

where:

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

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

$$\varepsilon_a = \frac{2\Delta V_n}{F_c \times 10^{-3}\left(V_{nom} - \Delta V_n \times 10^{-3}\right)} \tag{X1.3}$$

where:

ε_a = strain × 10^{-6}, m/m,
V_{nom} = nominal excitation voltage, V, and
ΔV_n = change in normalized output voltage, V, from the initial temperature to the test temperature.

SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the last edition (2008) that may impact the use of this standard. (Approved June 1, 2014)

(1) Edited Section 1. Made this standard SI units only.
(2) Edited Section 3, removed equations from definitions.
(3) Edited Sections 4 and 5.
(4) Updated Note 4 to be consistent with standard language.
(5) Edited Section 6 and added 6.6 and 6.7.
(6) Edited Sections 7, 8, and 9.
(7) Added Section 10 Preconditioning.
(8) Edited Sections 11, 12, and 13.
(9) Added Bias section in Section 14.
(10) Added “rock” and “contraction” to Keywords.