Designation: D7012 – 14$^{\varepsilon 1}$

Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures[1]

This standard is issued under the fixed designation D7012; 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.

ε^1 NOTE—Editorially corrected legend for Eq 3 in August 2017.

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1. Scope

1.1 These four test methods cover the determination of the strength of intact rock core specimens in uniaxial and triaxial compression. Methods A and B determine the triaxial compressive strength at different pressures and Methods C and D determine the unconfined, uniaxial strength.

1.2 Methods A and B can be used to determine the angle of internal friction, angle of shearing resistance, and cohesion intercept.

1.3 Methods B and D specify the apparatus, instrumentation, and procedures for determining the stress-axial strain and the stress-lateral strain curves, as well as Young's modulus, *E*, and Poisson's ratio, υ. These methods make no provision for pore pressure measurements and specimens are undrained (platens are not vented). Thus, the strength values determined are in terms of total stress and are not corrected for pore pressures. These test methods do not include the procedures necessary to obtain a stress-strain curve beyond the ultimate strength.

1.4 Option A allows for testing at different temperatures and can be applied to any of the test methods, if requested.

1.5 This standard replaces and combines the following Standard Test Methods: D2664 Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements; D5407 Elastic Moduli of Undrained Rock Core Specimens in Triaxial Compression Without Pore Pressure Measurements; D2938 Unconfined Compressive Strength of Intact Rock Core Specimens; and D3148 Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression. The original four standards are now referred to as Methods in this standard.

1.5.1 *Method A:* Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements.

1.5.1.1 Method A is used for obtaining strength determinations. Strain is not typically measured; therefore a stress-strain curve is not produced.

1.5.2 *Method B:* Elastic Moduli of Undrained Rock Core Specimens in Triaxial Compression Without Pore Pressure Measurements.

1.5.3 *Method C:* Uniaxial Compressive Strength of Intact Rock Core Specimens.

1.5.3.1 Method C is used for obtaining strength determinations. Strain is not typically measured; therefore a stress-strain curve is not produced.

1.5.4 *Method D:* Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression.

1.5.5 *Option A: Temperature Variation*—Applies to any of the methods and allows for testing at temperatures above or below room temperature.

1.6 For an isotropic material in Test Methods B and D, the relation between the shear and bulk moduli and Young's modulus and Poisson's ratio are:

$$G = \frac{E}{2(1+\upsilon)} \quad (1)$$

$$K = \frac{E}{3(1-2\upsilon)} \quad (2)$$

where:

G = shear modulus,
K = bulk modulus,
E = Young's modulus, and
υ = Poisson's ratio.

1.6.1 The engineering applicability of these equations decreases with increasing anisotropy of the rock. It is desirable to conduct tests in the plane of foliation, cleavage or bedding and at right angles to it to determine the degree of anisotropy. It is noted that equations developed for isotropic materials may give

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[1] These test methods are 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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***A Summary of Changes section appears at the end of this standard**

only approximate calculated results if the difference in elastic moduli in two orthogonal directions is greater than 10 % for a given stress level.

NOTE 1—Elastic moduli measured by sonic methods (Test Method D2845) may often be employed as a preliminary measure of anisotropy.

1.7 Test Methods B and D for determining the elastic constants do not apply to rocks that undergo significant inelastic strains during the test, such as potash and salt. The elastic moduli for such rocks should be determined from unload-reload cycles that are not covered by these test methods.

1.8 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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

1.9.1 The procedures 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.

1.10 *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.*

1.11 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

D2845 Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock (Withdrawn 2017)[3]

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4543 Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances (Withdrawn 2017)[3]

D6026 Practice for Using Significant Digits in Geotechnical Data

E4 Practices for Force Verification of Testing Machines

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

2.2 *ASTM Adjunct:*[4]

Triaxial Compression Chamber Drawings (3)

3. Terminology

3.1 *Definitions:*

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

4. Summary of Test Method

4.1 A rock core specimen is cut to length and the ends are machined flat. The specimen is placed in a loading frame and if necessary, placed in a loading chamber and subjected to confining pressure. For a specimen tested at a different temperature, the test specimen is heated or cooled to the desired test temperature prior to the start of the test. The axial load on the specimen is then increased and measured continuously. Deformation measurements are not obtained for Methods A and C, and are measured as a function of load until peak load and failure are obtained for Methods B and D.

5. Significance and Use

5.1 The parameters obtained from Methods A and B are in terms of undrained total stress. However, there are some cases where either the rock type or the loading condition of the problem under consideration will require the effective stress or drained parameters be determined.

5.2 Method C, uniaxial compressive strength of rock is used in many design formulas and is sometimes used as an index property to select the appropriate excavation technique. Deformation and strength of rock are known to be functions of confining pressure. Method A, triaxial compression test, is commonly used to simulate the stress conditions under which most underground rock masses exist. The elastic constants (Methods B and D) are used to calculate the stress and deformation in rock structures.

5.3 The deformation and strength properties of rock cores measured in the laboratory usually do not accurately reflect large-scale *in situ* properties because the latter are strongly influenced by joints, faults, inhomogeneity, weakness planes, and other factors. Therefore, laboratory values for intact specimens must be employed with proper judgment in engineering applications.

NOTE 2—The quality of the result produced by this standard is

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[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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Assembly and detail drawings of an apparatus that meets these requirements and which is designed to accommodate 54-mm diameter specimens and operate at a confining fluid pressure of 68.9 MPa are available from ASTM International Headquarters. Order Adjunct No. ADJD7012. Original adjunct produced in 1982.

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. 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 for evaluating some of those factors.

6. Apparatus

6.1 *Compression Apparatus:*

6.1.1 *Methods A to D:*

6.1.1.1 *Loading Device*—The loading device shall be of sufficient capacity to apply load at a rate conforming to the requirements specified in 9.4.1. It shall be verified at suitable time intervals in accordance with the procedures given in Practices E4 and comply with the requirements prescribed in the method. The loading device may be equipped with a displacement transducer that can be used to advance the loading ram at a specified rate.

NOTE 3—For Methods A and B, if the load-measuring device is located outside the confining compression apparatus, calibrations to determine the seal friction need to be made to make sure the loads measured meet the accuracy specified in Practices E4.

6.2 *Confining System:*[4]

6.2.1 *Methods A and B:*

6.2.1.1 *Confining Apparatus*[5]—The confining pressure apparatus shall consist of a chamber in which the test specimen may be subjected to a constant lateral fluid pressure and the required axial load. The apparatus shall have safety valves, suitable entry ports for filling the chamber, and associated hoses, gages, and valves as needed.

6.2.1.2 *Flexible Membrane*—This membrane encloses the rock specimen and extends over the platens to prevent penetration by the confining fluid. A sleeve of natural or synthetic rubber or plastic is satisfactory for room temperature tests; however, metal or high-temperature rubber (viton) jackets are usually necessary for elevated temperature tests. The membrane shall be inert relative to the confining fluid and shall cover small pores in the specimen without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the specimen provided these materials do not penetrate and strengthen or weaken the specimen. Care must be taken to form an effective seal where the platen and specimen meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes.

6.2.1.3 *Pressure-Maintaining Device*—A hydraulic pump, pressure intensifier, or other system having sufficient capacity to maintain the desired lateral pressure to within ±1 % throughout the test. The confining pressure shall be measured with a hydraulic pressure gauge or electronic transducer having an accuracy of at least ±1 % of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5 % of the confining pressure.

6.2.1.4 *Confining-Pressure Fluids*—Hydraulic fluids compatible with the pressure-maintaining device and flexible membranes shall be used. For tests using Option A, the fluid must remain stable at the temperature and pressure levels designated for the test.

6.2.2 *Option A:*

6.2.2.1 *Temperature Enclosure*—The temperature enclosure shall be either an internal system that fits inside the loading apparatus or the confining pressure apparatus, an external system enclosing the entire confining pressure apparatus, or an external system encompassing the complete test apparatus. For high or low temperatures, a system of heaters or coolers, respectively, insulation, and temperature-measuring devices are normally necessary to maintain the specified temperature. Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the specimen. The "average" specimen temperature, based on the mid-height sensor, shall be maintained to within ±1°C of the specified test temperature. The maximum temperature difference between the mid-height sensor and either end sensor shall not exceed 3°C.

NOTE 4—An alternative to measuring the temperature at three locations along the specimen during the test is to determine the temperature distribution in a specimen that has temperature sensors located in drill holes at a minimum of six positions: along both the centerline and specimen periphery at mid-height and each end of the specimen. The specimen may originate from the same batch as the test specimens and conform to the same dimensional tolerances and to the same degree of intactness. The temperature controller set point may be adjusted to obtain steady-state temperatures in the specimen that meet the temperature requirements at each test temperature. The centerline temperature at mid-height may be within ±1°C of the specified test temperature and all other specimen temperatures may not deviate from this temperature by more than 3°C. The relationship between controller set point and specimen temperature can be used to determine the specimen temperature during testing provided that the output of the temperature feedback sensor or other fixed-location temperature sensor in the triaxial apparatus is maintained constant within ±1°C of the specified test temperature. The relationship between temperature controller set point and steady-state specimen temperature may be verified periodically. The specimen is used solely to determine the temperature distribution in a specimen in the triaxial apparatus. It is not to be used to determine compressive strength or elastic constants.

6.2.2.2 *Temperature Measuring Device*—Special limits-of-error thermocouples or platinum resistance thermometers (RTDs) having accuracies of at least ±1°C with a resolution of 0.1°C shall be used.

6.2.3 *Bearing Surfaces:*

6.2.3.1 *Methods A to D:*

(1) Platens—Two steel platens are used to transmit the axial load to the ends of the specimen. They shall be made of tool-hardened steel to a minimum Rockwell Hardness of 58 on the "C" scale. One of the platens shall be spherically seated and the other shall be a plain rigid platen. The bearing faces shall not depart from a plane by more than 0.015 mm when the platens are new and shall be maintained within a permissible variation of 0.025 mm. The diameter of the spherical seat shall be at least as large as that of the test specimen, but shall not exceed twice the diameter of the test specimen. The center of the sphere in the spherical seat shall coincide with that of the bearing face of the specimen. The spherical seat shall be

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[5] Assembly and detail drawings of an apparatus that meets these requirements and which is designed to accommodate 21/8-in. (53.975-mm) diameter specimens and operate at a confining fluid pressure of 68.9 MPa are available from ASTM International Headquarters. Order Adjunct No. ADJD7012. Original adjunct produced in 1982.

properly lubricated to allow free movement. The movable portion of the platen shall be held closely in the spherical seat, but the design shall be such that the bearing face can be rotated and tilted through small angles in any direction. If a spherical seat is not used, the bearing surfaces shall be parallel to 0.0005 mm/mm of platen diameter. The platen diameter shall be at least as great as that of the specimen and have a thickness-to-diameter ratio of at least 1:2.

6.3 *Deformation Devices:*

6.3.1 *Methods B and D:*

6.3.1.1 *Strain/Deformation Measuring Devices*—Deformations or strains may be determined from data obtained by electrical resistance strain gages, compressometers, linear variable differential transformers (LVDTs), or other suitable means. The strain/deformation measuring system shall measure the strain with a resolution of at least 25×10^{-6} strain and an accuracy within 2 % of the value of readings above 250×10^{-6} strain and accuracy and resolution within 5×10^{-6} for readings lower than 250×10^{-6} strain, including errors introduced by excitation and readout equipment. The system shall be free from non-characterized long-term instability (drift) that results in an apparent strain of 10^{-8}/s or greater.

NOTE 5—The user is cautioned about the influence of pressure and temperature on the output of strain and deformation sensors located within the confining pressure apparatus.

6.3.1.2 *Determination of Axial Strain*—The design of the measuring device shall be such that the average of at least two axial strain measurements can be determined. Measuring positions shall be equally spaced around the circumference of the specimen, close to midheight. The gauge length over which the axial strains are determined shall be at least ten grain diameters in magnitude.

6.3.1.3 *Determination of Lateral Strain*—The lateral deformations or strains may be measured by any of the methods mentioned in 6.3.1.1. Either circumferential or diametric deformations or strains may be measured. A single transducer that wraps around the specimen can be used to measure the change in circumference. At least two diametric deformation sensors shall be used if diametric deformations are measured. These sensors shall be equally spaced around the circumference of the specimen close to midheight. The average deformation or strain from the diametric sensors shall be recorded.

NOTE 6—The use of strain gauge adhesives requiring cure temperatures above 65°C is not allowed unless it is known that microfractures do not develop and mineralogical changes do not occur at the cure temperature.

6.4 *Timing Devices*—A clock, stopwatch, digital timer, or alike readable to 1 minute.

7. Safety Precautions

7.1 Danger exists near confining pressure testing equipment because of the high pressures and loads developed within the system. Test systems must be designed and constructed with adequate safety factors, assembled with properly rated fittings, and provided with protective shields to protect people in the area from unexpected system failure. The use of a gas as the confining pressure fluid introduces potential for extreme violence in the event of a system failure.

7.2 Many rock types fail in a violent manner when loaded to failure in compression. A protective shield shall be placed around the uniaxial test specimen to prevent injury from flying rock fragments.

7.3 Elevated temperatures increase the risks of electrical shorts and fire. The flash point of the confining pressure fluid shall be above the operating temperatures during the test.

8. Test Specimens

8.1 *Specimen Selection*—The specimens for each sample shall be selected from cores representing a valid average of the type of rock under consideration. This sample selection can be achieved by visual observations of mineral constituents, grain sizes and shape, partings and defects such as pores and fissures, or by other methods such as ultrasonic velocity measurements. The diameter of rock test specimens shall be at least ten times the diameter of the largest mineral grain. For weak rock types, which behave more like soil, for example, weakly cemented sandstone, the specimen diameter shall be at least six times the maximum particle diameter. The specified minimum specimen diameter of approximately 47-mm satisfy this criterion in the majority of cases. When cores of diameter smaller than the specified minimum must be tested because of the unavailability of larger diameter core, as is often the case in the mining industry, suitable notation of this fact shall be made in the report.

8.1.1 Desirable specimen length to diameter ratios are between 2.0:1 and 2.5:1. Specimen length to diameter ratios of less than 2.0:1 are unacceptable. If it is necessary to test specimens not meeting the length to diameter ratio requirements due to lack of available specimens, the report shall contain a note stating the non-conformance with this standard including a statement explaining that the results may differ from results obtained from a test specimen that meets the requirements. Laboratory specimen length to diameter ratios must be employed with proper judgment in engineering applications.

8.1.2 The number of specimens necessary to obtain a specific level of statistical results may be determined using Test Method E122. However, it may not be economically possible to achieve a specific confidence level and professional judgment may be necessary.

8.2 *Preparation*—Test specimens shall be prepared in accordance with Practice D4543.

8.2.1 Test results for specimens not meeting the requirements of Practice D4543 shall contain a note describing the non-conformance and a statement explaining that the results reported may differ from results obtained from a test specimen that meets the requirements of Practice D4543.

8.3 Moisture condition of the specimen at the time of test can have a significant effect upon the deformation of the rock. Good practice generally dictates that laboratory tests shall be made upon specimens representative of field conditions. Thus, it follows that the field moisture condition of the specimen shall be preserved until the time of test. On the other hand, there may be reasons for testing specimens at other moisture contents, including zero. In any case, the moisture content of the test specimen shall be tailored to the problem at hand and determined according to the procedures given in Method D2216. If moisture condition is to be maintained and the temperature enclosure is not equipped with humidity control, the specimen shall be sealed using a flexible membrane or by applying a plastic or silicone rubber coating to the specimen sides. If the specimen is to be saturated, porous sandstones may present little or no difficulty. For siltstone, saturation may take longer. For tight rocks such as intact granite, saturation by water may be impractical.

9. Procedure

9.1 *Seating:*

9.1.1 *Methods A to D:*

9.1.1.1 The spherical seat shall rotate freely in its socket before each test.

9.1.1.2 The lower platen shall be placed on the base or actuator rod of the loading device. The bearing faces of the upper and lower platens and of the test specimen shall be wiped clean, and the test specimen shall be placed on the lower platen. The upper platen shall be placed on the specimen and aligned properly.

9.2 *Confining Stress:*

9.2.1 *Methods A and B:*

9.2.1.1 The membrane shall be fitted over the specimen and platens to seal the specimen from the confining fluid. The specimen shall be placed in the test chamber, ensuring proper seal with the base, and connection to the confining pressure lines. A small axial load, <1 % of anticipated ultimate strength, may be applied to the confining compression chamber by means of the loading device to properly seat the bearing parts of the apparatus.

9.2.1.2 The chamber shall be filled with confining fluid and the confining stress shall be raised uniformly to the specified level within 5 min. The lateral and axial components of the confining stress shall not be allowed to differ by more than 5 percent of the instantaneous pressure at any time.

9.2.1.3 The predetermined confining pressure shall be maintained approximately throughout the test.

9.2.1.4 To make sure that no confining fluid has penetrated into the specimen, the specimen membrane shall be carefully checked for fissures or punctures and the specimen shall be examined with a hand lens at the completion of each confining test.

9.3 *Option A:*

9.3.1 Install the elevated-temperature enclosure for the apparatus used. The temperature shall be raised at a rate not exceeding 2°C/min until the required temperature is reached (Note 7). The test specimen shall be considered to have reached pressure and temperature equilibrium when all deformation transducer outputs are stable for at least three readings taken at equal intervals over a period of no less than 30 min (3 min for tests performed at room temperature). Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations. Record the initial deformation readings, which are to be taken as zeroes for the test.

NOTE 7—It has been observed that for some rock types microcracking will occur for heating rates above 1°C/min. The operator is cautioned to select a heating rate such that microcracking does not significantly affect the test result.

9.4 *Applying Load:*

9.4.1 *Methods A to D:*

9.4.1.1 The axial load shall be applied continuously and without shock until the load becomes constant, is reduced, or a predetermined amount of strain is achieved. The load shall be applied in such a manner as to produce either a stress rate between 0.5 and 1.0 MPa/s or a strain rate as constant as feasible throughout the test. The stress rate or strain rate shall not be permitted at any given time to deviate by more than 10 % from that selected. The stress rate or strain rate selected shall be that which will produce failure of a cohort test specimen in compression, in a test time between 2 and 15 min. The selected stress rate or strain rate for a given rock type shall be adhered to for all tests in a given series of investigation (Note 8). Readings of deformation shall be observed and recorded at a minimum of ten load levels that are evenly spaced over the load range. Continuous data recording shall be permitted provided that the recording system meets the precision and accuracy requirements of 12.1.1. The maximum load sustained by the specimen shall be recorded. Load readings in kilonewtons shall be recorded to 2 decimal places. Stress readings in megapascals shall be recorded to 1 decimal place.

NOTE 8—Results of tests by other investigators have shown that strain rates within this range will provide strength values that are reasonably free from rapid loading effects and reproducible within acceptable tolerances. Lower strain rates may be permissible, if required by the investigation. The drift of the strain measuring system (see 6.3) may be constrained more stringently, corresponding to the longer duration of the test.

NOTE 9—Loading a high-strength specimen in load control to failure in a loading frame will often result in violent failure, which will tend to damage the strain/deformation measuring devices and be hazardous to the operator.

10. Calculations

10.1 For Methods C and D, the uniaxial compressive strength σ_u, of the test specimen shall be calculated as follows:

$$\sigma_u = \frac{P}{A} \quad (3)$$

where:

σ_u = uniaxial compressive strength (MPa),
P = failure load (N),
A = cross-sectional area (mm^2),

10.2 For Methods A and B, the triaxial compressive strength, σ, of the test specimen shall be calculated as follows:

$$\sigma = \sigma_1 - \sigma_3 \quad (4)$$

where:

σ = differential failure stress (MPa),
σ_1 = total failure stress (MPa), and
σ_3 = confining stress (MPa).

NOTE 10—Tensile stresses and strains are normally recorded as being positive. A consistent application of a compression-positive sign convention may be employed if desired. The sign convention adopted needs to be stated explicitly in the report. The formulas given are for engineering stresses and strains. True stresses and strains may be used, provided that the specimen diameter at the time of peak load is known.

NOTE 11—If the specimen diameter is not the same as the piston diameter through the triaxial apparatus, a correction may be applied to the measured load to account for the confining pressure acting on the difference in area between the specimen and the loading piston where it passes through the seals into the apparatus. The engineer must be knowledgeable in the differences in confinement test systems such as a Hoek cell, through piston chamber, integral load cell and external load cell.

10.3 *Methods B and D:*

10.3.1 Axial strain, ε_a and lateral strain, ε_l, shall be obtained directly from strain-indicating equipment or shall be calculated from deformation readings, depending on the type of apparatus or instrumentation employed. Strain readings shall be recorded to six decimal places.

10.3.2 Axial strain, ε_a shall be calculated as follows:

$$\varepsilon_a = \frac{\Delta L}{L} \tag{5}$$

where:

ε_a = axial strain (mm),
L = original undeformed axial gauge length (mm), and
ΔL = change in measured axial gauge length (mm).

NOTE 12—If the deformation recorded during the test includes deformation of the apparatus, suitable calibration for apparatus deformation shall be made. This may be accomplished by inserting into the apparatus a steel cylinder having known elastic properties and observing differences in deformation between the assembly and steel cylinder throughout the loading range. The apparatus deformation is then subtracted from the total deformation at each increment of load to arrive at specimen deformation from which the axial strain of the specimen is computed. The accuracy of this correction should be verified by measuring the elastic deformation of a cylinder of material having known elastic properties (other than steel) and comparing the measured and computed deformations.

10.3.3 Lateral strain, ε_1, shall be calculated as follows:

$$\varepsilon_1 = \frac{\Delta D}{D} \tag{6}$$

where:

ε_l = lateral strain (mm),
D = original undeformed diameter (mm), and
ΔD = change in diameter (mm); where positive is an increase in diameter and negative is a decrease in diameter.

NOTE 13—Many circumferential transducers measure change in chord length and not change in arc length (circumference). The geometrically nonlinear relationship between change in chord length and change in diameter must be used to obtain accurate values of lateral strain.

10.3.4 The stress-versus-strain curves shall be plotted for the axial and lateral directions, see Fig. 1. The complete curve gives the best description of the deformation behavior of rocks having nonlinear stress-strain relationships at low- and high-stress levels.

10.3.5 The value of Young's modulus, *E*, shall be calculated using any of several methods employed in engineering practice. The most common methods, described in Fig. 2, are as follows:

10.3.5.1 Tangent modulus at a stress level that is some fixed percentage, usually 50 % of the maximum strength.

10.3.5.2 Average slope of the straight-line portion of the stress-strain curve. The average slope shall be calculated either by dividing the change in stress by the change in strain or by making a linear least squares fit to the stress-strain data in the straight-line portion of the curve.

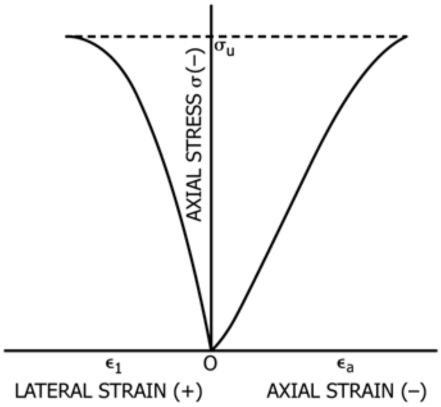


FIG. 1 Format for Graphical Presentation of Data

10.3.5.3 Secant modulus, usually from zero stress to some fixed percentage of maximum strength.

10.3.6 The value of Poisson's ratio, υ, is greatly affected by nonlinearity at low-stress levels in the axial and lateral stress-strain curves. It is desirable that Poisson's ratio shall be calculated from the following equation:

$$\upsilon = -\frac{\text{slope of axial curve}}{\text{slope of lateral curve}} \tag{7}$$

$$= -\frac{E}{\text{slope of lateral curve}}$$

where:

υ = Poisson's ratio
E = Young's modulus

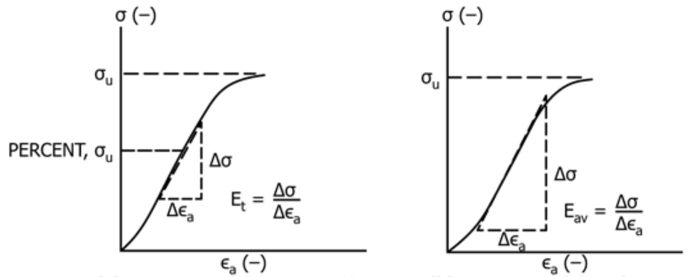
where the slope of the lateral curve is determined in the same manner as was done in 10.3.6 for Young's modulus, *E*.

NOTE 14—The denominator in Eq 7 will usually have a negative value if the sign convention is applied properly.

10.4 *Method A:*

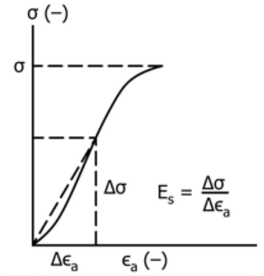
10.4.1 The Mohr stress circles shall be constructed on an arithmetic plot with shear stress as the ordinate and normal stress as the abscissa using the same scale. At least three triaxial compression tests should be conducted, each at a different confining pressure, on the same material to define the envelope to the Mohr stress circles. Because of the heterogeneity of rock and the scatter in results often encountered, good practice requires making at least three tests on essentially identical specimens at each confining pressure or single tests at nine different confining pressures covering the range investigated. Individual stress circles shall be plotted and used in drawing the envelope.

10.4.2 A "best-fit," smooth curve or straight line (Mohr envelope) shall be drawn approximately tangent to the Mohr circles, as shown in Fig. 3. The figure shall also include a brief note indicating whether a pronounced failure plane was or was not developed during the test and the inclination of this plane with reference to the plane of major principal stress. If the envelope is a straight line, the angle the line makes with the horizontal shall be reported as the angle of internal friction, φ, or the slope of the line as tan φ depending upon preference. The intercept of this line at the vertical axis is reported as the



(a) Tangent Modulus Measured at a Fixed Percentage of Ultimate Strength

(b) Average Modulus of Linear Portion of Axial Stress-Strain Curve



(c) Secant Modulus Measured up to a Fixed Percentage of Ultimate Strength

FIG. 2 Methods for Calculating Young's Modulus from Axial Stress-Axial Strain Curve

apparent cohesion intercept, *c*. If the envelope is not a straight line, values of φ or tan φ shall be determined by constructing a tangent to the Mohr circle for each confining pressure at the point of contact with the envelope and the corresponding cohesion intercept noted.

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

11.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s) as given below, is covered in 1.9 and Practice D6026.

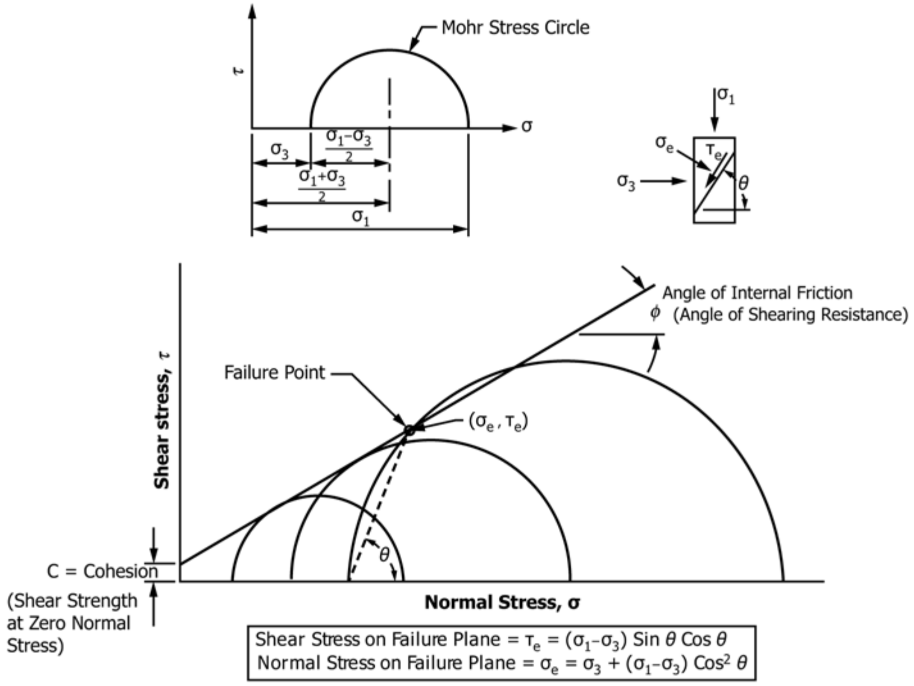


FIG. 3 Typical Mohr Stress Circles

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

11.2.1 *Methods A–D:*

11.2.1.1 Source of sample including project name and location. Often the location is specified in terms of the drill hole number, angle and depth of specimen from the collar of the hole,

11.2.1.2 Name or initials of the person(s) who performed the test and the date(s) performed,

11.2.1.3 Lithologic description of the test specimen, formation name, and load direction with respect to lithology,

11.2.1.4 Moisture condition of specimen at the start of shear,

11.2.1.5 Specimen diameter and height, conformance with dimensional requirements,

11.2.1.6 Description of physical appearance of specimen after test, including visible end effects such as cracking, spalling, or shearing at the platen-specimen interfaces,

11.2.1.7 A sketch or photograph of the fractured specimen is recommended,

11.2.1.8 The actual equipment, procedures and the reasons for any variations shall be presented in detail,

11.2.1.9 Temperature at which test was performed if other than room temperature, to the nearest 0.5°C,

11.2.1.10 Any non-conformances with D4543 and the length to diameter ratios, include the explanation statements as describe in 8.1.2 and 8.2.1,

11.2.1.11 Time to failure,

11.2.1.12 Loading, stress, or strain rate as applicable based on method performed.

11.3 Record as a minimum the following test specimen data:

11.3.1 *Methods B and D:*

11.3.1.1 Plot of the stress-versus-strain curves (see Fig. 1),

11.3.1.2 Young's modulus, *E*, method of determination as given in Fig. 2, and at which stress level or levels determined, and

11.3.1.3 Poisson's ratio, υ, method of determination in 10.3.6, and at what stress level or levels determined.

11.3.1.4 Rate of loading or deformation rate.

11.3.2 *Method A:*

11.3.2.1 Confining stress level at which a triaxial test was performed,

11.3.2.2 Plot of the Mohr stress circles (see Fig. 3), and

11.3.2.3 Triaxial compressive strength as determined in 10.1 to the nearest MPa.

11.3.3 *Method C:*

11.3.3.1 Uniaxial compressive strength as determined in 10.1 to the nearest MPa.

NOTE 15—If failure is ductile, with the load on the specimen still increasing when the test is terminated, the strain at which the compressive strength was calculated may be reported.

12. Precision and Bias

12.1 The data in Tables 1-5 are the products of the Interlaboratory Testing Program. Table 1 is the product of the work of seven laboratories with five replications. Table 5 is the product of the work of eight laboratories with five replications. Round 1 involved four rock types, but only the data from three were displayed here that were rock types used in all the series of tests. The remaining tables (Tables 6-10) are the products of Round 2 in which six laboratories each tested five specimens of three different rocks, three confining pressures and four replications. Details of the study are referenced in Section 2.2. The tables give the repeatability (within a laboratory) and reproducibility (between laboratories) for the compressive and confined methods and values for Young's Modulus and Poisson's ratio calculated for the intervals from 25 to 50 % and 40 to 60 % of the maximum differential stress at confining

TABLE 1 Compressive Strength (MPa) at 0 MPa Confining Pressure

	Berea Sandstone	Tennessee Marble	Barre Granite
Average Value	62.0	142.0	217.0
Repeatability	15.8	20.4	15.7
Reproducibility	22.4	38.0	27.7

TABLE 2 Compressive Strength (MPa) at 10 MPa Confining Pressure

	Berea Sandstone	Tennessee Marble	Barre Granite
Average Value	127.0	173.0	282.0
Repeatability	5.29	32.2	13.5
Reproducibility	22.5	38.3	25.7

TABLE 3 Compressive Strength (MPa) at 25 MPa Confining Pressure

	Berea Sandstone	Tennessee Marble	Barre Granite
Average Value	179.0	206.0	366.0
Repeatability	8.69	43.3	22.5
Reproducibility	34.7	51.8	31.0

TABLE 4 Compressive Strength (MPa) at 40 MPa Confining Pressure

	Berea Sandstone	Tennessee Marble	Barre Granite
Average Value	215.0	237.0	N/A
Repeatability	7.95	42.4	N/A
Reproducibility	52.0	73.5	N/A

TABLE 5 Young's Modulus (GPa) at 0 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25 %	50 %	25 %	50%	25 %	50 %
Average Value	12.4	16.7	76.3	74.2	46.9	54.2
Repeatability	3.37	4.15	14.8	10.1	6.12	6.75
Reproducibility	4.17	5.18	17.2	12.3	6.45	7.77

TABLE 6 Young's Modulus (GPa) at 25 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25-50 %	40-60 %	25-50 %	40-60 %	25-50 %	40-60 %
Average Value	23.5	22.5	71.1	65.2	60.4	59.8
Repeatability	0.90	1.28	11.4	9.15	2.53	2.49
Reproducibility	3.34	3.47	13.9	11.6	6.80	6.12

pressures of 10, 25, and 40 MPa and 25 % and 50 % for the compressive test case. Additional Reference Material found in ASTM Geotechnical Journal.[6,7]

TABLE 7 Young's Modulus (GPa) at 40 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25-50 %	40-60 %	25-50 %	40-60 %	25-50 %	40-60 %
Average Value	24.2	22.8	70.0	63.4	61.9	60.6
Repeatability	1.09	0.79	9.60	9.57	2.27	2.49
Reproducibility	3.82	3.57	9.69	9.57	5.95	5.34

TABLE 8 Poisson's Ratio at 10 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25-50 %	40-60 %	25-50 %	40-60 %	25-50 %	40-60 %
Average Value	0.28	0.34	0.30	0.33	0.26	0.30
Repeatability	0.03	0.04	0.03	0.07	0.03	0.03
Reproducibility	0.05	0.05	0.06	0.09	0.04	0.04

TABLE 9 Poisson's Ratio at 25 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25-50 %	40-60 %	25-50 %	40-60 %	25-50 %	40-60 %
Average Value	0.23	0.27	0.31	0.34	0.28	0.33
Repeatability	0.02	0.02	0.05	0.05	0.03	0.03
Reproducibility	0.04	0.04	0.06	0.05	0.04	0.05

TABLE 10 Poisson's Ratio at 40 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25-50 %	40-60 %	25-50 %	40-60 %	25-50 %	40-60 %
Average Value	0.20	0.24	0.32	0.34	0.29	0.33
Repeatability	0.01	0.02	0.04	0.05	0.03	0.04
Reproducibility	0.03	0.03	0.04	0.05	0.05	0.06

12.1.1 The probability is approximately 95 % that two test results obtained in the same laboratory on the same material will not differ by more than the repeatability limit *r*. Likewise, the probability is approximately 95 % that two test results obtained in different laboratories on the same material will not differ by more than the reproducibility limit *R*. The precision statistics are calculated from:

$$r = 2\left(\sqrt{2}\right)s_r \tag{8}$$

where:

r = repeatability limit, and
s_r = repeatability standard deviation.

$$R = 2\left(\sqrt{2}\right)s_R \tag{9}$$

where:

R = reproducibility limit, and
s_R = reproducibility standard deviation.

12.2 *Bias*—Bias cannot be determined since there is no standard value of each of the elastic constants that can be used to compare with values determined using this test method.

13. Keywords

13.1 bulk modulus; compression testing; compressive strength; confined compression; elastic moduli; loading tests; modulus of elasticity; Mohr stress circle; Poisson's ratio; repeatability; reproducibility; rock; shear modulus; triaxial compression; uniaxial compression; Young's modulus

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[6] Pincus, H. J., "Interlaboratory Testing Program for Properties: Round One-Longitudinal and Transverse Pulse Velocities, Unconfined Compressive Strength, Uniaxial Modulus, and Splitting Tensile Strength," *ASTM Geotechnical Journal*, Vol 16, No. 1, March 1993, pp. 138–163; and Addendum Vol 17, No. 2, June 1993, and 256–258.

[7] Pincus, H. J., "Interlaboratory Testing Program for Rock Properties: Round Two- Confined Compression: Young's Modulus, Poisson's Ratio, and Ultimate Strength," *ASTM Geotechnical Testing Journal*, Vol 19, No. 3, September 1996, pp. 321–336.