Designation: D 5407 – 95 (Reapproved 2000)

Standard Test Method for Elastic Moduli of Undrained Intact Rock Core Specimens in Triaxial Compression Without Pore Pressure Measurement[1]

This standard is issued under the fixed designation D 5407; 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 determination of elastic moduli of intact rock core specimens in undrained triaxial compression. It specifies 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, v.

NOTE 1—This test method does not include the procedures necessary to obtain a stress-strain curve beyond the ultimate strength.

1.2 For an isotropic material, the relation between the shear and bulk moduli and Young's modulus and Poisson's ratio are:

$$G = \frac{E}{2(1 + v)} \tag{1}$$

$$K = \frac{E}{3(1 - 2v)} \tag{2}$$

where:

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

1.2.1 The engineering applicability of these equations is decreased if the rock is anisotropic. When possible, it is desirable to conduct tests in the plane of foliation, bedding, etc., and at right angles to it to determine the degree of anisotropy. It is noted that equations developed for isotropic materials may give only approximate calculated results if the difference in elastic moduli in any two directions is greater than 10 % for a given stress level.

NOTE 2—Elastic moduli measured by sonic methods may often be employed as preliminary measures of anisotropy.

1.3 This test method given for determining the elastic constants does 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 is not covered by this test method.

1.4 The values stated in SI units are to be regarded as the standard.

1.5 *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.* Specific safety precautions are given in Section 6.

2. Referenced Documents

2.1 *ASTM Standards:*

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[2]
D 4543 Practice for Determining Dimensional and Shape Tolerances of Rock Core Specimens[2]
E 4 Practices for Load Verification of Testing Machines[3]

3. Summary of Test Method

3.1 A rock core sample is cut to length and the ends are machined flat. The specimen is placed in a triaxial loading chamber, subjected to confining pressure and, if required, heated to the desired test temperature. Axial load is continuously increased on the specimen, and deformation is monitored as a function of load.

4. Significance and Use

4.1 Deformation and strength of rock are known to be functions of confining pressure. The triaxial compression test is commonly used to simulate the stress conditions under which most underground rock masses exist.

4.2 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, inhomogeneities, weakness planes, and other factors. Therefore, laboratory values for intact specimens must be employed with proper judgment in engineering applications.

5. Apparatus

5.1 *Loading Device*—The loading device shall be of sufficient capacity to apply load at a rate conforming to the requirements specified in 9.6. It shall be verified at suitable time intervals in accordance with the procedures given in

---

[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 Dec. 10, 1995. Published June 1996. Originally published as D 5407 – 93. Last previous edition D 5407 – 93.

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

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

Practice E 4 and comply with the requirements prescribed in this test 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—If the load measuring device is located outside the triaxial apparatus, calibrations to determine the seal friction need to be made to ensure the accuracy specified in Practice E 4.

5.2 *Triaxial Apparatus*—The triaxial 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.

5.3 *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 (for example, viton) jackets are usually required 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 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.

5.4 *Pressure-Maintaining Device*—A hydraulic pump, pressure intensifier, or other system of sufficient capacity to maintain constant the desired lateral pressure. The pressurization system shall be capable of maintaining the confining pressure constant to within ±1 % throughout the test. The confining pressure shall be measured with a hydraulic pressure gage 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.

5.5 *Confining-Pressure Fluids*—For room temperature tests, hydraulic fluids compatible with the pressure-maintaining device should be used. For elevated temperature tests, the fluid must remain stable at the temperature and pressure levels designated for the test.

5.6 *Elevated-Temperature Enclosure*— The elevated-temperature enclosure may be either an internal system that fits in the triaxial apparatus, an external system enclosing the entire triaxial apparatus, or an external system encompassing the complete test apparatus. For high temperatures, a system of heaters, insulation, and temperature measuring devices are normally required to maintain the specified temperature. Temperature shall be measured at three locations, with one sensor near the top, one at midheight, and one near the bottom of the specimen. The average specimen temperature based on the midheight sensor shall be maintained to within ±1°C of the required test temperature. The maximum temperature difference between the midheight 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 dummy specimen that has temperature sensors located in drill holes at a minimum of six positions: along both the centerline and specimen periphery at midheight and each end of the specimen. The temperature controller set point shall be adjusted to obtain steady-state temperatures in the dummy specimen that meet the temperature requirements at each test temperature (the centerline temperature at midheight shall be within ±1°C of the required test temperature, and all other specimen temperatures shall not deviate from this temperature by more than 3°C. The relationship between controller set point and dummy 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 required test temperature. The relationship between temperature controller set point and steady-state specimen temperature shall be verified periodically. The dummy specimen is used solely to determine the temperature distribution in a specimen in the triaxial apparatus—it is not to be used to determine elastic constants.

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

5.8 *Platens*—Two steel platens are used to transmit the axial load to the ends of the specimen. They shall have a hardness of not less than 58 HRC. One of the platens should be spherically seated and the other 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 properly lubricated to assure 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 faces of the blocks shall be parallel to 0.0005 mm/mm of platen diameter. The platen diameter shall be at least as great as the specimen, but shall not exceed the specimen diameter by more than 1.50 mm. This platen diameter shall be retained for a length of at least one-half the specimen diameter.

5.9 *Strain/Deformation Measuring Devices*—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 noncharacterizable long-term instability (drift) that results in an apparent strain of 10^{-8}/s.

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

5.9.1 *Axial Strain Determination*—The axial 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 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 gage length over which the axial strains are determined shall be at least ten grain diameters in magnitude.

5.9.2 *Lateral Strain Determination*—The lateral deformations or strains may be measured by any of the methods mentioned in 5.9.1. 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 gage adhesives requiring cure temperatures above 65°C is not allowed unless it is known that microfractures do not develop at the cure temperature.

6. Hazards

6.1 Danger exists near triaxial testing equipment because of the high pressures and loads developed within the system. Elevated temperatures increase the risks of electrical shorts and fire. 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. The flash point of the confining pressure fluid should be above the operating temperatures during the test.

7. Sampling

7.1 Select the specimen from the cores to represent a valid average of the type of rock under consideration. This 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.

8. Test Specimens

8.1 *Preparation*—Prepare test specimens in accordance with Practice D 4543.

8.2 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 be made upon specimens representative of field conditions. Thus, it follows that the field moisture condition of the specimen should 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 should be tailored to the problem at hand and reported in accordance with 11.1.3. If the moisture content of the specimen is to be determined, follow the procedures given in Test Method D 2216.

9. Procedure

9.1 Check the ability of the spherical seat to rotate freely in its socket before each test.

9.2 Place the lower platen on the base or actuator rod of the loading device. Wipe clean the bearing faces of the upper and lower platens and of the test specimen, and place the test specimen on the lower platen. Place the upper platen on the specimen and align properly. Fit the membrane over the specimen and platens to seal the specimen from the confining fluid. Place the specimen in the test chamber, ensuring proper seal with the base, and connect the confining pressure lines. A small axial load, approximately 100 *N*, may be applied to the triaxial compression chamber by means of the loading device to properly seat the bearing parts of the apparatus.

9.3 When appropriate, install elevated-temperature enclosure and deformation transducers for the apparatus and sensors used.

9.4 Put the confining fluid in the chamber and raise the confining stress uniformly to the specified level within 5 min. Do not allow the lateral and axial components of the confining stress to differ by more than 5 % of the instantaneous pressure at any time.

9.5 If testing at elevated temperature, raise the temperature at a rate not exceeding 2°C/min until the required temperature is reached (see 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. Consider this to be the zero 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 is not significant.

9.6 Apply the axial load continuously and without shock until the load becomes constant, reduces, or a predetermined amount of strain is achieved. Apply the load in such a manner as to produce either a stress rate or a strain rate as constant as feasible throughout the test. Do not permit the stress rate or strain rate at any given time to deviate by more than 10 % from that selected. The stress rate or strain rate selected should be that which will produce failure of a similar test specimen in unconfined 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 (see Note 8). Maintain constant the predetermined confining pressure throughout the test and observe and record readings of deformation at a minimum of ten load levels that are evenly spaced over the load range. Continuous data recording is permitted provided that the recording system meets the precision and accuracy requirements of 5.9.

NOTE 8—Results of tests by other investigators have shown that strain rates within this range will provide strength and moduli values that are reasonably free from rapid loading effects and reproducible within acceptable tolerances. Lower strain rates are permissible, if required by the investigation. The drift of the strain measuring system (see 5.9) shall be more stringent, corresponding to the longer duration of the test.

9.7 To make sure that no testing fluid has penetrated into the specimen, carefully check the specimen membrane for fissures or punctures at the completion of each triaxial test.

10. Calculation

10.1 The axial strain, ϵ_a and lateral strain, ϵ_1, may be obtained directly from strain-indicating equipment or may be calculated from deformation readings, depending on the type of apparatus or instrumentation employed.

10.1.1 Calculate the axial strain, ϵ_a as follows:

$$\epsilon_a = \frac{\Delta L}{L} \tag{3}$$

where:

L = original undeformed axial gage length, and

ΔL = change in measured axial length (negative for decrease in length).

NOTE 9—Tensile stresses and strains are used 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, if desired.

NOTE 10—In the deformation recorded during the test includes deformation of the apparatus, suitable calibration for apparatus deformation must 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.

10.1.2 Calculate the lateral strain, ϵ_1, as follows:

$$\epsilon_1 = \frac{\Delta D}{D} \tag{4}$$

where:

D = original undeformed diameter, and

ΔD = change in diameter (positive for increase in diameter).

NOTE 11—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.

10.2 Calculate the compressive stress in the test specimen from the compressive load on the specimen and the initial computed cross-sectional area as follows:

$$\sigma = \frac{P}{A} \tag{5}$$

where:

σ = stress,

P = load, and

A = area.

NOTE 12—If the specimen diameter is not the same as the piston diameter through the triaxial apparatus, a correction must 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 triaxial apparatus.

10.3 Plot the stress-versus-strain curves 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.

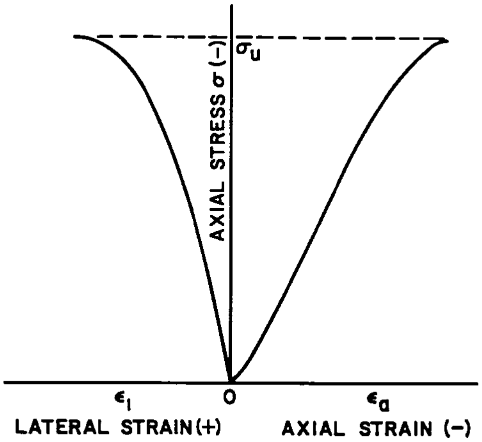


FIG. 1 Format for Graphical Presentation of Data

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

10.4.1 Tangent modulus at a stress level that is some fixed percentage (usually 50 %) of the maximum strength.

10.4.2 Average slope of the more-or-less straight-line portion of the stress-strain curve. The average slope may 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.

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

10.5 The value of Poisson's ratio, v, is greatly affected by nonlinearities at low-stress levels in the axial and lateral stress-strain curves. It is suggested that Poisson's ratio be calculated from the following equation:

$$v = -\frac{\text{slope of axial curve}}{\text{slope of lateral curve}} \tag{6}$$

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

where the slope of the lateral curve is determined in the same manner as was done in 10.4 for Young's modulus, E.

NOTE 13—The denominator in the equation in 10.5 will usually have a negative value if the sign convention is applied properly.

11. Report

11.1 Report the following information:

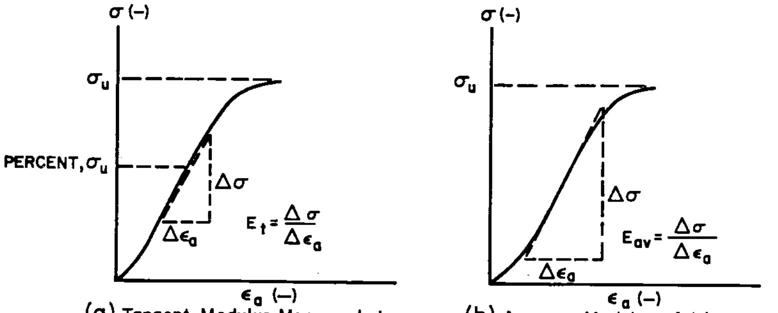
11.1.1 Source of sample including project name and location (often the location is specified in terms of the drill hole number and depth of specimen from the collar of the hole),

11.1.2 Lithologic description of the rock, formation name, and load direction with respect to lithology,

11.1.3 Moisture condition of specimen before test,

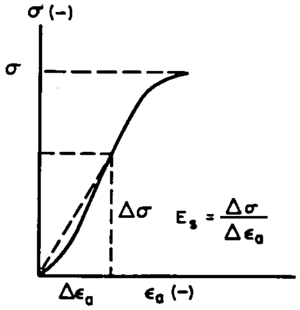
11.1.4 Specimen diameter and height, conformance with dimensional requirements,

11.1.5 Confining stress level at which the test was performed,



(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

11.1.6 Temperature at which the test was performed,

11.1.7 Rate of loading or deformation rate,

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

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

11.1.10 Poisson's ratio, *v*, method of determination in 10.5, and at what stress level or levels determined,

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

11.1.12 If the actual equipment or procedure has varied from the requirements contained in this test method, each variation and the reasons for it shall be discussed.

12. Precision and Bias

12.1 An interlaboratory study was conducted in which six laboratories each tested five specimens of three different rocks, three confining pressures and four replications. The specimens were prepared by a single laboratory from a common set of samples and randomly distributed to the testing laboratories for testing. The study was carried out in accordance with Practice E 691. Details of the study are given in ISR Research Report "Interlaboratory Testing Program for Rock Properties (ITP/RP) Round Two", 1994. Values for Young's Modulus and Poisson's ratio were calculated for the intervals from 25–50 % and 40–60 % of the maximum differential stress. The tables below give the repeatability (within a laboratory) and reproducibility (between laboratories) for the method at confining pressures of 10, 25 and 40 MPa.

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. 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.

Young's Modulus (GPa) @ 10 MPa Confining Pressure

	Berea Sandstone		Tennessee Marble		Barre Granite	
	25–50 %	40–60 %	25–50 %	40–60 %	25–50 %	40–60 %
Average Value	21.4	21.3	73.2	70.6	56.6	57.3
Repeatability	1.19	1.26	9.13	16.4	2.20	2.19
Reproducibility	3.25	3.12	12.2	19.1	7.32	6.90

Young's Modulus (GPa) @ 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

Young's Modulus (GPa) @ 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

Poisson's Ratio @ 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

Poisson's Ratio @ 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

Poisson's Ratio @ 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

12.2 *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 compression testing; loading tests; modulus of elasticity; modulus–Young's; rock; triaxial compression

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org).