



Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock¹

This standard is issued under the fixed designation D 2845; 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 describes equipment and procedures for laboratory measurements of the pulse velocities of compression waves and shear waves in rock **(1)**² (Note 2) and the determination of ultrasonic elastic constants (Note 1) of an isotropic rock or one exhibiting slight anisotropy.

NOTE 1—The elastic constants determined by this test method are termed ultrasonic since the pulse frequencies used are above the audible range. The terms sonic and dynamic are sometimes applied to these constants but do not describe them precisely **(2)**. It is possible that the ultrasonic elastic constants may differ from those determined by other dynamic methods.

1.2 This test method is valid for wave velocity measurements in both anisotropic and isotropic rocks although the velocities obtained in grossly anisotropic rocks may be influenced by such factors as direction, travel distance, and diameter of transducers.

1.3 The ultrasonic elastic constants are calculated from the measured wave velocities and the bulk density. The limiting degree of anisotropy for which calculations of elastic constants are allowed and procedures for determining the degree of anisotropy are specified.

1.4 The values stated in U.S. customary units are to be regarded as the standard. The metric equivalents of U.S. customary units are rationalized.

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.*

2. Referenced Documents

2.1 ASTM Standards:

D 653 Terminology Relating to Rock, Soil, and Contained Fluids³

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.

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² The boldface numbers in parentheses refer to the list of references at the end of this test method.

³ *Annual Book of ASTM Standards*, Vol 14.02.

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction³

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method³

3. Terminology

3.1 For common definitions of terms in this standard, refer to Terminology D 653.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *compression wave velocity*—the dilational wave velocity which is the propagation velocity of a longitudinal wave in a medium that is effectively infinite in lateral extent. It is not to be confused with bar or rod velocity.

NOTE 2—The compression wave velocity as defined here is the dilational wave velocity. It is the propagation velocity of a longitudinal wave in a medium which is effectively infinite in lateral extent. It should not be confused with the bar or rod velocity.

4. Summary of Test Method

4.1 Details of essential procedures for the determination of the ultrasonic velocity, measured in terms of travel time and distance, of compression and shear waves in rock specimens include requirements of instrumentation, suggested types of transducers, methods of preparation, and effects of specimen geometry and grain size. Elastic constants may be calculated for isotropic or slightly anisotropic rocks, while anisotropy is reported in terms of the variation of wave velocity with direction in the rock.

5. Significance and Use

5.1 The primary advantages of ultrasonic testing are that it yields compression and shear wave velocities, and ultrasonic values for the elastic constants of intact homogeneous isotropic rock specimens **(3)**. Elastic constants are not to be calculated for rocks having pronounced anisotropy by procedures described in this test method. The values of elastic constants often do not agree with those determined by static laboratory methods or the *in situ* methods. Measured wave velocities likewise may not agree with seismic velocities, but offer good approximations. The ultrasonic evaluation of rock properties is useful for preliminary prediction of static properties. The test method is useful for evaluating the effects of uniaxial stress and

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

water saturation on pulse velocity. These properties are in turn useful in engineering design.

5.2 The test method as described herein is not adequate for measurement of stress-wave attenuation. Also, while pulse velocities can be employed to determine the elastic constants of materials having a high degree of anisotropy, these procedures are not treated herein.

NOTE 3—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent and objective testing and sampling. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D 3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *General*—The testing apparatus (Fig. 1) should have impedance matched electronic components and shielded leads to ensure efficient energy transfer. To prevent damage to the apparatus allowable voltage inputs should not be exceeded.

6.2 *Pulse Generator Unit*—This unit shall consist of an electronic pulse generator and external voltage or power amplifiers if needed. A voltage output in the form of either rectangular pulse or a gated sine wave is satisfactory. The generator shall have a voltage output with a maximum value after amplification of at least 50 V into a 50-Ω impedance load. A variable pulse width, with a range of 1 to 10 μs is desirable. The pulse repetition rate may be fixed at 60 repetitions per second or less although a range of 20 to 100 repetitions per second is recommended. The pulse generator shall also have a trigger-pulse output to trigger the oscilloscope. There shall be a variable delay of the main-pulse output with respect to the trigger-pulse output, with a minimum range of 0 to 20 μs.

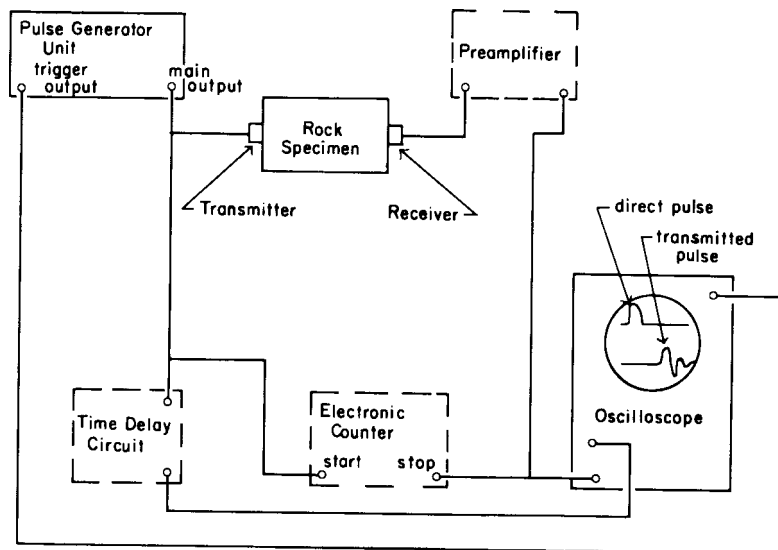
6.3 *Transducers*—The transducers shall consist of a transmitter that converts electrical pulses into mechanical pulses and a receiver that converts mechanical pulses into electrical pulses. Environmental conditions such as ambient temperature,

moisture, humidity, and impact should be considered in selecting the transducer element. Piezoelectric elements are usually recommended, but magnetostrictive elements may be suitable. Thickness-expander piezoelectric elements generate and sense predominately compression-wave energy; thickness-shear piezoelectric elements are preferred for shear-wave measurements. Commonly used piezoelectric materials include ceramics such as lead-zirconate-titanate for either compression or shear, and crystals such as a-c cut quartz for shear. To reduce scattering and poorly defined first arrivals at the receiver, the transmitter shall be designed to generate wavelengths at least $3 \times$ the average grain size of the rock.

NOTE 4—Wavelength is the wave velocity in the rock specimen divided by the resonance frequency of the transducer. Commonly used frequencies range from 75 kHz to 3 MHz.

6.3.1 In laboratory testing, it may be convenient to use unshoused transducer elements. But if the output voltage of the receiver is low, the element should be housed in metal (grounded) to reduce stray electromagnetic pickup. If protection from mechanical damage is necessary, the transmitter as well as the receiver may be housed in metal. This also allows special backings for the transducer element to alter its sensitivity or reduce ringing (4). The basic features of a housed element are illustrated in Fig. 2. Energy transmission between the transducer element and test specimen can be improved by (1) machining or lapping the surfaces of the face plates to make them smooth, flat, and parallel, (2) making the face plate from a metal such as magnesium whose characteristic impedance is close to that of common rock types, (3) making the face plate as thin as practicable, and (4) coupling the transducer element to the face plate by a thin layer of an electrically conductive adhesive, an epoxy type being suggested.

6.3.2 Pulse velocities may also be determined for specimens subjected to uniaxial states of stress. The transducer housings in this case will also serve as loading platens and should be designed with thick face plates to assure uniform loading over the ends of the specimen (5).



NOTE 1—Components shown by dashed lines are optional, depending on method of travel-time measurement and voltage sensitivity of oscilloscope.

FIG. 1 Schematic Diagram of Typical Apparatus

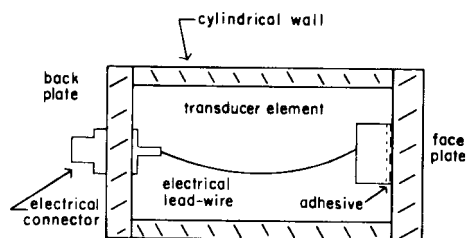


FIG. 2 Basic Features of a Housed Transmitter or Receiver

NOTE 5—The state of stress in many rock types has a marked effect on the wave velocities. Rocks *in situ* are usually in a stressed state and therefore tests under stress have practical significance.

6.4 *Preamplifier*—A voltage preamplifier is required if the voltage output of the receiving transducer is relatively low or if the display and timing units are relatively insensitive. To preserve fast rise times, the frequency response of the preamplifier shall drop no more than 2 dB over a frequency range from 5 kHz to $4 \times$ the resonance frequency of the receiver. The internal noise and gain must also be considered in selecting a preamplifier. Oscilloscopes having a vertical-signal output can be used to amplify the signal for an electronic counter.

6.5 *Display and Timing Unit*—The voltage pulse applied to the transmitting transducer and the voltage output from the receiving transducer shall be displayed on a cathode-ray oscilloscope for visual observation of the waveforms. The oscilloscope shall have an essentially flat response between a frequency of 5 kHz and $4 \times$ the resonance frequency of the transducers. It shall have dual beams or dual traces so that the two waveforms may be displayed simultaneously and their amplitudes separately controlled. The oscilloscope shall be triggered by a triggering pulse from the pulse generator. The timing unit shall be capable of measuring intervals between 2 μ s and 5 ms to an accuracy of 1 part in 100. Two alternative classes of timing units are suggested, the respective positions of each being shown as dotted outlines in the block diagram in Fig. 1: (1) an electronic counter with provisions for time interval measurements, or (2) a time-delay circuit such as a continuously variable-delay generator, or a delayed-sweep feature on the oscilloscope. The travel-time measuring circuit shall be calibrated periodically with respect to its accuracy and linearity over the range of the instrument. The calibration shall be checked against signals transmitted by the National Institute of Standards and Technology radio station WWV, or against a crystal controlled time-mark or frequency generator that can be referenced back to the signals from WWV periodically. It is recommended that the calibration of the time measuring circuit be checked at least once a month and after any severe impact that the instrument may receive.

7. Test Specimens

7.1 *Preparation*—Exercise care in core drilling, handling, sawing, grinding, and lapping the test specimen to minimize the mechanical damage caused by stress and heat. It is recommended that liquids other than water be prevented from contacting the specimen, except when necessary as a coupling medium between specimen and transducer during the test. The surface area under each transducer shall be sufficiently plane that a feeler gage 0.001 in. (0.025 mm) thick will not pass

under a straightedge placed on the surface. The two opposite surfaces on which the transducers will be placed shall be parallel to within 0.005 in./in. (0.1 mm/20 mm) of lateral dimension (Fig. 3). If the pulse velocity measurements are to be made along a diameter of a core, the above tolerance then refers to the parallelism of the lines of contact between the transducers and curved surface of the rock core. Moisture content of the test specimen can affect the measured pulse velocities (see 7.2). Pulse velocities may be determined on the velocity test specimen for rocks in the oven-dry state (0 % saturation), in a saturated condition (100 % saturation), or in any intermediate state. If the pulse velocities are to be determined with the rock in the same moisture condition as received or as exists underground, care must be exercised during the preparation procedure so that the moisture content does not change. In this case it is suggested that both the sample and test specimen be stored in moisture-proof bags or coated with wax and that dry surface-preparation procedures be employed. If results are desired for specimens in the oven-dried condition, the oven temperature shall not exceed 150°F (66°C). The specimen shall remain submerged in water up to the time of testing when results are desired for the saturated state.

7.2 *Limitation on Dimensions*—It is recommended that the ratio of the pulse-travel distance to the minimum lateral dimension not exceed 5. Reliable pulse velocities may not be measurable for high values of this ratio. The travel distance of the pulse through the rock shall be at least $10 \times$ the average grain size so that an accurate average propagation velocity may be determined. The grain size of the rock sample, the natural resonance frequency of the transducers, and the minimum lateral dimension of the specimen are interrelated factors that affect test results. The wavelength corresponding to the dominant frequency of the pulse train in the rock is approximately related to the natural resonance frequency of the transducer and the pulse-propagation velocity, (compression or shear) as follows:

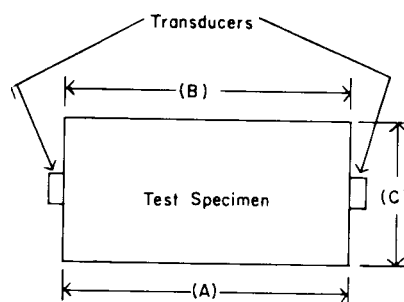
$$\Lambda \approx V/f, \quad (1)$$

where:

Λ = dominant wavelength of pulse train, in. (or m),

V = pulse propagation velocity (compression or shear), in./s (or m/s), and

f = natural resonance frequency of transducers, Hz.



NOTE 1—(A) must be within 0.1 mm of (B) for each 20 mm of width (C).

FIG. 3 Specification for Parallelism

The minimum lateral dimension of the test specimen shall be at least $5 \times$ the wavelength of the compression wave so that the true dilational wave velocity is measured (Note 6), that is,

$$D \geq 5\lambda, \quad (2)$$

where:

D = minimum lateral dimension of test specimen, in. (or m).

The wavelength shall be at least $3 \times$ the average grain size (See 4.3) so that

$$\lambda \geq 3d, \quad (3)$$

where:

d = average grain size, in. (or m).

Eq 1, Eq 2, and Eq 3 can be combined to yield the relationship for compression waves as follows:

$$D \geq 5(V_p/f) \geq 15d, \quad (4)$$

where:

V_p = pulse propagation velocity (compression), in./s (or m/s).

Since V_p and d are inherent properties of the material, f and D shall be selected to satisfy Eq 4 (Fig. 4) for each test specimen. For any particular value of V_p/f the permissible values of specimen diameter D lie above the diagonal line in Fig. 4, while the permissible values of grain size d lie below the diagonal line. For a particular diameter, the permissible values for specimen length L lie to the left of the diagonal line.

NOTE 6—Silaeva and Shamina (6) found the limiting ratio of diameter to wavelength to be about 2 for metal rods. Data obtained by Cannady (3) on rock indicate the limiting ratio is at least 8 for a specimen length-to-diameter ratio of about 8.

8. Procedure

8.1 *Determination of Travel Distance and Density*—Mark off the positions of the transducers on the specimen so that the line connecting the centers of the transducer contact areas is not inclined more than 2° (approximately 0.1 in. in 3 in. (1 mm in 30 mm)) with a line perpendicular to either surface. Then

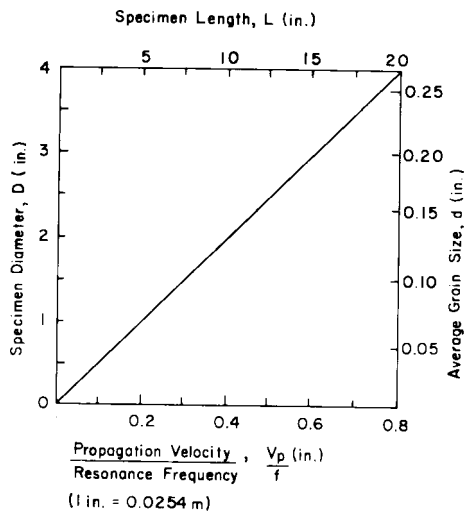


FIG. 4 Graph Showing Allowable Values of Specimen Diameter and Grain Size Versus the Ratio of Propagation Velocity to Resonance Frequency

measure the pulse-travel distance from center to center of the transducer contact area to within 0.1 %. The density of the test specimen is required in the calculation of the ultrasonic elastic constants (see 8.2). Determine the density of the test specimen from measurements of its mass and its volume calculated from the average external dimensions. Determine the mass and average dimensions within 0.1 %. Calculate the density as follows:

$$\rho = m/V$$

where:

ρ = density, lb sec²/in.⁴(or kg/m³),

m = mass of test specimen, lb sec²/386.4 in. (or kg), and

V = volume of test specimen, in³(or m³).

8.2 *Moisture Condition*—The moisture condition of the sample shall be noted and reported as explained in 8.1.3 .

8.3 Determination of Pulse-Travel Time:

8.3.1 Increase the voltage output of the pulse generator, the gain of the amplifier, and the sensitivity of the oscilloscope and counter to an optimum level, giving a steeper pulse front to permit more accurate time measurements. The optimum level is just below that at which electromagnetic noise reaches an intolerable magnitude or triggers the counter at its lowest triggering sensitivity. The noise level shall not be greater than one tenth of the amplitude of the first peak of the signal from the receiver. Measure the travel time to within 1 part in 100 for compression waves and 1 part in 50 for shear waves by (1) using the delaying circuits in conjunction with the oscilloscope (see section 7.1.1) or (2) setting the counter to its highest usable precision, (see section 6.3.2).

8.3.1.1 The oscilloscope is used with the time-delay circuit to display both the direct pulse and the first arrival of the transmitted pulse, and to measure the travel time. Characteristically, the first arrival displayed on the oscilloscope consists of a curved transition from the horizontal zero-voltage trace followed by a steep, more or less linear, trace. Select the first break in a consistent manner for both the test measurement and the zero-time determination. Select it either at the beginning of the curved transition region or at the zero-voltage intercept of the straight line portion of the first arrival.

8.3.1.2 The counter is triggered to start by the direct pulse applied to the transmitter and is triggered to stop by the first arrival of the pulse reaching the receiver. Because a voltage change is needed to trigger the counter, it can not accurately detect the first break of a pulse. To make the most accurate time interval measurements possible, increase the counter's triggering sensitivity to an optimum without causing spurious triggering by extraneous electrical noise.

8.3.2 Determine the zero time of the circuit including both transducers and the travel-time measuring device and apply the correction to the measured travel times. This factor remains constant for a given rock and stress level if the circuit characteristics do not change. Determine the zero time accordingly to detect any changes. Determine it by (1) placing the transducers in direct contact with each other and measuring the delay time directly, or (2) measuring the apparent travel time of some uniform material (such as steel) as a function of length, and then using the zero-length intercept of the line through the data points as the correction factor.

8.3.3 Since the first transmitted arrival is that of the compression wave, its detection is relatively easy. The shear-wave arrival, however, may be obscured by vibrations due to ringing of the transducers and reflections of the compression wave. The amplitude of the shear wave relative to the compression wave may be increased and its arrival time determined more accurately by means of thickness shear-transducer elements. This type of element generates some compressional energy so that both waves may be detected. Energy transmission between the specimen and each transducer may be improved by using a thin layer of a coupling medium such as phenyl salicylate, high-vacuum grease, or resin, and by pressing the transducer against the specimen with a small seating force.

8.3.4 For specimens subjected to uniaxial stress fields, first arrivals of compression waves are usually well defined. However, the accurate determination of shear-wave first arrivals for specimens under stress is complicated by mode conversions at the interfaces on either side of the face plate and at the free boundary of the specimen (4). Shear-wave arrivals are therefore difficult to determine and experience is required for accurate readings.

8.4 *Ultrasonic Elastic Constants*—The rock must be isotropic or possess only a slight degree of anisotropy if the ultrasonic elastic constants are to be calculated (Section 9). In order to estimate the degree of anisotropy of the rock, measure the compression-wave velocity in three orthogonal directions, and in a fourth direction oriented at 45° from any one of the former three directions if required as a check. Make these measurements with the same geometry, that is, all between parallel flat surfaces or all across diameters. The equations in 9.2 for an isotropic medium shall not be applied if any of the three compression-wave velocities varies by more than 2% from their average value. The error in E and G (see 9.2) due to both anisotropy and experimental error will then normally not exceed 6%. The maximum possible error in μ , λ , and K depends markedly upon the relative values of V_p and V_s as well as upon testing errors and anisotropy. In common rock types the respective percent of errors for μ , λ , and K may be large as or even higher than 24, 36, and 6. For greater anisotropy, the possible percent of error in the elastic constants would be still greater.

9. Calculation

9.1 Calculate the propagation velocities of the compression and shear waves, V_p and V_s respectively, as follows:

$$V_p = L_p/T_p$$

$$V_s = L_s/T_s$$

where:

V = pulse-propagation velocity, in./s (or m/s),

L = pulse-travel distance, in. (or m),

T = effective pulse-travel time (measured time minus zero time correction), s,

and subscripts p and s denote the compression wave and shear wave, respectively.

9.2 If the degree of velocity anisotropy is 2% or less, as specified in 6.4, calculate the ultrasonic elastic constants as follows:

$$E = [\rho V_s^2(3V_p^2 - 4V_s^2)](V_p^2 - V_s^2)$$

where:

E = Young's modulus of elasticity, psi (or Pa), and

ρ = density, lb/in.³ (or kg/m³);

$$G = \rho V_s^2$$

where:

G = modulus of rigidity or shear modulus, psi (or Pa);

$$\mu = (V_p^2 - 2V_s^2)[2(V_p^2 - V_s^2)]$$

where:

μ = Poisson's ratio;

$$\lambda = \rho(V_p^2 - 2V_s^2)$$

where:

λ = Lamé's constant, psi (or Pa); and

$$K = \rho(3V_p^2 - 4V_s^2)/3$$

where:

K = bulk modulus, psi (or Pa).

10. Report

10.1 The report shall include the following:

10.1.1 Identification of the test specimen including rock type and location,

10.1.2 Density of test specimen,

10.1.3 General indication of moisture condition of sample at time of test such as as-received, saturated, laboratory air dry, or oven dry. It is recommended that the moisture condition be more precisely determined when possible and reported as either water content or degree of saturation.

10.1.4 Degree of anisotropy expressed as the maximum percent deviation of compression-pulse velocity from the average velocity determined from measurements in three directions,

10.1.5 Stress level of specimens,

10.1.6 Calculated pulse velocities for compression and shear waves with direction of measurement,

10.1.7 Calculated ultrasonic elastic constants (if desired and if degree of anisotropy is not greater than specified limit),

10.1.8 Coupling medium between transducers and specimen, and

10.1.9 Other data such as physical properties, composition, petrography, if determined.

11. Precision and Bias

11.1 An interlaboratory study of longitudinal and transverse pulse velocity (LPV and TPV) of intact specimens of four rock types was conducted in accordance with Practice E 691 in six laboratories with five replications per rock type. The results of this study are reported in ISR Research Report No. PS D18.12-R01, 1992, and its Addendum, 1994.

11.2 The repeatability and reproducibility statistics reported in Table 1 refer to within-laboratory and between-laboratory

TABLE 1 Repeatability and Reproducibility Statistics

	Barre Granite	Berea Sandstone	Salem Limestone	Tennessee Marble
		LPV, km/s		
Mean \bar{x}	3.47	2.28	4.15	6.15
Repeatability limit r	0.22	0.15	0.27	0.44
Reproducibility limit R	0.48	0.30	0.58	0.45
		TPV, km/s		
Mean \bar{x}	2.37	1.45	2.30	3.33
Repeatability limit r	0.14	0.07	0.21	0.25
Reproducibility limit R	0.80	0.58	0.61	0.55

precision, respectively. Each entry in the tables has the dimensions of km/s.

11.3 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:

$$r = 2 \sqrt{2s_r}$$

where:

s_r = the repeatability standard deviation, and

$$R = 2 \sqrt{2s_R}$$

where:

s_R = the reproducibility standard deviation.

11.4 It should be noted here that the anisotropy for TPV in Barre Granite is about 5 %, depending on the orientation of the plane of polarization for shear waves. The data presented here are “average” results.

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

12. Keywords

12.1 compression testing; isotropy; ultrasonic testing; velocity-pulse

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SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the last edition (1995) that may impact the use of the standard.

- (1) Added section 1.5, safety caveat statement.
- (2) Added D 653 and D 3740 to *ASTM Standards* in section 2.1; added new section 3.2 *Definitions of Terms Specific to This Standard*; and moved Note 2 from Scope to 3.2.1.
- (3) Added Note 3 caveat regarding use of D 3740 to section 5

Significance and Use.

- (4) Changed the symbol “>” to “≥” in formulas (Eq 2) and (Eq 3) in section 7.2. *Limitation on Dimensions* because the narrative says “at least”.

 **D 2845**

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