



Designation: D7775 – 16

## Standard Guide for Measurements on Small Graphite Specimens<sup>1</sup>

This standard is issued under the fixed designation D7775; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

### 1. Scope\*

1.1 This guide covers best practice for properties measurements on small (nonstandard) graphite specimens and requirements for representing properties of the bulk material. This guide is aimed specifically at measurements required on nuclear graphites, where there may be constraints on the geometry or volume of the test specimen, or both. The objective of this guide is to provide advice on how the application of selected standards under noncompliant conditions can be tested for suitability.

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

1.3 *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:<sup>2</sup>

- C559 Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles
- C565 Test Methods for Tension Testing of Carbon and Graphite Mechanical Materials
- C611 Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature
- C651 Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Four-Point Loading at Room Temperature
- C695 Test Method for Compressive Strength of Carbon and Graphite
- C714 Test Method for Thermal Diffusivity of Carbon and

- Graphite by Thermal Pulse Method
- C747 Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance
- C748 Test Method for Rockwell Hardness of Graphite Materials
- C749 Test Method for Tensile Stress-Strain of Carbon and Graphite
- C769 Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Value of Young's Modulus
- C781 Practice for Testing Graphite Materials for Gas-Cooled Nuclear Reactor Components
- C886 Test Method for Scleroscope Hardness Testing of Carbon and Graphite Materials
- C1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature
- C1259 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration
- D7972 Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Three-Point Loading at Room Temperature
- E228 Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer
- E1461 Test Method for Thermal Diffusivity by the Flash Method

### 3. Summary of Guide

3.1 There is currently a suite of ASTM standards (see 2.1) that can be applied to graphite covering a range of physical, mechanical, electrical and thermal property measurements. Each of these standards has been developed with the objective of optimizing the method of measurement in the absence of any constraints on test specimen production. Without exception, these standards specify limits on the ratio between test specimen dimensions and coke and filler grain sizes or prescribe test specimen geometries or size ranges, or both. The default position for any user should be to follow these standards exactly as described. However, in some applications, available test material or experiment design constraints on test specimen sizes may result in noncompliance. The objective of this guide is to provide advice on how the application of selected standards under noncompliant conditions can be tested for

<sup>1</sup> This guide is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is the direct responsibility of Subcommittee D02.F0 on Manufactured Carbon and Graphite Products.

Current edition approved Dec. 15, 2016. Published February 2017. Originally approved in 2011. Last previous edition approved in 2015 as D7775 – 11 (2015). DOI: 10.1520/D7775-16.

<sup>2</sup> For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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

suitability. The ultimate objective is to provide guidance on the use of each of the ASTM standards listed. The 2016 issue of this guide addresses nine standards: Test Method **C559** for Bulk Density by Physical Measurement of Manufactured Carbon and Graphite Articles, Test Method **C611** for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature, Test Method **C747** for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance, Test Method **C769** for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining Young's Modulus, Test Method **C749** for Tensile Stress-Strain of Carbon and Graphite and Test Method **D7972** for Flexural Strength of Manufactured Carbon and Graphite Articles Using Three-Point Loading at Room Temperature, Test Method **E228** for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer, and Test Method **E1461** for Thermal Diffusivity by the Flash Method.

#### 4. Significance and Use

4.1 The purpose of this guide is to report considerations, which should be included in testing nonstandard specimens that lie outside the constraints imposed on size/volume in existing ASTM standards for graphite (noting that there are some generic ASTM standards with no such constraints). These constraints may be real or may be an artifact of the round-robin test program that supported the standard. It is the responsibility of the user to demonstrate that the application of a standard outside any specified constraints is valid and reasonably provides properties of the bulk material from which the nonstandard specimen was extracted.

#### 5. Test Specimen Volume/Size Constraints in Current Standards

5.1 *Test Method C559*—Applies to test specimens with rectangular parallelepiped or right circular cylinder geometry. The minimum test volume is specified as 500 mm<sup>3</sup>. The minimum test specimen dimension should be 10 times the length of the largest visible grain.

5.2 *Test Methods C565*—Applies to reduced diameter uniaxial tensile specimens. Grain size must be smaller than 0.79 mm; while not specified, it is assumed that this refers to average grain size. The acceptable fracture zone shall be 19 mm long with the centre of the zone at the point of minimum diameter. The ratio of specimen diameter to grain size or flaw size must be greater than 5.

5.3 *Test Method C611*—Applies to strip, rod, bar or tube geometries. Specimen length to maximum cross-sectional dimension should be 6:1. No dimension should be smaller than 5 times the length of the largest visible grain.

5.4 *Test Method C651*—Applies to rectangular parallelepiped geometries. The minimum dimension should be greater than 5 times the largest grain dimension. Test specimen length to thickness should be greater than 8. The ratio of test specimen width to thickness should be less than or equal to 2.

5.5 *Test Method C695*—Applies to right cylinder geometry. The test specimen diameter should be greater than 10 times the maximum grain size. The test specimen height to diameter

ratio should be in the range 1.9 to 2.1. The minimum test size is specified as 9.5 mm diameter and 19.1 mm height.

5.6 *Test Method C714*—Applies to circular disks, 2 to 4 mm thick and 6 to 12 mm in diameter. The diameter must not be too large relative to the flash source as the front surface needs to be heated uniformly. The specimen thickness must be selected such that  $\tau/t_{1/2}$  is smaller than 0.02, where  $\tau$  is the pulse time and  $t_{1/2}$  is the time for the rear surface temperature to rise to one half of its maximum value.

5.7 *Test Method C747*—Applies to slender rod or bar geometries. The test specimen length to thickness ratio should lie in the range 5 to 20:1.

5.8 *Test Method C748*—Applies to flat specimens of minimum thickness 6.35 mm. The grain size of the test material should be less than 0.8 mm, with a hardness range 0 to 120 Rockwell L.

5.9 *Test Method C749*—Applies to reduced-diameter uniaxial tensile test geometries as defined in Fig. 9 of that standard. Gauge diameter must be greater than 3 to 5 times the maximum grain size.

5.10 *Test Method C769*—Applies to right cylinder geometry. The user should minimize attenuation of the sonic pulse by selecting a wavelength appropriate to the grain size of the test material. If the test specimen is a few grains thick, acceptability of application should be tested over a range of lengths. Specimen should have a diameter of at least a factor of two and ideally a factor of five greater than the wavelength of sound within the material.

5.11 *Test Method C886*—Can be applied to any convenient test specimen size, but test surfaces smaller than 5 mm by 5 mm are not recommended. The material must have a grain size less than 0.8 mm. The minimum specimen thickness is 5 mm.

5.12 *Test Method C1161*—Applies to rectangular parallelepiped geometries and can be adapted for graphite. The average grain size should be less than 2% of the beam thickness. For beam lengths of 25 mm, 45 mm, and 90 mm, specified widths are 2 mm, 4 mm, and 8 mm, respectively, and specified depths are 1.5 mm, 3 mm, and 6 mm, respectively.

5.13 *Test Method C1259*—Can be applied to graphite test specimens with both round and rectangular cross sections. The ratio of test specimen length to minimal cross-sectional dimension should be greater than 10, and preferably greater than 20. For shear modulus measurements, the test specimen width to thickness ratio should be greater than 5.

5.14 *Test Method D7972*—Applies only to those specimen sizes and geometries selected for the interlaboratory study that underwrites the standard. Reference should be made to the table of specimen sizes and testing configurations included in the standard. It is recommended that the size of the test specimen is selected such that the minimum dimension of the specimen is greater than 5 times the largest particle dimension. It is recommended that the test specimen has a length to thickness/diameter ratio of at least 6, and a width to thickness ratio not greater than 2.

5.15 *Test Method E228*—Applies to right cylinder (preferable) or slab geometries. Ideally, test specimens should be 25 mm to 60 mm long and 5 mm to 10 mm in diameter or equivalent (although there is no fundamental limitation provided the instrument controls the maximum thermal gradient to better than  $\pm 2\text{ }^{\circ}\text{C}/50\text{ mm}$ ). The specimen length should be such that the accuracy of determining the expansion  $\Delta L/L_0$  is at least  $\pm 20\text{ mm/m}$ .

5.16 *Test Method E1461*—Applies to thin circular disk specimens with the front surface area less than that of the energy beam. Typically, test specimens should be 10 mm to 12.5 mm in diameter and 1 mm to 6 mm in thickness.

## 6. General Principle for Measurements Outside Specified Specimen Volume/Size Constraints in Current Standards

6.1 The default position for any user should be to follow these standards exactly as described.

6.2 Specimen size and volume constraints may be set by a particular measurement technique and hence apply to any test material, but some may depend upon the microstructure and composition of the material. In such cases, it is preferable to provide technical data and basis to support the choice of the adapted measurement technique and test specimen dimensions used.

6.3 A simple, general principle should be applied to any proposed measurements that are noncompliant with respect to volume/size.

6.3.1 The user must first specify the level of accuracy required for the measurements together with tolerable repeatability, tolerance, and bias uncertainties associated with the measured properties. This may need to take into account the number of specimens used for the measurements.

6.3.2 These qualifying measurement criteria must be demonstrated using representative material in a manner compliant with the ASTM standard. The user should take account of in-service changes to test material (for example, irradiation, oxidation) when selecting representative material for such a demonstration; as-manufactured material may not be sufficiently representative for such purposes.

6.3.3 The measurements should then be repeated on the same material, progressively reducing the volume/size of the specimen and repeating the measurements. Ideally, this procedure would involve the successive re-sizing of the starting specimen. This would ensure that no specimen to specimen variability affected the results. Consideration should be given to within specimen variability and any potential effects of specimen preparation that might affect the property measurement. This process should be continued until there are sufficient compliant data to benchmark the measurement technique against the material; there should be sufficient data at and below the desired test specimen geometry to characterize the dependence of the measured property upon volume/size. It may be necessary to study more than one parameter and these should be varied singly in order not to confound the results.

6.3.4 The results should be analyzed to establish either the standard can be applied directly to an extended specimen

volume/size range or it can be applied with volume/size corrections. In both cases, the accuracy and uncertainty of the measurement at the desired specimen volume/size should be evaluated and assessed for acceptability against the original specification.

6.3.5 It is good practice to retain the test specimens as checks or secondary standards in the subsequent measurement campaigns.

## 7. Bulk Density by Physical Measurement (Test Method C559)

7.1 Test Method C559 requires a mass measurement and a volume determination by mensuration on a test specimen with either a rectangular parallelepiped or right cylinder geometry. The standard specifies that the specimen volume should not be less than  $500\text{ mm}^3$  and the minimum dimension must be at least ten times the length of the largest visible grain. The minimum dimension should also be more than 2000 times the resolution of the measuring device. The volume determination involves four length measurements (longest dimension) either at the center of each long face in the case of the rectangular parallelepiped or  $90^{\circ}$  apart on the periphery of the circular end faces in the case of the right cylinder. For the rectangular parallelepiped, width and thickness at each end and at two intermediate points along the length are required. For the right cylinder, two sets of diameter measurements are required, each set consisting of four measurements, one at each end and two at two intermediate points along an axial line.

7.2 The accuracy of contact measuring devices must be assessed in the context of point and flat contact options.

7.3 Principal sources of mensuration error will arise from geometry irregularity and from surface condition.

7.4 For specimens of regular geometry, mensuration could be carried out with automated multi-measurement contact devices that record and analyze results for prescribed measurement patterns.

7.5 Non-contact scanning devices can also be used to determine volumes of both regular and non-regular geometry specimens. Such devices need careful qualification before use to ensure the detectors respond consistently for graphite surfaces. The calibration and accuracy of the device must be tested on volume standards made from materials that respond to the scanning beam in a simple manner to graphite.

7.6 Bulk density can also be determined using Archimedes' Principle, as an alternative to mensuration techniques. The specimen immersed in a fluid is subject to an upwards buoyancy force equal to the weight of the fluid displaced by the specimen. By measuring the weight of the immersed specimen, the buoyancy force can be deduced, and by using the measured mass of the dry specimen the density can be calculated. This "immersion" method has the advantage of being applicable to non-regular specimen geometries. For a porous material, the method depends upon a constant level of penetration of the open pores by the fluid. The level of penetration is not important provided it is reproducible between repeat immersions.



7.7 An application of the immersion method is described as follows:

7.7.1 The dry test specimen is first weighed then immersed in water and reweighed while immersed; the specimen is removed from the water and the excess water removed by blotting on a damp chamois leather. The “blotted” specimen is reweighed and then immersed and weighed again while immersed. The difference between these two measurements is calculated and the cycle of measurements is repeated until three consecutive pairs of measurements are achieved with prescribed limits. Assuming a density of water of  $\rho_0 = 1000 \text{ kg m}^{-3}$ , the density of the test specimen is:

$$\rho = \frac{W_1}{W_4} \rho_0 \quad (1)$$

where:

- $\rho$  = test specimen density,  $\text{kg m}^{-3}$ ,
- $\rho_0$  = density of water,  $\text{kg m}^{-3}$ ,
- $W_1$  = dry mass of test specimen, kg,
- $W_4$  = mass difference from  $(W_3 - W_2)$ , kg,
- $W_3$  = dried mass, kg, and
- $W_2$  = immersed mass, kg.

7.7.2 Corrections can be made to account for variations in the density of water due to temperature, dissolved air and purity. In practice, these effects are negligible compared to uncertainties in the overall method (and a water density of  $1.0 \text{ g cm}^{-3}$  is normally assumed). Surface tension forces associated with the pan suspension wire and the water may need to be accounted for in the claimed level of accuracy.

7.7.3 In principle, there are no constraints on test specimen geometry. In practice, irregular geometries may trap air bubbles and are more difficult to dry between immersions.

7.7.4 In principle, there is no limit on test specimen size although the practical limit is set by the size of the pan on the balance. Also, as the test specimen volume decreases, uncertainties in density determinations increase due to the increasing significance of surface effects.

7.7.5 The test method as described requires the density of the test specimen to be greater than that of water. For low density material, a fixed weight kept immersed in the water reservoir is placed on the immersed specimen and its mass subtracted in the density evaluation.

7.7.6 Uncertainties in measurement may arise if the graphite specimen is friable. This can be quantified by ensuring that the oven-dried weight of the test specimen is known before and after measurement.

7.7.7 For highly porous materials, varying penetration of the water between immersions may lead to uncertainties in bulk density determinations. Water may “drain” out of the test specimen during surface drying and repenetrate the porosity to a varying degree during immersion. This can be addressed by waxing the test specimen, where the open porosity is partly filled with wax and the surface tension on the surface of the specimen is changed to prevent water penetration. This treatment is invasive and only applicable if no further measurements on the specimen are required. Care needs to be taken in the evaluation of the bulk density. The dry mass of the test specimen must be the mass measured before waxing, the

difference in apparent weight between the test specimen immersed and the test specimen removed from the water being equal to the weight of the water being displaced by the removed specimen.

## 8. Electrical Resistivity (Test Method C611)

8.1 Test Method C611 applies to specimens in the form of a strip, rod, bar, or tube with a uniform cross-section. No dimension shall be smaller than five times the length of the largest visible grain.

8.2 The resistance of the material is measured by passing an electric current between two contact points on the specimen and measuring the potential drop. Numerous measurements are advised (16 is the recommended number) in order to minimize specimen or contact point artifacts which might lead to erroneous resistance values. The resistivity of the specimen is defined as  $\rho$  in the following relationship:

$$\rho = \frac{R \cdot A}{L} \quad (2)$$

where:

- $\rho$  = resistivity in  $\text{m}\Omega$  meters,
- $R$  = resistance of the material,
- $A$  = uniform cross section,  $\text{mm}^2$ , and
- $L$  = distance between potential contacts, mm.

8.3 The specimen geometry requirement of a specimen length to maximum cross-sectional dimension of at least 6:1 may pose a challenge to test specimens with specific size constraints when coupled with the 5:1 ratio of smallest dimension to grain or visible particle size.

8.4 For specimens with length to cross-section dimensions of less than 6:1, the number of measurements taken and resulting spread of data will indicate whether the measured resistivity values are reliable. Care should be taken to ensure that the length measurement between contact points can still be measured to within  $\pm 0.5 \%$ , as errors due to contact length variation will be magnified commensurate with the total length available for attachment of electrical contacts. Small specimen errors can again be “averaged” by multiple measurements, as required by the specification even for ideally sized test specimens.

8.5 Small specimens that will not meet the minimum required grain or particle size restriction should, where possible, be evaluated through a systematic set of resistivity measurements with progressively larger specimens. A measurable shift in resistivity as more grains are included in scoping specimen sets will provide the operator with an indication of the expected contribution of grain boundary effects in the electrical resistance of the cross-section of the material.

8.6 Reported results for resistivity measurements on specimens that do not meet the dimensional restrictions of Test Method C611, in addition to the resistivity value calculated from the average resistance measured, should also record each individual measurement so that an evaluation can be made with respect to the spread of values collected and precision of the measurement technique.

## 9. Moduli of Elasticity and Fundamental Frequencies by Sonic Resonance (Test Method C747)

9.1 Test Method C747 applies to specimen geometries that are straight and have uniform cross section. Accurate results will depend upon appropriate shape factors that rely on careful dimensional measurements, which are more prone to error or variation in smaller geometries.

9.2 Specimens having relatively small or large ratios of length to thickness may be difficult to excite in the fundamental frequency modes, and therefore a length to width ratio between 5 and 20 is required by this test method.

9.3 The elastic modulus or modulus of rigidity, as appropriate, is calculated in the transverse (or flexural) mode, the longitudinal mode, or the torsional mode based upon the use of the specimen's fundamental mode of vibration, appropriate to the calculated modulus.

9.4 Deviations from the recommended test specimen ratio range introduce an elevated level of difficulty in obtaining a measurable fundamental frequency. The modulus of the test material is first established from the measured frequency of a large test specimen and this modulus is used to estimate a frequency for the small test specimens. It is recommended that two additional guidelines be employed in order to increase the confidence in the recorded frequency:

9.4.1 Determine the fundamental frequency using specimens that are within the recommended length to width ratio of between 5 and 20, or use progressively larger specimens as necessary, in order to establish baseline frequency characteristics of the material being evaluated. The expected value for fundamental frequency of a nonstandard specimen can be calculated based upon the measured geometry and the known fundamental frequency of a standard specimen, and any deviation or shift can be appropriately noted.

9.4.2 In all cases, use the required procedural practices employed in Test Method C1259 for the number of readings taken. For small test specimens, there is a risk that the excited mode is not the intended mode and consequently the formula applied to calculate modulus from the frequency will be wrong. Spurious vibration modes are more easily discounted with the fundamental frequency of the required mode having been measured if the test is repeated on the same specimen until ten readings are within  $\pm 10\%$  of the mean. It is acknowledged that for less ideal specimen geometries, the frequency mean that is eventually used for the modulus calculation may require an extended number of measurements until an appropriate group of ten readings is obtained. In this case, the total number of measurements required to obtain the group of ten readings should be reported. It is good practice to confirm independently that the excited mode is the intended one by using an alternative experimental, numerical or analytical method.

9.5 The report shall contain additional information pertaining to the testing that may have been carried out per item 9.4.1, and the individual numerical values recorded and the mean value obtained per item 9.4.2.

## 10. Tensile Stress-Strain (Test Method C749)

10.1 Test Method C749 applies to reduced-diameter uniaxial tensile test geometries as defined in Fig. 9 of that standard. Gauge diameter must be greater than 3 to 5 times the maximum grain size.

10.2 Practice C781 includes an annex describing modifications to Test Method C749 to extend its application to small test specimens. This annex does not address gauge diameter to grain size constraints but it does describe how bonding connectors to specimens can extend applicability of the method described in Test Method C749 from the standard reduced-diameter uniaxial test geometry to a simple right cylindrical geometry. In order for this guide to contain a complete compilation of methods for small graphite specimens, the procedure in Annex A4 of Practice C781 has been reproduced here.

10.2.1 *Test Specimen*—The test specimen shall be cylindrical with ends machined perpendicular to the longitudinal axis.

10.2.1.1 The recommended test specimen size is 6.5 mm diameter.

10.2.1.2 The recommended height to diameter ratio for the specimen gauge section is 4.

10.2.1.3 The cylindrical surface shall be flat within 0.05 mm, and the minimum diameter must not occur at either end of the specimen. The end faces of the specimen shall be perpendicular to the cylindrical surface to within 0.025 mm/mm of diameter total indicator reading. Reasonable care shall be exercised to ensure that all edges are sharp and without chips or other flaws.

10.2.2 *Specimen Connectors*—The specimen connectors that are bonded to the specimen ends shall be sized to fit the gripping devices. The recommended material for the specimen connectors is 6061-T6 aluminum alloy. The end (bond) face of the connector shall be flat within 0.025 mm and perpendicular to the cylindrical axis of the connector within 0.02 mm/mm of diameter total indicator reading.

10.2.3 *Attachment of Test Specimens to Specimen Connectors*—Specimen connectors shall be bonded to the test specimen with an epoxy or cyanoacrylate adhesive.

10.2.3.1 The axial center line of the test specimen and specimen connectors shall be aligned during bonding using an appropriate alignment fixture. The run out tolerance for the finished assembly shall be within 0.025 mm total indicator reading.

10.2.3.2 An adhesive with a tensile shear strength (aluminum alloy to aluminum alloy) greater than 17 MPa is recommended.

10.2.3.3 The bond face of the specimen connector shall be etched or grit blasted, washed, dried, and degreased to promote a strong adhesive bond.

10.2.3.4 The ends of the specimen shall be dust-, grease-, and moisture-free.

10.2.4 *Test Procedures*—Follow the test procedures given in Sections 8.1 through 8.4 of Test Method C749.

10.2.4.1 If the fracture occurs within a distance less than 10 times the measured thickness of the adhesive joint at either end of the specimen, the strength results shall be reported but not included in the calculation of the average strength value.

Experience has shown that when testing high strength graphite or graphites that have a large Poisson's ratio mismatch with that of the adhesive, specimens may fail at or very near the adhesive joint and yield invalid measurements. Under these circumstances, consideration should be given to the use of a specimen with a reduced gauge section.

10.2.5 *Tensile Property Calculations*—Calculate the strength, modulus of elasticity, and strain-to-failure as indicated in Section 9 of Test Method C749.

10.2.6 *Precision and Bias*—A round-robin test is being planned to develop precision and bias statements for this test method.

10.3 When applying bonded connectors to small cylindrical specimens in order to measure strength, modulus of elasticity and strain-to-failure, the user should take account of the gauge diameter to grain size constraint in Test Method C749 when assessing the validity and applicability of test results.

## 11. Sonic Velocity for Use in obtaining Young's Modulus (Test Method C769)

11.1 Test Method C769 applies to right cylinder geometries. If the test specimen is a few grains thick, acceptability of application (that is, the measurement has been made over a volume representative of the bulk material) should be tested over a range of lengths. Specimen should have a diameter at least a factor 2 and ideally a factor 5 greater than the wavelength of sound within the material.

11.2 The velocity of longitudinal sound waves passing through the test specimen is determined by measuring the distance through the specimen and dividing by the time elapsed, between the transmitted pulse and the received pulse (1, 2).<sup>3</sup> Provided the wavelength of the transmitted pulse is a sufficiently small fraction of the test specimen lateral dimensions, a value for Young's modulus for isotropic graphite can then be obtained using Eq 3 and 4.

$$E = C_v \rho V^2 \quad (3)$$

where:

$E$  = Young's modulus of elasticity, Pa,

$\rho$  = density, kg/m<sup>3</sup>,

$V$  = longitudinal signal velocity, m/s, and

$C_v$  = Poisson's factor.

The Poisson's factor,  $C_v$ , is related to Poisson's ratio,  $\nu$ , by the equation:

$$C_v = \frac{(1+\nu)(1-2\nu)}{1-\nu} \quad (4)$$

11.3 If the wavelength is not a small fraction of the test specimen lateral dimensions, and instead is much larger than the specimen lateral dimensions, then the Young's modulus,  $E$ , is given by Eq 3 with  $C_v$  set to one.

11.4 If the grain size of the carbon or graphite is greater than or about equal to the wavelength of the sonic pulse, the method may not be providing a Young's modulus value representative of the bulk material. Therefore, it would be preferable to test at

a lower frequency (longer wavelength) to demonstrate that the sonic velocity is independent of frequency. Significant signal attenuation should be expected (and usually observed) when the grain size of the material is greater than or about equal to the wavelength of the transmitted sonic pulse.

11.5 If the test specimen is only a few grains thick, the acceptability of the test method's application should be demonstrated by initially performing measurements on a series of tests covering a range of test specimen lengths between the proposed test length and a test length incorporating sufficient grains to adequately represent the bulk material. However, it should be noted that increasing test specimen length on test specimens can lead to attenuation and dispersion of the sonic pulse and such effects may be more significant than issues relating to test specimen thickness and how representative the material over that length is of the bulk matrix.

11.6 Limitations on dimensions cannot be precisely specified as they will depend upon the properties of the material being tested. In order to satisfy the theory that supports Eq 3, as a guide, the specimen should have a diameter that is at least a factor two, and ideally a factor five, greater than the wavelength of sound in the material under test. It is good practice to run a series of tests with varying diameter to wavelength ratio to confirm the suitability of the test geometry. In practice, the length of the specimen will be determined taking account of the comments provided in 11.4 and 11.5.

11.7 The test method is satisfactory for test specimens greater than 6 mm length providing that the specimen diameter is greater than two wavelengths. For short test specimens it is very important to use a measure of time of flight that is reproducible. The onset of the pulse can be difficult to define giving poor repeatability. A number of other methods are available for estimating the time of flight from the received wave signal including: (1) measurement of the position of a number of the first peaks and troughs (for example, the first two) to form an average; (2) measurement of the zero positions in the signal to form an average; (3) determination of the onset of a peak or a trough by the moment when a fraction (for example, 5%) of its amplitude is reached. It is the responsibility of the user to choose a method for estimating the time of flight. Where the frequency of the transmitted signal has changed significantly due to the attenuation of high frequency components in the specimen, the user should check that the chosen method provides adequate timing accuracy, by carrying out tests on a range of materials standards covering the full range of measurements. The test method used to determine the time of flight should be recorded as part of the measurement data.

11.8 In all cases, it is incumbent upon the operator to appropriately couple the specimen to the transducers. Combinations of grain size, pulse wave characteristics, length and test specimen geometry constraints generally affect the measured wave speed values. Proper coupling minimizes signal measurement errors, which are more detrimental to the overall recorded values in reduced-size (relatively thin) or high modulus (for example, irradiated) specimens due to the shorter time of flight. Subsequent increases in signal gain could have the detrimental

<sup>3</sup> The boldface numbers in parentheses refer to a list of references at the end of this standard.