Designation: D6539 – 13

# Standard Test Method for Measurement of the Permeability of Unsaturated Porous Materials by Flowing Air [1]

This standard is issued under the fixed designation D6539; 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 laboratory determination of the coefficient of permeability for the flow of air through unsaturated porous materials.

1.2 This test method may be used with intact or compacted coarse grained soils, silts, or lean cohesive soils that have a low degree of saturation and that have permeability between $1.0 \times 10^{-15}$ $m^2$ (1.01 millidarcy) and $1.0 \times 10^{-10}$ $m^2$ (101 darcy).

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

1.3.1 By tradition in U.S. practice, the permeability of porous media is reported in units of darcy, although the SI unit for permeability is $m^2$.

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

1.4.1 For the purpose of comparing a measured or calculated value with specified limits, the measured or calculated value shall be rounded to the same precision as the specified limits.

1.4.2 The procedures used to specify how data are collected/recorded or calculated, in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

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:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft$^3$ (600 kN-m/m$^3$))

D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$))

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D3550 Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of Soils

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

D4220 Practices for Preserving and Transporting Soil Samples

D4525 Test Method for Permeability of Rocks by Flowing Air

D4564 Test Method for Density and Unit Weight of Soil in Place by the Sleeve Method (Withdrawn 2013)[3]

D4753 Guide for Evaluating, Selecting, and Specifying Balances and Standard Masses for Use in Soil, Rock, and Construction Materials Testing

D4767 Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils

D5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter

D5856 Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall,

[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.04 on Hydrologic Properties and Hydraulic Barriers.

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

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

Compaction-Mold Permeameter
D6026 Practice for Using Significant Digits in Geotechnical Data
E1 Specification for ASTM Liquid-in-Glass Thermometers
E145 Specification for Gravity-Convection and Forced-Ventilation Ovens
E2251 Specification for Liquid-in-Glass ASTM Thermometers with Low-Hazard Precision Liquids

## 3. Terminology

3.1 *Definitions*—For definitions of technical terms in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *darcy*—a porous medium has a permeability of one darcy when a single-phase fluid having a viscosity of $10^{-3}$ Pa·s (1-cP) that completely fills the voids of the medium will flow through it under laminar (viscous) flow conditions at a rate of 1 $m^3$ per 1 $m^2$ of cross-sectional area under a pressure gradient of $1.013 \times 10^5$ Pa/m (1 atm/m). (One darcy = $9.869 \times 10^{-13}$ $m^2$.)

3.2.2 *effective confining stress,* (Flexible Wall Method only)—the difference between the permeameter cell confining pressure and the mean specimen pore-air-water pressures.

3.2.2.1 The effective confining stress is assumed to be distributed as a radial vector exhibiting a linear gradient along the length of the specimen with a minimum at the inlet and a maximum at the outlet.

3.2.2.2 For the purposes of this test method, the effective confining stress is stated as a scalar value and calculated as the confining gage pressure minus the average of the specimen inlet and outlet gage pressures.

3.2.3 *gage pressure*—pressure measured relative to ambient atmospheric pressure.

3.2.4 *permeability*—the capacity of a porous medium to conduct gas in the presence of a gas (air) pressure gradient measured as the ratio of volumetric flow rate of air through a specimen to the resultant pressure drop across the specimen. (Also commonly known as *conductivity* or *permeability to air*.)

## 4. Significance and Use

4.1 This test method applies to the one-dimensional laminar (viscous) flow of air in porous materials such as soil.

NOTE 1—This test method deals with porous materials with both gaseous (air) and liquid (pore water) mobile fluids: The liquid phase is much less compressible, has a higher viscosity, and is much more tightly bound to the solid phase by chemical forces. The assumption of single-phase flow may still be presumed to be valid since the test gradient ensuring the conditions of laminar flow may be low enough that flow of the liquid phase is negligible.

4.2 The degree of saturation of the specimen shall be less than that which would produce significant internal transport of pore water or alter the continuity of air voids under the applied gradients. The maximum permissible degree of saturation must be evaluated by an experienced analyst. In no instance shall the specimen be so saturated that pore water appears at the exit of the permeameter cell during the test.

4.3 This test method is based on the assumption that the rate of mass flow through the specimen is constant with time.

NOTE 2—When a specimen contains volatile materials this assumption is violated. The mass of gas flowing out will be greater than that flowing in, the gradient cannot be determined and the test may become meaningless. Such specimens pose special problems and must be decontaminated before analysis in order to minimize health and safety concerns and to prevent contamination of the test apparatus.

4.4 The permeability of porous materials may be strongly dependent on a variety of physical properties including the void ratio, the degree of saturation, and percent and direction of compaction. It is beyond the scope of this test method to elaborate upon these dependencies. Rather, this test method is intended to be a measurement technique for determining the permeability under a certain set of laboratory conditions. It is the responsibility of the test requestor to specify which soil parameters must be controlled to ensure a valid extension of the test results to field conditions.

4.5 Calculation of the permeability using Darcy's law requires laminar flow conditions through the soil specimen. The conditions for laminar flow shall be evaluated by plotting the volumetric flow rate of air through the specimen against the pressure drop across the specimen. If the individual test points lie within 25 % of a straight line passing through the origin, then laminar flow conditions are present and Darcy's law may be used to calculate the permeability.

NOTE 3—The permeability calculated using this standard is valid only when the degree of saturation does not change over time. Long measurement times associated with the use of bubble meters and manometers may indirectly lead to variability when measuring flow versus pressure drop (see 8.2) due to evaporation. The recommended use of digital electronic flow and pressure sensors leads to considerably reduced measurement times because the user can quickly determine by inspection when a steady state condition has been reached. At that point only a single reading needs to be taken for a reliable measurement. A rapid course of measurement will minimize dehydration of unsaturated specimens.

NOTE 4—Humidifying the test gas to minimize specimen dehydration is not recommended because: (*1*) there is no practical way to either measure or control the relative humidity of the test gas, either at the inlet or outlet of the specimen; (*2*) the calibration of typical digital flowmeters are generally for dry air only and would become unreliable in the presence of water vapor, especially in view of the potential for irreversible adsorption of moisture on the sensor elements; (*3*) there is a danger of permanent water condensation in the static transfer lines and other apparatus dead volumes; and (*4*) the test apparatus would become more complex and difficult to use.

4.6 This test method covers the use of two different types of permeameter cells (flexible and rigid wall permeameters) and two types of air flow regulation (mass flow control and pressure control).

4.7 A flexible wall permeameter is the preferred means for confining the test specimen in accordance with Test Methods D5084, D4525, and D4767. This test method may still be performed using a rigid wall permeameter, but all reference to effective confining stress and the permeameter cell pressure system shall then be disregarded.

4.8 For some specimens, the permeability will be strongly dependent on the effective confining stress due to porosity reduction. Whenever possible, the requestor shall specify the field overburden conditions at which this test method is to be performed. In some specimens, this stress will vary significantly with flow in an indeterminate way. All specimens shall be evaluated for this effect by performing this test method at

two or more different confining stress values when a flexible wall permeameter is used.

4.9 This test method is intended to support soil remediation operations such as: soil vapor extraction, air sparging, backfilling of soils in utility trenches, and similar engineering activities.

4.10 The correlation between results obtained with this test method and in situ field measurements has only been partially established. The small laboratory specimen used in this method may not be representative of the distributed condition on-site due to vadose zone fluctuations, changes in soil stratigraphy, and so forth. For this reason, caution should be used by qualified personnel when applying laboratory test results to field situations.

NOTE 5—This test method is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies which meet the criterion of Practice D3740 are generally considered capable of competent and objective testing.

## 5. Apparatus

5.1 *Permeameter*—The permeameter shall be capable of rapidly establishing a constant flow of air through the test specimen and measuring the consequent pressure drop across it. A schematic diagram is shown in Fig. 1.

5.1.1 *Air Supply*—The compressed air supplied to the system shall:

5.1.1.1 Be pulsation-free, have sufficient volumetric capacity at all anticipated flow rates, be free of water vapor to a dew point of −70°C or less, and be free of oil,

5.1.1.2 Be free of particulate matter greater than 5 μm in diameter, and

5.1.1.3 Be provided with a monitoring gage and regulator to deliver a pressure of at least 350 ± 5 kPa.

NOTE 6—Other gases than air may be used when specified by the requestor. It is important that the electronic flowmeter is calibrated for the test gas. Nitrogen is often preferred as having more uniform viscosity and low water content. In flow meters, 1 cc equals 0.000001 $m^3$.

5.1.2 *Flow Control*—The flow rate of air shall be regulated upstream from the specimen by a mass flow controller (flow control method) or a back pressure regulator (pressure control method), or both. The flow control shall be capable of regulating air flow between $1.67 \times 10^{-10}$ and $1.67 \times 10^{-5}$ $m^3/s$ (0.01 to 1000 $cm^3$/min) to ±5 %. Two test methods of flow control are required to adapt to a wide range of specimen permeability:

5.1.2.1 *Test Method A, Flow Control Mode*—This test method is preferred for high-permeability specimens (greater than 0.1 darcy) that require flows in the range from $3.33 \times 10^{-8}$ and $1.67 \times 10^{-5}$ $m^3/s$ (2 to 1000 $cm^3$/min) and low specimen inlet pressures. The mass flow controller is set for the desired flow through the specimen. It shall automatically adjust its

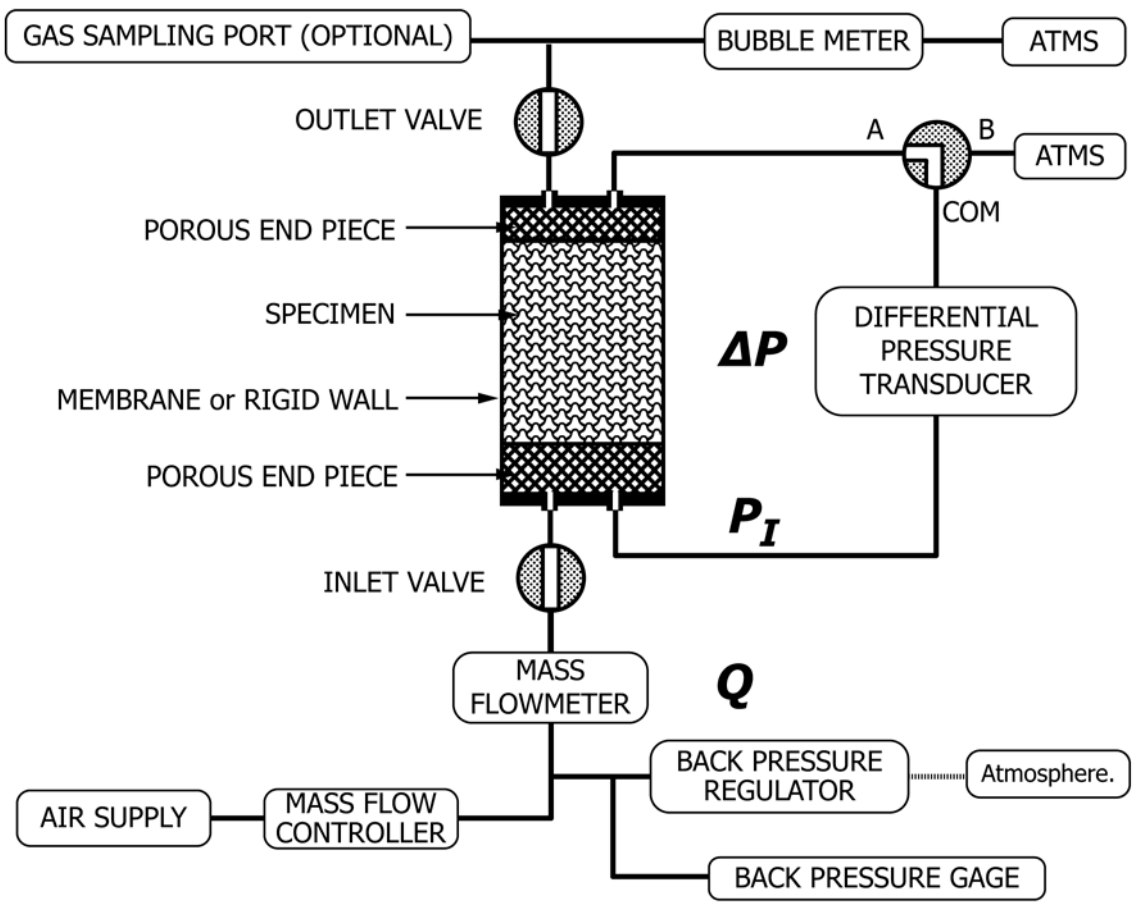


**FIG. 1 Permeameter for Measurement of the Permeability of Unsaturated Materials**

downstream pressure as needed to maintain constant mass flow rate of air regardless of temperature or pressure.

5.1.2.2 *Test Method B, Pressure Control Mode*—This test method is preferred for low-permeability specimens (less than 0.1 darcy) that require control of pressure between 5 and 35 kPa at low flow rates. The back pressure regulator shall act as a variable pressure relief valve that can be adjusted to produce a fixed inlet pressure. The mass flow controller is set to produce an air flow rate slightly in excess of the test maximum.

NOTE 7—The back pressure regulator diverts to the atmosphere a portion of the flow to maintain a constant inlet pressure to produce the required specimen flow rate.

5.2 *Flow Measurement:*

5.2.1 The rate of air flowing into the specimen, $Q$, shall be measured to a precision better than 3 %. The preferred device is a digital electronic mass flowmeter upstream from the specimen. If such a flowmeter is not available, a bubble meter at the outlet of the permeameter may be used.

NOTE 8—When repetitious, rapid measurements are required, the digital electronic mass flowmeters will prove more convenient to use than a bubble meter, especially at high flow rates. The need for careful hand-eye coordination technique is minimized, and the condition of constant flow is easily recognized without recording repeated measurements. Electronic flowmeters measure the mass of gas flowing through the flowmeter. The volume of the gas at any point in the system is known from Boyles Law, given the pressure and temperature at that point. Flowmeters are insensitive to temperature and pressure changes over the range of operating conditions specified by the manufacturer. Flowmeters are sensitive to the composition of the gas flowing through the flowmeters and their sensing elements are subject to long-term drift. For this reason, flowmeters must be installed upstream from the specimen where they will not be exposed to any moisture or trace volatiles that may be expelled from the specimen.

NOTE 9—The electronic flowmeter is best suited for air flow rates of $3.33 \times 10^{-8}$ and 1.67 × 10-5 $m^3/s$ (2 to 1000 $cm^3$/ min).

5.2.2 Rates of air flow less than the range of the electronic flowmeter shall be measured with a stopwatch and a bubble meter placed downstream from the specimen where the air flow exits to the atmosphere. The bubble meter shall be used as specified by the manufacturer with due regard to ambient temperature and barometric pressure corrections. Measurements shall be repeated until a stable reading is obtained.

NOTE 10—The bubble meter is best suited for low air flow rates of $1.67 \times 10^{-10}$ and $1.67 \times 10^{-7}$ $m^3/s$ (0.01 to 10 $cm^3$/min).

NOTE 11—Rotameter and orifice-type flowmeters are not acceptable substitutes for the bubble meter. Moisture in the exit air, even if transient, will cause rotameter balls to stick and flow orifices to change effective diameters.

NOTE 12—When using a soap-film bubble meter, be aware that it will generate a back pressure of 10 to 50 Pa at the specimen outlet that is easily detectable by the differential pressure transducer. This back pressure will vary as the bubbles break at the top of the meter. This variation in pressure will be minimized if there are five or more soap films ascending simultaneously.

NOTE 13—Very low-permeability specimens with low flow rates may take a long time for their pressure gradients to stabilize. Repeated bubble meter measurements are essential to ensure that an equilibrium state has been reached.

5.3 *Pressure Measuring Devices:*

5.3.1 *Specimen Pressure Drop*—\The pressure drop across the specimen, $\Delta P$, shall be measured with a digital electronic differential pressure transducer. If such a device is not available, a differential mechanical (Bourdon tube) pressure gage or liquid (water or mercury) manometer may be used. The pressure inlets shall be connected to the end pieces in the permeameter cell using static pressure lines that carry no net gas flow. (**Warning—**Mercury has been designated by the United States Environmental Protection Agency (EPA) and many state agencies as a hazardous material that can cause central nervous system, kidney and liver damage. Mercury, or its vapor, may be hazardous to health and corrosive to materials. Caution should be taken when handling mercury and mercury containing products. See the applicable product Material Safety Data Sheet (MSDS) for details and EPA's website—http://www.epa.gov/mercury—for additional information. Users should be aware that selling mercury, mercury containing products, or both, into your state may be prohibited by state law.)

5.3.2 *Specimen Inlet Gage Pressure*—The specimen inlet pressure, $P_I$, shall be measured, relative to atmospheric pressure, with a digital electronic gage pressure transducer or liquid (water or mercury) manometer.

NOTE 14—The requirements of 5.3.1 and 5.3.2 may be satisfied with a single pressure measuring device if a two-way valve is installed in the specimen outlet pressure transfer line as follows: The valve common port shall be connected to the pressure measuring device port, the normally open port shall be connected to the specimen outlet port, and the normally closed port vented to atmosphere. When in the normally open position (Position A, Fig. 1), the device measures pressure drop across the specimen, $\Delta P$; when in the normally closed position (Position B), the device measures the specimen inlet gage pressure, $P_I$.

5.3.3 *Back Pressure Gage*—This gage shall monitor the pressure down stream from the mass flow controller and upstream from the specimen inlet with a precision of ±1 kPa, a range of 100 kPa and a precision of 5 % of full scale.

NOTE 15—The back pressure gage is essential for the flexible wall test method to facilitate the maintenance of a constant effective confining stress.

5.4 *Over-Pressure Control* (Flexible Wall Test Method only)—In addition to the requirement of 7.6.2 that the effective confining stress must remain within limits at different flow rates, the specimen inlet pressure shall not be allowed to exceed the specimen confinement pressure when a flexible wall permeameter is used.

NOTE 16—The over-pressure control test method requires close monitoring of the difference between the specimen inlet pressure and the confining pressure. The operator must ensure that the inlet pressure is never allowed to increase to 7 kPa less than the confinement pressure. In the flow control test method, the back pressure regulator shall be used as a variable pressure relief valve and must be set to the confinement pressure less 7 kPa.

NOTE 17—If the specimen inlet pressure exceeds the confining pressure, two problems will arise: (*1*) The membrane will pull away from the specimen and the air flow will divert around the specimen; and (*2*) The "O"-rings that seal the membrane to the permeameter base may be breached with the consequent release of air into the confinement annulus. This may drive the confining water back into the external pressurizing system with possibly damaging results. In either case, the results will be invalidated.

5.5 *Permeameter Cell:*

5.5.1 A permeameter cell shall be provided in which the specimen and porous end pieces are confined and subjected to a controlled flow of air. Depending upon the type of soil, the

type of sampler used for recovering intact soil or the type of compaction equipment used, either a flexible wall- or rigid wall-type permeameter may be used. The flexible wall permeameter is described in Test Method D5084. The rigid wall permeameter is similar to the description in Test Method D5856. Soils with air permeability greater than 1 darcy may be tested in a rigid wall permeameter consisting of metal or rigid plastic liners, in thin-walled tubes or in molds, with appropriate top and bottom end attachments and connections to the system in accordance with 5.5.2, 5.5.3, and 5.5.5.

5.5.2 The permeameter cell must be equipped with a pair of transfer lines at the inlet and a pair of transfer lines at the outlet. These lines connect the specimen and end pieces to the system.

5.5.2.1 One line of each pair shall be reserved for the dynamic transfer of air flow to and from the specimen.

5.5.2.2 The other line shall be reserved for the static transfer of the pressures at the ends of the specimen to the differential pressure transducer.

NOTE 18—Because there is no net flow of air through the differential pressure transducer, there is no pressure drop in the static lines that can bias the measurement of the pressure drop across the specimen. Static pressure lines must never be directly connected to a dynamic flow line. This will introduce false readings due to venturi effects and pressure drops in the connecting tubing.

5.5.3 *Porous End Pieces,* shall be provided to serve the dual purpose of: ( *1*) uniformly diffusing/collecting the flow of air across the end faces of the specimen; and (*2*) providing an efficient buffer zone between the static and flow lines.

5.5.3.1 The end pieces shall be cylindrical disks made of any rigid material with a uniform porosity that is easily cleaned, resistant to breakage, and not chemically attacked by the specimen. Sintered silicon carbide, bronze, and aluminum oxide have proved satisfactory. Dispersion plates using radial and concentric groves are an acceptable alternative.

5.5.3.2 The thickness of the end pieces shall not be less than 6 mm.

5.5.3.3 The diameter of the end pieces shall be the diameter of the specimen to a tolerance of +5 % and −0 %.

5.5.3.4 The permeability of the porous end pieces shall be greater than two times the permeability of the specimen.

5.5.3.5 The end pieces shall be free of cracks, chips, and nonuniformities and shall have smooth surfaces with parallel faces.

5.5.3.6 The permeability of the end pieces shall be periodically measured by this test method to ensure they are not clogged.

5.5.3.7 The end pieces shall be free of water or other volatile components.

5.5.4 *Head Losses*—Pressure drops across the end pieces may lead to error. To guard against such errors, the permeameter shall be assembled with end pieces but no specimen and connected to the system. An air flow rate more than the test maximum air flow rate shall be applied and the resultant permeability calculated. The permeability without a specimen shall be greater than two times the permeability when the specimen is present.

5.5.5 *Cap and Base* (Flexible Wall Test Method)—The cap and base shall connect the dual transfer lines to radial and concentric grooves facing the end piece to improve the uniform dispersion of the airflow.

5.6 *Permeameter Cell Pressure System (Flexible Wall Method)*—The system for pressurizing the permeameter cell shall be capable of applying and controlling the cell pressure to within 5 % in accordance with the section on Permeameter Cell Pressure Systems in Test Method D5084. However, the effective confining stress on the test specimen shall be maintained to the target value with an accuracy of 10 % or better.

5.7 *Temperature*—The temperature of the testing environment shall not vary more than ±2°C over the course of test or a series of related tests. Normally, this is accomplished by performing the test method in a room with a relatively constant temperature.

5.8 *Gas Sampling Port,* may be installed at the specimen exit to facilitate the collection of specimen effluent gases for analysis. This port should be located between the outlet valve and the bubble meter.

5.9 *Sample Extruder*— The extruder must disturb the specimen as little as possible. Acceptable methods include: (*1*) sub-coring a test specimen, and (*2*) cutting the thin-walled tube or liner.

5.10 *Trimming Equipment*—Spatulas, knives, wire saw, rasp, cradle, split trimming molds, straightedge, trimming platform, and drying pans.

5.11 *Stopwatch*—A stopwatch or electronic timer accurate to 1 s for use with the bubble meter,

5.12 *Soap Solution,* for use with the bubble meter.

NOTE 19—A suitable soap solution may be made with 1 volume glycerin, 1 volume of a concentrated liquid dishwashing detergent, and 7 to 10 volumes of particulate free deionized water.

5.13 *Drying Oven*— The drying oven shall be thermostatically regulated at 110 ± 5°C. The drying oven shall be in accordance with Specification E145.

5.14 *Measuring Devices*—Devices for measuring the length and diameter of the test specimen, permeameter caps, and porous end pieces shall be capable of measuring to the nearest 0.3 mm and shall be constructed such that their use will not disturb the specimen.

5.15 *Balance*—The balance shall be in accordance with Specification D4753. Specimen mass shall be determined to an accuracy of 0.1 g for specimens up to 1000 g and 1 g for specimens greater than 1000 g.

5.16 *Thermometer*—The thermometer shall have a range from –10 to 50 °C, an accuracy to 0.5 °C, and be in accordance with Specification E1 or Specification E2251. Temperature measuring devices such as thermistors and industrial platinum resistance thermometers meeting the accuracy requirement may also be used

5.17 *Barometer*—Any device for measuring atmospheric pressure to an accuracy of 50 Pa may be used. If an aneroid instrument is used, it shall be calibrated yearly.

5.18 *Equipment for Mounting the Specimen:*

5.18.1 *(Flexible Wall TestMethod Only)*—The equipment shall include a membrane stretcher, and "O"-ring expander for placing "O"-rings on the base and top cap to seal the membrane.

5.18.2 *(Flexible Wall Method Only) Membranes*—The membrane used to encase the specimen shall provide reliable protection against leakage, abrasion, and chemical attack. The membrane shall be carefully inspected before use. If any flaws or pinholes are evident, the membrane shall be discarded. To minimize strain on the specimen, the diameter or width of the unstretched membrane shall be between 90 and 95 % of the specimen. The "O"-rings used to seal the membrane shall have an unstretched inside diameter less than 90 % of the base and cap diameters.

5.19 *Compaction Equipment*—Compaction equipment, when used, shall be suitable for the method of compaction specified by the requester.

5.20 *Humidity Chamber,* to prevent desiccation of specimens with more than 10 % clay content.

## 6. Test Specimen

6.1 The test specimen shall be a right circular cylinder with the following dimensions:

6.1.1 *Test Specimen Diameter*—Recommended to be at least 51 mm.

6.1.2 *Test Specimen Length*—Recommended to be as follows:

6.1.2.1 Greater than 1.3 times the diameter of the test specimen,

6.1.2.2 Greater than five times the combined thickness of the porous end pieces, and

6.1.2.3 Greater than six times the largest particle size within the test specimen. Oversized particles must be indicated on the report.

6.1.3 A minimum of three diameter and three height measurements shall be made. The surface of the specimen may be uneven but the height and diameter of any indentation or protrusion must not result in the length or diameter varying by more than ±5 %.

6.2 *Intact Test Specimens*—Test specimens shall be prepared from a representative portion of intact samples obtained in accordance with Test Methods D1557, Practice D3550, or Test Method D4564 and preserved and transported in accordance with the requirements for Group C materials in Practices D4220. The horizontal and vertical planes of layered test specimens may be identified, prepared, and tested separately as requested. Specimens are trimmed to the desired height by cutting the end surfaces plane and perpendicular to the longitudinal axis. The ends of the test specimen shall be cut and not troweled, to prevent smearing and sealing off cracks, slicken sides, or seams of more pervious intrusions. Specimens shall be trimmed, whenever possible, in an environment where changes in water content are minimized. Determine the dimensions and mass of the test specimen to the tolerances given in 5.14 and 5.15.

6.3 *Laboratory-Compacted Specimens*—The soil shall be prepared and compacted inside a mold in a manner specified by the requester. If the test specimen is placed and compacted in layers, the surface of each layer previously compacted shall be lightly scarified (roughened) with a fork, serrated knife, or similar tool. Test Methods D698 and D1557 describe two methods of compaction, but any other test method specified may be used, provided it is described in the report. If the test specimen contains clods of soil, the clods shall be reduced to less than ⅙ of the height of the test specimen. After compaction, the test specimen shall be removed from the mold for a flexible wall-type test. The ends shall be scarified. Determine the dimensions and mass of the test specimen to the tolerances given in 5.14 and 5.15.

6.4 *In-tube, In-liner, and In-mold Test Specimens*—Measure the mass of the container. Measure the inside diameter of the container directly, or measure the outside diameter and subtract twice the container wall thickness. Measure the height of the container. For test specimens inset into the container, measure the length of recess or measure the height of the test specimen directly and determine the total mass of the assembly.

## 7. Procedure

7.1 *Specimen Setup:*

7.1.1 *Flexible Wall Method:*

7.1.1.1 Place the membrane onto the membrane stretcher. Place one porous end piece on the base followed by the specimen. Place the second porous end piece on top of the specimen, followed by the top cap. Place the membrane around the specimen and, using the "O"-ring expander, place one or more "O"-rings to seal the membrane to the base and one or more additional "O"-rings to seal the membrane to the top cap.

7.1.1.2 Attach the tubing to the top cap, assemble the permeameter cell, and fill the confinement annulus with water.

7.1.1.3 Permit the specimen to adjust under the effective confinement. When low effective confining pressures (less than 14 kPa) are applied to somewhat dense or stiff specimens, the recompression or primary compression phase will be nearly instantaneous and insignificant. For loose or soft specimens and for higher effective confining pressures, volume change readings shall be taken with a burette or other measuring device to determine when primary compression has been achieved.

7.1.1.4 If simulation of effective overburden is requested, adjust the cell pressure to the desired effective confinement. For high confining pressure, it may be necessary to increase the pressure in increments and to measure the volume change of the specimen through the cell in accordance with Test Methods D4767 or D5084.

7.1.2 *Rigid Wall Method:*

7.1.2.1 The specimen shall be confined in a tube, liner, or mold consistent with the rigid wall assembly or in accordance with Test Method D5856.

7.2 *Apparatus Setup:*

7.2.1 The permeameter transfer lines, valves, end pieces, and fittings shall be dry and free of foreign matter.

7.2.2 Attach the permeameter cell transfer lines to the system.

7.2.3 If an electronic flowmeter is used, perform a one-point (minimum) calibration check as follows:

7.2.3.1 Connect the four permeameter cell transfer lines together using a four-way union.

7.2.3.2 Using the flow control mode, establish an airflow at 50 % of the flowmeter full-scale range.

7.2.3.3 Attach a suitable bubble meter to the exit of the outlet valve.

7.2.3.4 Measure the actual flow until a steady reading is obtained with both the flowmeter and bubble meter.

7.2.3.5 If the flowmeter reading and the bubble meter reading (corrected for ambient temperature and barometric pressure in accordance with the manufacturer's instructions) agree within ±5 %, the flowmeter may be regarded as accurate. If the flowmeter proves inaccurate, do not proceed until the problem is corrected and the flowmeter recalibrated.

7.3 *Perform a Leak Check:*

7.3.1 Set the back pressure to 0 Pa.

7.3.2 Set the mass flow controller to 10 $cm^3$/min.

7.3.3 Close the outlet valve.

7.3.4 Increase the back pressure to 7 kPa.

7.3.5 Observe the transient flow and pressure changes as the system pressurizes. The mass flowmeter and differential pressure readings should return to their initial readings; otherwise, there is leakage that must be corrected before starting the test.

7.3.6 Return the back pressure to zero.

7.3.7 Open the outlet valve.

7.4 Record the ambient temperature, $T$, to the nearest 0.5°C and the barometric pressure, $P_B$, to the nearest 50 Pa.

7.5 Record initial values under conditions of zero-flow:

7.5.1 (Flexible Wall Test Method Only)—Record the initial confining pressure, $P°_c$.

7.5.2 Set the back pressure to zero.

7.5.3 Close the inlet valve and wait for the flowmeter and differential pressure transducer readings to stabilize under no flow conditions.

7.5.4 Record the no-flow transducer readings for the mass flow, $Q°_s$, the pressure drop across the specimen, $\Delta P°$, and the specimen inlet pressure $P°_1$.

NOTE 20—These initial (tare) values, signified by the superscript zero ($X°$), typically are not equal to zero and vary slightly with time and temperature. They shall be subtracted from all subsequent specimen measurements.

7.5.5 Open the inlet valve.

7.6 *Test Method A: Mass Flow Control:*

7.6.1 Set the back pressure regulator to operate as a relief valve to open to about 7 kPa greater than maximum expected specimen inlet pressure.

7.6.1.1 Close the inlet valve.

7.6.1.2 Temporarily disconnect the inlet flow transfer line.

7.6.1.3 Temporarily set the mass flow control to 50 $cm^3$/min.

7.6.1.4 Adjust the back pressure regulator to the target pressure.

7.6.1.5 Return the mass flow control to its minimum value.

7.6.1.6 Open the inlet valve and release the built-up back pressure.

7.6.1.7 Reconnect the inlet flow transfer line.

7.6.2 *(Flexible Wall Test Method Only)*—Adjust the confining pressure as needed to maintain the effective confining stress to within 5 % or 3.5 kPa, whichever is greater. Record the confining pressure, $P_c$.

7.6.3 When the flow and pressure drop readings stabilize, record the mass outflow of gas from the specimen, $Q$, the pressure drop across the specimen, $\Delta P$, and the specimen inlet pressure, $P_I$.

7.6.4 Increase the flow rate by a factor of 2.

7.6.5 Repeat 7.6.2 – 7.6.4 for a minimum of four data points at increasing flows.

7.6.6 Repeat 7.6.2 – 7.6.4, except decreasing the flow rates, for a minimum of four additional data points. It is neither necessary nor desirable to replicate the increasing and decreasing flow rates.

7.7 *Test Method B: Back Pressure Control Method:*

7.7.1 Set the back pressure to zero.

7.7.2 Set the mass flow controller to any value greater than the maximum expected flow rate.

7.7.3 *(Flexible Wall Method Only)* —Adjust the confining pressure as needed to maintain the desired effective confining stress to within 10 %. Record the confining pressure, $P_c$.

7.7.4 When the flow and pressure drop readings stabilize, record the mass outflow of gas from the specimen, $Q$, the pressure drop across the specimen, $\Delta P$, and the specimen inlet pressure, $P_I$.

7.7.5 Increment the back pressure to increase the air flow by a factor of 2. For the first increment, slowly increase the back pressure just enough to produce a measurable change in the pressure drop.

7.7.6 Repeat the steps in 7.7.3 – 7.7.5 for a minimum of four data points at increasing flows.

7.7.7 Repeat the steps in 7.7.3 – 7.7.5, except decreasing the flow rates, for a minimum of four additional data points. It is neither necessary nor desirable to replicate the increasing and decreasing flow rates.

7.8 *Post Run Procedures:*

7.8.1 Record the ambient temperature, $T$, to the nearest 0.5°C and the barometric pressure, $P_B$, to the nearest 50 Pa.

7.8.2 Disconnect, drain, disassemble, and clean the permeameter with minimum disturbance to the specimen.

7.8.3 Measure the dimension and mass of the specimen to the tolerance given in 5.14 and 5.15.

7.8.4 Determine the water content of the specimen in accordance with Test Method D2216.

## 8. Calculation

8.1 Calculate, for each test point, the average volumetric flow rate of air at the center of the specimen, $Q_{AV}$, as follows:

8.1.1 When a flowmeter is used, calculate in accordance with Eq 1:

$$Q_{AV} = Q \cdot \frac{P_S}{\left(P_I + P_B - \frac{\Delta P}{2}\right)} \cdot \frac{T}{T_S} \quad (1)$$

where:

$Q_{AV}$ = average volumetric flow rate of air at the average pressure and temperature of the laboratory during testing, $m^3/s$,
$Q$ = flow of air into specimen at STP, $m^3/s$,
$P_B$ = barometric pressure at the time of testing, Pa,
$P_I$ = specimen inlet gage pressure, Pa,
$P_S$ = reference pressure at STP, Pa,
$\Delta P$ = pressure drop across the specimen, Pa,
$T_S$ = reference temperature at STP, Kelvin, and
$T$ = test temperature, Kelvin.

NOTE 21—Definition of STP: The arbitrarily defined standard pressure and temperature at which the flowmeter is calibrated. Typically: 20°C and $1.013 \times 10^5$ Pa (1 atm).

NOTE 22—The temperature in Kelvin can be obtained as follows: $T_{Kelvin} = T_{Celsius} + 273.15$.

8.1.2 When a bubble meter is used, calculate in accordance with Eq 2:

$$Q_{AV} = Q \cdot \frac{P_B}{\left(P_I + P_B - \frac{\Delta P}{2}\right)} \quad (2)$$

where:

$Q_{AV}$ = average volumetric flow rate of air at the average pressure and temperature of the laboratory during testing, m3/s,
$Q$ = flow rate of air out of specimen, $m^3/s$,
$P_B$ = barometric pressure at the time of testing, Pa,
$P_I$ = specimen inlet gage pressure, Pa, and
$\Delta P$ = pressure drop across the specimen, Pa.

8.2 Plot $Q_{AV}$ versus $\Delta P$ for each test point. An example plot is shown in Fig. 2.

8.3 *Identification of Outliers*—Discard test points that fail Darcy's law as described in Note 3.

8.3.1 Draw the best-fit straight line that passes through the origin and the test points.

8.3.2 Draw an upper limit line that passes through the origin with slope 1.25 times the slope determined in 8.3.1.

8.3.3 Draw a lower limit line that passes through the origin with slope 0.75 times the slope determined in 8.3.1

8.3.4 Discard all test points that lie outside the upper and lower limit lines.

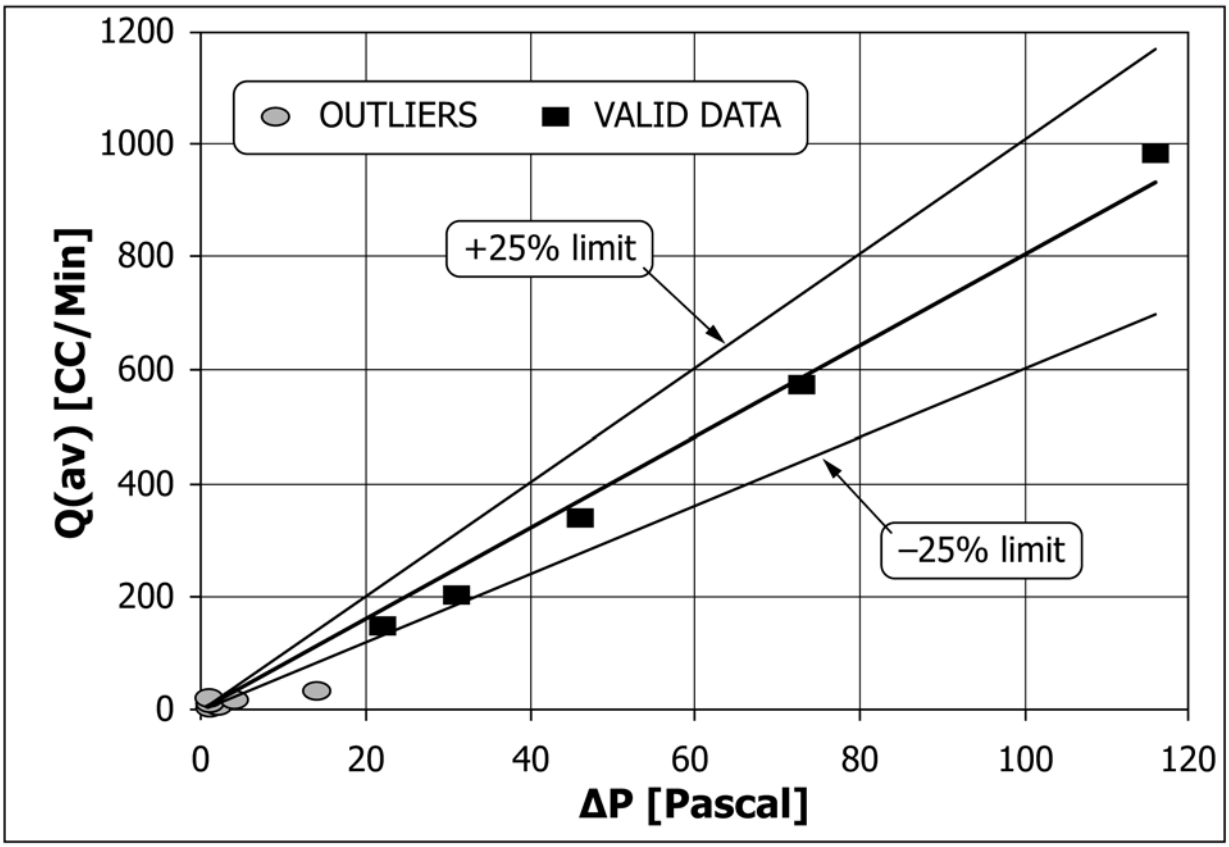


**FIG. 2 Average Air Flow Rate Versus Pressure Drop Across the Specimen (1 $cm^3/min = 1.67 \times 10^{-8}$ $m^3/s$)**

8.3.5 If there are fewer than 3 or 50 % of the test points remaining, at unique flow rates, the test does not follow Darcy's law and shall be repeated under different conditions.

8.4 Calculate the coefficient of permeability, $K_P$, for each valid test point in accordance with Eq 3:

$$K_P = \frac{Q_{AV}}{\Delta P}\cdot\frac{L}{A}\cdot\mu\cdot 1.013\times 10^{12} \quad (3)$$

where:

$K_P$ = permeability, darcy,
$Q_{AV}$ = average volumetric flow rate of air through the specimen, $m^3/s$,
$\Delta P$ = pressure drop across the specimen, Pa,
$L$ = specimen length, m,
$A$ = specimen cross-sectional area, $m^2$, and
μ = viscosity of air at the test temperature (see Table 1), Pa·s.

8.5 The average value of $K_P$ for all valid test points shall be reported as the permeability of the test specimen.

## 9. Report

9.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.4.

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

9.2.1 Sample/specimen identifying information, such as Project No., Boring No., Sample No., and Depth (units).

9.2.2 Any special selection and preparation processes, including but not limited to:

9.2.2.1 A description of intrusions, such as contaminants, oversized particles (in accordance with 6.1.2.3), foreign materials, lenses, or laminations of differing composition, if present.

9.2.2.2 If the specimen is intact or compacted.

9.2.2.3 For layered specimens, note whether the flow axis was in the horizontal or vertical plane.

9.2.2.4 The test gas, if other than air.

9.2.3 If the specimen is reconstituted, remolded or trimmed in a specialized manner, provide information on the method of reconstitution, remolding, etc.

9.3 Record as a minimum the following test specimen data:

9.3.1 The initial mass, dimensions (length and diameter), area and volume of the specimen, to either three or four significant digits.

**TABLE 1 Viscosity of Air, μ, as a Function of Temperature**

| Temperature, °C | Viscosity, Pa·s |
|---|---|
| 12 | $1.778\times10^{-5}$ |
| 14 | $1.788\times10^{-5}$ |
| 16 | $1.798\times10^{-5}$ |
| 18 | $1.808\times10^{-5}$ |
| 20 | $1.818\times10^{-5}$ |
| 22 | $1.828\times10^{-5}$ |
| 24 | $1.837\times10^{-5}$ |
| 26 | $1.847\times10^{-5}$ |
| 28 | $1.857\times10^{-5}$ |

9.3.2 The initial gravimetric water content (nearest 0.1 percent) and dry unit weight (three or four significant digits) and degree of saturation (nearest percent) of the test specimen.

9.3.3 The final or after consolidation mass, dimensions (length and diameter), area and volume of the specimen, to either three or four significant digits.

9.3.4 The final (or after consolidation) gravimetric water content (nearest 0.1 percent) and dry unit weight (three or four significant digits) and degree of saturation (nearest percent) of the test specimen.

9.3.5 Any other applicable auxiliary test data which is typically summarized with this type of test result, such as specific gravity, Atterberg limits and percent fines.

9.4 Record as a minimum the following test boundary conditions:

9.4.1 The magnitude of the cell pressure (two or three significant digits).

9.4.2 The magnitude of the back pressure (two or three significant digits).

9.4.3 The magnitude of the effective isotropic consolidation stress (two or three significant digits).

9.4.4 The permeameter used in testing (flexible wall permeameter or rigid wall permeameter) and the types of air flow regulation (mass flow control or pressure control).

9.4.5 The type of flowmeter used, along with its range and precision.

9.4.6 Capacity and calibration constants for the differential pressure transducer.

9.4.7 The test temperature, barometric pressure and reference temperature and pressure at STP (see 8.1.1).

9.4.8 The viscosity of air for the test temperature.

9.5 Record as a minimum the following permeability data:

9.5.1 The average value of KP as determined in 8.4 at each valid test point shall be reported with no more than two significant digits and in units of darcy or millidarcy. Example: "72 millidarcy."

9.5.2 A table of the measured values of the average volumetric air flow rate $Q_{AV}$, calculated using Eq 1 or Eq 2 (depending on the type of flowmeter used), the pressure drop across the specimen $\Delta P$.

9.5.3 A plot of the average volumetric air flow rate $Q_{AV}$ versus the pressure drop across the specimen, $\Delta P$ for each test point (see example plot in Fig. 2). The specimen length shall be reported in the plot. Valid test points shall be distinguished from outliers.

9.5.4 A log-log graph of the average volumetric air flow rate $Q_{AV}$, versus the pressure drop across the specimen, $\Delta P$, at each test point (see example plot in Fig. 3). The specimen length shall be reported in the plot. Valid test points shall be distinguished from outliers.

## 10. Precision and Bias

10.1 *Precision*—Permeability values shall not be reported to more than two significant digits. Data are being evaluated to determine the precision of this test method and its correlation with measurements made in the field. Preliminary data indicates a wider range of permeability is found in field testing compared to laboratory testing of similar soil. Due to the nature

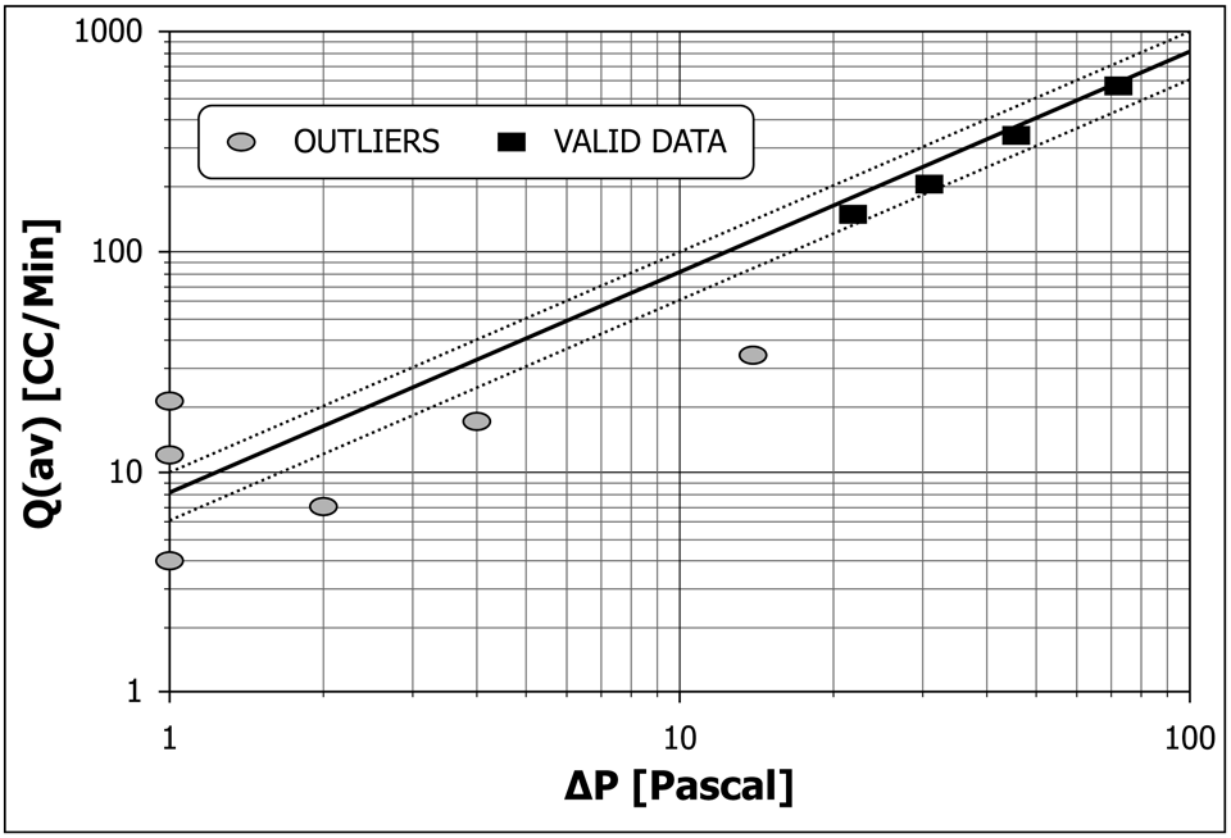


**FIG. 3 Log-Log Plot of Air Flow Rate Versus Pressure Drop Across the Specimen**

of the soil or rock materials tested by this test method, it is either not feasible or too costly at this time to produce multiple specimens that have uniform properties. Any variation observed in the data is just as likely to be due to specimen variation as to operator or laboratory testing variation. Subcommittee D18.04 on Hydrologic Properties and Hydraulic Barriers is seeking data from the users of this test method that might be used to make a limited statement on precision.

10.2 *Bias*—The variability of soil and resultant inability to determine a true reference value prevents development of a meaningful statement of bias.

## 11. Keywords

11.1 airflow; flexible wall permeameter; permeability; permeameter; permeability; rigid wall permeameter