Designation: D7100 – 11

# Standard Test Method for Hydraulic Conductivity Compatibility Testing of Soils with Aqueous Solutions [1]

This standard is issued under the fixed designation D7100; 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 hydraulic conductivity compatibility testing of saturated soils in the laboratory with aqueous solutions that may alter hydraulic conductivity (for example, waste related liquids) using a flexible-wall permeameter. A hydraulic conductivity test is conducted until both hydraulic and chemical equilibrium are achieved such that potential interactions between the soil specimen being permeated and the aqueous solution are taken into consideration with respect to the measured hydraulic conductivity.

1.2 This test method is applicable to soils with hydraulic conductivities less than approximately $1 \times 10^{-8}$ m/s.

1.3 In addition to hydraulic conductivity, intrinsic permeability can be determined for a soil if the density and viscosity of the aqueous solution are known or can be determined.

1.4 This test method can be used for all specimen types, including undisturbed, reconstituted, remolded, compacted, etc. specimens.

1.5 A specimen may be saturated and permeated using three methods. Method 1 is for saturation with water and permeation with aqueous solution. Method 2 is for saturation and permeation with aqueous solution. Method 3 is for saturation with water, initial permeation with water, and subsequent permeation with aqueous solution.

1.6 The amount of flow through a specimen in response to a hydraulic gradient generated across the specimen is measured with respect to time. The amount and properties of influent and effluent liquids are monitored during the test.

1.7 The hydraulic conductivity with an aqueous solution is determined using procedures similar to determination of hydraulic conductivity of saturated soils with water as described in Test Methods D5084. Several test procedures can be used, including the falling headwater-rising tailwater, the constant-head, the falling headwater-constant tailwater, or the constant rate-of-flow test procedures.

1.8 *Units*—The standard units for the hydraulic conductivity values are the SI units. The inch-pound units given in parentheses are mathematical conversions which are provided for information purposes only and are not considered standard.

1.8.1 Hydraulic conductivity has traditionally been expressed in cm/s in the U.S., even though the official SI unit for hydraulic conductivity is m/s.

1.8.2 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs.

1.8.3 The slug unit of mass is almost never used in commercial practice; i.e., density, balances, etc. Therefore, the standard unit for mass in this standard is either kilogram (kg) or gram (g), or both. Also, the equivalent inch-pound unit (slug) is not given/presented in parentheses. However, the use of balances or scales recording pounds of mass (lbm) or recording density in lbm/ft $^3$ shall not be regarded as nonconformance with this standard.

1.9 This standard contains a Hazards section related to using hazardous liquids (Section 7).

1.10 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 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$^3$))

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[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.

D854 Test Methods for Specific Gravity of Soil Solids by Water Pycnometer
D888 Test Methods for Dissolved Oxygen in Water
D1125 Test Methods for Electrical Conductivity and Resistivity of Water
D1293 Test Methods for pH of Water
D1429 Test Methods for Specific Gravity of Water and Brine
D1498 Test Method for Oxidation-Reduction Potential of Water
D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$))
D1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes
D1889 Test Method for Turbidity of Water (Withdrawn 2007)[3]
D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2435 Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading
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
D3977 Test Methods for Determining Sediment Concentration in Water Samples
D4128 Guide for Identification and Quantitation of Organic Compounds in Water by Combined Gas Chromatography and Electron Impact Mass Spectrometry
D4220 Practices for Preserving and Transporting Soil Samples
D4327 Test Method for Anions in Water by Suppressed Ion Chromatography
D4448 Guide for Sampling Ground-Water Monitoring Wells
D4691 Practice for Measuring Elements in Water by Flame Atomic Absorption Spectrophotometry
D4696 Guide for Pore-Liquid Sampling from the Vadose Zone
D4700 Guide for Soil Sampling from the Vadose Zone
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
D4972 Test Method for pH of Soils
D5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
D5673 Test Method for Elements in Water by Inductively Coupled Plasma—Mass Spectrometry
D5790 Test Method for Measurement of Purgeable Organic Compounds in Water by Capillary Column Gas Chromatography/Mass Spectrometry
D6001 Guide for Direct-Push Groundwater Sampling for Environmental Site Characterization
D6026 Practice for Using Significant Digits in Geotechnical Data
D6151 Practice for Using Hollow-Stem Augers for Geotechnical Exploration and Soil Sampling
D6286 Guide for Selection of Drilling Methods for Environmental Site Characterization
D6517 Guide for Field Preservation of Groundwater Samples
D6519 Practice for Sampling of Soil Using the Hydraulically Operated Stationary Piston Sampler
D6919 Test Method for Determination of Dissolved Alkali and Alkaline Earth Cations and Ammonium in Water and Wastewater by Ion Chromatography
E70 Test Method for pH of Aqueous Solutions With the Glass Electrode
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

## 3. Terminology

3.1 *Definitions:*

3.1.1 *hydraulic conductivity, k*—(also referred to as coefficient of permeability or permeability) the rate of discharge of a permeant liquid under laminar flow conditions through a unit cross-sectional area of porous medium under a unit hydraulic gradient and at standard temperature (20°C).

3.1.2 *permeameter*—the apparatus (cell) containing the test specimen in a hydraulic conductivity test.

3.1.2.1 *Discussion*—The apparatus for this test standard is a flexible-wall cell that includes top and bottom specimen caps, including porous stones and filter paper, a flexible membrane, an annulus chamber containing water, top and bottom plates, valves, and fittings.

3.1.3 *head loss, h*—the change in total head of liquid across a given distance.

3.1.3.1 *Discussion*—The change in total head typically is measured using heads acting at influent and effluent ends of a specimen, and the given distance typically is the length of the test specimen.

3.1.4 *pore volume of flow*—the cumulative quantity of flow through a test specimen divided by the total volume of voids in the specimen.

3.1.4.1 *Discussion*—The volume of voids in a specimen that is effective in conducting flow may be lower than the total volume of voids. The voids that conduct flow are represented by an *effective porosity*. The effective porosity is lower than the total porosity. This difference affects the accuracy for determining the actual pore volumes of flow associated with a test. However, the presence and magnitude of effective porosity in a soil specimen is usually not known *a priori*. Therefore, for the purposes of this standard, the determination of the pore volumes of flow will be based on the total porosity of the specimen.

3.1.5 *back pressure*—a pressure applied to the specimen pore liquid to force any air present in the specimen to compress and to therefore pass into the pore liquid resulting in an increase of the degree of saturation of the specimen.

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

3.2 Refer to Terminology D653 for definitions of other terms in this standard.

## 4. Significance and Use

4.1 This test method is used to measure one-dimensional flow of aqueous solutions (for example, landfill leachates, liquid wastes and byproducts, single and mixed chemicals, etc., from hereon referred to as the permeant liquid) through initially saturated soils under an applied hydraulic gradient and effective stress. Interactions between some permeant liquids and some clayey soils have resulted in significant increases in the hydraulic conductivity of the soils relative to the hydraulic conductivity of the same soils permeated with water (**1**).[4] This test method is used to evaluate the presence and effect of potential interactions between the soil specimen being permeated and the permeant liquid on the hydraulic conductivity of the soil specimen. Test programs may include comparisons between the hydraulic conductivity of soils permeated with water relative to the hydraulic conductivity of the same soils permeated with aqueous solutions to determine variations in the hydraulic conductivity of the soils due to the aqueous solutions.

4.2 Flexible-wall hydraulic conductivity testing is used to determine flow characteristics of aqueous solutions through soils. Hydraulic conductivity testing using flexible-wall cells is usually preferred over rigid-wall cells for testing with aqueous solutions due to the potential for sidewall leakage problems with rigid-wall cells. Excessive sidewall leakage may occur, for example, when a test soil shrinks during permeation with the permeant liquid due to interactions between the soil and the permeant liquid in a rigid-wall cell. In addition, the use of a rigid-wall cell does not allow for control of the effective stresses that exist in the test specimen.

4.3 Darcy's law describes laminar flow through a test soil. Laminar flow conditions and, therefore, Darcy's law may not be valid under certain test conditions. For example, interactions between a permeating liquid and a soil may cause severe channeling/cracking of the soil such that laminar flow is not maintained through a test specimen containing large open pathways for flow.

4.4 Interactions that may clog the pore spaces of test soils (for example, precipitation) may occur during permeation with some permeant liquids. Flow through test soils may be severely restricted in these cases. In cases where the measured hydraulic conductivity is less than $1 \times 10^{-12}$ m/s, unsteady state analysis may be used to determine the hydraulic conductivity of test soils (**2**).

4.5 Specimens of initially water-saturated soils (for example, undisturbed natural soils) may be permeated with the permeant liquid. Specimens of water unsaturated soils (for example, compacted soils) may be fully saturated with water or the permeant liquid and then permeated with the permeant liquid. Specimens of soils initially partly or fully saturated with a particular liquid (for example, specimens collected from a containment facility subsequent to a period of use) may be fully saturated and then permeated with the same or another liquid. The use of different saturating and permeating liquids can have significant effects both on the results and the interpretation of the results of a test (**1**). Selection of type and sequence of liquids for saturation and permeation of test specimens is based on the characteristics of the test specimens and the requirements of the specific application for which the hydraulic conductivity testing is being conducted in a test program. The user of this standard is responsible for selecting and specifying the saturation and permeation conditions that best represent the intended application.

4.6 Hydraulic conductivity of a soil with water and aqueous solution can be determined using two approaches in a test program for comparisons between the hydraulic conductivity based on permeation with water and the hydraulic conductivity based on permeation with aqueous solution. In the first approach, specimens are initially saturated (if needed) and permeated with water and then the permeating liquid is switched to the aqueous solution. This testing sequence allows for determination of both water and aqueous solution hydraulic conductivities on the same specimen. Obtaining water and aqueous solution values on the same specimen reduces the uncertainties associated with specimen preparation, handling, and variations in test conditions. However, such testing sequences may not represent actual field conditions and may affect the results of a test. In the second approach, two specimens of the same soil are permeated, with one specimen being permeated with water and the other specimen being permeated with the aqueous solution. The specimens are prepared using the same sample preparation and handling methods and tested under the same testing conditions. This approach may represent actual field conditions better than the first approach, however, uncertainties may arise due to the use of separate specimens for determining hydraulic conductivities based on permeation with water and the aqueous solution. Guidelines for preparing and testing multiple specimens for comparative studies are provided in Practice E691. The user of this standard shall be responsible for selecting and specifying the approach that best represents the intended application when comparisons of hydraulic conductivity are required.

4.7 Termination criteria used in the test method are based on both achieving steady-state conditions with respect to flow and equilibrium between the chemical composition of the effluent (outflow) relative to the influent (inflow).

4.8 Intrinsic permeability can be determined in addition to hydraulic conductivity using results of permeation tests described in this standard.

4.9 The correlation between results obtained using this test method and the hydraulic conductivities of in-place field materials has not been completely determined. Differences may exist between the hydraulic conductivities measured on small test specimens in the laboratory and those obtained for larger volumes in the field. Therefore, the results obtained using this standard should be applied to field situations with caution and by qualified personnel.

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[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

4.10 While not required for determining the hydraulic conductivity of soils with aqueous solutions, soil chemical properties such as pH, electrical conductivity, exchangeable metals (cations), and cation exchange capacity as well as the mineralogical composition of the soil may be useful in the interpretation and explanation of the test results.

NOTE 1—The quality of the result produced by this standard is dependent of the competence of the personnel using this standard and the suitability of the equipment and facilities. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of these factors.

## 5. Apparatus

5.1 Schematics of the various components of a measurement system are provided in Fig. 1 (permeant interface device) and Fig. 2 (testing apparatus including hydraulic system, flow-measurement system, and permeameter). Compatibility of all of the testing components that come into contact with the permeant liquid shall be determined prior to testing. This determination applies not only to the testing apparatus and peripheral equipment used to measure the hydraulic conductivity, but also to the auxiliary equipment and apparatus used for determining both the chemical properties of the permeant liquid (density, pH, etc.) and the physical properties of the test specimens (dimensions, moisture content, etc.). Determination of compatibility is particularly critical if aqueous solutions that contain more than 50 % of miscible organic liquids are used in a test program.

5.2 *Permeant Interface Device (Bladder Accumulator)* —A schematic of a permeant interface device, also referred to as a bladder accumulator, is presented in Fig. 1 (see Refs **1** and **3** for additional detail). The device is divided into two chambers. One chamber contains water and is connected to hydraulic and flow-measurement systems. The other chamber contains the permeant liquid and is connected to permeameter cell and thus the specimen. The chambers are separated by a chemically resistant flexible bladder. Pressure applied to the water is fully transferred to the accompanying permeant liquid in the adjacent chamber through the membrane. Drainage lines and/or sampling ports are included in the design of permeant interface devices for rapid filling or drainage and also for sampling of the permeant liquid during permeation. The permeant interface device shall prevent release of the permeant liquid to the surrounding environment and also shall prevent contact of the permeant liquid with the hydraulic system and the flow-measurement system. Permeant interface devices shall be used when the test liquid is hazardous or volatile. Permeant interface devices may also be used for non-hazardous permeant liquids. Use of bladder accumulators minimizes the need for involved

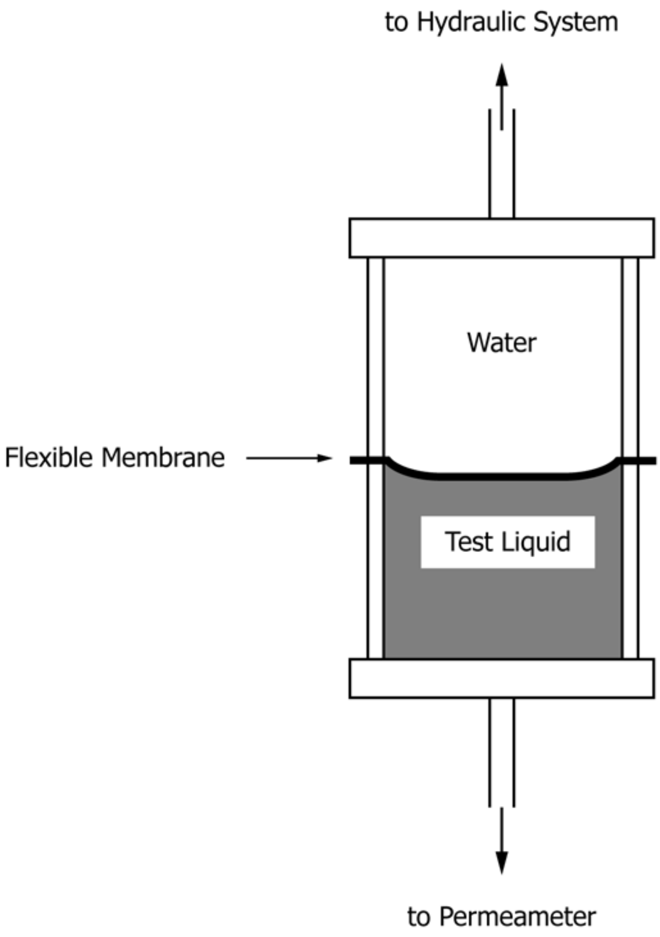

**FIG. 1 Permeant Interface Device (Bladder Accumulator) [see Refs 1 and 3 for additional detail]**

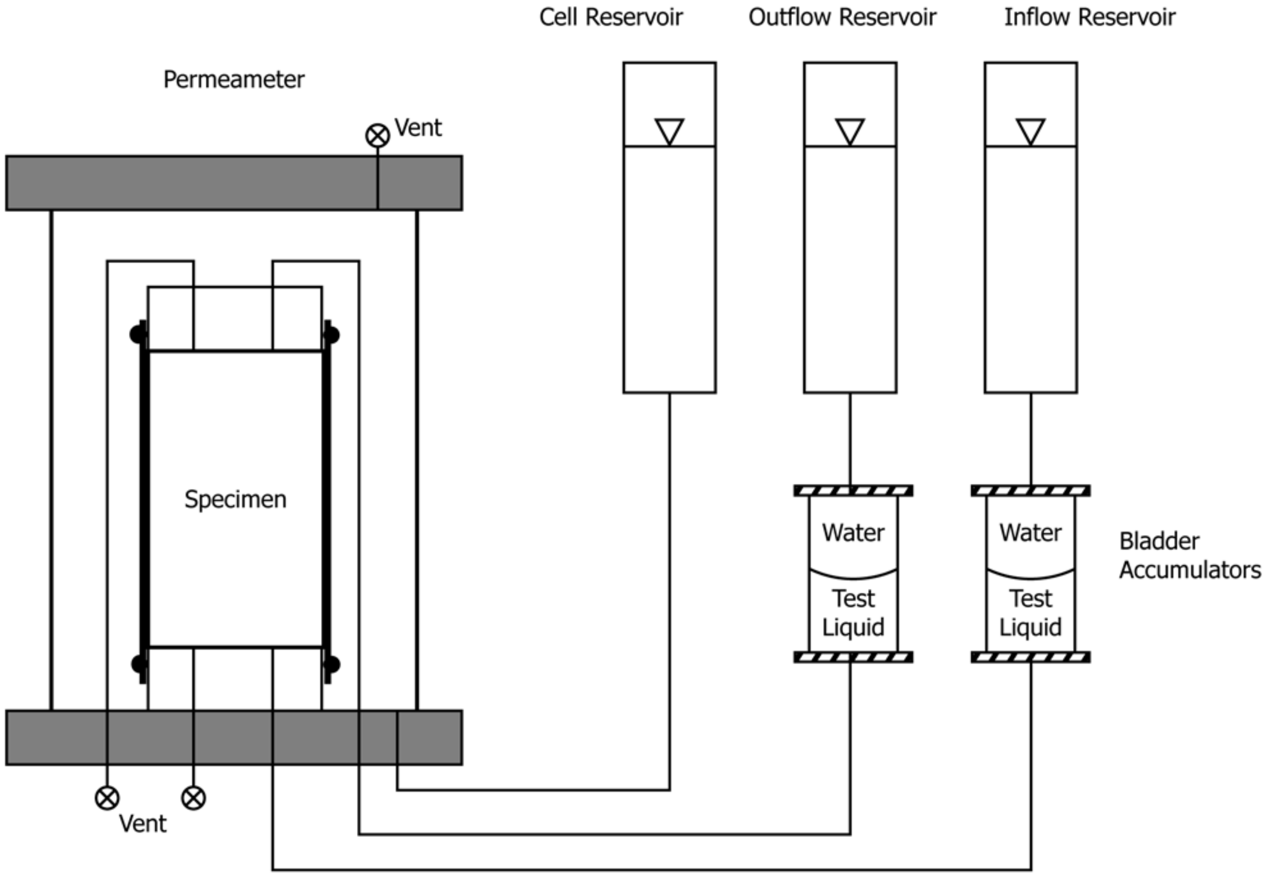

FIG. 2 Example of Test Setup

clean-up procedures for the hydraulic and flow-measurement systems. When used, two bladder accumulators are required, one connected to the influent line and the other connected to the effluent line.

5.2.1 The permeant interface device shall be constructed of stainless steel of sufficient grade or other material that is resistant to the permeant liquid. All fittings shall be constructed of materials resistant to the permeant liquid. All tubing shall also be resistant to the permeant liquid. Teflon® may be used for tubing that comes in contact with the permeant liquid. The bladder shall be constructed of a flexible and chemically resistant material. Materials such as viton, nitrile, or ethylene propylene are commonly used for the bladder, but other materials that are resistant to the permeant liquid may also be used. The long-term compatibility of all components with test liquids shall be verified.

5.2.2 The bladder shall be carefully inspected prior to use. The bladder shall be discarded if any defects such as pinholes are observed. The device shall be checked for leaks at the maximum expected test pressure prior to testing by filling one of the chambers with water and the other chamber with colored water. The device shall be connected to the permeameter cell for this verification. Any mixing of the clear water with the colored water indicates leaks through the bladder. Also, the pressure lines and fittings as well as around the bladder interface shall be inspected for any leaks.

5.3 *Hydraulic System*—The hydraulic system is used to apply, maintain, and measure heads and resulting hydraulic gradients in a test. The hydraulic system consists of reservoirs that hold water and/or the test liquid, pressure application setups that are used to pressurize influent and effluent liquids, and associated piping, tubing, valves, and connections (Fig. 2). The hydraulic conductivity can be measured using one of the following test procedures: falling headwater-rising tailwater, constant head, falling headwater-constant tailwater, or constant rate of flow. The requirements for hydraulic systems for each procedure are provided below:

5.3.1 *Falling Headwater–Rising Tailwater*—The system shall allow for measurement of the applied head, the variations in head, and the gradient to within ±5 % or better accuracy during a test. The head shall be measured with a pressure gage, electronic pressure transducer, engineer's scale, graduated pipette, or any other device that has the resolution required for the determination of head and gradient to the accuracy provided above.

5.3.2 *Constant Head*—The system shall allow for maintaining constant hydraulic head to within ±5 % or better accuracy during a test. The system shall allow for measurement of the constant head to within ±5 % or better accuracy during a test. The head shall be measured with a pressure gage, electronic pressure transducer, engineer's scale, graduated pipette, or any other device that has the resolution required for the determination of head to the accuracy provided above.

5.3.3 *Falling Headwater-Constant Tailwater*—The requirements are similar to 5.3.1 for the falling headwater elevation. For the constant tailwater elevation, the system shall allow for maintaining a constant hydraulic head to within ±5 % or better accuracy at the tailwater. The system shall also allow for the measurement of the constant head to within ±5 % or better accuracy during a test. The requirements for measurement of the constant head are similar to 5.3.2.

5.3.4 *Constant Rate of Flow*—The system shall allow for maintaining a constant rate of flow through a specimen to within ±5 % or better accuracy. Flow shall be measured by calibrated syringe, graduated pipette, or other device that has the precision required for the determination of flow to the accuracy provided above. The head loss across the specimen shall be measured to within ±5 % or better accuracy using an electronic pressure transducer or other device of suitable resolution.

5.3.5 *System De-airing*—The hydraulic system shall be designed to facilitate rapid and complete removal of free air bubbles from flow lines. This can be accomplished for example by using properly sized tubing and ball valves, and fittings without pipe threads. Properly sized components are small enough to prevent entrapment of air bubbles, but are large enough not to cause head losses as described in 5.5.4.

5.3.6 *Back-Pressure System*—The hydraulic system shall be equipped to apply back pressure to the specimen to facilitate saturation. The system shall be equipped to maintain the applied back pressure throughout the duration of hydraulic conductivity measurements. The back-pressure system shall allow for applying, controlling, and measuring the back pressure to within ±5 % or better accuracy. The back pressure may be provided by a compressed gas supply, a deadweight acting on a piston, or any other method that has the resolution required for application of back pressure to the accuracy provided above.

NOTE 2—Application of gas pressure directly to a liquid will dissolve gas in the liquid. A variety of techniques are available to minimize dissolution of gas in the back-pressure liquid, including separation of gas and liquid phases with a bladder and frequent replacement of the liquid with de-aired liquid.

5.4 *Flow-Measurement System*—Flow-measurement system is used to determine the amount of inflow and outflow from a specimen during a test. The measurement device shall allow for the measurement of the quantity of flow (both inflow and outflow) over an interval of time to within ±5 % or better accuracy. Flow-measurement system consists of a graduated accumulator, graduated pipette, vertical standpipe in conjunction with an electronic pressure transducer, or other volume-measuring device that has the resolution required for the determination of flow to the accuracy provided above (Fig. 2). In most cases, these devices are common to the hydraulic system.

5.4.1 *De-airing and Dimensional Stability of the System*—The flow-measurement system shall contain a minimum of dead space and shall be equipped to allow for complete and rapid de-airing. Dimensional stability of the system with respect to changes in pressure shall be ensured by using a stiff flow-measurement system that includes glass pipe or rigid metallic or thermoplastic tubing.

5.5 *Permeameter*—The permeameter shall allow for applying a controlled cell pressure around a specimen and for transmitting a permeant liquid through a specimen under applied inflow and outflow pressures. The permeameter shall consist of a permeameter cell and attached equipment that allow for connecting the permeameter to the hydraulic system and the flow-measurement system as well as provisions to support a specimen and to permeate a specimen. The permeameter cell shall consist of a cover plate, base plate, annulus chamber, and attachments to hold the components together without leakage during a test (Fig. 2).

5.5.1 *Cell Pressure System*—The system for pressurizing the permeameter cell shall allow for applying and controlling the cell pressure to within ±5 % or better accuracy. The effective stress on the test specimen (that is the difference between the cell pressure and the pore liquid pressure) shall be maintained to the desired value with an accuracy of ±10 % or better. The cell pressure system may consist of a reservoir connected to the permeameter cell and partially filled with de-aired water, with the upper part of the reservoir connected to a compressed gas supply or other source of pressure (see Note 3). The gas pressure shall be controlled by a pressure regulator and measured by a pressure gage, electronic pressure transducer, or any other device that has the resolution required to apply and control the pressure to the accuracy provided above. A hydraulic system pressurized by deadweight acting on a piston or any other pressure device that allows for applying and controlling the permeameter cell pressure within the tolerance prescribed above may also be used.

NOTE 3—De-aired water is commonly used for the cell liquid to minimize potential for diffusion of air through the membrane into the specimen. Other liquids that have low gas solubilities such as oils, are also acceptable, provided they do not react with the membrane and the components of the permeameter.

5.5.2 The specimen shall be overlain and underlain by porous end pieces and encased in a flexible membrane. Filter paper shall be placed between the porous end pieces and the specimen. A top cap and a bottom cap shall be used at the top and bottom ends of a specimen, respectively. The components shall be assembled such that the specimen and the influent and the effluent lines that are connected to these components shall be sealed against the surrounding cell liquid.

5.5.2.1 *Porous End Pieces*—Porous end pieces shall be used to distribute permeant liquid uniformly over the surfaces of a test specimen (that is, areas perpendicular to the direction of flow). Porous end pieces shall be constructed of silicon carbide, aluminum oxide, or other material that does not react with the specimen or the permeant liquid. The end pieces shall have plane and smooth surfaces and be free of cracks, chips, and discontinuities. The porous end pieces shall have the same diameter or width (±5 % or better accuracy) as the specimen, and they shall have sufficient thickness to prevent breaking. The end pieces shall be free from clogging. The hydraulic conductivity of the porous end pieces shall be significantly greater than that of the specimen to be tested. The requirements outlined in 5.5.4 ensure that this criterion is met.

5.5.2.2 *Filter Paper*—One or more layers of filter paper shall be placed between the top and bottom porous end pieces and the specimen to prevent intrusion of material from the specimen into the pores of the porous end pieces. The paper shall not impede the flow of liquid in and out of a specimen. The requirements outlined in 5.5.4 ensure that this criterion is met.

5.5.2.3 *Top Cap and Bottom Cap*—A top cap and a bottom cap shall be used to support the specimen and to facilitate transmission of permeant liquid to and from the specimen. The top cap and the bottom cap shall be constructed of rigid material with provisions for transmission of permeant liquid. The diameter or width of the caps shall be equal to the diameter or width of the specimen to within ±5 % or better accuracy. The bottom cap shall prevent leakage, lateral motion, and tilting. If deformation/height change measurements are conducted, the top cap shall be designed to receive the probe (or piston) used in height measurement such that the piston-to-top cap contact area is concentric with the cap. The surfaces of the caps that contact the membrane to form a seal shall be smooth and clean, free of any external materials and scratches.

5.5.2.4 *Flexible Membrane*—A flexible membrane shall be used to encase the specimen to provide reliable protection against leakage. The membrane shall be carefully inspected prior to use. The membrane shall be discarded if any defects such as pinholes are observed. The diameter or width of the un-stretched membrane shall be between 90 to 95 % of the width of the specimen to minimize lateral compression of the specimen. The membrane shall be sealed to the specimen base and cap with rubber O-rings or by any other method that will produce an adequate seal. The membrane shall be compatible with the permeant liquid. Adverse interactions between commonly used latex membranes and organic test liquids have been reported in the literature (**1**). When compatible membranes are not available, the specimen may be wrapped in a thin and flexible sheet, film, or tape of chemically resistant and compatible material such as Teflon® prior to encasement in a flexible membrane. Multiple layers of wrapping may be required in some cases.

5.5.3 In order to facilitate gas removal, and thus saturation of the hydraulic system, four drainage lines leading to the specimen (two lines to the bottom cap and two lines to the top cap) are recommended. The drainage lines shall be operated by zero volume-change valves, such as ball valves, and shall be designed to minimize dead space in the lines.

5.5.4 *Deformation Measurement*—The permeameter may be equipped for determination of deformation of a specimen during a test. Axial and lateral deformation of a specimen may be monitored in a test. The deformation of a specimen shall be determined to the nearest 0.3 mm (0.01 in.). The height and width of a specimen may be monitored by direct observation through the cell wall using a cathetometer, camera setup, or other instrument that has the resolution required for the determination of deformation as prescribed above. The height of a specimen may be monitored using a deformation gage connected to the top cap above a specimen or a deformation gage attached to a loading piston connected to the top cap above a specimen. The deformation can be determined using a dial gage, LVDT, or other device that has the resolution required for the determination of deformation as prescribed above. The deformation measurement device or the loading piston shall be sealed in a manner to prevent leaks at the location where the device exits the permeameter under the maximum cell pressure used in a test.

5.6 *Equipment for Compacting a Specimen*—For compacted specimens, equipment (including compactor and mold) suitable for the method of compaction specified by the requester shall be used. The surfaces of compacted lifts shall be scarified to ensure complete bonding of the lifts to prevent preferential (interlift flow). Care shall be taken not to smooth or smear the inflow and outflow faces of the specimen as smoothing or smearing last lift may reduce the measured hydraulic conductivity.

5.7 *Sample Extruder*—For field recovered samples, the sample extruder shall be capable of extruding a soil core from a sampling tube in the same direction of travel in which the sample entered the tube and with minimum disturbance to the sample. If the soil core is not extruded vertically, care should be taken to avoid bending stresses on the core due to gravity. Conditions at the time of sample extrusion may dictate the direction of removal to guarantee minimum disturbance to the sample. For laboratory compacted samples, the extruder shall be capable of extruding a soil specimen from a compaction mold in the same direction as the sample is compacted and with minimum disturbance to the compacted soil.

5.8 *Trimming Equipment*—Specific equipment for trimming the specimen to the desired dimensions vary as a function of the quality and characteristics of the soil. The following devices have been used successfully: lathe, wire saw with a wire approximately 0.3 mm (0.01 in.) in diameter, spatulas, knives, steel rasp for very hard clay specimens, cradle or split mold for trimming specimen ends, and steel straight edge for final trimming of specimen ends. As per 5.6, care shall be taken not to smooth or smear the inflow and outflow faces of the specimen since smoothing or smearing last lift may reduce the measured hydraulic conductivity.

5.9 *Devices for Measuring the Dimensions of the Specimen*—The dimensions of a specimen shall be measured with a resolution of 0.1 mm or 0.01 in. or better. The design of the devices shall be such that their use will not disturb a specimen.

5.10 *Balances*—The balance shall be suitable for determining the mass of a specimen. The balance shall be selected based on the guidelines provided in Specification D4753. The mass of specimens less than 100 g shall be determined to the nearest 0.01 g. The mass of specimens between 100 g and 999 g shall be determined to the nearest 0.1 g. The mass of specimens greater than 999 g shall be determined to the nearest g.

5.11 *Equipment for Mounting the Specimen*—Equipment for mounting the specimen in the permeameter cell includes a membrane stretcher or cylinder, and ring for expanding and placing O-rings on the bottom and top cap to seal the membrane.

5.12 *Vacuum Pump*—A vacuum pump may be used to assist with de-airing of water or permeant liquid and also saturation of specimens.

5.13 *Samplers for Permeant Liquid and Storage Containers*—The samplers and containers shall be selected based on the source for the permeant liquid (for example, landfill leachate, vadose zone sample, groundwater sample, etc.) and the characteristics of the permeant liquid (non-hazardous or hazardous).

5.14 *Moisture Content Containers*—The containers shall be in accordance with Test Method D2216.

NOTE 4—Other containers shall be used if the specimens are not compatible with the containers in Test Method D2216.

5.15 *Drying Oven*—The oven shall be in accordance with Test Method D2216.

5.16 *Time Measurement Devices*—Devices to measure the duration of each permeation trial, such as a clock with second hand or stop watch (or equivalent), or both.

5.17 *Devices for Determining Properties of Water and Permeant Liquid*—Devices to determine specific gravity in accordance with Test Methods D1429 for all liquids; pH meter in accordance with Test Methods D1293 for water and Test Method E70 for permeant liquid; EC (electrical conductivity or specific conductance) meter in accordance with Test Methods D1125 for all liquids; flame atomic absorption spectroscopy, flame emission spectroscopy or flame photometry, graphite furnace atomic absorption, inductively coupled plasma (ICP) spectroscopy, ion chromatography (IC), and distillation devices for inorganic chemical constituents in accordance with various standards under Committee 19.05 (examples of applicable standards include Test Method D4327, Practice D4691, Test Method D5673, and Test Method D6919, various additional standards are available for specific inorganic chemicals in water); gas chromatography (GC), mass spectrometry (MS), TOC (total organic carbon) analyzer, and fluorescence spectroscopy devices for organic constituents in accordance with various standards under Committee 19.06 (examples of applicable standards include Test Method D5790 and Guide D4128, various additional standards are available for specific organic chemicals in water); viscometers; equipment including turbidity meters in accordance with Test Method D1889, dissolved oxygen (DO) measurement devices in accordance with Test Methods D888, oxidation-reduction (redox) potential measurement devices in accordance with Practice D1498, devices for determining sediment concentration in accordance with Test Methods D3977; ovens, balances, glassware. The user shall be responsible for selecting the appropriate devices for measurement of the properties of aqueous test liquids.

5.18 *Devices for Determining Properties of Test Specimen*—Devices for measurement of soil pH in accordance with Test Method D4972; devices for determination of electrical conductivity of soils; devices for determination of cation exchange capacity of soils; devices for determining exchangeable cations (metals); devices for determination of mineralogical composition of soils. The user shall be responsible for selecting the appropriate devices for measurement of the properties of test specimen.

## 6. Reagents

6.1 *Water*—Water may be used to compact a specimen and to saturate a specimen, and also may be used in permeation prior to switching to the permeant liquid as described in 4.5 and 4.6.

6.1.1 The actual water to be used in the application is preferred for use as the compaction water, the saturation water, and/or the permeant liquid. When the actual water is not readily available, a suitable water with a similar composition as that for the actual water maybe used as a substitute. In the case where the composition of the actual water is unknown or cannot be readily determined, either potable tap water or a salt solution described in Test Methods D5084 may be used. The 0.01 molar $CaCl_2$ solution can be obtained for example, by dissolving 11.1 g of reagent-grade $CaCl_2$ in 10 L of de-aired, de-ionized, distilled water (commercial grade). In all cases where the chemical composition of the water being used is unknown, the chemical composition including chemical species, pH, and electrical conductivity or specific conductance shall be determined, since the chemical composition of the water can affect the hydraulic conductivity of the test soil. The type of water used shall be indicated in the test data sheet/form.

NOTE 5—Other types of water such as de-ionized water, distilled water, de-ionized and distilled water, and various salt solutions with compositions and concentrations other than those for the 0.01 molar $CaCl_2$ have also been used. Interactions between these liquids and the soil can affect the results of the test and these liquids should not be used in determination of hydraulic conductivity of soils with aqueous solutions.

6.2 *Permeant Liquid*—This is the aqueous liquid that may be used to saturate a specimen and that is used to permeate a specimen.

6.2.1 Permeant liquid may be obtained from various sources and may possess various characteristics. Aqueous liquids from the subsurface shall be obtained in accordance with Guide D4448, Guide D6001, or Guide D4696. All the available information shall be obtained for a test liquid. The permeant liquid shall be transported, handled, and stored in accordance with the requirements based on its source and characteristics. In addition, the permeant liquid shall be stored and handled such that the physical, chemical, and biological characteristics of the liquid shall not be altered throughout the entire duration of a test program.

6.2.2 Chemical composition and pH shall be determined as a minimum for all permeant liquids. Electrical conductance shall be determined for inorganics and dielectric constant shall be determined for organics. When needed, the density and viscosity of the permeant liquid shall also be determined. Additional characteristics that may be determined include, but are not necessarily limited to, total dissolved solids, chemical oxygen demand, and biological oxygen demand. Applicable ASTM standards are provided in 5.17.

6.2.3 Certain permeant liquids may be hazardous. Precautions described in Section 7 shall be used with these liquids.

## 7. Hazards

7.1 **Warning**—Certain test liquids may be hazardous with serious health effects. These liquids may pose health risks upon inhalation or contact with the skin. The effects may be cumulative.

7.1.1 Tubing composed of glass or other brittle materials may explode/shatter when under pressure, particularly under air pressure. Therefore, such tubing should be enclosed. Allowable working pressures for tubing shall be established and not exceeded during a test. Appropriate types of tubing may include polyethylene, polypropylene, Teflon®, and stainless steel tubing.

7.2 *Precaution*—In addition to other precautions for hazardous liquids (which may be explosive, toxic, corrosive, and/or reactive), the hazardous liquids shall be stored in sealed shatterproof containers to control evaporation in a well-ventilated area or under a fume hood. Bladder accumulators shall be assembled and filled with hazardous permeant liquids in a well-ventilated area or under a fume hood. Rubber gloves shall be used at all times when contacting hazardous liquids.

7.2.1 Spills shall be cleaned up immediately using a procedure recommended explicitly for the particular test liquid.

7.2.2 Excess permeant liquids or any wastes contaminated with a permeant liquid shall be disposed in a safe and environmentally acceptable manner.

7.3 **Warning**—Certain test specimens may contain hazardous constituents or pore liquids that may pose serious health effects. Originally non-hazardous specimens may become hazardous due to permeation with a hazardous permeant liquid. The hazardous substances may pose health risks upon inhalation or contact with the skin. The effects may be cumulative. Use procedures described in 7.1 and 7.2 when testing specimens containing hazardous liquids.

7.3.1 Hazardous specimens shall be sampled, prepared, and mounted in a permeameter prior to a hydraulic conductivity test, and dismounted from a permeameter subsequent to a hydraulic conductivity test in a well-ventilated area or under a fume hood. Rubber gloves shall be used at all times when contacting hazardous specimens.

## 8. Test Specimens

8.1 *Size*—Specimens shall have a minimum diameter of 50 mm (2.0 in.). The diameter and height of a specimen shall be measured with a resolution of 0.1 mm or 0.01 in. or better. The height and diameter shall not vary more than ±5 %. The surface of the test specimen may be uneven, but indentations must not be so deep that the height or diameter vary by more than ±5 %. If visual observation indicates that oversized particles are present after completion of a test, that information shall be indicated in the data sheet/form. If special equipment for testing prismatic test specimens is used, the reference to "diameter" applies to the shortest dimension of the prismatic test specimen.

NOTE 6—Soil specimens that are obtained using 2 in. O.D. thin wall tube samplers are acceptable even though the diameters of these specimens (48 mm) are slightly lower than 50 mm.

8.2 *Undisturbed Specimens*—Undisturbed test specimens shall be prepared from a representative portion of undisturbed samples obtained in accordance with Practice D1587, Practice D3550, Practice D6151, Practice D6519, or Guide D4700 (block sampling may also be used). Additional guidance on other drilling and sampling methods is provided in Guide D6286. Samples shall be preserved and transported in accordance with requirements under Group C in Practice D4220 and as described in Guide D6286. Specimens obtained by tube sampling or coring may be tested without trimming except for cutting and leveling the end surfaces perpendicular to the longitudinal axis of the specimen. The ends of a test specimen shall be cut. A wire saw shall be used for cutting specimens. A sharp blade may be used to cut some features, such as plant remains, debris, etc., that may be present in a sample. Methods that may smear the ends of specimens and seal off cracks, slickensides, or other secondary features that may conduct flow (for example, troweling) shall be avoided. Specimens shall be trimmed in an environment where changes in moisture content, physical and chemical composition of the pore liquid, and volatilization of pore liquid constituents are minimized. A controlled humidity room may be useful for this purpose. Specimens containing hazardous constituents shall be prepared in a well-ventilated area or under a fume hood. The dimensions of the test specimen shall be determined to the required resolution provided in 8.1. The mass of the test specimen shall be determined to the resolution provided in 5.10. The test specimen shall be mounted immediately in the permeameter. The moisture content of the trimmings shall be determined in accordance with Test Method D2216, using a resolution of 0.1 % or better.

NOTE 7—Test Method D2216 may not be directly applicable to samples with pore liquids other than water. Effects of heating and range of temperatures used shall be determined prior to determining the moisture content of such samples using oven drying.

8.2.1 If the sampling operation causes disturbance of the soil, the disturbed material shall be trimmed. If voids are generated on the surface of the specimen due to trimming that result in variation of height or diameter by more than ±5 %, the voids shall be filled with remolded material obtained from the trimmings.

8.3 *Laboratory-Compacted Specimens*—The material to be tested shall be prepared and compacted in a mold as specified by the requester. If the specimen is placed and compacted in layers, the surface of each previously-compacted layer shall be lightly scarified (roughened) with a spatula or other suitable object, unless the requester specifically states that scarification is not to be performed. Test Methods D698 and D1557 describe two methods of compaction, but any other method specified by the requester may be used as long as the method is fully described and documented in the report. Large clods of material should not be broken down prior to compaction unless *a priori* knowledge indicates they will be broken in field construction, or the requester specifically requests that the clod size be reduced. Subsequent to compaction, the test specimen shall be removed from the mold. The ends of the specimen shall be trimmed. A wire saw shall be used for cutting specimens. A sharp blade may be used to cut some features, such as plant remains, debris, etc., that may be present in a sample. Methods that may smear the ends of specimens and seal off cracks, slickensides, or other secondary features that may conduct flow (for example, troweling) shall be avoided. The dimensions and mass shall be determined to the resolutions provided in 5.9 and 5.10, respectively. The test specimen shall be immediately mounted in the permeameter subsequent to the determination of the dimensions and the mass. The moisture content of the trimmings shall be determined in accordance with Test Method D2216 using a resolution of 0.1 % or better.

NOTE 8—Test Method D2216 may not be directly applicable to specimens compacted using liquids other than water. Effects of heating and range of temperatures used shall be determined prior to determining the moisture content of such specimens using oven drying.

8.4 *Other Preparation Methods*—Other methods of preparation of a test specimen are permitted if specifically requested. The method of specimen preparation shall be fully described, documented, and identified in the data sheet/form.

8.5 After the height, diameter, mass, and moisture content of the test specimen have been determined, the dry density shall be calculated. Also, the initial degree of saturation shall be calculated using the known or measured specific gravity. If the specific gravity is not known or measured, it may be estimated to determine the initial saturation. Saturation information may be used in the back-pressure saturation stage (see 9.6).

8.6 Certain specimens may contain hazardous constituents. Precautions described in Section 7 shall be used with these specimens.

## 9. Procedure

9.1 *Determination of Head Losses*—Excessive head losses in the tubes, valves, porous end pieces, and filter paper may lead to errors in measurements in the tests. Head losses are affected by the viscosity of the permeating liquid. Head losses shall be determined using the actual permeant liquid that will be used in a test program. For test programs with more than one permeant liquid (for example, comparative studies), two approaches may be used. In the first approach, head losses are measured with a single determination using the permeant liquid with the highest viscosity in the test program. This approach is a conservative and will provide the highest head losses in the system and thus verify the effectiveness of the flow-measurement system with respect to the highest viscosity liquid as well as all other liquids with lower viscosity. In the second approach, head losses are determined for all of the permeant liquids to be used in a test program. The second approach shall be used when the viscosity of permeant liquids is not known or determined in a hydraulic compatibility test program. The permeameter shall be assembled without a specimen and then a permeant liquid shall be passed through the system to determine head losses in the system (be sure to include the permeant interface device described in 5.2 when the device is to be used in a test program). The hydraulic pressures or heads that will be used in testing a specimen shall be applied, and the rate of flow shall be measured to within ±5 % or better accuracy. This rate of flow shall be at least ten times greater than the rate of flow that is measured when a specimen is placed inside the permeameter and the same hydraulic pressures or heads are applied.

9.2 *Permeant Interface Device Setup*—For non-hazardous permeant liquids, directly fill one of the chambers of the permeant interface device with the permeant liquid and the other chamber with water. Attach the device to the influent line of the permeameter. Repeat the same procedure for the second device, and attach the device to the effluent line of the permeameter. For hazardous permeant liquids, follow 7.1 and 7.2 while filling the device with the permeant liquid. Fill both accumulators with the permeant liquid and water and connect to the influent and effluent lines. For volatile permeant liquids, the liquids can be injected into the chamber in the device while a pressure equal to the vapor pressure of the liquid (if known or determined) can be maintained in the chamber. Ensure that both chambers are filled entirely with the liquids with no air or gas space remaining above the liquids.

NOTE 9—Maintain the bladder accumulators at least half full to prevent excessive stretching of the membrane during a test.

9.3 *Specimen Setup:*

9.3.1 Cut two filter paper sheets to approximately the same shape as the cross section of the test specimen. Soak the two porous end pieces and filter paper sheets in a container of permeant water if the specimen is to be saturated or initially permeated with water. Soak the two porous end pieces and filter paper sheets in a container of permeant liquid if the specimen is to be saturated and then permeated with permeant liquid or if the specimen is already saturated with the permeant liquid and will be permeated with permeant liquid. If the specimen is initially saturated with water and will be immediately permeated with the permeant liquid, soak the inflow end piece and filter paper with the permeant liquid and soak the outflow end piece and filter paper with water. Overall, if multiple liquids are used in a test program, soak the end pieces and filter papers in liquids that they will first contact. For hazardous test liquids, follow 7.2 while soaking the end pieces and filter paper with the permeant liquid. If the test liquid is volatile, ensure that the composition of the liquid is not changing while the end pieces and filter paper are soaked with the liquid.

9.3.2 Place the membrane on the membrane expander by stretching the membrane and rolling the ends of the membrane over the ends of the stretcher. Place two or more O-rings over the expander positioning them approximately in the middle of the expander away from the ends with the rolled membrane. Apply a thin coat of silicon high-vacuum grease to the sides of the end caps. Assemble the components in a column in the permeameter in the following order: attach the bottom cap to the base of the permeameter, place one porous end piece on the cap, place one filter paper sheet on the porous end piece followed by the test specimen, then place the second filter paper sheet on top of the specimen followed by the second porous end piece and finally place the top cap to complete the column assembly. Place the membrane around the specimen by placing the membrane expander over the column and releasing the membrane from the expander. Make sure that the membrane extends to the base of the permeameter covering the bottom cap and also to the top of the top cap (extra membrane may be present above the top cap, this material can be rolled back onto itself and kept in place using O-rings). Slide one or more O-rings out of the expander to seal the membrane to the bottom cap and repeat the same procedure using one or more O-rings to seal the membrane to the top cap.

9.3.3 Attach flow tubing to the top cap, assemble the permeameter cell, and fill the cell with de-aired water or other cell liquid. Attach the cell pressure reservoir to the permeameter cell line. Fill the cell pressure reservoir with de-aired water or other suitable liquid.

9.3.3.1 Attach the hydraulic system to the influent and effluent lines of the permeameter directly, when bladder accumulators are not used. Fill the hydraulic system with de-aired permeating liquid (water or permeant liquid). Apply a small confining pressure of 7 to 35 kPa (1 to 5 psi) to the cell and apply a pressure less than the confining pressure to both the influent and effluent systems, and flush permeating liquid through the flow system (without allowing the flushing liquid to go through the specimen, two lines connected to both the top and bottom caps ensure that this can be achieved). After all visible air has been removed from the flow lines, close the control valves.

9.3.3.2 When bladder accumulators are used, attach the devices, which are already connected to the influent and effluent lines of the permeameter, to the hydraulic system. Apply a small confining pressure of 7 to 35 kPa (1 to 5 psi) to the cell and apply a pressure less than the confining pressure to both the influent and effluent systems, and flush the permeant liquid through the flow system (without allowing the flushing liquid to go through the specimen). In case of testing using hazardous or highly volatile liquids, follow 7.2. In addition, attach tubing to vent lines that terminate in sealed containers to collect flushing permeant liquid without allowing exposure of the permeant liquid to the atmosphere. After all visible air has been removed from the flow lines, close the control valves.

9.4 *Specimen Soaking (Optional)*—To aid in saturation, specimens may be soaked under partial vacuum applied to the top of the specimen. Water or permeant liquid under atmospheric pressure shall be applied to the specimen base through the influent lines. The magnitude of the vacuum shall be adjusted to generate a hydraulic gradient across the specimen less than the gradient that will be used during hydraulic conductivity measurements.

NOTE 10—Soaking under vacuum is applicable when there are continuous air voids in the specimen, for example, specimens having a degree of saturation less than approximately 85 %. The specimen may swell when exposed to water or the test liquid due to the physical process of the liquid filling the pore spaces of the specimen (or potentially due to absorption of the liquid by clay minerals in a specimen). The applied effective stress will tend to counteract the swelling. However, for materials that tend to swell, unless the applied effective stress is greater than or equal to the swell pressure, the specimen will swell. For guidance on avoiding excessive consolidation in the use of vacuum for specimen saturation, consult 8.2 in Test Method D4767. Also, the specimen may shrink or swell when it is exposed to the permeant liquid due to mineralogical and chemical interactions. Soaking shall not be used when premature shrinkage or swelling of the specimen in contact with the permeation liquid is expected (prior to initiation of hydraulic conductivity measurements). Guidance on potential interactions between a specimen and permeant liquid is provided in (**1**).

9.5 *Consolidation*—The hydraulic conductivity test shall be conducted at an effective stress representative of the anticipated field stresses for the intended application unless otherwise specified by the requester. The effective stress is the difference between the confining stress (that is, cell pressure) and the pore pressure applied through influent and effluent pressures. The specimen shall be consolidated to this effective stress prior to the permeation stage. The specimen may be consolidated to this effective stress prior to saturation, during saturation, or subsequent to saturation. The specimen may be consolidated to the required effective stress during one or more of these periods. For example, the specimen may be consolidated to a fraction of the required effective stress during saturation and then fully consolidated subsequent to saturation. The effective stress used for consolidation shall be equal to or less than the effective stress used during the permeation stage. Consideration shall be given to using the lowest effective stress in cases where the test soil will be subjected to varying effective stresses in the field. High effective stresses in flexible wall testing may conceal the severity of interactions between the test specimen and the permeant liquid (for example, high confining stresses may prevent full development of cracks in a test soil due to the interactions with a permeant liquid). Consolidation shall be accomplished in stages, with the increase in effective stress used in each new stage equal to or less than the effective stress used in the previous stage (that is, load increment ratio of one or less). Use procedures described in Test Method D2435 or D4767 for specimen consolidation.

9.5.1 Water is used for the consolidation step for Methods 1 and 3 and permeant liquid is used in the consolidation step for Method 2. The procedures for consolidation are essentially the same for all the three methods. If hazardous permeant liquids are used, precautions described in Section 7 shall be used.

9.5.2 Adjust the confining pressure and the influent and effluent pressures to apply necessary effective stresses. Drainage may be allowed from the base or top of the specimen, or simultaneously from both ends.

9.5.3 The end of consolidation may be determined using procedures described in Test Method D2435 or D4767. This step is optional when the specimen is consolidated prior to or during saturation since the consolidation of the specimen is confirmed when the saturation of a specimen is verified at the end of the back-pressure saturation step. The end of consolidation shall be verified if the specimen is consolidated subsequent to saturation.

9.6 *Back-Pressure Saturation*—To saturate the specimen, application of back pressure is usually necessary. Fig. 3 (adapted from Ref **4**) provides guidance on the back pressure required to attain saturation using water. Additional guidance on the back-pressure saturation process using water is provided in Refs (**5**) and (**6**). The relationships provided in Fig. 3 are assumed to be generally applicable to aqueous solutions that are used as permeant liquids.

NOTE 11—The relationships presented in Fig. 3 are based on the assumption that the water used in the back-pressure saturation process is de-aired and that the only source for air to dissolve into the water is air from the test specimen. If air pressure is used to control the back pressure, pressurized air will also dissolve into the water, thus reducing the capacity of the water used for back pressure to dissolve air present in the pores of the test specimen. The problem is minimized by using a long (>5 m) tube that is impermeable to air between the air-water interface and test specimen, by separating the back-pressure water from the air by a solid material or liquid that is relatively impermeable to air, by periodically replacing the back-pressure water with de-aired water, or by other means.

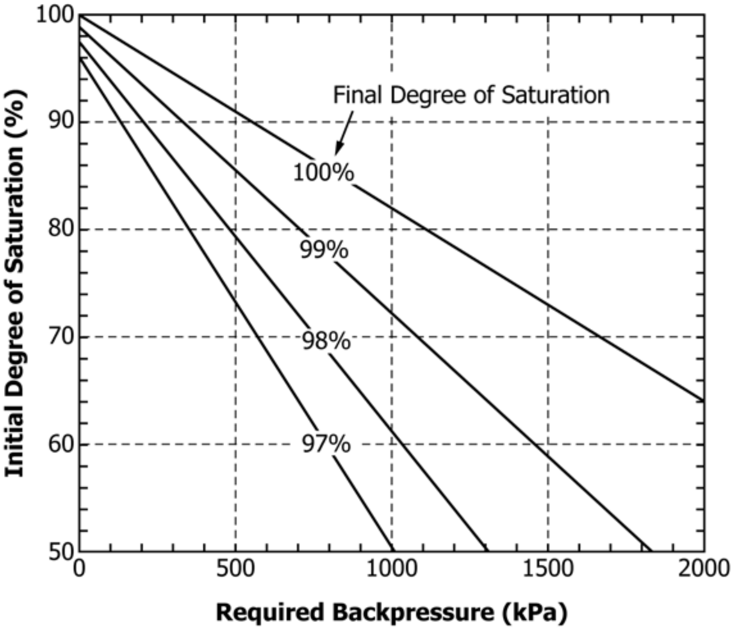

FIG. 3 Back Pressure to Attain Various Degrees of Saturation (adapted from Ref 4)

9.6.1 Water is used in the back-pressure saturation step for Methods 1 and 3 and permeant liquid is used in the back-pressure saturation step for Method 2. The procedures for back-pressure saturation are essentially the same for all the three methods. If hazardous permeant liquids are used, precautions described in Section 7 are applicable.

9.6.2 During the saturation process, any change in the volume (swelling or compression) of a test specimen should be minimized. Volume change may be monitored by measuring the height of a specimen during the back-pressure saturation process. Detailed analysis of effects of axial strain on hydraulic conductivity of soils is provided in Test Method D5084.

9.6.2.1 Saturation with the test liquid shall not be conducted if the test liquid will cause rapid and excessive volume change in the specimen when Method 2 is used. For these cases, the specimen shall be saturated with water (even though this may not represent the conditions to which the specimen will be exposed) and then permeated with the test liquid. Any changes in the intended test sequence shall be included in the test report.

NOTE 12—Published data may be consulted to estimate potential effects of a permeant liquid on a test soil. In addition, Atterberg limits (**7-9**), hydrometer (**10**), or swelling (**11**) tests may be conducted to provide a qualitative estimate for the potential for adverse interactions between the permeant liquid and the test soil in a relatively short period of time.

9.6.3 If monitored, initial specimen height should be measured and recorded prior to start of back-pressure saturation. If an electronic pressure transducer or other measuring device is used during the test to measure pore pressures, any entrapped air should be bled from the device.

9.6.4 The confining pressure and the influent and effluent pressures should be adjusted to initiate back-pressure saturation.

9.6.4.1 The influent and effluent pressures should be similar during saturation. However, a small (<5) hydraulic gradient may be applied across the specimen by varying the influent and effluent pressures by a sufficient amount to induce flow to assist in removal of entrapped air. The applied pressures shall be adjusted such that the effective stress acting on the specimen (the difference between the confining stress and the pore pressure applied through influent and effluent pressures) at no time shall be less than 7 kPa (1 psi) or more than the effective stress that will be used during the permeation stage of the test. The minimum effective stress of 7 kPa (1 psi) is required to prevent the potential separation of the flexible membrane from the test specimen. The effective stress used during saturation is maintained equal to or less than the average effective stress used during the permeation stage to prevent stress-induced volume change of the specimen during the permeation stage. A constant effective stress shall be maintained in the specimen during the back-pressure saturation process.

9.6.4.2 The confining pressure and the influent and effluent pressures should be increased simultaneously in equal increments to increase the pore pressure in a specimen while maintaining a constant effective stress (the increased pore pressure will cause air to go into solution). Each increment of pressure should be maintained for a period of a few minutes to a few hours, depending upon the hydraulic conductivity and initial degree of saturation of the specimen, before new increments in pressure are applied. Ideally, each back-pressure increment shall be applied until the pore pressures throughout the specimen are equalized.

9.6.5 Saturation of the specimen can be verified using one of the three following methods:

9.6.5.1 Saturation may be verified by measuring the pore pressure parameter *B*. The parameter is determined in an undrained state (that is, when specimen drainage lines are closed). The parameter *B* is the quotient of the change in pore pressure in the specimen caused by an induced change in confining cell pressure to the induced change in the cell pressure. The parameter $B$ may be determined for each stress increment applied to the specimen. At completion of a stress increment (determined by the constant pore pressure in the specimen as described in 9.6.4.2), the influent and effluent lines of the permeameter are closed. The cell pressure is increased by the desired amount and then the pore pressure generated in the specimen due to the applied confining stress is measured immediately to calculate $B$. The influent and effluent lines are then opened and the pore pressure is adjusted rapidly to maintain the required effective stress in the specimen (as per 9.6.4.1). The test specimen shall be considered to be adequately saturated if the $B$ value is $\geq 0.95$. If $B$ is determined to be less than 0.95, then further stress increments are used until $B$ reaches a value $\geq 0.95$. Additional information about determination of $B$ is provided in Test Method D4767.

9.6.5.2 Saturation of the test specimen may be verified at the completion of the entire hydraulic conductivity test by calculating the final degree of saturation. The final degree of saturation shall be >95 %. This approach is not recommended since long tests may need to be re-conducted if the test specimen is determined not to be adequately saturated subsequent to a test.

9.6.5.3 Other means, such as observing the flow of water or permeant liquid into the specimen when the back pressure is increased, can be used for verifying saturation provided data are available for similar materials to establish that the procedure used confirms saturation as required in 9.6.5.1 or 9.6.5.2.

9.7 *Permeation*—Specimens shall be permeated using the permeant liquid in Methods 1 and 2. Permeation of specimens using Method 3 shall initiate with water and then the permeating liquid shall be switched to test liquid. The permeating liquid shall be switched when termination criteria for water permeation is satisfied (see 9.7.10 and 9.7.10.1). If hazardous permeant liquids are used, precautions described in Section 7 shall be used.

9.7.1 Measurements during permeation may be made by reading water/permeant liquid levels directly from reservoirs containing these liquids in a test setup. These measurements include head and flow measurements. In the case of flow, the measured liquid level is multiplied with the area of the reservoir that holds the liquid to determine flow volumes. The last digit may be estimated when directly reading liquid levels from graduated reservoirs. The use of estimated digits for such measurements are provided in Practice D6026. When the last digit is estimated in a measurement where the reading is a function of the elevation/location of the eye, a mirror or another device is required to reduce the reading error caused by parallax.

9.7.2 *Hydraulic Gradient*—The hydraulic gradient ($i = h/L$, for definitions of notation see Section 10) used for hydraulic conductivity testing should be similar to that expected in the field, when possible. However, the use of small hydraulic gradients may lead to very long testing times for materials with low hydraulic conductivity (less than approximately $1 \times 10^{-8}$ m/s). Somewhat larger hydraulic gradients are usually used in the laboratory to accelerate testing, but excessive gradients may cause high seepage pressures that can consolidate the material, washing of material from the specimen, or migration of fine particles that may plug the outflow end of the test specimen. These effects could increase or decrease hydraulic conductivity. If no gradient is specified by the requester, the following guidelines may be used:

| Hydraulic Conductivity (m/s) | Recommended Maximum Hydraulic Gradient |
|---|---|
| $1 \times 10^{-5}$ to $1 \times 10^{-6}$ | 2 |
| $1 \times 10^{-6}$ to $1 \times 10^{-7}$ | 5 |
| $1 \times 10^{-7}$ to $1 \times 10^{-8}$ | 10 |
| $1 \times 10^{-8}$ to $1 \times 10^{-9}$ | 20 |
| $< 1 \times 10^{-9}$ | 30 |

NOTE 13—Seepage pressures associated with large hydraulic gradients can consolidate soft, compressible specimens and reduce their hydraulic conductivity. Smaller hydraulic gradients (<10) may be required for such specimens.

9.7.3 *Initialization*—Initiate permeation of the specimen by increasing the influent (headwater) pressure and decreasing the effluent (tailwater) pressure by an equal amount to induce the desired hydraulic gradient on the specimen. The average effective stress on the specimen is maintained when the influent and effluent pressures are varied by an equal amount. If only the influent pressure is increased or the effluent pressure is decreased, the average effective stress acting on the specimen will increase or decrease, respectively. Consideration shall be given to air bubbles that were dissolved in the specimen pore liquid during back pressuring coming out of solution when the effluent pressure is decreased.

NOTE 14—A potential exists for consolidation and swelling of the specimen due to increased and decreased effective stress, respectively. The applied stresses shall be adjusted, if excessive variation in the volume of the specimen is observed.

9.7.3.1 The headwater pressure shall be increased such that at least the minimum required effective stress of 7 kPa (1 psi) shall be maintained in the specimen.

9.7.3.2 At the start ($t_1$) and end ($t_2$) of each permeation trial, the test temperature shall be measured and recorded to the nearest 0.1°C.

9.7.4 *Time Measurements*—The time at the start and end of each permeation trial shall be measured and recorded. The permeation duration shall be measured to the nearest second.

9.7.5 *Falling Headwater-Rising Tailwater Tests*—Measure and record the heads applied to the specimen at the inflow and outflow ends to the resolution stated in 5.3.1 at the start and end of each permeation trial (as a minimum). Determine the head loss across the specimen using measured heads. The head loss across the specimen at any given time shall be more than 75 % of the maximum head loss across the specimen during the hydraulic conductivity determination (see Note 15). The volumes of inflow and outflow shall be measured and recorded to the resolution stated in 5.4 at the start and end of each permeation trial (as a minimum). If monitored, the height of the test specimen shall be measured and recorded at the start and end of each trial (as a minimum) and changes in height shall be determined using the measured heights.

9.7.6 *Constant-Head Tests*—Measure and record the heads applied to the specimen at the inflow and outflow ends to the resolution stated in 5.3.2 at the start and end of each permeation trial (as a minimum). Determine the head loss across the specimen using measured heads. The head loss across the permeameter shall be kept constant to within ±5 % or better during permeation. The volumes of inflow and outflow shall be measured and recorded to the resolution stated in 5.4 at the start and end of each permeation trial (as a minimum). If monitored, the height of the test specimen shall be measured and recorded at the start and end of each trial (as a minimum) and changes in height shall be determined using the measured heights.

9.7.7 *Falling Headwater-Constant Tailwater Tests*—Follow procedures similar to those provided in 9.7.5 and maintain measurement resolution provided in 5.3.3. In addition, the head loss across the permeameter shall be kept constant to within ±5 % or better.

9.7.8 *Constant Rate of Flow Tests*—Permeation of the specimen shall be initiated by imposing a constant flow rate. The flow rate shall be selected such that the hydraulic gradient does not exceed the value specified or recommended. The head loss across the test specimen shall be determined and recorded to the resolution stated in 5.3.4. If monitored, the height of the test specimen shall be measured and recorded at the start and end of each trial (as a minimum) and changes in height shall be determined using the measured heights.

NOTE 15—When the pore liquid pressure in a test specimen changes and the applied total stress is constant, the effective stress in the test specimen changes, which can cause volume changes that can invalidate the test results. The requirement that the head loss not decrease below a certain value is intended to limit the variation in the effective stress to an acceptable level. For extremely soft, compressible test specimens, even more restrictive criteria may be needed. When the initial and final head losses over an interval of time do not differ by more than ±5 %, a test is considered as a constant-head test (9.7.6).

9.7.9 *Permeant Liquid Monitoring*—The properties and composition of the effluent test liquid shall be monitored over the duration of a test. The properties and composition of the influent permeant liquid shall not change over the duration of a hydraulic conductivity test. Chemical composition, pH, and electrical conductivity (EC) or specific conductance or dielectric constant (based on the type of permeant liquid) shall be determined. The permeant liquid shall be sampled such that the composition of the permeant liquid and also the pressure conditions on the specimen shall not be altered during sampling. Contact of the permeant liquid with the surrounding environment that may alter its properties or composition shall be prevented. The test liquid should be monitored frequently at the beginning of a test. The monitoring frequency may be decreased after some time. The frequency of monitoring may be adjusted based on specimen volume or pore volumes of flow from a specimen. The following provides an example sampling scheme (only an example, specifics should be considered based on available data): a minimum of one sample per every quarter pore volume of flow for the first two pore volumes of flow, a minimum of one sample per every half pore volume of flow between 2 and 4 pore volumes of flow, and a minimum of one sample per pore volume of flow thereafter.

9.7.10 *Termination*—Continue permeation until at least four values of hydraulic conductivity are obtained over an interval of time considering all of the following criteria: *(1)* the ratio of outflow to inflow, *(2)* steadiness of hydraulic conductivity, *(3)* pore volumes of flow, and *(4)* consistency of the characteristics of the effluent and the influent liquids (that is, chemical equilibrium). The ratio of outflow to inflow shall be between 0.75 and 1.25. The hydraulic conductivity shall be considered steady if four or more consecutive hydraulic conductivity determinations fall within ±25 % or better of the mean value for $k \geq 1 \times 10^{-10}$ m/s or within ±50 % or better for $k < 1 \times 10^{-10}$ m/s, and a plot or tabulation of the hydraulic conductivity versus time shows no significant upward or downward trend. At least 2 pore volumes of flow shall occur through the specimen. Chemical equilibrium shall be considered to be reached when the variation in chemical composition, as measured by solute concentration, (for solute(s) specified in the test program), pH, electrical conductance and/or dielectric constant (based on the type of test liquid) of the effluent, is within ±10 % of that for the influent with no significant increasing or decreasing trends. Additional physical and chemical criteria for characteristics of test liquids may be used for termination.

NOTE 16—Severe effects on specimens, such as excessive volume change, excessive cracking, and opening of large channels, may occur during some tests. In these cases, a test may be terminated without meeting one or more of the criteria in 9.7.10.

NOTE 17—Variation in concentration of certain individual solutes in the effluent may be allowed to be up to ± 50% of that for the influent for organic solutions or for specimens containing cementitious or pozzolanic materials. This allowance is not intended for all organic solutions or specimens containing cementitious or pozzolanic materials. The applicability of the allowance for particular solutes and specimens should be made on a case-by-case basis.

9.7.10.1 Criteria *(1)*, *(2)*, and *(3)* provided above (9.7.10) shall be used as the termination criteria with respect to the water permeation stage in Method 3. Once these termination criteria are satisfied for water permeation, the permeating liquid may be switched to the permeant liquid to be used in the test program. All four termination criteria specified in (9.7.10) are then applicable for permeation with the test liquid.

9.8 *Final Dimensions, Mass, Moisture Content, and Degree of Saturation of the Specimen*—After completion of permeation, the applied confining, influent, and effluent pressures shall be reduced in a manner that does not cause significant volume change of the test specimen, the permeameter cell shall be carefully disassembled, and the specimen shall be carefully removed. The final height, diameter, and total mass of the specimen shall be measured and recorded. Dimensions and mass of the test specimen shall be measured with the resolutions specified in 5.9 and 5.10, respectively. The final water content of the specimen shall be determined in accordance with Test Method D2216 (see 5.14 and Note 4). The final degree of saturation of the specimen shall be determined using basic mass-volume relationships for soils to the nearest percent. When dealing with hazardous test liquids and specimens that may have become hazardous due to permeation with hazardous test liquids, the precautions described in Section 7 are applicable.

NOTE 18—The specimen may swell after removal of back pressure as a result of air coming out of solution. A correction may be made for this effect, provided that changes in the length of the specimen are monitored during the test. The strain caused by dismantling the cell is computed from the length of the specimen before and after dismantling the cell. The same strain is assumed to have occurred in the diameter. The corrected diameter and actual length before the back pressure was removed are used to compute the volume of the test specimen prior to dismantling the cell. The volume prior to dismantling the cell is used to determine the final dry density and degree of saturation.

9.8.1 Dimensions of the specimen and mass and volume of the gas, liquid, and solid phases in the specimen may be altered when severe interactions (such as those described in Note 16) occur between specimens and permeant liquids during permeation. Excessive effects on the dimensions and mass of the specimens shall be reported. Any changes in these parameters shall be measured and included in the determination of the final moisture content and the degree of saturation of the specimens.

## 10. Calculation

10.1 *Falling Headwater–Rising Tailwater Tests*—Calculate the hydraulic conductivity, $k$, as follows:

$$k = \frac{a_{in} \cdot a_{out} \cdot L}{(a_{in} + a_{out}) \cdot A \cdot \Delta t} \cdot \ln \frac{h_1}{h_2} \tag{1}$$

where:

$k$ = hydraulic conductivity (m/s or cm/s),
$a_{in}$ = cross-sectional area of the reservoir containing the influent liquid (m$^2$ or cm$^2$),
$a_{out}$ = cross-sectional area of the reservoir containing the effluent liquid (m$^2$ or cm$^2$),
$L$ = length of specimen (m or cm),
$A$ = cross-sectional area of specimen (m$^2$ or cm$^2$),
$\Delta t$ = interval of time ($t_2 - t_1$) for the head change $h_1$ to $h_2$ to occur (s),
$t_1$ = time at start of permeation trial, date:hr:min:sec,
$t_2$ = time at end of permeation trial, date:hr:min:sec,
$h_1$ = head loss across the specimen at $t_1$ (m or cm), and
$h_2$ = head loss across the specimen at $t_2$ (m or cm).

10.1.1 When $a_{out} = a_{in} = a$, the equation for calculating $k$ for a falling headwater–rising tailwater test is:

$$k = \frac{a \cdot L}{2 \cdot A \cdot \Delta t} \cdot \ln \frac{h_1}{h_2} \tag{2}$$

where:

$a$ = area of the reservoirs containing the influent or effluent liquid (m$^2$ or cm$^2$).

10.2 *Constant-Head Tests*—Calculate the hydraulic conductivity, $k$, as follows:

$$k = \frac{\Delta Q \cdot L}{A \cdot h \cdot \Delta t} \tag{3}$$

where:

$\Delta Q$ = quantity of flow for given time interval, $\Delta t$ ($t_2 - t_1$), (m$^3$ or cm$^3$), and
$h$ = head loss ($h_1 - h_2$) across the specimen (m or cm).

10.3 *Falling Headwater–Constant Tailwater Tests*—Calculate the hydraulic conductivity, $k$, as follows:

$$k = \frac{a_{in} \cdot L}{A \cdot \Delta t} \cdot \ln \frac{h_1}{h_2} \tag{4}$$

10.4 *Constant Rate-of-Flow Tests*—Calculate the hydraulic conductivity, $k$, as follows:

$$k = \frac{\Delta Q \cdot L}{A \cdot h \cdot \Delta t} \tag{5}$$

NOTE 19—For all of the tests, the measurements and calculations may be made in other units and may be converted to the units listed above using appropriate unit conversion factors.

10.5 *Hydraulic Conductivity at Standard Temperature*—The measured hydraulic conductivity shall be corrected to that for 20°C (68°F), $k_{20}$, by multiplying the measured $k$ by the ratio of the viscosity of liquid at test temperature to the viscosity of liquid at 20°C (68°F), $R_T$ :

$$k_{20} = R_T \cdot k \tag{6}$$

where:

$$R_T = \frac{2.2902 \cdot 0.9842^T}{T^{0.1702}} \tag{7}$$

and:

$k_{20}$ = hydraulic conductivity at standard temperature, 20°C, (m/s or cm/s),
$R_T$ = ratio of the viscosity of liquid at test temperature to the viscosity of liquid at 20°C,
$T$ = average test temperature (($T_1 + T_2$)/2) during the permeation trial (°C),
$T_1$ = test temperature at start of permeation trial (°C), and
$T_2$ = test temperature at end of permeation trial (°C).

10.6 *Intrinsic Permeability*—Intrinsic permeability, $K$, may be calculated using the following equation:

$$K = k \cdot \frac{\mu}{\gamma} \tag{8}$$

where:

$K$ = intrinsic permeability of soil (m$^2$),
$k$ = hydraulic conductivity of soil (m/s),
$\mu$ = dynamic viscosity of liquid (Pa s), and
$\gamma$ = unit weight of liquid (N/m$^3$).

10.6.1 The following equation may be used for comparing the hydraulic conductivity to the permeant liquid with the hydraulic conductivity to water. This equation allows for differentiating between the effects of unit weight and viscosity of permeant liquids and changes in the structure of a test soil on the resulting hydraulic conductivity.

$$\frac{k_{pl}}{k_w} = \frac{K_{pl} \cdot \mu_w \cdot \gamma_{pl}}{K_w \cdot \mu_{pl} \cdot \gamma_w} \tag{9}$$

where:

$k_{pl}$ = hydraulic conductivity with permeant liquid (m/s),
$K_{pl}$ = intrinsic permeability with test liquid (m$^2$),
$\mu_{pl}$ = dynamic viscosity of permeant liquid (cP),
$\gamma_{pl}$ = unit weight of permeant liquid (N/m$^3$),
$k_w$ = hydraulic conductivity with water (m/s),
$K_w$ = intrinsic permeability with water (m$^2$),
$\mu_w$ = dynamic viscosity of water (cP), and
$\gamma_w$ = unit weight of water (N/m$^3$).

10.6.2 Viscosity and density of water and various aqueous solutions as a function of temperature are provided in Ref (**12**). Specific gravity (and hence unit weight) of water and aqueous solutions can be determined using Test Methods D1429.

10.7 *Pore Volume of Flow*—Use the following equation to calculate pore volumes of flow, *PVF*:

$$PVF = \frac{\sum V_{outflow}}{V_v} \tag{10}$$

where:

$PVF$ = pore volumes of flow,

$\Sigma V_{outflow}$ = cumulative amount of effluent collected during test ($m^3$ or $cm^3$), and

$V_v$ = volume of voids in the specimen ($m^3$ or $cm^3$).

NOTE 20—The total volume of voids ($V_v$) may not be equal to effective volume of voids ($V_{ve}$), which are the voids that allow for transport of liquid. If the effective volume of voids ($V_{ve}$) is known, this value shall be used for $V_v$ in Eq 10.

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

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

11.1.1 Sample/specimen identifying information, such as Project No., Boring No., Sample No., Depth, etc.

11.1.2 Any special selection and preparation process, such as removal of gravel or other materials, or identification of their presence, if "undisturbed" specimen.

11.1.3 If the specimen is reconstituted, remolded, or trimmed in a specialized manner (for example, to determine horizontal hydraulic conductivity), provide information on method of reconstitution, remolding, etc.

11.1.4 Information to identify permeant liquid such as source, chemical composition, physical properties, etc.

11.2 Record as a minimum the following test specimen data:

11.2.1 The measured specific gravity (Test Method D854) or assumed value.

11.2.2 The initial dimensions, length and diameter (use resolution provided in 5.9 and 8.1), mass (use resolution provided in 5.10), area (nearest 0.1 $mm^2$ or better), and volume (nearest 0.1 $mm^3$ or better) of the specimen.

11.2.3 The initial moisture content (nearest 0.1 %), dry unit weight (nearest 0.01 $kN/m^3$), and saturation (nearest percent) of the test specimen. See Note 21.

NOTE 21—The dry unit weight equals the dry density ($kg/m^3$) times 9.8067 (g), see definitions under unit weight (*grouping* ) in Terminology D653.

11.2.4 The final dimensions, length and diameter, (use resolution provided in 5.9 and 8.1), mass (use resolution provided in 5.10), area (nearest 0.1 $mm^2$ or better), and volume (nearest 0.1 $mm^3$ or better) of the specimen.

11.2.5 The moisture content (nearest 0.1 %), dry unit weight (nearest 0.01 $kN/m^3$), and saturation (nearest percent) of the test specimen.

11.3 Record as a minimum the following test conditions:

11.3.1 The sequence of testing conducted including saturation (if any) and permeation steps.

11.3.2 The type of liquid used in various stages.

11.3.3 The magnitude of final back pressure (as specified in 5.3.6).

11.3.4 The effective consolidation stress (nearest 0.1 kPa).

11.3.5 The area (nearest 0.1 $mm^2$ or better) of the headwater and tailwater tubes (such as burettes, reservoirs, etc.), as applicable.

11.3.6 The length (use resolution provided in 8.1) and area (nearest 0.1 $mm^2$ or better) of the test specimen during permeation.

11.3.6.1 These values can be determined based on either *(a)* the initial dimensions of specimen plus any length/height and volume changes occurring during consolidation and saturation; or *(b)* final dimensions of the test specimen, see 11.2.4.

11.4 Record as a minimum the following permeation data:

11.4.1 For each permeation trial, the start and end date and time and elapsed duration (nearest second); the start and end temperature (nearest 0.1°C); the start and end head readings (as specified in 5.3.1 – 5.3.3); the start and end flow reading(s) (as specified in 5.3.4 and 5.4) when applicable; and deformation readings (as specified in 5.5.4) when applicable.

11.4.2 The maximum, minimum, and average effective stresses in the specimen during permeation (nearest 0.1 kPa).

11.4.3 The calculated initial hydraulic gradient and final value if falling head methods are used to two or more significant digits.

11.4.4 The calculated hydraulic conductivity to two or more significant digits in units of m/s or other units (for example, customary units in the U.S.), for example, $7.15 \times 10^{-10}$ m/s or $7.15 \times 10^{-8}$ cm/s.

11.4.5 The average corrected hydraulic conductivity ($k_{20}$) to two or three significant digits in units of m/s or other units (for example, customary units in the U.S.), for example, $7.15 \times 10^{-10}$ m/s or $7.15 \times 10^{-8}$ cm/s.

11.4.6 At a minimum, hydraulic conductivity results shall be presented as hydraulic conductivity versus time and versus pore volumes of flow in tabular and/or graphical form.

11.4.7 All pertinent chemical properties of influent and effluent liquids versus time and versus pore volumes of flow in tabular and/or graphical form.

11.5 If comparisons are made between the hydraulic conductivity with the permeant liquid and water, report the hydraulic conductivity, intrinsic permeability, viscosity, and unit weight for both permeant liquids.

## 12. Precision and Bias

12.1 *Precision*—Test data on precision are not presented due to the nature of the soils and permeant liquids tested by this standard. It is either not feasible or too costly at this time to have ten or more laboratories participate in a round-robin testing program.

12.1.1 Subcommittee D18.04 is seeking any pertinent data from users of these test methods that might be used to make a limited statement on precision.

12.2 *Bias*—There is no accepted reference value for these test methods, therefore, bias cannot be determined.

## 13. Keywords

13.1 constant head; falling head; hydraulic barrier; hydraulic compatibility; hydraulic conductivity; intrinsic permeability; liner

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