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Soil quality — Determination of hydraulic conductivity of saturated porous materials using a flexible wall permeameter

Qualité du sol — Détermination de la conductivité hydraulique de matériaux poreux saturés à l'aide d'un perméamètre à paroi flexible

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 17313 was prepared by Technical Committee ISO/TC 190, *Soil quality*, Subcommittee SC 5, *Physical methods*.

Introduction

The rate of water flow through the soil is of considerable importance in many aspects of agricultural and urban life. The entry of water into soil, the movement of water to plant roots, the flow of water to drains and wells, and the evaporation of water from the soil surface are but a few of the obvious situations in which the rate of water flow plays an important role. Also in cases of soil pollution and polluted groundwater, prediction of the rate of movement of soil water is of great importance in obtaining information about the spreading of pollutants.

The soil properties that determine the behaviour of soil water flow systems are the hydraulic conductivity and water retention characteristics. The hydraulic conductivity of soil is a measure of its ability to transmit water. The water retention characteristics are an expression of its ability to store water. These properties determine the response of a soil water system to imposed boundary conditions.

Soil quality — Determination of hydraulic conductivity of saturated porous materials using a flexible wall permeameter

1 Scope

This International Standard specifies a test method for laboratory measurement of the hydraulic conductivity of water-saturated porous materials using a flexible wall permeameter.

This International Standard is applicable to undisturbed or compacted specimens that have a hydraulic conductivity between 1×10^{-5} m/s (1×10^{-3} cm/s) and 1×10^{-11} m/s (1×10^{-9} cm/s). Typical soil types falling in this category are clay, clay and sand tills, silt, peat, mud, etc.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
hydraulic conductivity
k
rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20 °C)

2.2
pore volume of flow
cumulative quantity of flow into a test specimen divided by the volume of voids in the specimen

2.3
hydraulic gradient
change in total hydraulic head of water per unit distance of flow

3 Significance and use

This test method applies to the one-dimensional, laminar flow of water from bottom to top within porous materials such as soil and rock.

The hydraulic conductivity of porous materials generally decreases with an increasing amount of air in the pores of the material. This test method applies to water-saturated porous materials containing almost no air.

This test method applies to permeation of porous materials with water. Permeation with other liquids, such as chemical wastes, can be accomplished using procedures similar to those described in this test method. However, this test method is only intended for use when water is the permeant liquid.

It is assumed that Darcy's law is valid and that the hydraulic conductivity is essentially unaffected by hydraulic gradient. The validity of Darcy's law can be evaluated by measuring the hydraulic conductivity of the specimen at three hydraulic gradients; if all measured values are similar (within about 25 %), then Darcy's law may be taken as valid. However, when the hydraulic gradient acting on a test specimen is changed, the state of stress will also change, and, if the specimen is compressible, the volume of the specimen will change. Thus, some change in hydraulic conductivity can occur when the hydraulic gradient is altered, even in cases where Darcy's law is valid.

Normally, hydraulic conductivity measured by laboratory testing is different from large-scale field-test results. The reason is that samples of the size described in this International Standard are representative for homogeneous soil, but seldom for stratified, fissured or other non-homogeneous soil. In order to obtain results representing the hydraulic conductivity in the field in these cases, large-scale samples or field-testing shall be considered.

4 Reagents

4.1 Permeant water, as specified by the requester.

If no specification is made, tap water shall be used for the permeant liquid. The type of water utilized shall be indicated in the test report.

4.2 De-aerated water.

To avoid introducing air, and to aid in removing as much air from the test specimen as possible, de-aerated water shall be used. To prevent dissolution of air back into the water, de-aerated water shall not be exposed to air for prolonged periods.

5 Apparatus

5.1 Hydraulic system

Constant head (Method A), falling head (Methods B and C), or constant rate of flow (Method D) systems may be utilized provided they meet the criteria outlined as follows.

a) Constant head (Method A)

   The system shall be capable of maintaining constant hydraulic pressure. Pressures shall be measured by a pressure gauge, electronic pressure transducer or any other device of suitable accuracy.

b) Falling head

   The system shall allow for measurement of the loss of applied head. The head loss shall be measured with a pressure gauge, electronic pressure transducer, engineer's scale, graduated pipette, or any other device of suitable accuracy. Falling head tests may be performed with either a constant tail water elevation (Method B) or a rising tail water elevation (Method C).

c) Constant rate of flow (Method D)

   The system shall be capable of maintaining a constant rate of flow through the specimen to within $\pm$ 5 % or better. Flow measurement shall be by calibrated syringe, graduated pipette, or other device of suitable accuracy.

The hydraulic system shall be designed to facilitate rapid and complete removal of free air bubbles from flow lines.

The hydraulic system shall have the capability to apply back-pressure to the specimen to facilitate saturation. The back-pressure may be provided by a compressed gas supply, a deadweight acting on a piston, or any other method capable of applying and controlling the back-pressure to the tolerance required.

The above-mentioned test methods are considered equivalent. The accuracy of the test results depends on the instruments used.

5.2 Flow measurement system.

Both inflow and outflow volumes shall be measured, unless the lack of leakage, continuity of flow and cessation of consolidation or swelling can be verified by other means. Flow volumes shall be measured by a graduated accumulator, graduated pipette or vertical standpipe in conjunction with an electronic pressure transducer or other column-measuring device of suitable accuracy.

Head losses in the tubes, valves, porous end pieces, and filter paper may lead to error, and shall be less than 10 % of the head loss of the sample.

5.3 System for pressurizing the permeameter cell.

The pressurizing system may consist of a reservoir connected to the permeameter cell and partially filled with de-aerated water, with the upper part of the reservoir connected to a compressed gas supply or other source of pressure. The gas pressure shall be controlled by a pressure regulator and measured by a pressure gauge, electronic pressure transducer or any other device capable of measuring to the tolerance required. A hydraulic system pressurized by deadweight acting on a piston or any other pressure device capable of applying and controlling the permeameter cell pressure to the tolerance required may be used.

5.4 Permeameter cell, in which the specimen and porous end pieces, enclosed by a membrane sealed to the cap and base, are subjected to controlled fluid pressures.

A cell (5) in a typical permeameter system is shown in Figure 1. The permeameter cell may allow for observation of changes in height (l_0) of the soil sample.

In order to facilitate gas removal, and thus saturation of the hydraulic system, drainage lines lead to the test specimen, to the base and top cap. The drainage lines shall be controlled by no-volume-change valves, such as ball valves, and shall be designed to minimize dead space in the lines.

5.5 Top cap and base, impermeable and rigid, to support the specimen and provide for transmission of permeant liquid to and from the specimen.

5.6 Flexible membrane, used to encase the specimen and provide reliable protection against leakage.

The membrane shall be carefully inspected prior to use, and if any flaws or pinholes are evident, the membrane shall be discarded. To minimize restraint of the specimen, the diameter or width of the unstretched membrane shall be between 90 % and 95 % that of the specimen. The membrane shall be sealed to the specimen base and cap by rubber O-rings for which the unstressed, inside diameter is less than 90 % of the diameter of the base and cap, or by any other method that will produce an adequate seal.

5.7 Porous end pieces, of silicon carbide, aluminium oxide, or other material that is not attacked by the specimen or permeant liquid.

The end pieces shall have plane and smooth surfaces and be free of cracks, chips and non-uniformities. They shall be checked regularly to ensure that they are not clogged. The hydraulic conductivity of the porous end pieces shall be significantly greater than that of the specimen to be tested.

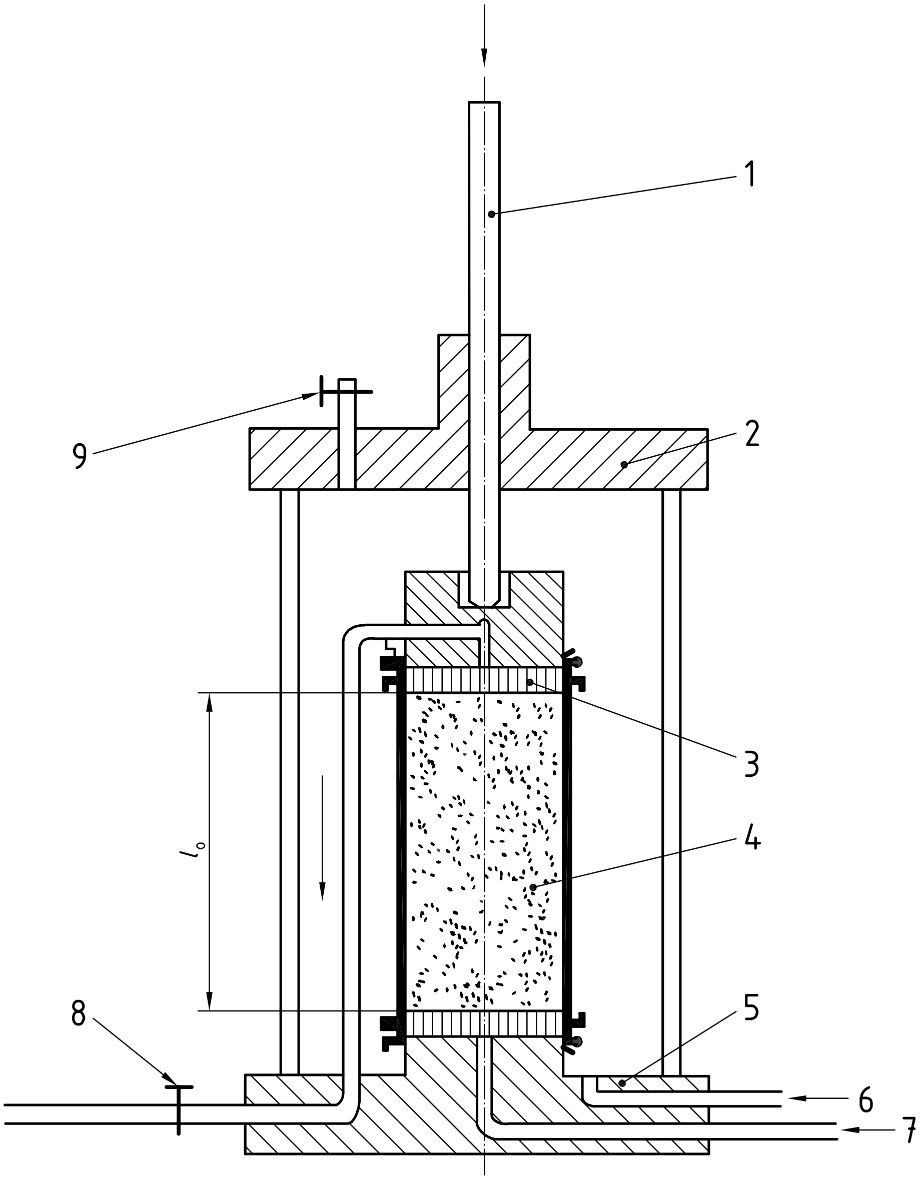
5.8 Filter paper (optional), to prevent intrusion of material into the pores of the porous end pieces.

If necessary, one or more sheets of filter paper shall be placed between the top and bottom porous end pieces and the specimen. The paper shall have a negligibly small hydraulic resistance.

5.9 Equipment (including compactor and mould) suitable **for compacting a specimen** by the method of compaction specified by the requester**.**

5.10 Sample extruder.

When the material being tested is a soil core, the soil core shall usually be removed from the sampler with an extruder.



Key

1 observation of changes of height

2 cell

3 porous end piece

4 soil test specimen

5 cell

6 cell pressure line

7 inlet line

8 outlet line

9 vent

Figure 1 — Schematic diagram of a typical permeameter system

5.11 Equipment for trimming the specimen to the desired dimensions.

This equipment will vary depending on the quality and characteristics of the sample. The following items may be used:

a) lathe,

b) wire saw with a wire about 0,3 mm in diameter,

c) spatulas,

d) knives,

e) steel rasp for very hard clay specimens,

f) cradle or split mould for trimming specimen ends,

g) steel straight edge for final trimming of specimen ends.

5.12 Equipment for mounting the specimen in the permeameter cell, including a membrane stretcher or cylinder, and ring for expanding and placing O-rings on the base and top cap to seal the membrane.

5.13 Temperature-maintaining device.

The temperature of the permeameter, test specimen and reservoir of permeant liquid shall not vary more than ± 3 °C. Normally, this is accomplished by performing the test in a room with a relatively constant temperature. If such a room is not available, the apparatus shall be placed in a water bath, insulated chamber, or other device that maintains a constant temperature. The temperature shall be periodically measured and recorded.

6 Test specimen

6.1 Specimen dimensions

Specimens shall have a minimum diameter of 70 mm and a minimum height of 25 mm. The diameter and height of the specimen shall each be at least six times greater than the largest particle size within the specimen. If, after completion of a test, it is found based on visual observation that oversized particles are present, that information shall be indicated in the test report.

6.2 Undisturbed specimen

Specimens obtained by tube sampling or coring may be tested without trimming, except for cutting the end surfaces plane and perpendicular to the longitudinal axis of the specimen, provided soil characteristics are such that no significant disturbance results from sampling. If the sampling operation has caused disturbance of the soil, the disturbed material shall be trimmed. If removal of pebbles or crumbling resulting from trimming causes voids in the surface of the specimen, the voids shall be filled with remoulded material obtained from the trimmings. The ends of the test specimen shall be cut and not trowelled (trowelling can seal off cracks, slicken sides or other secondary features that might conduct water flow). Specimens shall be trimmed whenever possible in an environment where changes in moisture content are minimized. A controlled high-humidity room is usually used for this purpose. The mass and dimensions of the test specimens shall be determined. The test specimens shall be mounted immediately in the permeameter. The water content of the trimmings shall be determined.

6.3 Laboratory-compacted specimen

The material to be tested shall be prepared and compacted inside a mould in a manner specified by the requester. Neither hard clods nor individual particles of the material shall exceed 1/6 of either the height or the diameter of the specimen. After compaction, the test specimen shall be removed from the mould, the ends scarified, and the dimensions and mass determined. The test specimen shall then be immediately mounted in the permeameter. The water content of the trimmings shall be determined.

6.4 Other preparation methods

Other methods of preparation of a test specimen are permitted if specifically requested. The method of specimen preparation shall be identified in the test report.

After the height, diameter, mass and water content of the test specimen have been determined, the dry unit mass shall be calculated. Also, the initial degree of saturation shall be estimated (this information may be used later in the back-pressure stage).

7 Procedure

7.1 Specimen set-up

7.1.1 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, if used, in a container of permeant water.

7.1.2 Place the membrane on the membrane expander. Apply a thin coat of silicon high-vacuum grease to the sides of the end caps. Place one porous end piece on the base and place one filter-paper sheet, if used, on the porous end piece, followed by the test specimen. Place the second filter-paper sheet, if used, on top of the specimen followed by the second porous end piece and the top cap. Place the membrane around the specimen and, using the membrane expander or other suitable O-ring expander, place one or more O-rings to seal the membrane to the base and one or more additional O-rings to seal the membrane to the top cap.

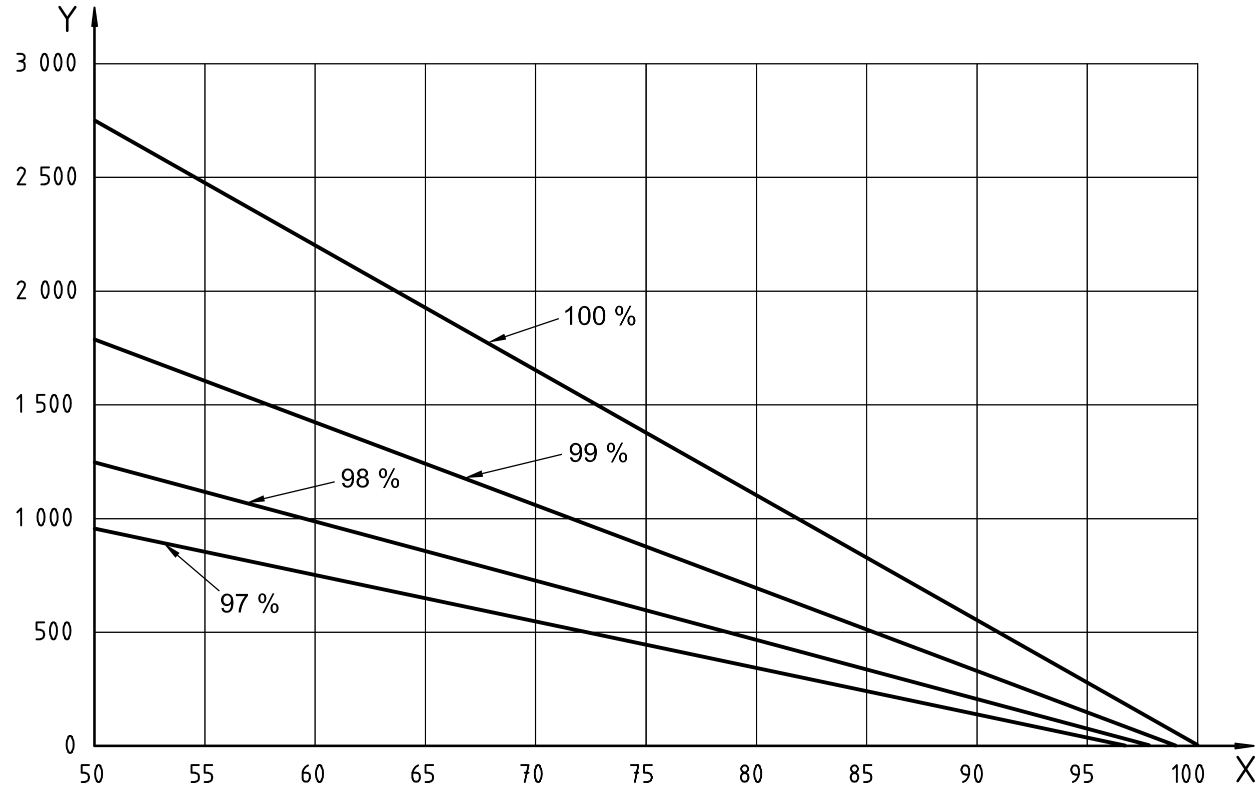
7.1.3 Attach flow tubing to the top cap (if not already attached), assemble the permeameter cell, and fill it with de-aerated water or other cell fluid. Attach the cell pressure reservoir to the permeameter cell line, and the hydraulic system to the inlet and outlet lines. Fill the cell pressure reservoir with de-aerated water or other suitable liquid and the hydraulic system with de-aerated permeant water. Apply a small confining pressure of 7 kPa to 35 kPa to the cell, and apply a pressure less than the confining pressure to both the inlet and outlet systems. Flush permeant water through the flow system. After all visible air has been removed from the flow lines, close the control valves. At no time during saturation of the system and specimen or hydraulic conductivity measurements shall the maximum applied effective stress be allowed to exceed that to which the specimen is to be consolidated.

7.2 Specimen soaking

To aid in saturation, specimens may be soaked under a partial vacuum applied to the top of the specimen. Apply atmospheric pressure to the specimen base through the inlet lines, and set the magnitude of the vacuum to generate a hydraulic gradient across the specimen which is less than that to be used during hydraulic conductivity measurements.

7.3 Back-pressure saturation

To saturate the specimen, back-pressuring is usually necessary. Figure 2 provides guidance on back-pressure required to attain the required degree of saturation.



Key

Y required back-pressure, kPa

X initial degree of saturation, %

Figure 2 — Guidance on back-pressure required to attain the required degree of saturation

Follow the procedure given below.

a) Open flow line valves and flush out of the system any free air bubbles, using the procedure outlined in 7.1.3. If an electronic pressure transducer or other measuring device is to be used during the test to measure pore pressures or applied hydraulic gradient, it should be bled of any trapped air. Take and record an initial reading of specimen mass, if being monitored.

b) Adjust the applied confining pressure to the value to be used during saturation of the sample. Apply back-pressure by simultaneously increasing the cell pressure and the inlet and outlet pressures in increments. The maximum value of an increment in back-pressure shall be sufficiently low so that no point in the specimen is exposed to an effective stress in excess of that to which the specimen will be subsequently consolidated. Maintain each increment of pressure for a period of a few minutes to a few hours, depending upon the characteristics of the specimen, to induce flow.

7.4 Consolidation

The specimen shall be consolidated to the effective stress specified by the requester. Consolidation may be accomplished via the following stages, if desired.

a) Record the specimen height, if being monitored, prior to application of consolidation pressure and periodically during consolidation.

b) Increase the cell pressure to the level necessary to develop the desired effective stress, and begin consolidation. Drainage may be allowed from the base or top of the specimen, or simultaneously from both ends.

c) (Optional) Record outflow volumes to confirm that primary consolidation has been completed prior to initiation of the hydraulic conductivity test. Alternatively, measurements of the change in height of the test specimen can be used to confirm completion of consolidation.

7.5 Permeation

7.5.1 Hydraulic gradient

When possible, the hydraulic gradient used for hydraulic conductivity measurements should be similar to the one expected to occur in the field. In general, hydraulic gradients from < 1 to 5 cover most field conditions. However, the use of small hydraulic gradients can lead to very long testing times for materials having low hydraulic conductivity (less than about 1×10^{-8} m/s). Somewhat larger hydraulic gradients are usually used in the laboratory to accelerate testing, but excessive gradients must be avoided because high seepage pressures may consolidate the material, material may be washed from the specimen, or fine particles may be washed downstream and plug the effluent end of the test specimen. These effects can increase or decrease hydraulic conductivity. If no gradient is specified by the requester, the guidelines given in Table 1 may be followed.

Table 1 — Guidelines for hydraulic conductivity

Hydraulic conductivity m/s	**Recommended maximum hydraulic gradient**
10^{-5} to 10^{-6}	2
10^{-6} to 10^{-7}	5
10^{-7} to10^{-8}	10
10^{-8} to 10^{-9}	20
less than 10^{-9}	50

7.5.2 Steady-state conditions

Evaluation of the hydraulic conductivity from Darcy’s law using either the inflow or the outflow rate during the transient portion of the test is not valid, and needs to be delayed untill steady-state is reached and confirmed as described in 7.5.3 to 7.5.5.

7.5.3 Constant-head test (Method A)

Measure and record the head loss across the test specimen. The head loss across the specimen shall be kept constant. Measure and record periodically the volume outflow. Also measure and record any changes in height of the test specimen, if being monitored.

Continue permeation until at least four values for hydraulic conductivity are obtained over an interval of time in which

a) the ratio of outflow rate to inflow rate is between 0,75 and 1,25, and

b) the hydraulic conductivity is steady.

The hydraulic conductivity shall be considered steady if four or more consecutive hydraulic conductivity determinations fall within ± 25 % of the mean value for $k \leqslant 1 \times 10^{-10}$ m/s or within ± 50 % for $k < 1 \times 10^{-10}$ m/s, and a plot of the hydraulic conductivity versus time shows no significant upward or downward trend.

7.5.4 Falling-head tests (Methods B and C)

7.5.4.1 General

Measure and record the head loss across the test specimen. For falling-head tests, at no time shall the loss in applied head across the specimen be less than 75 % of the initial (maximum) head loss during each individual hydraulic conductivity determination. Periodically measure and record any changes in the height of the specimen, if being monitored.

Continue permeation until at least four values for hydraulic conductivity are obtained over an interval of time in which

a) the ratio of outflow to inflow rate is between 0,75 and 1,25, and

b) the hydraulic conductivity is steady.

7.5.4.2 Test with constant tail-water level (Method B)

If the water pressure at the downstream (tail-water) end of the test specimen is kept constant, periodically measure and record either the volume of inflow or the level of water in the inlet standpipe; measure and record the volume of outflow from the test specimen.

7.5.4.3 Test with increasing tail-water level (Method C)

If the water pressure at the downstream end of the test specimen rises during an interval of time, periodically measure and record either the volume of inflow and outflow or the changes in water levels in the inlet and outlet standpipes.

7.5.5 Test with constant flow rate (Method D)

Initiate permeation of the specimen by imposing a constant flow rate. Choose the flow rate so the hydraulic gradient does not exceed the value specified, or if none is specified, the value recommended in 7.5.1. Periodically measure the rate of inflow, the rate of outflow, and head loss across the test specimen. Also, measure and record any changes in specimen height, if being monitored. Continue permeation until at least four values of hydraulic conductivity are obtained over an interval of time in which a) the ratio of inflow to outflow rates is between 0,75 and 1,25, and b) hydraulic conductivity is steady (see 7.5.3).

7.6 Final dimensions of the specimen

After completion of permeation, reduce the applied confining, influent and effluent pressures in a manner that does not generate significant volume change of the test specimen. Then carefully disassemble the permeate cell and remove the specimen. Measure and record the final height, diameter, total mass and the water content of the specimen.

8 Calculation

8.1 Tests at constant head and constant flow rate (Methods A and D)

Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{V \cdot l}{A \cdot t \cdot h} \quad (1)$$

where

k is the hydraulic conductivity, in metres per second;

V is the volume of flow, taken as the average of inflow and outflow, in cubic metres;

l is the length of specimen along the path of flow, in metres;

A is the cross-sectional area of the specimen, in square metres;

t is the interval of time, in seconds, over which the flow V occurs;

h is the difference in hydraulic head across the specimen, in metres of water.

8.2 Falling-head tests

8.2.1 Constant tail-water pressure (Method B)

Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{a_{\text{in}} \cdot l}{A \cdot t} \ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

where

a_{in} is the cross-sectional area of the reservoir containing the inflow liquid, in square metres;

l is the length of the specimen (measured in the flow direction), in metres;

A is the cross-sectional area of the specimen, in square metres;

t is the elapsed time, in seconds, between determinations of h_1 and h_2;

h_1 is the head loss across the specimen at time t_1, in metres, and

h_2 is the head loss across the specimen at time t_2, in metres.

8.2.2 Increasing tail-water pressure (Method C)

Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{a_{\text{in}} \cdot a_{\text{out}} \cdot l}{A \cdot t \cdot (a_{\text{in}} + a_{\text{out}})} \ln\left(\frac{h_1}{h_2}\right) \tag{3}$$

where

a_{in} is the cross-sectional area of the reservoir containing the inflow liquid, in square metres;

a_{out} is the cross-sectional area of the reservoir containing the outflow liquid, in square metres;

l is the length of the specimen, in metres;

A is the cross-sectional area of the specimen, in square metres;

t is the elapsed time, in seconds, between determination of h_1 and h_2;

h_1 is the head loss across the specimen at time t_1, in metres, and

h_2 is the head loss across the specimen at time t_2, in metres.

8.2.3 Correction for temperature

Correct the hydraulic conductivity to that for 20 °C, using the correction factor R_T from Table 2, as follows:

$$k_{20} = R_T k \tag{4}$$

Table 2 — Correction factor R_T for viscosity of water at various temperatures

Temperature °C	R_T	Temperature °C	R_T
0	1,783	25	0,889
1	1,723	26	0,869
2	1,664	27	0,850
3	1,611	28	0,832
4	1,560	29	0,814
5	1,511	30	0,797
6	1,465	31	0,780
7	1,421	32	0,764
8	1,379	33	0,749
9	1,339	34	0,733
10	1,301	35	0,719
11	1,265	36	0,705
12	1,230	37	0,692
13	1,197	38	0,678
14	1,165	39	0,665
15	1,135	40	0,653
16	1,106	41	0,641
17	1,077	42	0,629
18	1,051	43	0,618
19	1,025	44	0,607
20	1,000	45	0,598
21	0,976	46	0,585
22	0,953	47	0,575
23	0,931	48	0,565
24	0,910	49	0,556

9 Test report

The test report shall include the following information:

a) sample identification;

b) any special selection and preparation process, such as removal of stones or other materials, or indication of their presence, if undisturbed specimen;

c) descriptive information on method of compaction;

d) initial dimensions of the specimen;

e) initial water content and dry unit mass of the specimen;

f) type of permeant liquid used;

g) magnitude of total back-pressure;

h) maximum and minimum effective consolidation stresses;

i) height of specimen after completion of consolidation, if monitored;

j) range of hydraulic gradient used;

k) final length, diameter, water content, dry unit mass and degree of saturation of the test specimen;

l) average hydraulic conductivity for the last four determinations of hydraulic conductivity (obtained as described in 7.5.3 and 7.5.4), reported to two significant figures, e.g. $7,1 \times 10^{-10}$ m/s, and expressed in metres per second (plus additional units, if requested or customary);

m) preferably also a graph or table of hydraulic conductivity versus time or pore volumes of flow.

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