

Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties

PART 1: SUGGESTED METHODS FOR DETERMINING WATER CONTENT, POROSITY, DENSITY, ABSORPTION AND RELATED PROPERTIES

NOTES

(i) Mechanical significance of porosity and density data

The presence of pores in the fabric of a rock material decreases its strength, and increases its deformability. A small volume fraction of pores can produce an appreciable mechanical effect.

Information on the porous nature of rock materials is frequently omitted from petrological descriptions, but is required if these descriptions are to be used as a guide to mechanical performance. Sandstones and carbonate rocks in particular occur with a wide range of porosities and hence of mechanical character; igneous rocks that have been weakened by weathering processes also have typically high porosities.

Most rocks have similar grain densities and therefore have porosity and dry density values that are highly correlated (see note (v) equation 4). A low density rock is usually highly porous. It is often sufficient, therefore, to quote values for porosity alone, but a complete description requires values for both porosity and density.

Microscopic techniques used to determine volumetric content of mineral grains, do not provide a sufficiently accurate estimate of volumetric pore content, and experimental techniques are required. However, microscopy and also techniques such as mercury injection and permeability testing, can provide useful supplementary information on the shape and size of pores.

(ii) Nature of the rock sample

A representative sample for testing should generally comprise several rock lumps, each an order of magnitude larger than the largest grain or pore size. Micro-fissures of similar size to that of a rock will cause erratic results; their presence should be noted and if possible the lump size increased or reduced to specifically include or exclude the influence of such fissures.

The sample should if possible be large, to minimise the influence of experimental error. Alternative test methods are available calling for samples in different form; selection from among these should be based on the nature of rock to be tested.

(iii) Rock constituents

The following terms and symbols will be used to denote the masses and volumes of rock constituents when calculating physical properties such as porosity or density.

Grains (the solid component of the sample), mass M_s , volume V_s

Pore water, mass M_w and volume V_w

Pore air, zero mass and volume V_a

Pores (voids), with volume $V_v = V_w + V_a$

Bulk sample mass $M = M_s + M_w$

Bulk sample volume $V = V_s + V_v$

Density of water $\rho_w =$ mass of water per unit volume

(iv) Definitions, terminology and preferred S.I. units

Those physical properties pertinent to the methods of test about to be described may be defined in terms of the rock sample constituents listed above.

$$\text{Water content } w = \frac{M_w}{M_s} \times 100 \quad (\%)$$

$$\text{Degree of saturation } S_r = \frac{V_w}{V_v} \times 100 \quad (\%)$$

$$\text{Porosity } n = \frac{V_v}{V} \times 100 \quad (\%)$$

$$\text{Void ratio } e = \frac{V_v}{V_s} \quad (-)$$

$$\text{Density} = \text{bulk density } \rho = \frac{M}{V} = \frac{M_s + M_w}{V} \quad \frac{(\text{kg})}{(\text{m}^3)}$$

(mass density)

Relative density d (specific gravity)	$= \frac{\rho}{\rho_w}$	(-)	The sample should not take up water in the interval between drying and mass determination. Where necessary the sample container should be covered with an airtight lid and stored in a dessicator during cooling.
Dry density ρ_d	$= \frac{M_s}{V}$	$\frac{(\text{kg})}{(\text{m}^3)}$	
Dry relative density (dry) d_d (specific gravity)	$= \frac{\rho_d}{\rho_w}$	(-)	(vii) <i>Determination of the bulk volume V</i> <i>Caliper method.</i> The bulk volume of specimens in the form of regularly shaped prisms or cylinders may be calculated from vernier or micrometer caliper measurements. An average of several readings for each dimension, each accurate to 0.1 mm, should be used in the calculation of bulk volume.
Saturated density ρ_{sat}	$= \frac{M_s + V_v \rho_w}{V}$	$\frac{(\text{kg})}{(\text{m}^3)}$	<i>Buoyancy method.</i> The bulk volume of regular or irregular specimens may be calculated using Archimedes principle, from the difference between saturated-surface-dry and saturated-submerged sample weights. The method is not suited to friable, swelling or slaking rocks.
Saturated relative density d_{sat} (saturated specific gravity)	$= \frac{\rho_s}{\rho_w}$	(-)	The sample is then transferred underwater to a basket in an immersion bath. Its saturated-submerged least one hour, with periodic agitation to remove trapped air.
Grain density ρ_s (density of solids)	$= \frac{M_s}{V_s}$	$\frac{(\text{kg})}{(\text{m}^3)}$	The sample is then transferred underwater to a basket in an immersion bath. Its saturated-submerged mass M_{sub} is determined to an accuracy of 0.1 g from the difference between the saturated-submerged mass of the basket plus sample and that of the basket alone.
Grain relative density d_s (grain specific gravity)	$= \frac{\rho_s}{\rho_s}$	(-)	The sample is then removed from the immersion bath and surface dried with a moist cloth, care being taken to remove only surface water and to ensure that no rock fragments are lost. Its saturated-surface-dry mass M_{sat} is determined to an accuracy of 0.1 g.
Unit weight γ	$= \rho g$	$\frac{(\text{N})}{(\text{m}^3)}$	The sample bulk volume is calculated as

(v) *Interdependence equations*

The physical properties defined above are interrelated, so that any one property may be calculated if others are known.

For simplicity only three properties will be referred to in the text, namely, water content, porosity and dry density of rock. The equations listed below may be used to calculate any of the remaining properties from these three.

Whereas water content, degree of saturation and porosity are usually expressed as percentages, the void ratio is usually expressed as a dimensionless ratio. The following interdependence equations have been given to conform to the above.

$$S_r = \frac{100w\rho_d}{n\rho_w} \quad (\%)$$

$$e = \frac{n}{100 - n} \quad (-)$$

$$\rho = \left(1 + \frac{w}{100}\right)\rho_d \quad \frac{(\text{kg})}{(\text{m}^3)}$$

$$\rho_s = \frac{100\rho_d}{100 - n} \quad \frac{(\text{kg})}{(\text{m}^3)}$$

(vi) *Determination of the grain mass M_s*

The grain mass M_s of the sample is defined as the equilibrium mass of the sample after oven drying at a temperature of 105°C.

A thermostatically controlled, ventilated drying oven capable of maintaining a temperature of 105°C accurate to 3°C for a period of at least 24 h is required.

The sample is regarded as 'oven dry' when successive mass determinations at intervals of 4 hr yield values differing by less than 0.1% of the sample mass.

Mercury displacement method. High surface tension prevents mercury penetrating all but the largest pores in rock. The specimen is forced under mercury and its volume determined from the displaced fluid volume. A calibrated tube may be incorporated in the apparatus for this purpose, or the displacement may be measured by a micrometer screw gauge—electric contact technique. Alternatively a technique may be employed where the displaced mercury volume is obtained by mass determination. The apparatus should give results accurate to 0.5% of the specimen bulk volume, and should be periodically calibrated using a standard sphere or cylinder.

Water displacement method. The bulk volume of a saturated-surface-dry sample may be determined by water displacement using a technique similar to that for mercury displacement. Alternatively the dry or partially dry sample may be coated in wax or plastic and its bulk volume determined from the water volume displaced by the coated sample, corrected for the volume of coating material. The method requires accurate determination of coating volume and is best applied to large bulk samples where other techniques are impractical.

(viii) Determination of pore volume (volume of voids) V_v

Saturation method—the pore volume of a rock sample may be determined from the difference between saturated-surface-dry and oven-dry masses. The sample is saturated by water immersion in a vacuum and its saturated-surface-dry mass M_{sat} is determined. It is then oven dried to determine the grain mass M_s .

The pore volume V_v is calculated as

$$V_v = \frac{M_{\text{sat}} - M_s}{\rho_w}$$

The Washburn–Bunting method (Washburn & Bunting, 1922). A rock specimen is oven-dried and immersed in mercury. The pressure on the mercury is reduced that the pore air expands, leaves the rock and is trapped above the mercury column. The volume of pore air V_a is measured directly in a calibrated tube, after pressure has been equalised with that of the atmosphere. The method is rapid but is best suited to rocks with high porosity.

(ix) Determination of grain volume V_s

Boyle's law method. The pressure-volume relationship for a container filled with gas only is obtained, then for the same container filled with specimen plus gas. The difference in compressibility is due to the volume V_s of incompressible grains, and this volume may be calculated from the results. One type of Boyle's law single-cell porosimeter employs a graduated mercury pump to measure volume displacement, together with a Bourdon gauge to measure pressure change. Boyle's law double cell techniques employ pressure equalization between two containers at different initial pressures.

Pulverization method. After determination of bulk volume and grain mass, the oven-dry sample is pulverized and its grain volume G_v determined by displacement of an equivalent volume of liquid (e.g. toluene) in a volumetric flask.

Porosity calculated from bulk volume and grain volume using the pulverization method is termed *total* porosity, since the pore volume obtained includes that of 'closed' pores. Other techniques give *effective* porosity values since they measure the volume of interconnected pores only.

1. SUGGESTED METHOD FOR DETERMINATION OF THE WATER CONTENT OF A ROCK SAMPLE

1. SCOPE

This test is intended to measure the mass of water contained in a rock sample as a percentage of the oven-dry sample mass.

2. APPARATUS

(a) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 24 hr.

(b) A sample container of non-corrodible material, including an airtight lid.

(c) A dessicator to hold sample containers during cooling.

(d) A balance of adequate capacity, capable of weighing to an accuracy of 0.01% of the sample weight.

3. PROCEDURE

(a) The container with its lid is cleaned and dried, and its mass A determined.

(b) A representative sample comprised at least 10 lumps each having either a mass of at least 50 g or a minimum dimension of ten times the maximum grain size, whichever is the greater, is selected. For *in situ* water content determination sampling, storage and handling precautions should be such that water content remains within 1% of the *in situ* value.

(c) The sample is placed in the container, the lid replaced and the mass B of sample plus container determined.

(d) The lid is removed and the sample dried to constant mass at a temperature of 105°C.

(e) The lid is replaced and the sample allowed to cool in the dessicator for 30 min. The mass C of sample plus container is determined.

4. CALCULATION

$$\begin{aligned} \text{Water content } w &= \frac{\text{pore water Mass } M_v}{\text{grain Mass } M_s} \times 100\% \\ &= \frac{B - C}{C - A} \times 100\%. \end{aligned}$$

5. REPORTING OF RESULTS

The water content should be reported to the nearest 0.1% stating whether this corresponds to *in situ* water content, in which case precautions taken to retain water during sampling and storage should be specified.

2. SUGGESTED METHOD FOR POROSITY/DENSITY DETERMINATION USING SATURATION AND CALIPER TECHNIQUES

1. SCOPE

(a) This test is intended to measure the porosity, the dry density and related properties of a rock sample in the form of specimens of regular geometry.

(b) The method should only be used for non-friable, coherent rocks that can be machined and do not appreciably swell or disintegrate when oven dried or immersed in water. The method is recommended when regularly shaped specimens are required for other test purposes.

2. APPARATUS

- (a) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 24 hr.
- (b) A dessicator to hold specimens during cooling.
- (c) A measuring instrument such as vernier or micrometer caliper, capable of reading specimen dimensions to an accuracy of 0.1 mm.
- (d) Vacuum saturation equipment such that the specimens can be immersed in water under a vacuum of less than 800 Pa (6 torr) for a period of at least one hour.
- (e) A balance of adequate capacity, capable of determining the mass of a specimen to an accuracy of 0.01%.

3. PROCEDURE

- (a) At least three specimens from a representative sample of a material are machined to conform closely to the geometry of a right cylinder or prism. The minimum size of each specimen should either be such that its mass is at least 50 g (for an average density rock a cube with sides of 27 mm will have sufficient mass) or such that its minimum dimension is at least ten times the maximum grain size, whichever is the greater.
- (b) The specimen bulk volume V is calculated from an average of several caliper readings for each dimension. Each caliper reading should be accurate to 0.1 mm.
- (c) The specimen is saturated by water immersion in a vacuum of less than 800 Pa (6 torr) for a period of at least 1 hr, with periodic agitation to remove trapped air.
- (d) The specimen is removed and surface dried using a moist cloth, care being taken to remove only surface water and to ensure that no fragments are lost. Its saturated-surface-dry mass M_{sat} is determined.
- (e) The specimen is dried to constant mass at a temperature of 105°C, allowed to cool for 30 min in a dessicator, and its mass is determined to give grain mass M_s . Specimens in this test are generally of sufficient coherence not to require containers, but these should be used if the rock is at all friable or fissile.

4. CALCULATIONS

$$\text{Pore volume} \quad V_v = \frac{M_{sat} - M_s}{\rho_w}$$

$$\text{Porosity} \quad n = \frac{100V_v}{V} \%$$

$$\text{Dry density of rock} \quad \rho_d = \frac{M_s}{V}$$

5. REPORTING OF RESULTS

- (a) Individual results for at least three specimens per rock sample should be reported, together with average results for the sample.

(b) Density values should be given to the nearest 10 kg/m³ and porosity values to the nearest 0.1%.

(c) The report should specify that bulk volume was obtained by caliper measurement and that pore volume was obtained by water saturation.

3. SUGGESTED METHOD FOR POROSITY/DENSITY DETERMINATION USING SATURATION AND BUOYANCY TECHNIQUES

1. SCOPE

- (a) The test is intended to measure the porosity, the dry density and related properties of a rock sample in the form of lumps or aggregate of irregular geometry. It may also be applied to a sample in the form of specimens of regular geometry.
- (b) The method should only be used for rocks that do not appreciably swell or disintegrate when oven-dried and immersed in water.

2. APPARATUS

- (a) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 24 hr.
- (b) A sample container of non-corrodible material, including an air-tight lid.
- (c) A dessicator to hold sample containers during cooling.
- (d) Vacuum saturation equipment such that the sample can be immersed in water under a vacuum of less than 800 Pa (6 torr) for a period of at least 1 hr.
- (e) A balance of adequate capacity, capable of determining the mass of a specimen to an accuracy of 0.01%.
- (f) An immersion bath and a wire basket or perforated container, such that the sample immersed in water can be freely suspended from the stirrup of the balance to determine the saturated-submerged mass. The basket should be suspended from the balance by a fine wire so that only the wire intersects the water surface in the immersion bath.

3. PROCEDURE

- (a) A representative sample comprising at least 10 lumps of regular or irregular geometry, each having either a mass of at least 50 g or a minimum dimension of at least 10 times the maximum grain size, whichever is the greater, is selected. The sample is washed in water to remove dust.
- (b) The sample is saturated by water immersion in a vacuum of less than 800 Pa (6 torr) for a period of at least one hour, with periodic agitation to remove trapped air.
- (c) The sample is then transferred under water to the basket in the immersion bath. Its saturated-submerged mass M_{sub} is determined to an accuracy of 0.1 g from the difference between the saturated-submerged

mass of the basket plus sample and that of the basket alone.

(d) The sample container with its lid is cleaned and dried, and its mass A is determined.

(e) The sample is removed from the immersion bath and surface-dried with a moist cloth, care being taken to remove only surface water and to ensure that no rock fragments are lost. The sample is transferred to the sample container, the lid replaced, and the mass B of saturated-surface-dry sample plus container is determined.

(f) The lid is removed and the sample dried to constant mass at a temperature of 105°C, the lid replaced and the sample allowed to cool for 30 min in a desiccator. The mass C of oven-dry sample plus container is measured.

4. CALCULATIONS

4. Saturated-surface-dry mass	$M_{\text{sat}} = B - A$
Grain weight	$M_s = C - A$
Bulk volume	$V = \frac{M_{\text{sat}} - M_{\text{sab}}}{\rho_w}$
Pore volume	$V_v = \frac{M_{\text{sat}} - M_s}{\rho_w}$
Porosity	$n = \frac{100V_v}{V} \%$
Dry density of rock	$\rho_d = \frac{M_s}{V}$

5. REPORTING OF RESULTS

(a) The report should include porosity and dry density values for the sample, and should specify that bulk volume was obtained by a buoyancy technique and that pore volume was obtained by water saturation.

(b) Density values should be given to the nearest 10 kg/m³ and porosity values to the nearest 0.1%.

4. SUGGESTED METHOD FOR POROSITY/DENSITY DETERMINATION USING MERCURY DISPLACEMENT AND GRAIN SPECIFIC GRAVITY TECHNIQUES

1. SCOPE

(a) The test is intended to measure the porosity, the dry density and related properties of a rock sample in the form of lumps or aggregate of irregular geometry. It is particularly suitable if the rock material is liable to swell or disintegrate if immersed in water. The test may also be applied to regularly shaped rock specimens or to coherent rock materials, but other techniques are usually found more convenient in these cases.

2. APPARATUS

(a) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 24 hr. It should have forced ventilation exhausting to outside atmosphere.

(b) Specimen containers of non-corrodible material, including airtight lids.

(c) A desiccator to hold specimen containers during cooling.

(d) A balance of adequate capacity, capable of mass determination to 0.001 g.

(e) A mercury-displacement volume measuring apparatus capable of measuring specimen volume to 0.5%.

(f) Grinding equipment to reduce the sample to a pulverized powder less than 150 μm in grain size.

(g) A calibrated volumetric flask and stopper (conveniently 50 cm³).

(h) A constant temperature water bath.

(i) A vacuum apparatus capable of maintaining a vacuum with a pressure of less than 800 Pa (6 torr).

(j) A soft brush of camel hair or of a similar softness.

3. PROCEDURE

(a) A representative sample is selected comprising at least ten rock lumps, the shape and size of lumps suiting the capabilities of the volume measuring apparatus. The minimum size of each lump should preferably be either such that its mass exceeds 50 g or such that its minimum dimension is at least ten times the maximum grain size, whichever is the greater. Specimens of swelling or fissile rock should be sampled and stored to retain water content to within 1% of its *in situ* value prior to testing.

(b) Each specimen is brushed to remove loose material and its volume V is measured by mercury displacement. Mercury adhering to the specimen is carefully removed, ensuring that no rock fragments are lost.

(c) The specimen container with its lid is cleaned, dried and its mass A is determined.

(d) The specimen is placed in the container, the lid replaced and mass B of container plus specimen at initial water content is determined.

(e) The lid is removed and the specimen oven dried to constant mass at a temperature of 105°C and allowed to cool for 30 min in a desiccator. The mass C of container plus oven-dry specimen is determined.

(f) Steps (b)–(e) are repeated for each specimen in the sample.

(g) Together the specimen was crushed and ground to a grain size no exceeding 150 μm. A number of representative sub samples of about 15 g of the pulverized material are selected and oven-dried.

(h) The mass D of a clean, dry volumetric flask plus stopper is determined to 0.001 g.

(i) The flask is filled with a fluid such as toluene that is non-reactive with the rock, is brought to equilibrium temperature in the constant temperature bath, and the

liquid level is adjusted accurately to the 50 cm³ graduation. The flask is removed, stoppered and its mass E determined to 0.001 g.

(j) The flask is emptied and dried, and the 15 g subsample of dry, pulverized rock added with the aid of a funnel. The mass F of flask, sample and stopper is measured to 0.001 g.

(k) The flask and subsample are evacuated for about 20 min and sufficient fluid added to thoroughly wet the sample. Further fluid is then added and the flask carefully evacuated to remove air. The flask is replaced in the constant temperature water bath and the liquid level adjusted accurately to the 50 cm³ graduation.

(l) The stoppered flask with its contents is allowed to cool and its mass G is determined to 0.001 g.

(m) Steps (j)–(l) are repeated for each subsample of pulverized material.

4. CALCULATIONS

(a) Water content $w = \frac{B - C}{C - A} \times 100\%$

(b) Grain density $\rho_s = \frac{F - D}{V_f \left(1 - \frac{G - F}{E - D}\right)}$

where V_f = calibrated volume of flask, usually 50 cm³

(c) Grain mass $M_s = C - A$

(d) Dry density of rock $\rho_d = \frac{M_s}{V}$

(e) Porosity $n = \frac{100(\rho_s - \rho_d)}{\rho_s} \%$

5. REPORTING OF RESULTS

(a) Individual dry density values for each specimen in the sample should be reported, together with average values for the sample. Porosity values for each subsample should also be reported together with the average value.

(b) The report should specify that the bulk volume was obtained using a mercury displacement technique, and that the porosity was calculated from grain volume measurements using a pulverization technique.

(c) The grain density or grain specific gravity for the sample should be reported. The water content at which bulk volume measurement took place should be specified, stating whether this corresponds to *in situ* water content.

(d) Density values should be given to the nearest 10 kg/m³ and porosity values to the nearest 0.1 percent.

5. SUGGESTED METHOD FOR POROSITY/DENSITY DETERMINATION USING MERCURY DISPLACEMENT AND BOYLE'S LAW TECHNIQUES

1. SCOPE

(a) This test is intended to measure the porosity, the dry density and related properties of a rock sample. A sample in the form of specimens of a specific size and shape to suit the apparatus is usually required to ensure accurate results.

(b) The method should only be used for rocks that do not shrink appreciably during oven-drying.

2. APPARATUS

The procedure given below relates to a test using the Kobe type of single cell Boyle's Law porosimeter (Fig. 1). Any similar apparatus of equivalent accuracy may however be used. The apparatus consists essentially of the following:

Oven drying equipment:

(a) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 24 hr.

(b) A specimen container of non-corrodible material including an airtight lid.

(c) A dessicator to hold specimen containers during cooling.

(d) A balance of adequate capacity, capable of determining the mass of a specimen to an accuracy of 0.01%. A Boyle's law porosimeter such as a Kobe porosimeter having the following features:

(e) A mercury screw-piston pump with micrometer graduated to measure the volume of displaced mercury to an accuracy of 0.01 cm³. Conveniently one turn of the screw pump changes the volume of the specimen chamber by 1 cm³.

(f) A specimen chamber with removable cap to allow insertion of the specimen.

(g) A sight glass inscribed with a reference line, an electric indicator-contact or other means of registering a mercury datum level in the cap.

(h) A gas inlet and outlet, each with a shutoff valve, also a source of inert gas such as helium. Air may be used with some loss of accuracy, but must be adequately dried.

(i) A precision pressure gauge or pressure transducer with a range from 100 kPa to about 400 kPa, connected to measure the gas pressure in the specimen chamber.

3. PROCEDURE

(a) At least three specimens are selected from a representative sample of material and each specimen is tested separately to obtain an average result for the sample. The size and shape of a specimen should allow only a small clearance with the specimen chamber to

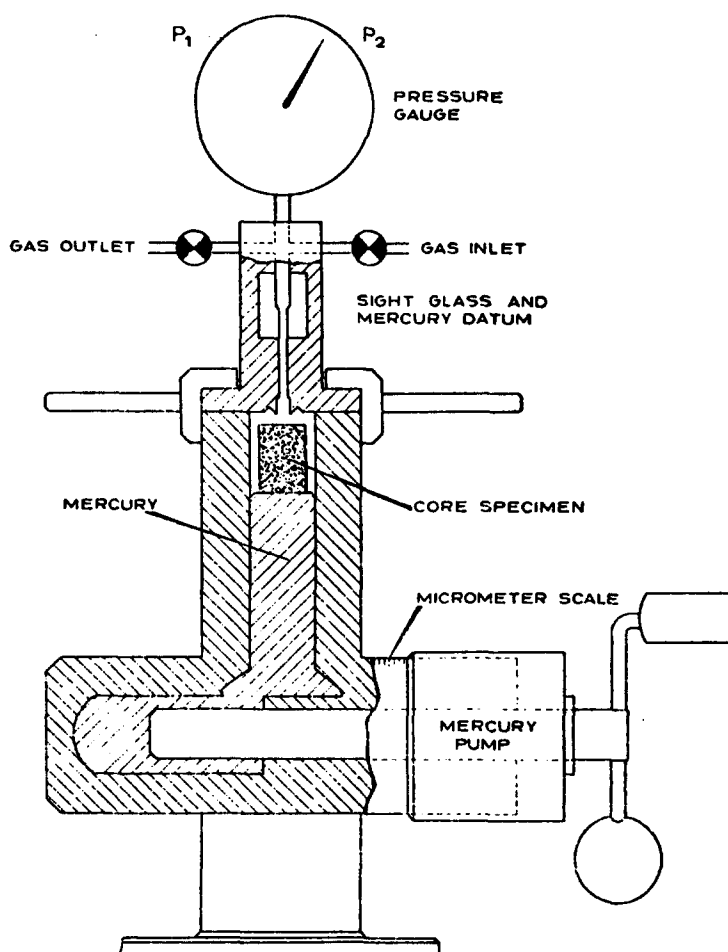


Fig. 1. Schematic diagram of a Kobe Boyle's law porosimeter.

ensure accurate results. The chamber is usually cylindrical and accepts a standard size of rock core. The size of each specimen should preferably be either such that its mass is a minimum of 50 g or that its minimum dimensions are at least ten times the maximum grain size, whichever is the greater.

(b) The specimen container with its lid is cleaned, dried and its mass A is determined.

(c) The specimen is placed in the container, dried to constant mass at a temperature of 105°C and the lid is replaced. It is allowed to cool for 30 min in a dessicator, and the mass B of oven-dry specimen plus container is determined.

(d) Use of the porosimeter: the mercury pump reading at the start of each compression or displacement cycle is termed the 'start point'. Inlet and outlet valves are closed at the start of a compression cycle so that the initial pressure P_1 is atmospheric. The start point and also the pressure P_2 at the end of a compression cycle are usually selected as standard for the apparatus, to ensure that the specimen still floats on mercury at the end of the cycle, hence avoiding imbibition that might occur if specimens became deeply immersed.

(e) To flush the specimen chamber with gas; inlet valve is closed, the outlet opened and the pump advanced until mercury reached the datum. The outlet is then half shut, the inlet opened and the pump

retracted to beyond the start point. The inlet, then the outlet valve is closed.

(f) To determine the compression factor C_f for the cell: the specimen chamber is first flushed with gas, the outlet valve opened and the pump advanced to the start point. The outlet valve is shut with the specimen chamber at atmospheric pressure P_1 . The pump is advanced and a micrometer reading C_0 taken when the pressure reaches P_2 . The chamber is again flushed with gas, and with the outlet valve open the pump is advanced to a new start point 10 cm^3 beyond the original one. The outlet is closed with the chamber at atmospheric pressure P_1 and the pump advanced, a micrometer reading C_1 being taken when the pressure again reaches P_2 .

The compression factor is computed from the formula:

$$C_f = \frac{10}{10 - (C_0 - C_1)}$$

This factor is dependent on ambient pressure and should be periodically checked.

(g) Each test comprises a displacement stroke followed by a compression stroke with the specimen chamber empty (a blank run), then a displacement

stroke followed by a compression stroke with the specimen in the chamber. The procedure is as follows:

(h) With the inlet valve shut and the outlet open, the pump is advanced until the mercury reaches the datum. The micrometer reading R_1 is recorded.

(i) The chamber is flushed with gas, the pump advanced to the start point and the valves closed with the chamber at atmospheric pressure P_1 . The pump is advanced and a micrometer reading R_2 recorded when the pressure reaches P_2 .

(j) The specimen is removed from the dessicator and inserted in the chamber. The chamber is flushed with gas and step (h) repeated, recording the displacement stroke micrometer reading R_3 at which mercury reaches the datum.

(k) Step (i) is repeated, recording the compression stroke micrometer reading R_4 when the pressure again reaches P_2 .

4. CALCULATIONS

Bulk volume	$B_v = R_3 - R_1$
Grain volume	$G_v = C_f(R_4 - R_2)$
Grain weight	$G_w = B - A$
Porosity	$n = \frac{B_v - G_v}{B_v} \times 100\%$
Dry density of rock	$\rho_d = G_w/B_v$

5. REPORTING OF RESULTS

(a) Individual dry density and porosity values for each specimen in the sample should be recorded, together with average values for the sample.

(b) The report should specify that the bulk volume was obtained using a mercury displacement technique, and that the porosity was calculated from grain volume measurements using a Boyle's law technique.

(c) Density values should be given to the nearest kg/m^3 and porosity values to the nearest 0.1 porosity percent.

6. SUGGESTED METHOD FOR VOID INDEX DETERMINATION USING THE QUICK ABSORPTION TECHNIQUE

1. SCOPE

(a) This test is intended to measure the void index, defined as the mass of water contained in a rock sample after a one hour period of immersion, as a percentage of its initial dessicator-dry-mass.

(b) The index is correlated with porosity, hence also with such properties as degree of weathering or alteration. The test is designed to call for a minimum of equipment. Where suitable equipment is available,

however, the porosity and density of the rock material should be determined directly using techniques such as those proposed earlier (methods 2-5).

(c) The test should only be used for rocks that do not appreciably disintegrate when immersed in water.

2. APPARATUS

(a) A sample container of non-corrodible material, water tight and of sufficient capacity to contain the sample packed in dehydrated silica gel.

(b) A quantity of dehydrated silica gel.

(c) A balance of adequate capacity, accurate to 0.5 g.

3. PROCEDURE

(a) A representative sample is selected comprising at least ten rock lumps. The size of each lump should be such that its mass exceeds 50 g or such that its minimum dimension is at least ten times the maximum grain size, whichever is the greater.

(b) The sample in an air-dry condition is packed into the container, each lump separated from the next and surrounded by crystals of dehydrated silica gel. The container is left to stand for a period of 24 hr.

(c) The container is emptied, the sample removed, brushed clean of loose rock and silica gel crystals and its mass A determined to 0.5 g.

(d) The sample is replaced in the container and water is added until the sample is fully immersed. The container is agitated to remove bubbles of air and is left to stand for a period of one hour.

(e) The sample is removed and surface-dried using a moist cloth, care being taken to remove only surface water and to ensure that no fragments are lost. The mass B of the surface-dried sample is determined to 0.5 g.

4. CALCULATION

$$\text{Void index} \quad I_v = \frac{B - A}{A} \times 100\%.$$

5. REPORTING OF RESULTS

(a) The void index for the sample should be reported to the nearest 1%.

(b) The report should specify that the void index is defined as the water content after dessicator drying followed by a one-hour period of immersion.

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PART 2: SUGGESTED METHODS FOR DETERMINING SWELLING AND SLAKE-DURABILITY INDEX PROPERTIES

NOTES

(i) *Mechanical significance of swelling and slake-durability data*

An abundant class of rock materials, notably those with high clay content, are prone to swelling, weakening or disintegration when exposed to short term weathering processes of a wetting and drying nature. Special tests are necessary to predict this aspect of mechanical performance. These tests are index tests; they are best used in classifying and comparing one rock with another. The swelling strain index should not, for example, be taken as the actual swelling strain that would develop *in situ*, even under similar conditions of loading and of water content.

These tests simulate natural wetting and drying processes. Other types of test are better suited to estimating resistance to such weathering agencies as frost, salt crystallization or attrition (De Puy, 1965).

(ii) *Nature of the rock sample*

Where possible undisturbed rock specimens should be tested, since rock fabric has an important effect on the other properties to be measured. Where the sample is too weak or too broken to allow preparation of undisturbed specimens, as is usually the case with joint-filling materials for example, the swelling tests may be carried out on remoulded specimens. Remoulding should be according to standard procedures for soil compaction, and the procedure followed should be described when reporting the test results.

(iii) *Application of the tests to hard and soft rocks*

These tests are commonly required for classification or characterization of the softer rock materials. They may also be used, however, for characterization of harder rocks where the rock condition, its advanced state of weathering for example, indicates that they are appropriate.

Rocks that disintegrate during the tests should be further characterized using soil classification tests such

as determination of the liquid and plastic limits, the grain size distribution, or the content and type of clay minerals present.

1. SUGGESTED METHOD FOR DETERMINATION OF THE SWELLING PRESSURE INDEX UNDER CONDITIONS OF ZERO VOLUME CHANGE

1. SCOPE

This test is intended to measure the pressure necessary to constrain an undisturbed rock specimen at constant volume when it is immersed in water.

2. APPARATUS

The apparatus may be adapted from that used for soil consolidation testing, and consists essentially of the following:

(a) A metal ring for rigid radial restraint of the specimen, polished and lubricated to reduce side friction and of depth at least sufficient to accommodate the specimen.

(b) Porous plates to allow water access at top and bottom of the specimen, the top plate of such a diameter to slide freely in the ring. Filter papers may be inserted between specimen and plates.

(c) A cell to contain the specimen assembly, capable of being filled with water to a level above the top porous plate. The principal features of the cell and specimen assembly are illustrated in Fig. 2.

(d) A micrometer dial gauge or other device reading to 0.0025 mm, mounted to measure the swelling displacement at the central axis of the specimen.

(e) A load measuring device capable of measuring to an accuracy of 1%, the force required to resist swelling.

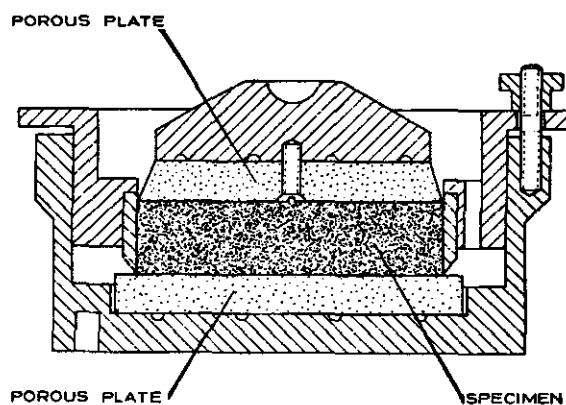


Fig. 2. Cell and specimen assembly for confined swelling tests.

(f) A loading device such as a screw jack, capable of continuous adjustment to maintain the specimen at constant volume as swelling pressure develops. The force should be applied through rigid members to ensure that the porous plates remain flat, a spherical seat allowing rotation of the top porous plate.

3. PREPARATION OF THE TEST SPECIMENS

(a) For testing at natural initial water content, preparation should be such as to retain water content to within 1% of its *in situ* value. Duplicate specimens should be prepared from the same sample, one being used for water content determination and the other for swell testing.

(b) For testing at an artificially controlled initial water content the sample may be brought to equilibrium mass in a constant humidity environment. Duplicate specimens should then be prepared from the same sample, one being used for water content determination and the other for swell testing.

(c) The specimen should conform closely to the geometry of a right cylinder. It should have a diameter not less than 2.5 times its thickness. The thickness should exceed 15 mm or ten times the maximum grain diameter, whichever is greater. The specimen should be a close fit in the ring.

(d) The inclination of bedding or foliation with respect to the specimen axis should be recorded.

4. PROCEDURE

(a) The apparatus is assembled and a small axial force say about 10 kPa is applied to the specimen.

(b) The cell is then flooded with water to cover the top porous plate, and the swelling force is recorded as a function of time elapsed.

(c) The applied force is regularly adjusted to maintain zero specimen swell throughout the test. The thickness of the specimen should be maintained to within 0.01 mm.

(d) Swelling force should continue to be recorded until it reaches a constant level or passes a peak.

5. CALCULATION

The swelling pressure index is calculated as follows:

$$\text{Swelling pressure index} = \frac{F}{A}$$

where: F = maximum axial swelling force recorded during the test; A = cross sectional area of the specimen.

6. REPORTING OF RESULTS

Results should be presented for at least three specimens per sample. The report should include the following information for each specimen:

(a) The swelling pressure index.

(b) The initial water content of the specimen; whether this corresponds to the natural water content, and if so the method of storage prior to testing.

(c) The diameter and thickness of the specimen, together with the inclination of bedding or foliation with respect to the specimen axis.

2. SUGGESTED METHOD FOR DETERMINATION OF THE SWELLING STRAIN INDEX FOR A RADIALLY CONFINED SPECIMEN WITH AXIAL SURCHARGE

1. SCOPE

This test is intended to measure the axial swelling strain developed against a constant axial pressure or surcharge, when a radially confined, undisturbed rock specimen is immersed in water.

2. APPARATUS

The apparatus may be adapted from that used for soil consolidation testing, and consists essentially of the following:

(a) A metal ring for rigid radial restraint of the specimen, polished and lubricated to reduce side friction and of depth at least sufficient to accommodate the specimen when fully swollen.

(b) Porous plates to allow water access at top and bottom of the specimen, the top plate of such a diameter to slide freely in the ring. Filter papers may be inserted between specimen and plates.

(c) A cell to contain the specimen assembly, capable of being filled with water to a level above the top porous plate. The principal features of the cell and specimen assembly are illustrated in Fig. 2.

(d) A micrometer dial gauge or other device reading to 0.0025 mm, mounted to measure the swelling displacement at the central axis of the specimen.

(e) A loading device such as a dead mass, or mass and lever system, capable of applying a sustained pressure of 5 kPa to the specimen, this pressure to be maintained within 1% throughout the swelling of the speci-

men. The force should be applied through rigid members so as to ensure that the porous plates remain flat, a spherical seat allowing rotation of the top porous plate.

3. PREPARATION OF THE TEST SPECIMENS

(a) For testing at natural initial water content, preparation should be such as to retain water content to within 1% of its *in situ* value. Duplicate specimens should be prepared from the same sample, one being used for water content determination and the other for swell testing.

(b) For testing at an artificially controlled initial water content the sample may be brought to equilibrium mass in a constant humidity environment. Duplicate specimens should then be prepared from the same sample, one being used for water content determination and the other for swell testing.

(c) The specimen should conform closely to the geometry of a right cylinder. It should have a diameter not less than four times its thickness. The thickness should exceed 15 mm or ten times the maximum grain diameter, whichever is greater. The specimen should be a close fit in the ring.

(d) The inclination of bedding or foliation with respect to the specimen axis should be recorded.

4. PROCEDURE

(a) The initial thickness and diameter of the specimen are recorded to 0.1%.

(b) The apparatus is assembled and the specimen loaded axially to a surcharge pressure of 3 kPa.

(c) The cell is then flooded with water to cover the top porous plate, and the swelling displacement recorded as a function of time elapsed.

(d) Swelling displacement should continue to be recorded until it reaches a constant level or passes a peak.

5. CALCULATION

The swelling strain index is calculated as follows:

$$\text{Swelling strain index} = \frac{d}{L} \times 100\%$$

where: d = maximum swelling displacement recorded during the test; L = initial thickness of the specimen.

6. REPORTING OF RESULTS

Results should be presented for at least three specimens per sample. The report should clearly indicate that the specimen was radially confined during the swelling test. The report should include the following information for each specimen:

(a) The swelling strain index.

(b) The initial water content of the specimen; whether this corresponds to the natural water content, and if so the method of storage prior to testing.

(c) The initial diameter and thickness of the specimen, together with the inclination of bedding or foliation with respect to the specimen axis.

3. SUGGESTED METHOD FOR DETERMINATION OF THE SWELLING STRAIN DEVELOPED IN AN UNCONFINED ROCK SPECIMEN

1. SCOPE

This test is intended to measure the swelling strain developed when an unconfined, undisturbed rock specimen is immersed in water. The test should only be applied to specimens that do not change their geometry appreciably on slaking; less durable rocks are better tested using a confined swelling test.

2. APPARATUS

The apparatus consists essentially of the following:

(a) A cell to contain the specimen assembly, capable of being filled with water to a level above the top of the specimen. The principal features of the cell and specimen assembly are illustrated in Fig. 3.

(b) A micrometer dial gauge or other device reading to 0.0025 mm, mounted to measure the swelling displacement on the central axis of the specimen. Additional gauges may be employed to simultaneously measure swelling displacements in directions orthogonal to the first.

(c) Bearing plates of glass or other hard material which may be cemented to the specimen with water-stable adhesive. These plates should be small compared with the area of specimen exposed to water, and are positioned at points of gauging and of support to prevent indentation of the specimen.

3. PREPARATION OF THE TEST SPECIMENS

(a) For testing at natural initial water content, preparation should be such as to retain water content to within 1% of its *in situ* value. Duplicate specimens should be prepared from the same sample, one being used for water content determination and the other for swell testing.

(b) For testing at an artificially controlled initial water content the sample may be first prepared into specimens, then brought to equilibrium mass in a constant humidity environment. Duplicate specimens should be prepared from the sample, one being used for water content determination and the other for swell testing.

(c) The specimen may take the form of a right cylinder or a rectangular prism. The minimum speci-

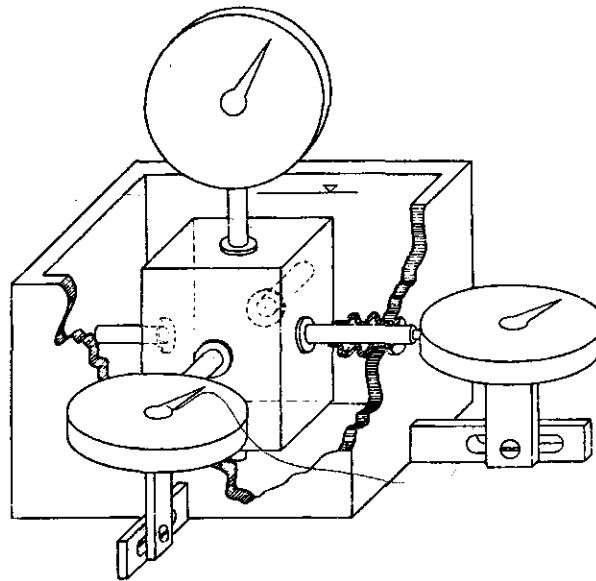


Fig. 3. Cell and specimen assembly for unconfined swelling tests.

men dimension should exceed 15 mm or ten times the maximum grain diameter, whichever is greater.

(d) The specimen should preferably be machined so that an axis is perpendicular to any bedding or foliation. The inclination of the directions of swell measurement with respect to this bedding or foliation should be recorded.

4. PROCEDURE

(a) Gauge points are marked to coincide with the axis or axes of the specimen. The initial specimen dimensions are measured between these gauge points to an accuracy better than 0.1%.

(b) Bearing plates are then positioned at each gauge point and the apparatus assembled. The specimen should be supported only at gauge points on the specimen axes.

(c) The cell is then flooded with water to cover the specimen, and the swelling displacement or displacements recorded as a function of time elapsed.

(d) Swelling displacement should continue to be recorded until it reaches a constant level or passes a peak.

5. CALCULATION

The unconfined swelling is calculated for each direction of measurement as follows:

$$\text{Unconfined swelling strain in direction X} = \frac{d}{L} \times 100\%$$

where:

X is a direction relative to the bedding or foliation
 d = maximum swelling displacement recorded in direction X during the test

* International Standards Organization R 565 *Woven Wire Cloth and Perforated Plates in Test Sieves* (1967).

L = initial distance between gauge points in direction X.

6. REPORTING OF RESULTS

Results should be presented for at least three specimens per sample. The report should clearly indicate that the specimen was *not* radially confined during the swelling test. The report should include the following information for each specimen:

(a) Unconfined swelling strains and their directions with respect to bedding or foliation.

(b) The initial water content of the specimen; whether this corresponds to the natural water content, and if so the method of storage prior to testing.

(c) The shape and initial dimensions of the specimen.

(d) A description of any visible deterioration during slaking.

4. SUGGESTED METHOD FOR DETERMINATION OF THE SLAKE-DURABILITY INDEX

1. SCOPE

This test is intended to assess the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting.

2. APPARATUS

The apparatus consists essentially of the following:

(a) A test drum comprising a 2.00 mm standard mesh* cylinder of unobstructed length 100 mm and diameter 140 mm, with solid fixed base. The drum must withstand a temperature of 105 C. The drum has a

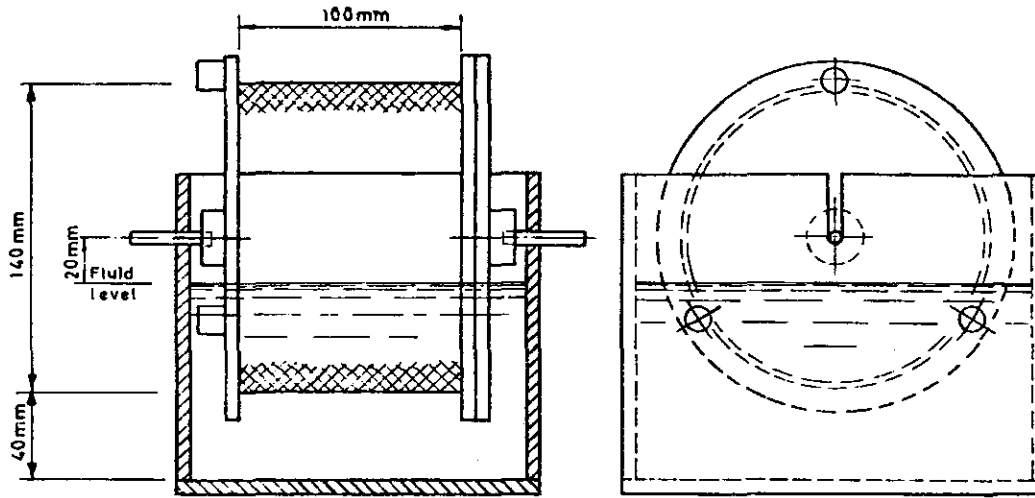


Fig. 4. Critical dimensions of slake-durability test equipment.

solid removable lid. The drum must be sufficiently strong to retain its shape during use, but neither the exterior of the mesh nor the interior of the drum should be obstructed, for example by reinforcing members.

(b) A trough, to contain the test drum supported with axis horizontal in a manner allowing free rotation, capable of being filled with a slaking fluid such as water to a level 20 mm below the drum axis. The drum is mounted to allow 40 mm unobstructed clearance between the trough and the base of the mesh. The principal features of the trough and drum assembly are illustrated in Fig. 4.

(c) A motor drive capable of rotating the drum at a speed of 20 rpm, the speed to be held constant to within 5% for a period of 10 min.

(d) An oven capable of maintaining a temperature of 105°C to within 3°C for a period of at least 12 hr.

(e) A balance capable of weighing the drum plus sample to an accuracy of 0.5 g.

3. PROCEDURE

(a) A representative sample is selected comprising ten rock lumps, each with a mass of 40–60 g, to give a total sample mass of 450–550 g. The maximum grain size of the rock should not be more than 3 mm. Lumps should be roughly spherical in shape, and corners should be rounded during preparation.

(b) The sample is placed in a clean drum and is dried to constant mass at a temperature of 105°C, usually requiring from 2 to 6 hr in the oven. The mass A of the drum plus sample is recorded. The sample is then tested after cooling.

(c) The lid is replaced, the drum mounted in the trough and coupled to the motor.

(d) The trough is filled with slaking fluid, usually tap water at 20°C, to a level 20 mm below the drum axis, and the drum rotated for 200 revolutions during a period of 10 min to an accuracy of 0.5 min.

(e) The drum is removed from the trough, the lid removed from the drum, and the drum plus retained portion of the sample dried to constant mass at 105°C. The mass B of the drum plus retained portion of the sample is recorded after cooling.

(f) Steps (c)–(e) are repeated and the mass C of the drum plus retained portion of the sample is recorded.

(g) The drum is brushed clean and its mass D is recorded.

4. CALCULATION

The slake-durability index (second cycle) is calculated as the percentage ratio of final to initial dry sample masses as follows:

$$\text{slake-durability index } I_{d2} = \frac{C - D}{A - D} \times 100\%$$

5. REPORTING OF RESULTS

The report should include the following information for each sample tested:

(a) The slake-durability index (second cycle) to the nearest 0.1%.

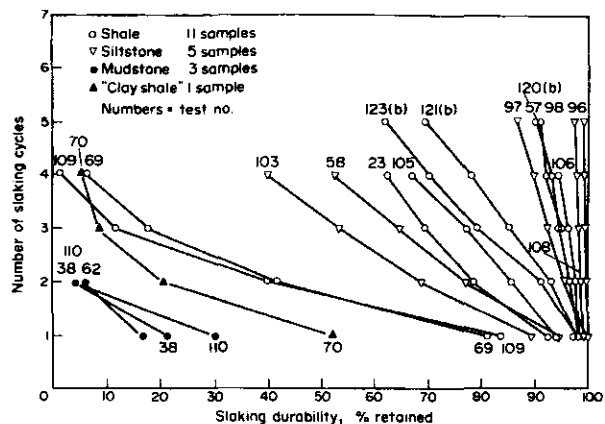


Fig. 5. Influence of the number of slaking cycles on slake-durability (Gamble, 1971).

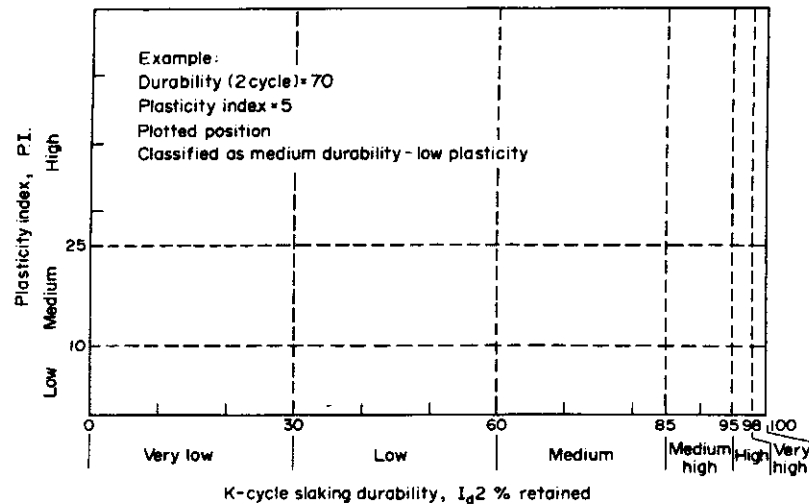


Fig. 6. A suggested durability-plasticity classification (Gamble, 1971).

(b) The nature and temperature of the slaking fluid: usually tap water at 20°C, but for example distilled water, natural ground water, sea water, a dilute acid or a dispersing agent may be specified.

(c) The appearance of fragments retained in the drum.

(d) The appearance of material passing through the drum.

6. NOTES

The second cycle slake-durability index, calculated as in para. 4 above, with tap water at 20°C, is proposed for use in rock classification. However, samples with second cycle indexes from 0 to 10% should be further characterized by their first cycle slake-durability indexes as follows:

$$\text{slake-durability index } I_{d1} = \frac{B - D}{A - D} \times 100\%$$

Indexes taken after three or more cycles of slaking and drying may be useful when evaluating rocks of higher durability (Fig. 5).

7. Rocks giving low slake-durability results should be subjected to soils classification tests, such as determination of Atterberg limits or sedimentation-size analysis. A classification combining slake-durability index and plasticity index (Fig. 6) is suggested in cases where a greater depth of characterization, particularly of argillaceous rocks, is required.

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