

**CVG4184 / 6305: Rock Mechanics  
Winter 2020**

# **Chapter 3: Rock Properties and Laboratory Testing**

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# Introduction

- **Rock mass** consists of intact rock blocks, separated by various discontinuities.
- Rock fragments and rock cores used in **laboratory tests** are generally all **intact rocks**.
- The intact rock itself is a non-homogeneous, anisotropic and inelastic material.
- The engineering performance of a rock mass under external loadings is very often **governed by the strength and orientation of the discontinuities** rather than the properties of the intact rock.
- Other factors that influence rock behavior are the presence of **water** and the **in-situ stresses** within the rock mass.

# Index properties of intact rocks

- The **index properties** of intact rocks can help describe rocks quantitatively and can be used for estimating mechanical and hydraulic properties of rocks.
- **Porosity,  $n$**

$$n = \frac{V_v}{V} = \frac{V - V_s}{V}$$

Where:

$V$  = total volume;  $V_v$  = pore volume;  $V_s$  = volume of solids

- **Porosity** varies significantly for different rocks and even for the same rock due to different factors such as grain size distribution, grain shape, and depth and overburden stress.
- **Porosity** generally decreases with increasing depth or vertical effective stress.

# Index properties of intact rocks

- **Density**: depends on the mineral composition, the porosity and the filling material in the voids.

➤ Bulk density,  $\rho$

$$\rho = \frac{M}{V} = \left( \frac{G_s + Se}{1 + e} \right) \rho_w$$

➤ Dry density,  $\rho_d$

$$\rho_d = \frac{M_s}{V} = \left( \frac{G_s}{1 + e} \right) \rho_w$$

➤ Saturated density,  $\rho_{sat}$

$$\rho_{sat} = \frac{M_s + M_w}{V} = \left( \frac{G_s + e}{1 + e} \right) \rho_w$$

# Index properties of intact rocks

- Density

Typical values of density of intact rocks (after Lama & Vutukuri, 1978).

| Rock type                | Range of density (kg/m <sup>3</sup> ) | Mean density (kg/m <sup>3</sup> ) |
|--------------------------|---------------------------------------|-----------------------------------|
| <i>Igneous rocks</i>     |                                       |                                   |
| Granite                  | 2516 – 2809                           | 2667                              |
| Granodiorite             | 2668 – 2785                           | 2716                              |
| Syenite                  | 2630 – 2899                           | 2757                              |
| Quartz diorite           | 2680 – 2960                           | 2806                              |
| Diorite                  | 2721 – 2960                           | 2839                              |
| Norite                   | 2720 – 3020                           | 2984                              |
| Gabbro                   | 2850 – 3120                           | 2976                              |
| Diabase                  | 2804 – 3110                           | 2965                              |
| Peridotite               | 3152 – 3276                           | 3234                              |
| Dunite                   | 3204 – 3314                           | 3277                              |
| Pyroxenite               | 3100 – 3318                           | 3231                              |
| Anorthosite              | 2640 – 2920                           | 2734                              |
| <i>Sedimentary rocks</i> |                                       |                                   |
| Sandstone                | 2170 – 2700                           | –                                 |
| Limestone                | 2370 – 2750                           | –                                 |
| Dolomite                 | 2750 – 2800                           | –                                 |
| Chalk                    | 2230                                  | –                                 |
| Marble                   | 2750                                  | –                                 |
| Shale                    | 2060 – 2660                           | –                                 |
| <i>Metamorphic rocks</i> |                                       |                                   |
| Gneiss                   | 2590 – 3060                           | 2703                              |
| Schist                   | 2700 – 3030                           | 2790                              |
| Slate                    | 2720 – 2840                           | 2810                              |
| Amphibolite              | 2790 – 3140                           | 2990                              |
| Granulite                | 2630 – 3100                           | 2830                              |
| Eclogite                 | 3338 – 3452                           | 3392                              |

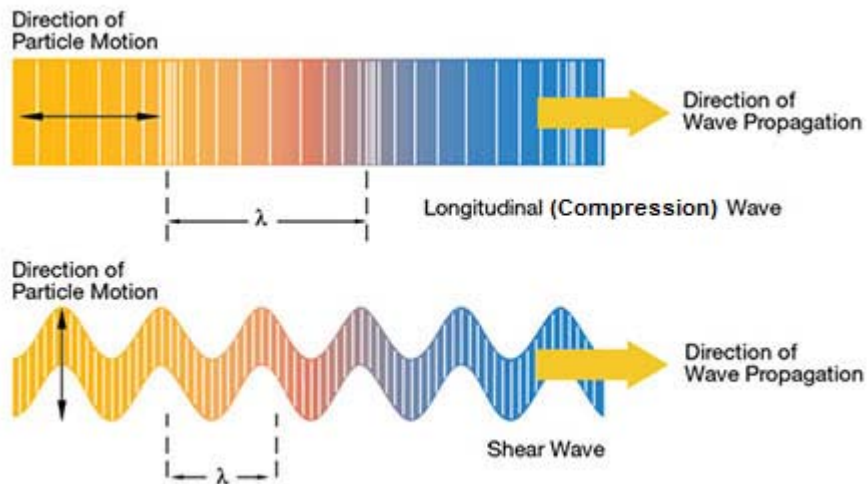
Note: The values listed in the table are for the bulk density determined at natural water content.

# Index properties of intact rocks

- **Wave velocity (ultrasonic testing)**: ultrasound compression (P-wave) and shear (S-wave) waves are transmitted through homogeneous isotropic rock specimens.
- The ultrasonic **elastic constants** are calculated from the measured travel time and distance of compression and shear waves in a rock specimen.
- Useful for **rock classification** purposes and the evaluation of static and dynamic properties at small strains.
- Ultrasonic results provide an index of the **degree of fissuring** within the rock mass.
- Test is inexpensive to perform and is nondestructive.

# Index properties of intact rocks

- Samples may be prepared in a **variety of shapes and sizes** as long as they have two flat, parallel surfaces for transducer coupling.
- Commonly they will be cylinders or blocks with thicknesses ranging from 50 mm to 250 mm in the direction of measurement.



# Index properties of intact rocks

- Wave velocity (ultrasonic testing):

| Type of formation                 | P wave velocity (m/s) | S wave velocity (m/s) | Density (g/cm <sup>3</sup> ) | Density of constituent crystal (g/cm <sup>3</sup> ) |
|-----------------------------------|-----------------------|-----------------------|------------------------------|-----------------------------------------------------|
| Scree, vegetal soil               | 300-700               | 100-300               | 1.7-2.4                      | -                                                   |
| Dry sands                         | 400-1200              | 100-500               | 1.5-1.7                      | 2.65 quartz                                         |
| Wet sands                         | 1500-2000             | 400-600               | 1.9-2.1                      | 2.65 quartz                                         |
| Saturated shales and clays        | 1100-2500             | 200-800               | 2.0-2.4                      | -                                                   |
| Marls                             | 2000-3000             | 750-1500              | 2.1-2.6                      | -                                                   |
| Saturated shale and sand sections | 1500-2200             | 500-750               | 2.1-2.4                      | -                                                   |
| Porous and saturated sandstones   | 2000-3500             | 800-1800              | 2.1-2.4                      | 2.65 quartz                                         |
| Limestones                        | 3500-6000             | 2000-3300             | 2.4-2.7                      | 2.71 calcite                                        |
| Chalk                             | 2300-2600             | 1100-1300             | 1.8-3.1                      | 2.71 calcite                                        |
| Salt                              | 4500-5500             | 2500-3100             | 2.1-2.3                      | 2.1 halite                                          |
| Anhydrite                         | 4000-5500             | 2200-3100             | 2.9-3.0                      | -                                                   |
| Dolomite                          | 3500-6500             | 1900-3600             | 2.5-2.9                      | (Ca, Mg)<br>CO <sub>3</sub> 2.8-2.9                 |
| Granite                           | 4500-6000             | 2500-3300             | 2.5-2.7                      | -                                                   |
| Basalt                            | 5000-6000             | 2800-3400             | 2.7-3.1                      | -                                                   |
| Gneiss                            | 4400-5200             | 2700-3200             | 2.5-2.7                      | -                                                   |
| Coal                              | 2200-2700             | 1000-1400             | 1.3-1.8                      | -                                                   |
| Water                             | 1450-1500             | -                     | 1.0                          | -                                                   |
| Ice                               | 3400-3800             | 1700-1900             | 0.9                          | -                                                   |
| Oil                               | 1200-1250             | -                     | 0.6-0.9                      | -                                                   |

# Types of laboratory tests

- **Characterization**

- Porosity, density, water content
- Absorption
- Point load strength index
- Uniaxial compressive strength and deformability
- Swelling and slake-durability
- Wave velocity

- **Engineering design**

- Triaxial strength and deformability test
- Tensile strength test
- Permeability

# Soils versus rocks

- Soils versus rocks

- A commonly used cut-off is the uniaxial compressive strength (UCS) of **1 MPa**.
- Soils have their **UCS and  $E$**  generally reported in **kPa and MPa**, respectively.
- In rocks, they are orders of magnitude greater and are reported in **MPa and GPa**, respectively.

- Specimen preparation

- Laboratory tests such as UCS, triaxial and point load tests require cylindrical specimens that have their ends cut parallel and flat, such that they are perpendicular to the longitudinal axis of the specimen.

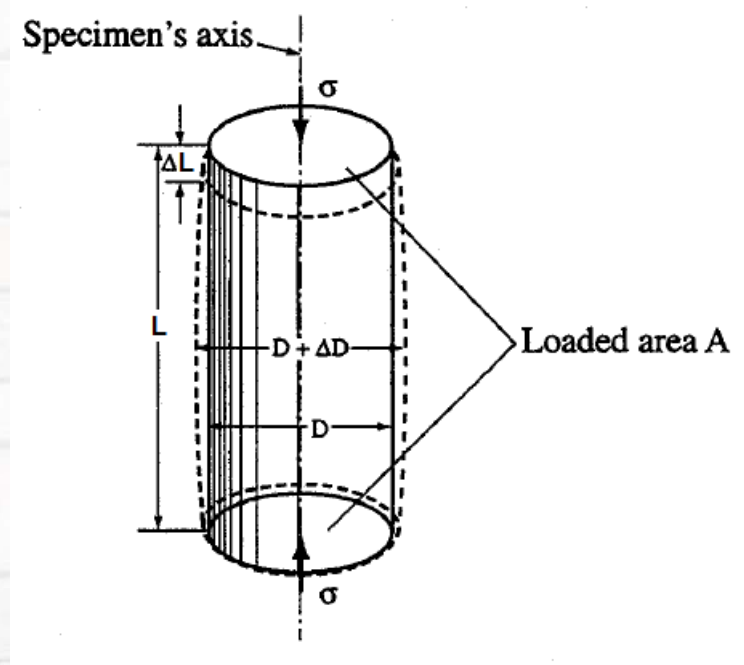
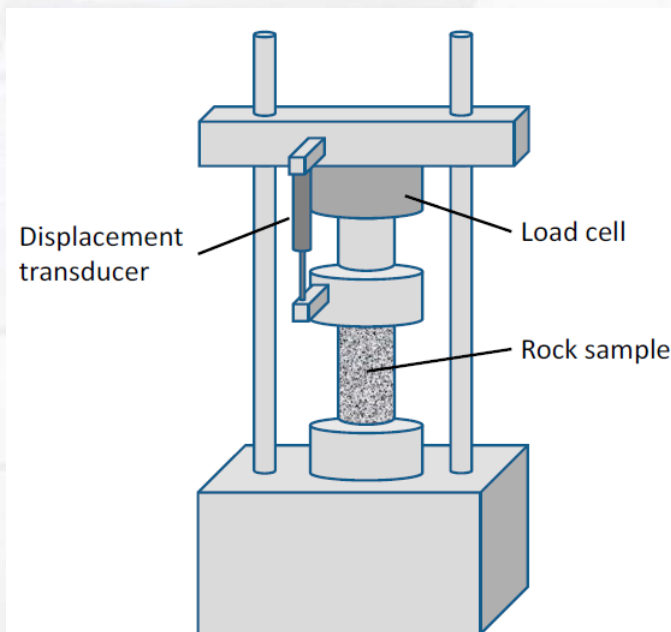
# Uniaxial Compressive Strength (UCS)

- **Uniaxial Compressive Strength (UCS)**
  - A cylindrical rock specimen is subjected to an axial load, without any lateral confinement.
  - The axial load is increased gradually until the specimen fails and the **vertical normal stress at failure** is known as the unconfined compressive strength or **uniaxial compressive strength ( $\sigma_c$ )**.
  - Test is also used to compute the **elastic (Young's) modulus ( $E$ )** and the **Poisson's ratio ( $\nu$ )**.

# Uniaxial Compressive Strength (UCS)

- Uniaxial Compressive Strength (UCS)

- Cylindrical test specimens having a height to diameter ratio of 2.5–3.0 and a diameter preferably of not less than NX core size (54 mm).



$$\sigma_1 = \sigma$$

$$\sigma_2 = \sigma_3 = 0$$

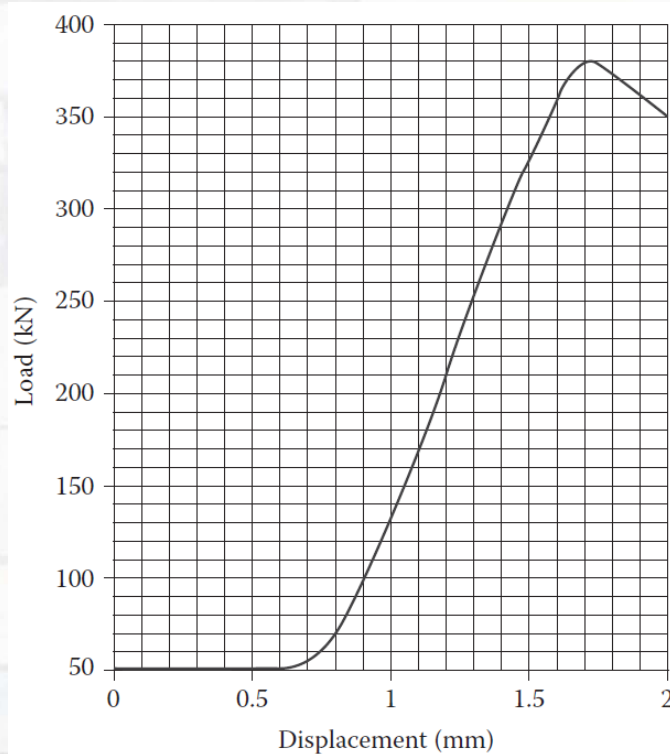
$$\varepsilon_a = \frac{\Delta L}{L}$$

$$\varepsilon_l = \frac{\Delta D}{D}$$

# Uniaxial Compressive Strength (UCS)

- Uniaxial Compressive Strength (UCS)

- The specimen is loaded axially at a constant rate of strain or stress such that it fails in 5–15 minutes.



$$\sigma_c = \frac{P_{\max}}{A}$$

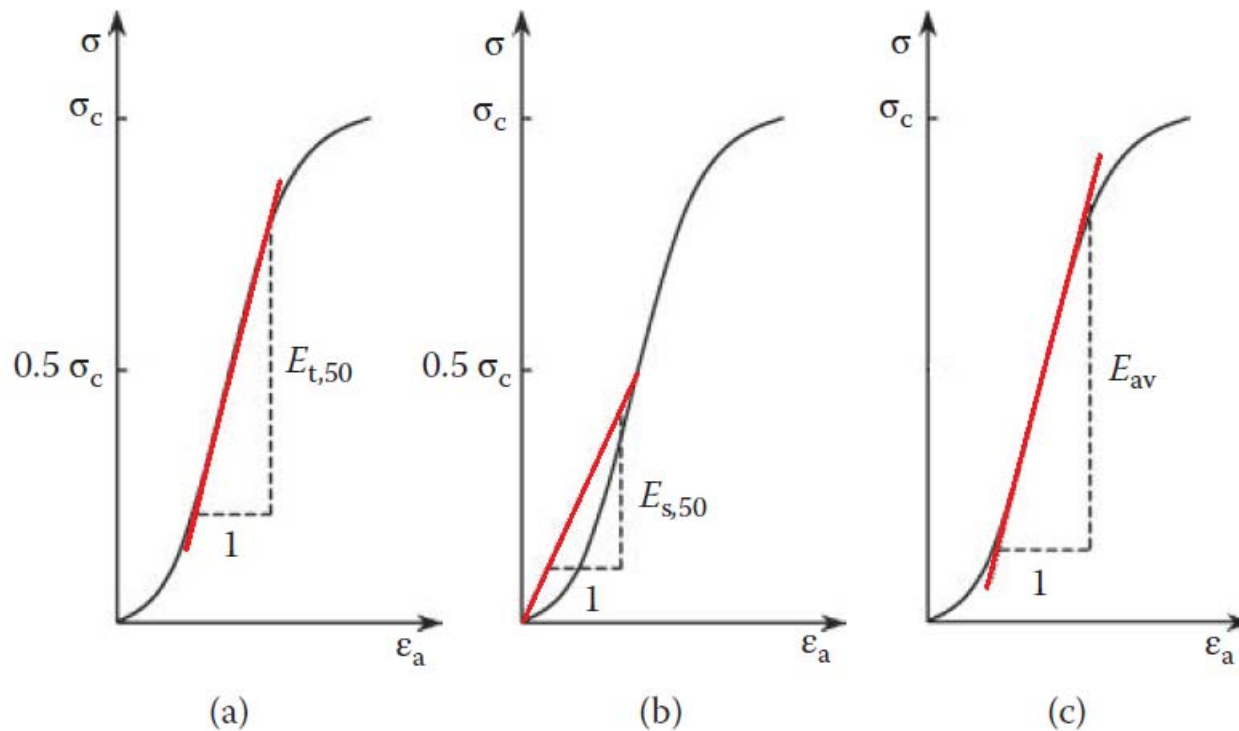
Unlike saturated undrained clays, the friction angle of a rock specimen is not zero, and hence, the Mohr–Coulomb failure envelope is not horizontal:

$$\sigma_c = \frac{2c \cos \phi}{1 - \sin \phi}$$

# Elastic Constants

- Elastic (Young's) modulus ( $E$ ):** both axial (or vertical) and lateral (or diametral) strains are measured during compression.

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

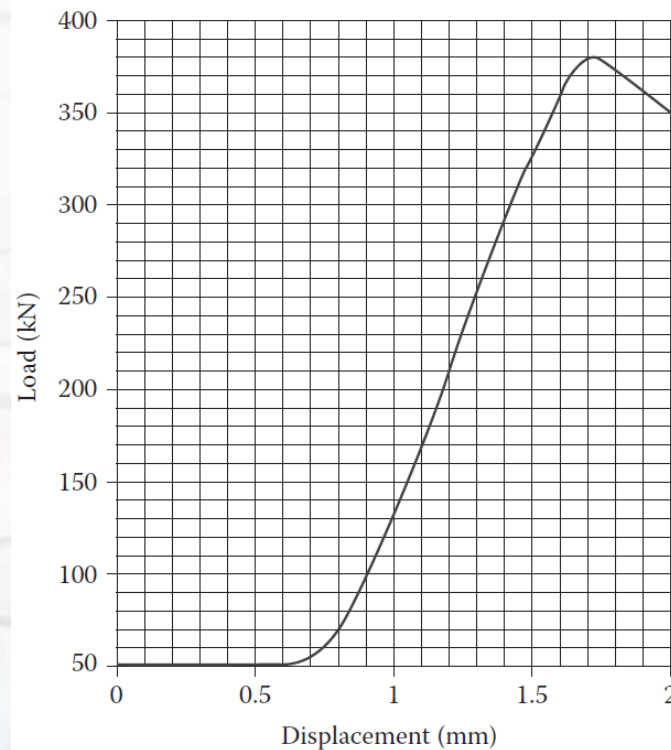


Young's modulus: (a) tangent modulus, (b) secant modulus, and (c) average modulus.

# Elastic Constants

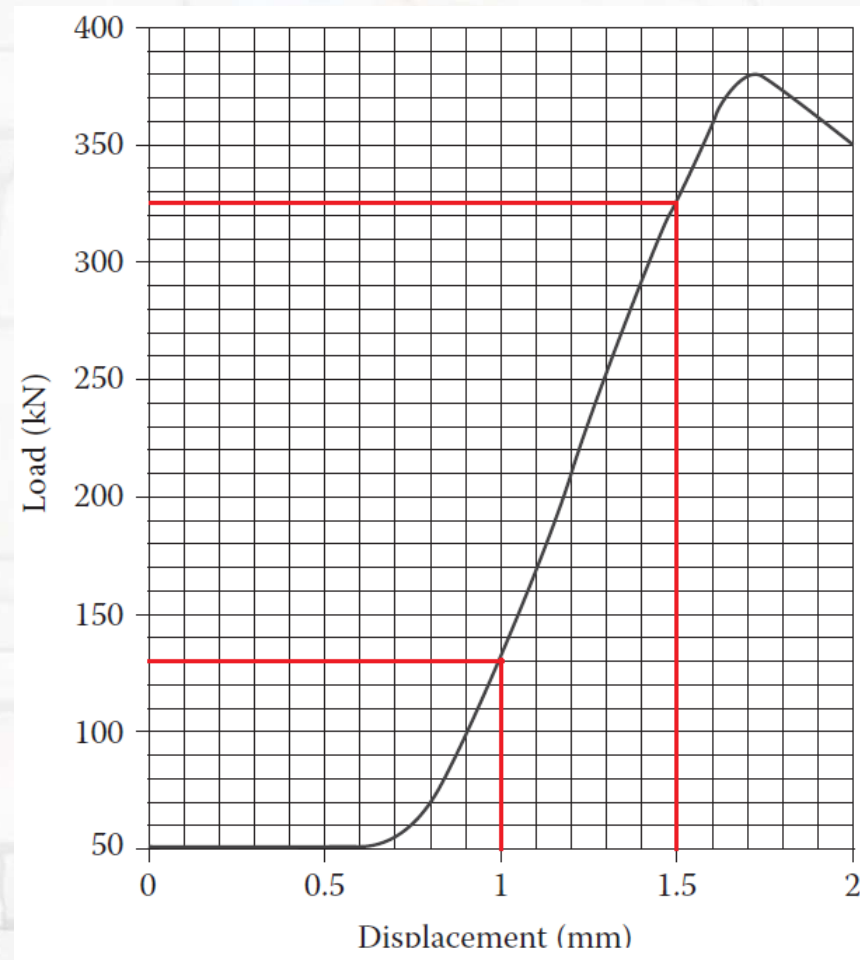
## Example 1

A 50.5 mm-diameter, 129 mm-long rock specimen is subjected to a uniaxial compression test. The load–axial displacement plot is shown below. Determine the UCS and Young's modulus of the intact rock specimen.



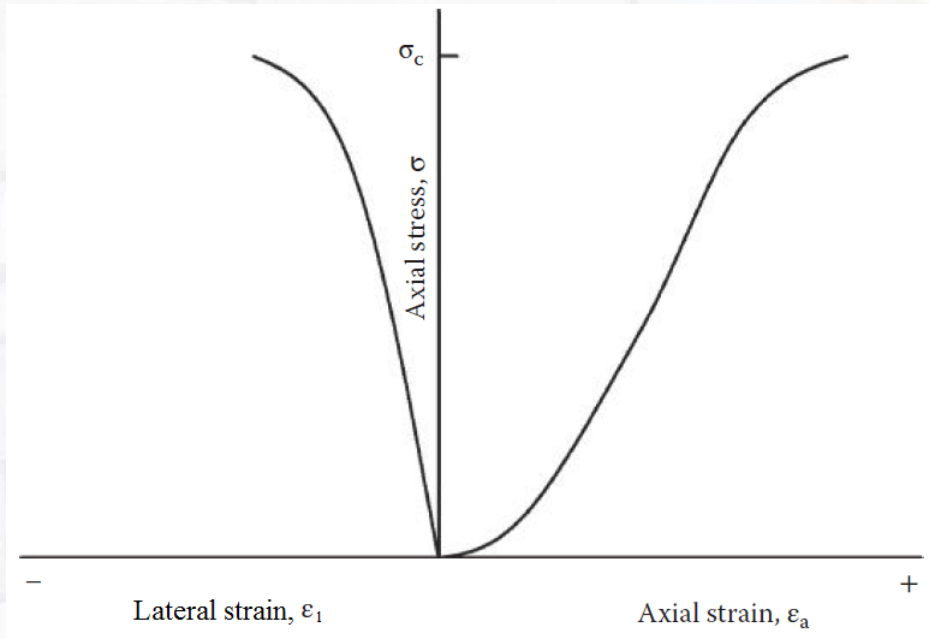
# Elastic Constants

## Example 1 – Solution



# Elastic Constants

- Poisson's ratio ( $\nu$ )



$$\nu = - \frac{\text{Lateral strain}}{\text{Axial strain}} = - \frac{\epsilon_l}{\epsilon_a}$$

Table 3.3 Typical values of Poisson's ratio for rocks

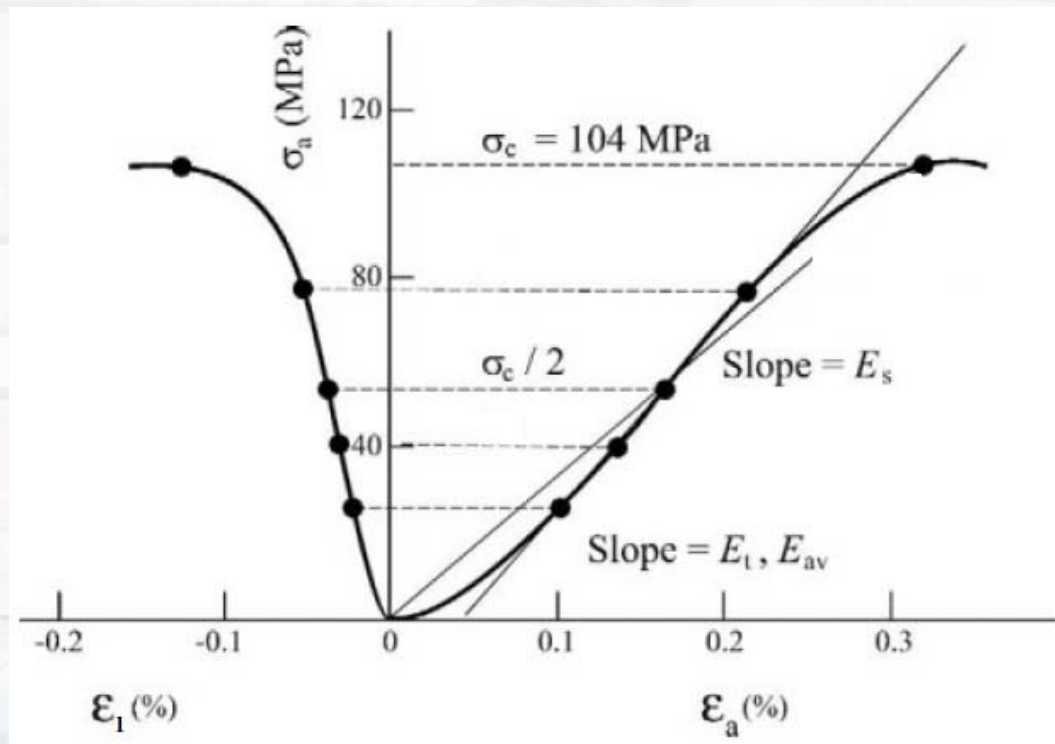
| Rock type    | $\nu$     |
|--------------|-----------|
| Andesite     | 0.20–0.35 |
| Basalt       | 0.10–0.35 |
| Conglomerate | 0.10–0.40 |
| Diabase      | 0.10–0.28 |
| Diorite      | 0.20–0.30 |
| Dolerite     | 0.15–0.35 |
| Dolomite     | 0.10–0.35 |
| Gneiss       | 0.10–0.30 |
| Granite      | 0.10–0.33 |
| Granodiorite | 0.15–0.25 |
| Greywacke    | 0.08–0.23 |
| Limestone    | 0.10–0.33 |
| Marble       | 0.15–0.30 |
| Marl         | 0.13–0.33 |
| Norite       | 0.20–0.25 |
| Quartzite    | 0.10–0.33 |
| Rock salt    | 0.05–0.30 |
| Sandstone    | 0.05–0.40 |
| Shale        | 0.05–0.32 |
| Siltstone    | 0.05–0.35 |
| Tuff         | 0.10–0.28 |

Source: Gercek, H., *Int. J. Rock Mech. Min. Sci.*, 44, 1–13, 2007.

# Elastic Constants

## Example 2

The stress-strain plots obtained from a uniaxial compression test on rock are shown below. Determine the tangent, secant and average moduli of elasticity and the corresponding values of the Poisson's ratio.



# Elastic Constants

- Bulk modulus ( $K$ )

$$K = \frac{E}{3(1-2\nu)}$$

- Shear modulus ( $G$ )

$$G = \frac{E}{2(1+\nu)}$$

- Volumetric strain

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_l$$

- Modulus ratio: the ratio of the Young's modulus ( $E$ ) to the uniaxial compressive strength ( $\sigma_c$ ).

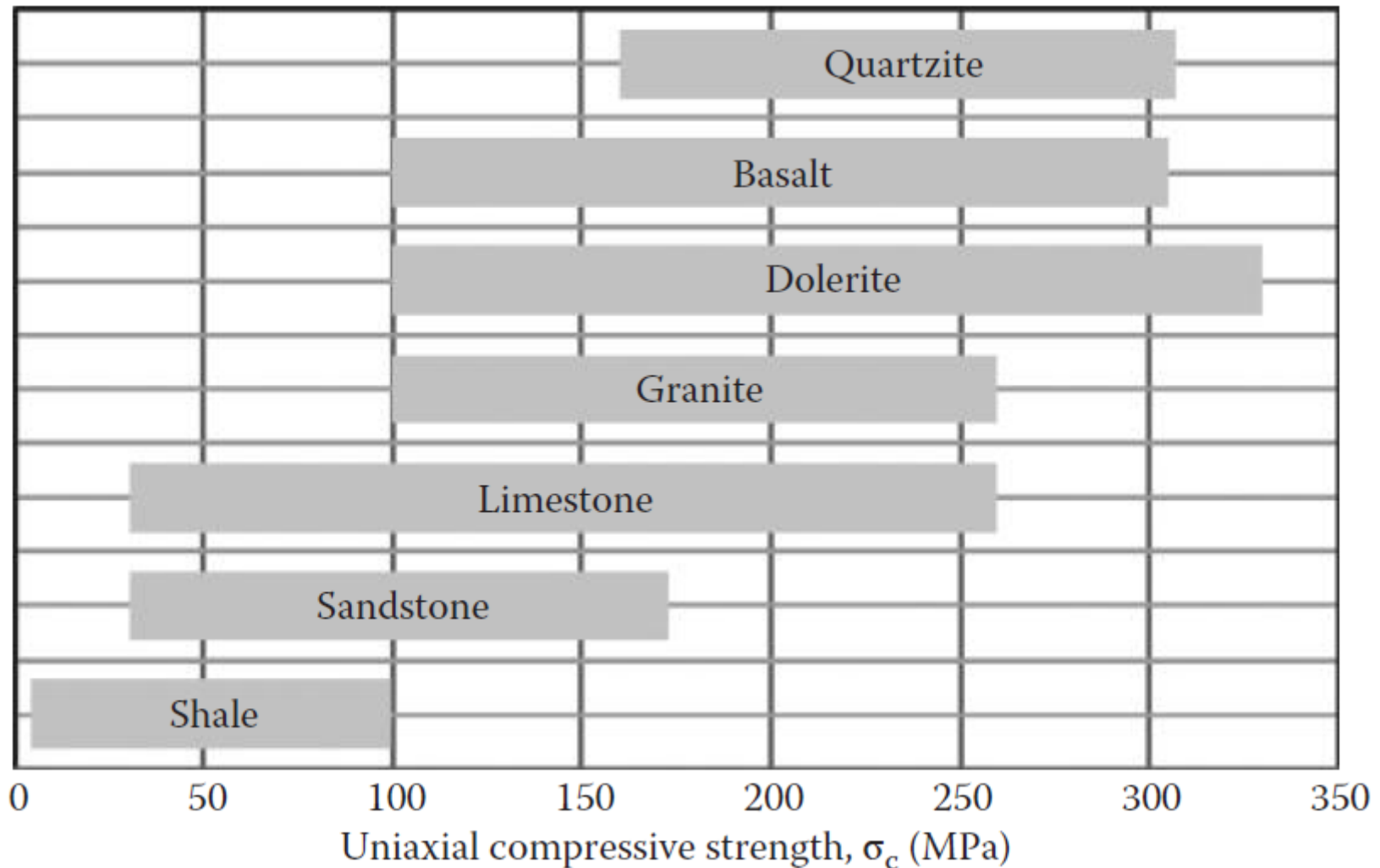
Table 3.4 Relative ductility based on axial strain at peak load

| Classification                                 | Axial strain (%) |
|------------------------------------------------|------------------|
| Very brittle                                   | <1               |
| Brittle                                        | 1–5              |
| Moderately brittle <sup>a</sup> (transitional) | 2–8              |
| Moderately ductile                             | 5–10             |
| Ductile                                        | > 10             |

Source: Handin, J., *Handbook of Physical Constants*, Geological Society of America, New York, 1966.

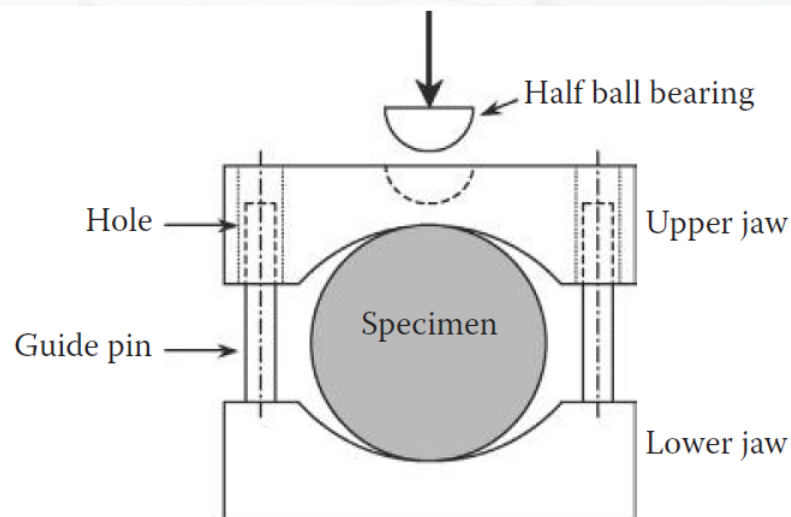
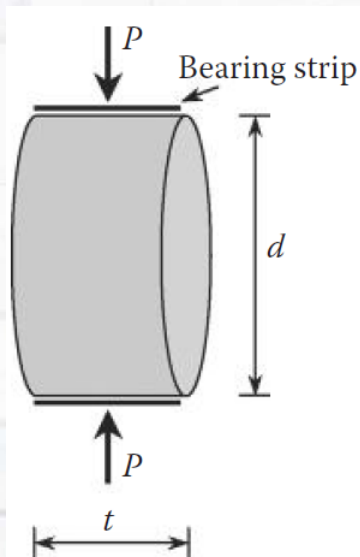
# Typical values of UCS

- Typical values of UCS of common rock types



# Indirect Tensile Strength

- Indirect Tensile Strength (ITS) Test (Brazilian test):
  - The tensile strength of a rock is required in design and analysis of excavations, tunnels, and slopes.
  - Test provides **indirect** way of measuring the **tensile strength** of a cylindrical rock specimen having the shape of a **disc** ( $T/D=0.5$ ).



# Indirect Tensile Strength

- Indirect Tensile Strength (ITS) Test (Brazilian test):
  - The test specimen diameter should be at least of NX core size (54 mm).
  - The loading rate should be selected such that the specimen fails in 1–10 minutes.
  - The **tensile strength** of the rock ( $\sigma_t$ ) is given by

$$\sigma_t = \frac{2P}{\pi d t}$$

Where:

$d$  = specimen diameter

$P$  = the load at failure

$t$  = specimen thickness

# Indirect Tensile Strength

- Indirect Tensile Strength (ITS) Test (Brazilian test):
  - In the absence of measurements,  $\sigma_t$  is assumed to be 1/5 to 1/20 of  $\sigma_c$ .

Table 3.7 Typical  $\sigma_c/\sigma_t$  values

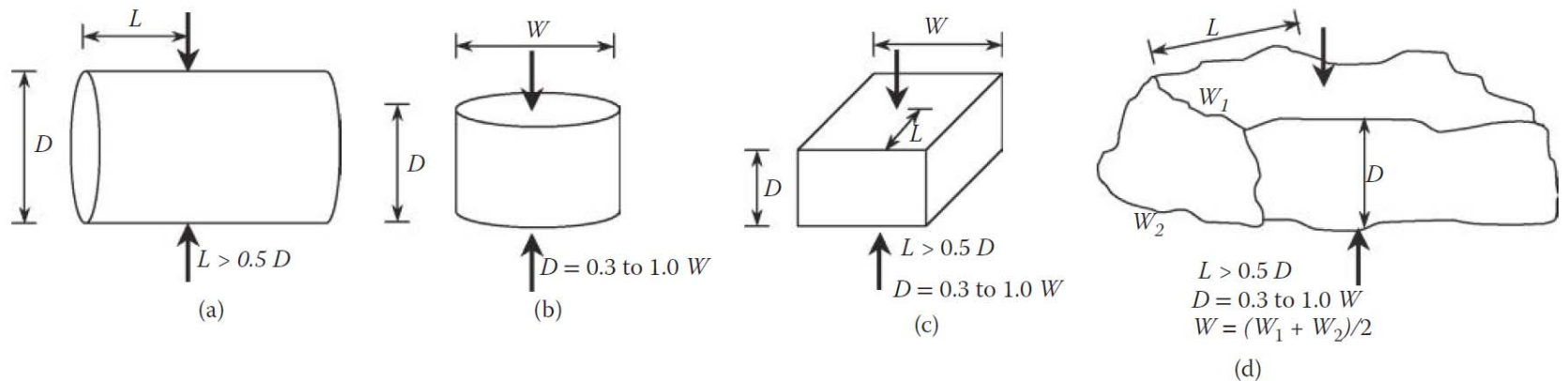
| Rock type                                                | $\sigma_c$ (MPa) | $\sigma_t$ (MPa) | $\sigma_c/\sigma_t$ |
|----------------------------------------------------------|------------------|------------------|---------------------|
| Coarse-grained Nevada granodiorite                       | 141.1            | 11.7             | 12.1                |
| Cedar City tonalite, somewhat weathered quartz monzonite | 101.5            | 6.4              | 15.9                |
| Fine olivine Nevada basalt                               | 148.0            | 13.1             | 11.3                |
| Nevada tuff – welded volcanic ash with 19.8% porosity    | 11.3             | 1.1              | 10.0                |

Source: Goodman (1989).

# Point Load Strength

- **Point Load Strength Test**

- Oldest index test for strength classification of rocks.
- Quick test (10-60s) that can be conducted on regular rock cores or irregular rock fragments.



Possible specimen shapes and loading directions: (a) diametrical, (b) axial, (c) block and (d) irregular.

# Point Load Strength

- Point Load Strength Test

- The load is increased to failure and the point load strength index  $I_s$  is calculated based on the failure load and the distance  $D$  between the cone tips:

$$I_s = \frac{P}{D_e^2}$$

Where:

$D_e$  = equivalent specimen diameter;

$D_e = D$  for diametrical test;

In axial, block or irregular tests:

$$D_e = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4WD}{\pi}}$$



# Point Load Strength

- Point Load Strength Test

- The index,  $I_s$ , varies with  $D_e$  and so size correction must be applied to obtain a unique point load strength index for a particular rock sample for use for strength classification;
- The size-corrected point load strength index,  $I_{s(50)}$ , is defined as the value of  $I_s$  that would have been measured in a diametrical test with  $D = 50$  mm.

$$I_{s(50)} = I_s \times \left( \frac{D_e}{50} \right)^{0.45} \quad \text{where } D_e \text{ is in mm.}$$

# Point Load Strength

- Point Load Strength Test

- Correlation between  $I_{s(50)}$  and  $\sigma_c$ :

$$\sigma_c \approx (22 - 24) I_{s(50)}$$

- Correlation between  $I_{s(50)}$  and  $\sigma_t$ :

$$\sigma_t \approx 1.25 I_{s(50)}$$

- Point load strength anisotropy index  $I_{a(50)}$ : the ratio of  $I_{s(50)}$  obtained when testing perpendicular and parallel to the planes of weakness.

$$I_{a(50)} = \frac{I_{s(50)\perp}}{I_{s(50)\parallel}}$$

# Point Load Strength

- Point Load Strength Test – typical test results

Table 3.8 Point load test data

| No. | Type | W<br>(mm) | D (mm) | P (kN) | $D_e$ (mm) | $I_s$ (MPa) | $I_{s(50)}$<br>(MPa) |
|-----|------|-----------|--------|--------|------------|-------------|----------------------|
| 1   | i ⊥  | 30.4      | 17.2   | 2.687  | 25.8       | 4.04        | <del>3.00</del>      |
| 2   | i ⊥  | 16.0      | 8.0    | 0.977  | 12.8       | 5.99        | 3.24                 |
| 3   | i ⊥  | 19.7      | 15.6   | 1.962  | 19.8       | 5.01        | 3.30                 |
| 4   | i ⊥  | 35.8      | 18.1   | 3.641  | 28.7       | 4.41        | 3.44                 |
| 5   | i ⊥  | 42.5      | 29.0   | 6.119  | 39.6       | 3.90        | 3.51                 |
| 6   | i ⊥  | 42.0      | 35.0   | 7.391  | 43.3       | 3.95        | <del>3.70</del>      |
| 7   | b ⊥  | 44        | 21     | 4.600  | 34.3       | 3.91        | 3.30                 |
| 8   | b ⊥  | 40        | 30     | 5.940  | 39.1       | 3.89        | 3.48                 |
| 9   | b ⊥  | 19.5      | 15     | 2.040  | 19.3       | 5.48        | <del>3.57</del>      |
| 10  | b ⊥  | 33        | 16     | 2.870  | 25.9       | 4.27        | <del>3.10</del>      |
| 11  | d // | –         | 49.93  | 5.107  | 49.93      | 2.05        | 2.05                 |
| 12  | d // | –         | 49.88  | 4.615  | 49.88      | 1.85        | 1.85                 |
| 13  | d // | –         | 49.82  | 5.682  | 49.82      | 2.29        | <del>2.29</del>      |
| 14  | d // | –         | 49.82  | 4.139  | 49.82      | 1.67        | <del>1.66</del>      |
| 15  | d // | –         | 49.86  | 4.546  | 49.86      | 1.83        | 1.83                 |
| 16  | d // | –         | 25.23  | 1.837  | 25.23      | 2.89        | 2.12                 |
| 17  | d // | –         | 25.00  | 1.891  | 25         | 3.03        | 2.21                 |
| 18  | d // | –         | 25.07  | 2.118  | 25.07      | 3.37        | <del>2.47</del>      |
| 19  | d // | –         | 25.06  | 1.454  | 25.06      | 2.32        | <del>1.70</del>      |
| 20  | d // | –         | 25.04  | 1.540  | 25.04      | 2.46        | 1.80                 |

a = axial

b = block

d = diametrical

i = irregular lump

⊥ = loaded perpendicular to plane of weakness

// = loaded parallel to plane of weakness

Mean  $I_{s(50) \perp}$  3.38 MPa

Mean  $I_{s(50) //}$  1.98 MPa

$I_{a(50)}$  1.71

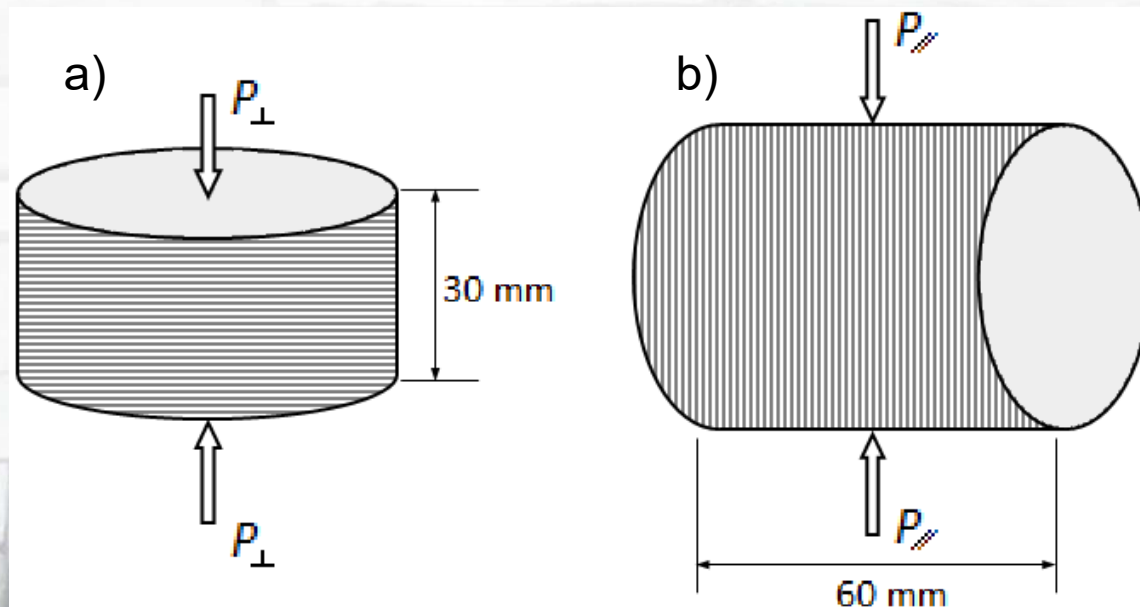
**Note1:** the highest and the lowest values are discarded and the average of the remaining values is reported as the point load strength index,  $I_{s(50)}$ .

**Note2:** Point load test results are not acceptable if the failure plane lies partially along a pre-existing fracture in the rock, or is not coincident with the line between the platens.

# Point Load Strength

## Example 3

Point load tests were carried out on two sedimentary rock specimens of 54 mm diameter (NX core), as shown the following figure. The loads  $P_{\perp}$  and  $P_{//}$  at failure are 6.28 kN and 4.71 kN, respectively. Find the point load strength index  $I_{s(50)}$  in the two directions and compute the point load strength anisotropy index  $I_{a(50)}$ .



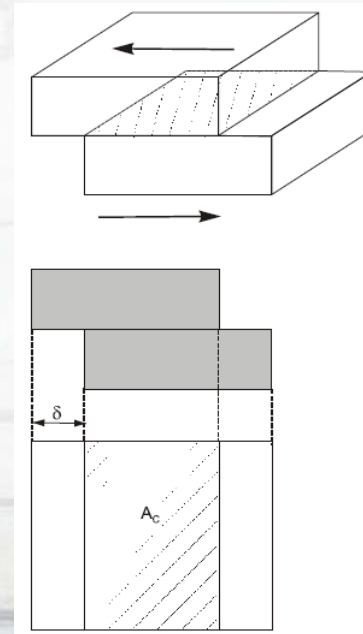
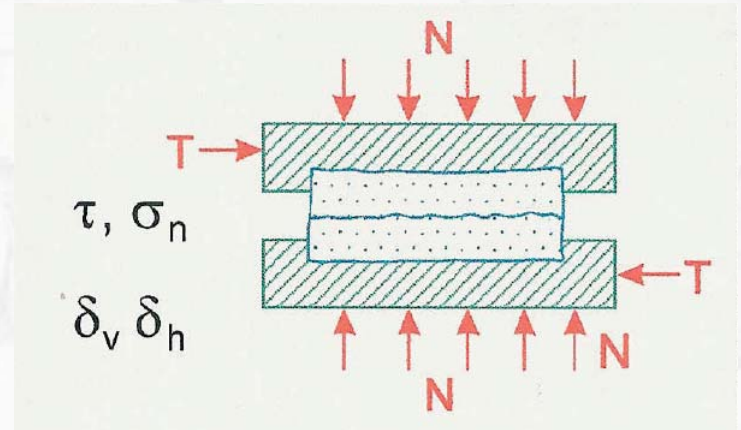
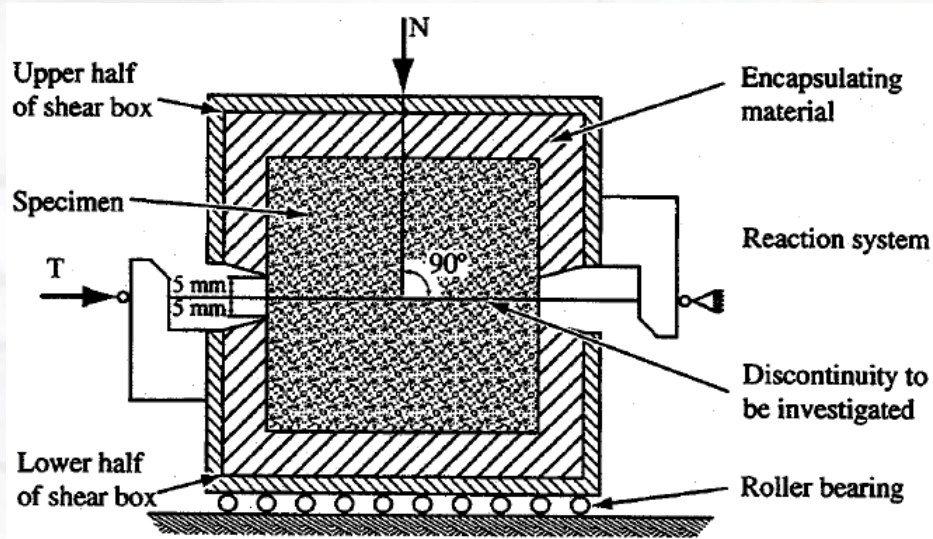
# Direct Shear Strength

- Direct Shear Strength Test

- A rock specimen is placed in the lower half of the shear box and encapsulated in either synthetic resin or mortar.
- The specimen must be positioned so that the line of shear force lies in the plane of the discontinuity to be investigated.
- The specimen is then mounted in the upper shear box and the normal load ( $N$ ) and shear force ( $T$ ) are applied.
- Used to assess peak and residual shear strength of discontinuity.

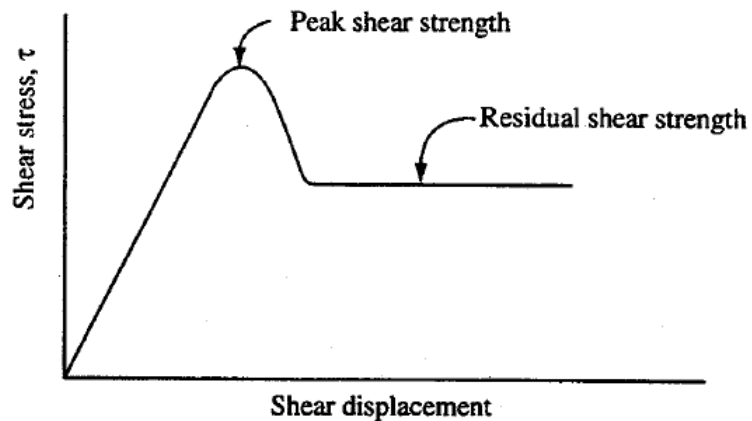
# Direct Shear Strength

- Direct Shear Strength Test



$$\sigma_n = \frac{N}{A_c}$$

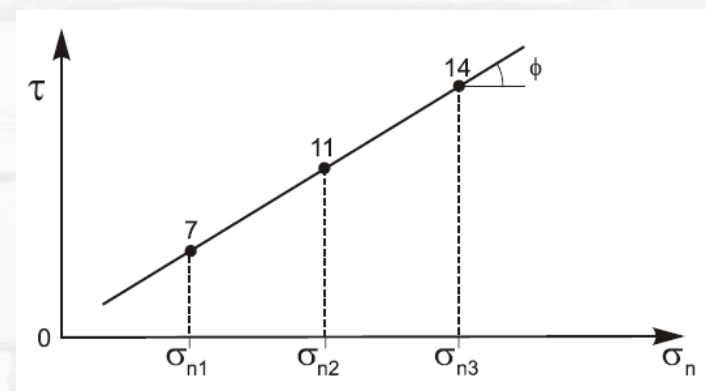
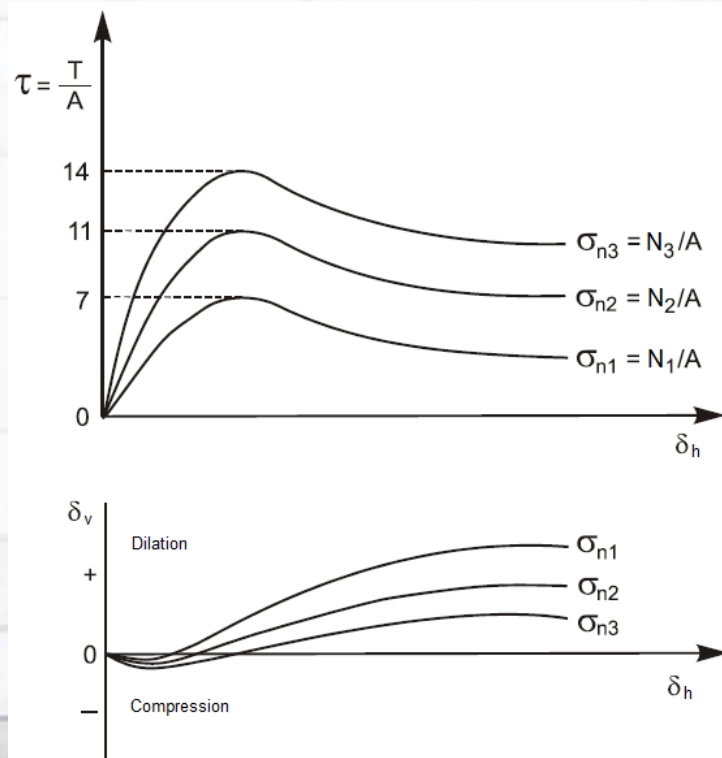
$$\tau = \frac{T}{A_c}$$



# Direct Shear Strength

- Direct Shear Strength Test

- Usually three tests are performed and plots of shear stress versus shear displacement and normal displacement versus shear displacement are prepared.



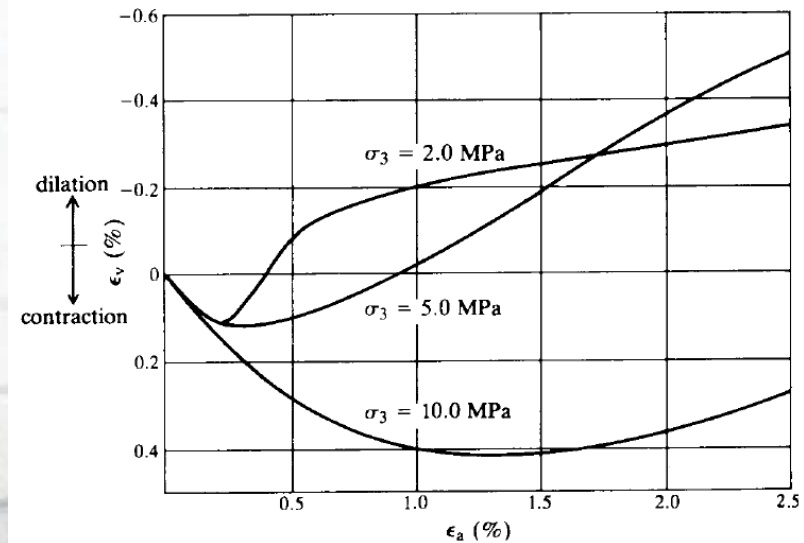
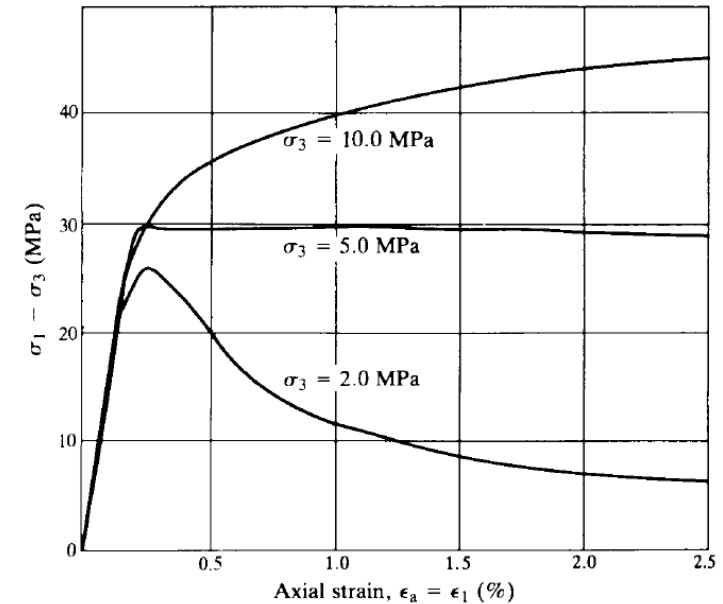
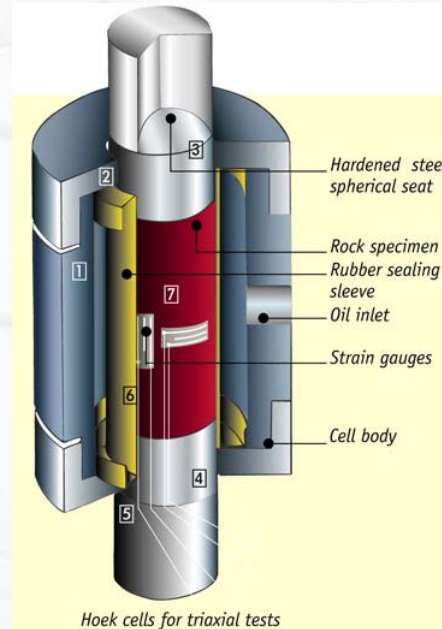
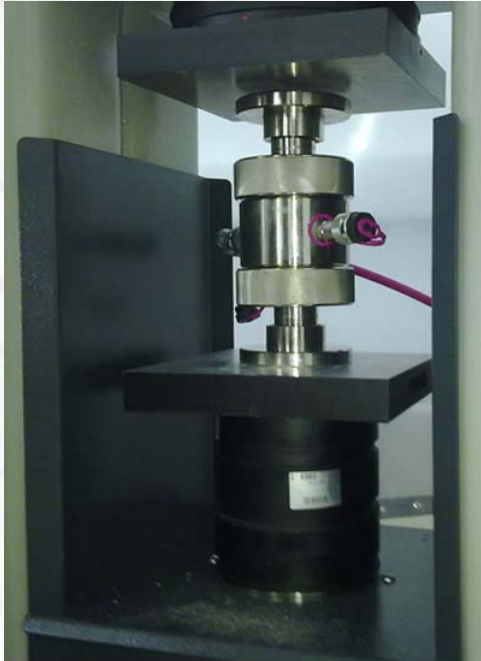
# Triaxial compression

- **Triaxial Test**

- Cylindrical rock specimen having a **height to diameter ratio of 2.0–3.0** and a diameter preferably of not less than **NX core** size (54 mm).
- The specimen is encased in a **flexible impervious membrane** to prevent the confining fluid (oil) from entering the specimen pores.
- The vertical stress ( $\Delta\sigma$ ) is increased at a **constant stress/strain rate** until failure occurs (5–15 min).
- The **vertical stress at failure** ( $\sigma_1$ ) is given by  $\sigma_1 + \Delta\sigma$ .
- **Axial load and axial deformation are measured**, but pore water pressure or drainage are not.

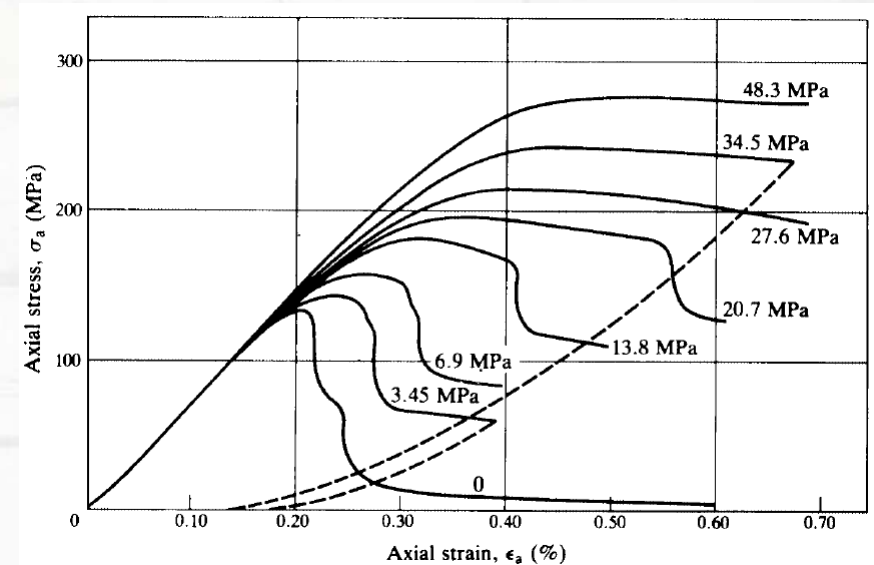
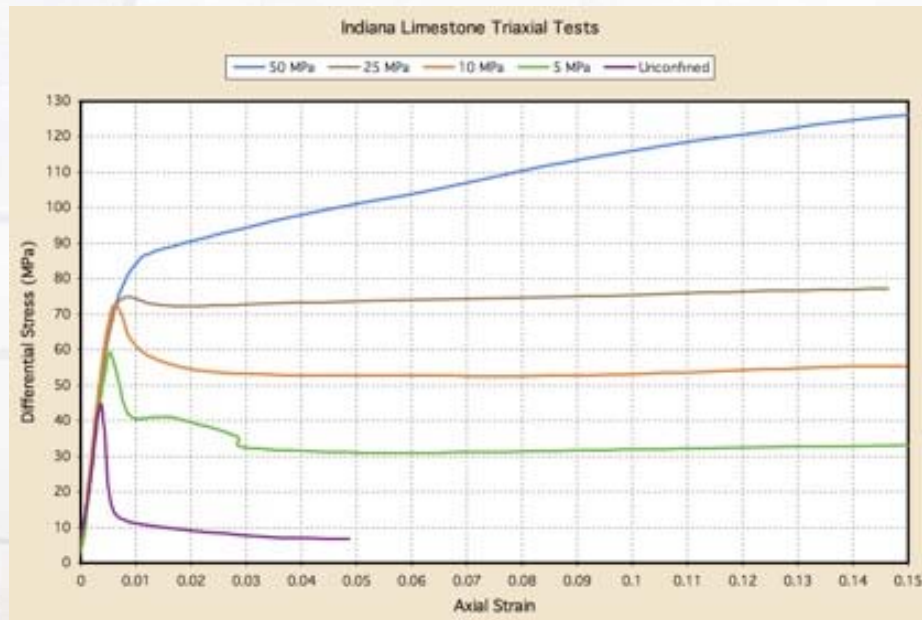
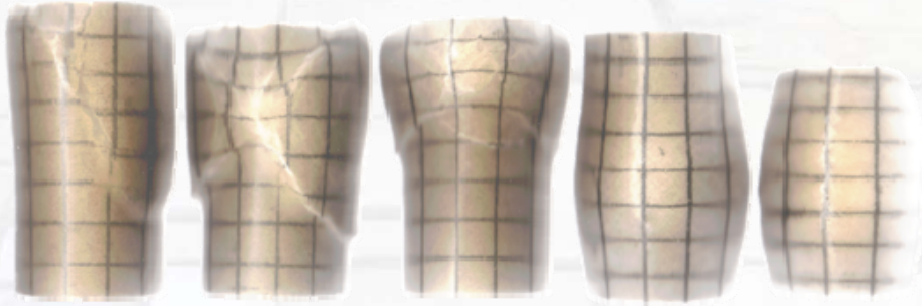
# Triaxial compression

- Triaxial Test



# Triaxial compression

- Behaviour of isotropic rock material in triaxial compression



Complete axial stress– axial strain curves obtained in triaxial compression tests on Tennessee Marble

# Triaxial compression

- With **increasing the confining pressure**,
  - the peak strength increases;
  - there is a transition from typically brittle to fully ductile behaviour;
  - the region incorporating the peak of the  $\Delta\sigma_a - \varepsilon_a$  curve flattens and widens;
  - the post-peak drop in stress to the residual strength reduces and disappears at high values of  $\sigma_3$ .
  - The confining pressure at which the post-peak reduction in strength disappears and the behaviour becomes fully ductile is known as the **brittle–ductile transition** pressure and varies with rock type.

# Triaxial compression

## Example 4

The following table shows data obtained from a single-stage triaxial compression test on a cylindrical rock sample, conducted at a confining stress of 10.0 MPa. The pore water pressure was not measured during the test. Estimate:

- a) The peak strength;
- b) The residual strength;
- c) The tangent Young's modulus  $E_{tan}$  at 50% peak stress; and
- d) The tangent Poisson's ratio at 50% peak axial stress.

| Total Axial Load,<br>P | Sample Height,<br>L | Sample Diameter,<br>D |
|------------------------|---------------------|-----------------------|
| (kN)                   | (mm)                | (mm)                  |
| 19.79                  | 100.84              | 50.200                |
| 39.68                  | 100.8               | 50.201                |
| 59.39                  | 100.77              | 50.203                |
| 83.20                  | 100.74              | 50.205                |
| 108.47                 | 100.71              | 50.208                |
| 135.98                 | 100.68              | 50.212                |
| 164.48                 | 100.65              | 50.216                |
| 181.81                 | 100.63              | 50.222                |
| 205.05                 | 100.58              | 50.236                |
| 210.45                 | 100.56              | 50.246                |
| 211.82                 | 100.54              | 50.253                |
| 200.06                 | 100.52              | 50.258                |
| 157.40                 | 100.49              | 50.265                |
| 135.64                 | 100.46              | 50.271                |
| 121.78                 | 100.43              | 50.277                |
| 117.83                 | 100.4               | 50.283                |
| 116.84                 | 100.37              | 50.283                |

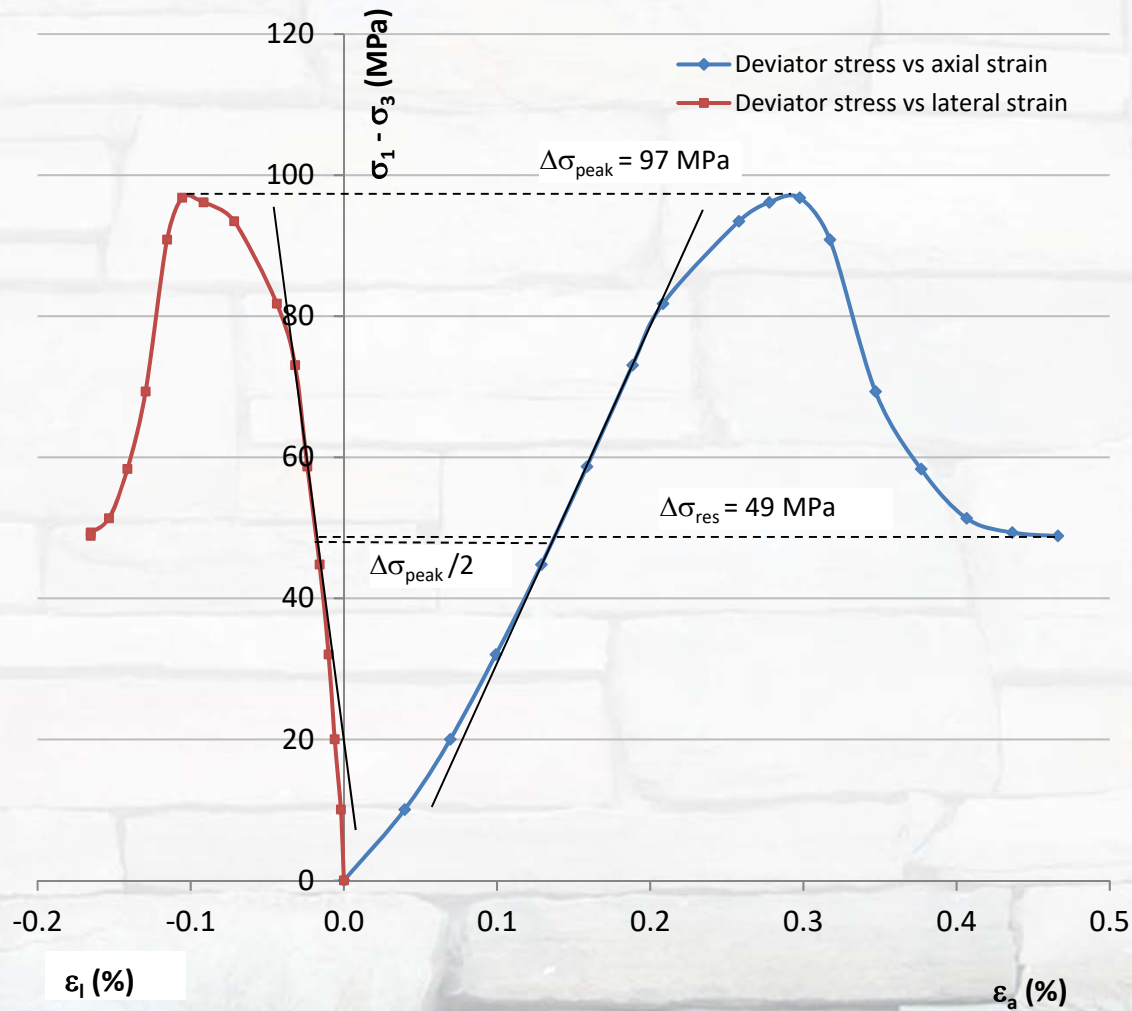
# Triaxial compression

## Example 4 – Solution

| Total Axial Load,<br>P | Sample Height,<br>L | Sample Diameter,<br>D | Axial Stress,<br>$\sigma_1$ | Deviator Stress,<br>$\sigma_1 - \sigma_3$ | Axial Strain,<br>$\epsilon_a$ | Lateral Strain,<br>$\epsilon_l$ |
|------------------------|---------------------|-----------------------|-----------------------------|-------------------------------------------|-------------------------------|---------------------------------|
| (kN)                   | (mm)                | (mm)                  | (MPa)                       | (MPa)                                     | (%)                           | (%)                             |
| 19.79                  | 100.84              | 50.200                | 10.00                       | 0.00                                      | 0.0000                        | 0.0000                          |
| 39.68                  | 100.8               | 50.201                | 20.05                       | 10.05                                     | 0.0397                        | -0.0020                         |
| 59.39                  | 100.77              | 50.203                | 30.01                       | 20.01                                     | 0.0694                        | -0.0060                         |
| 83.20                  | 100.74              | 50.205                | 42.03                       | 32.03                                     | 0.0992                        | -0.0100                         |
| 108.47                 | 100.71              | 50.208                | 54.79                       | 44.79                                     | 0.1289                        | -0.0159                         |
| 135.98                 | 100.68              | 50.212                | 68.67                       | 58.67                                     | 0.1587                        | -0.0239                         |
| 164.48                 | 100.65              | 50.216                | 83.05                       | 73.05                                     | 0.1884                        | -0.0319                         |
| 181.81                 | 100.63              | 50.222                | 91.78                       | 81.78                                     | 0.2083                        | -0.0438                         |
| 205.05                 | 100.58              | 50.236                | 103.45                      | 93.45                                     | 0.2578                        | -0.0717                         |
| 210.45                 | 100.56              | 50.246                | 106.13                      | 96.13                                     | 0.2777                        | -0.0916                         |
| 211.82                 | 100.54              | 50.253                | 106.80                      | 96.80                                     | 0.2975                        | -0.1056                         |
| 200.06                 | 100.52              | 50.258                | 100.85                      | 90.85                                     | 0.3173                        | -0.1155                         |
| 157.40                 | 100.49              | 50.265                | 79.32                       | 69.32                                     | 0.3471                        | -0.1295                         |
| 135.64                 | 100.46              | 50.271                | 68.34                       | 58.34                                     | 0.3768                        | -0.1414                         |
| 121.78                 | 100.43              | 50.277                | 61.34                       | 51.34                                     | 0.4066                        | -0.1534                         |
| 117.83                 | 100.4               | 50.283                | 59.34                       | 49.34                                     | 0.4363                        | -0.1653                         |
| 116.84                 | 100.37              | 50.283                | 58.84                       | 48.84                                     | 0.4661                        | -0.1653                         |

# Triaxial compression

## Example 4 – Solution



# Slake Durability

- **Slake Durability Test**

- The **slake durability index** quantifies the resistance of a rock to wetting and drying cycles and is a measure of the durability of the rock.
- Test is mainly used for **weak rocks** (shales, mudstones, claystones and siltstones).
- Dried fragments of rock are placed in a drum made of wire mesh partially submerged in distilled water.
- The drum is rotated for 10 minutes, allowing for disintegrated fragments to leave the drum through the 2-mm sieve mesh. The remaining fragments in the drum are dried and weighed.
- Test is repeated over a second cycle of slaking.

# Slake Durability

- Slake Durability Test

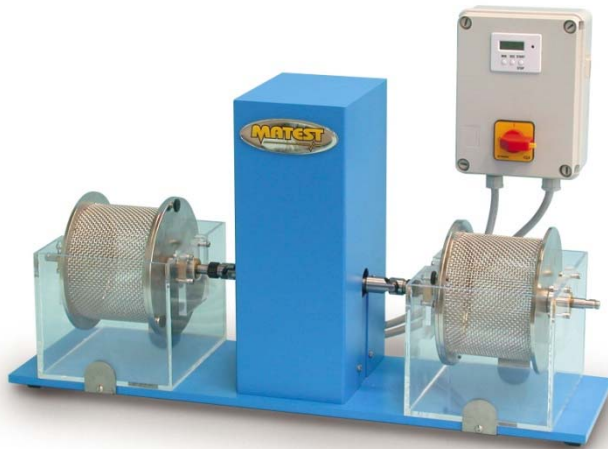


Table 3.9 Durability classification based on slake durability index

| Durability  | $I_{d1}$ | $I_{d2}$ |
|-------------|----------|----------|
| Very high   | >99      | 98–100   |
| High        | 98–99    | 95–98    |
| Medium high | 95–98    | 85–95    |
| Medium      | 85–95    | 60–85    |
| Low         | 60–85    | 30–60    |
| Very low    | <60      | 0–30     |

Source: Gamble, J.C., *Durability—Plasticity classification of shales and other argillaceous rocks*, PhD thesis, University of Illinois at Urbana-Champaign, IL, 1971.

$$I_{d1} = \frac{m_2}{m_1} \times 100$$

Where:

$m_1$  = dry mass of the original lumps in the drum

$$I_{d2} = \frac{m_3}{m_1} \times 100$$

$m_2$  = dry mass of the material retained in the drum after the first cycle

$m_3$  = dry mass of the material retained after the second cycle

# Slake Durability Test – typical results

- Slake Durability Test – typical test results

Table 3.10 Slake durability test datasheet

| Sample no.                                                | Porcellanite2 | Porcellanite7 | Claystone1 | Claystone3 | Claystone8 |
|-----------------------------------------------------------|---------------|---------------|------------|------------|------------|
| Mass of drum + dry sample ( $m_1$ ), g                    | 1476          | 1457          | 1464       | 1493       | 1503       |
| Mass of drum + dry sample after first cycle ( $m_2$ ), g  | 1472          | 1452          | 1125       | 1114       | 1103       |
| Mass of drum + dry sample after second cycle ( $m_3$ ), g | 1467          | 1446          | 1013       | 1004       | 1009       |
| Mass of drum ( $m_4$ ), g                                 | 971           | 970           | 968        | 969        | 968        |
| Second-cycle slake durability index, $I_{d2}$             | 98.2          | 97.7          | 9.1        | 6.7        | 7.7        |
| First-cycle slake durability index, $I_{d1}$              | 99.2          | 99.0          | 31.7       | 27.7       | 25.2       |
| Slaking fluid                                             | Seawater      |               |            | Tap water  |            |
| Temperature of slaking fluid                              | 26°C          | 26°C          | 27°C       | 27°C       | 27°C       |

**Note1:** The second-cycle slake durability index  $I_{d2}$  is the one that is commonly used as a measure of rock durability. Only in rocks that are classified as very low in durability with  $I_{d2} < 10\%$ , it is recommended to include  $I_{d1}$  as well.

# Schmidt Hammer Test

- Schmidt Hammer Test

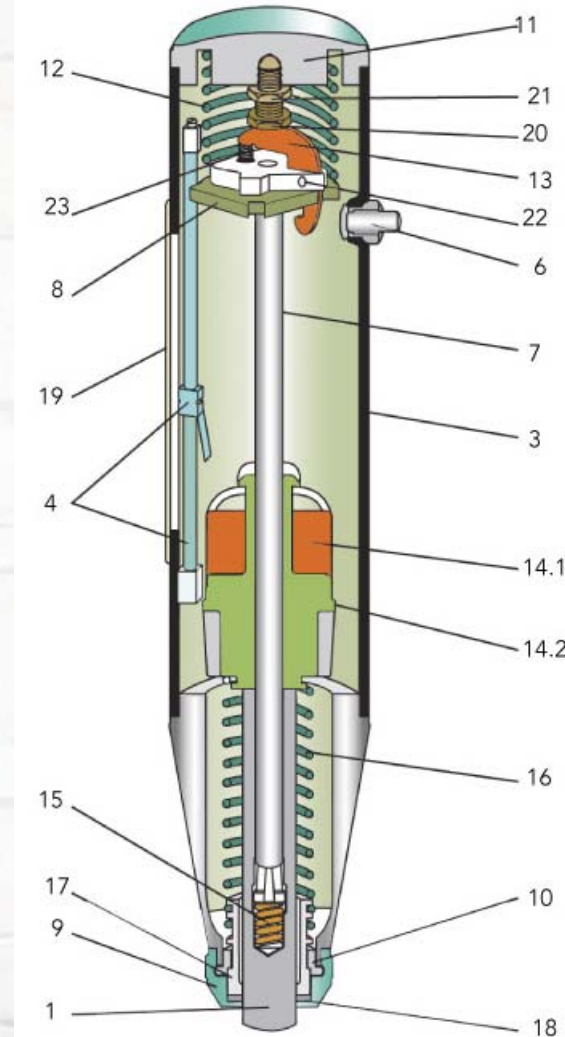
- To determine the rebound hardness value,  $R$  ( $0 < R < 100$ ) for intact rock specimens in the laboratory or in-situ.
- Performed on rocks with UCS of 20–150 MPa (ISRM, 1978).
- Two types of Schmidt hammers are commonly used: L-type with an impact energy of 0.735 N·m and N-type with an impact energy of 2.207 N·m.



# Schmidt Hammer Test

- **Schmidt Hammer Test**

- The spring-loaded metal piston is released when the plunger is pressed against the rock surface.
- The impact of the piston onto the plunger transfers the energy to the rock.
- How much of this energy is recovered depends on the hardness of the rock and is measured by the rebound height of the piston.
- The harder the surface, the greater the rebound.



| Key | Description           |
|-----|-----------------------|
| 1   | Impact Plunger        |
| 3   | Housing, complete     |
| 4   | Rider with Guide Rod  |
| 6   | Push-button, complete |
| 7   | Hammer Guide Bar      |
| 8   | Guide Disk            |
| 9   | Cap                   |
| 10  | Two-part Ring         |
| 11  | Rear Cover            |
| 12  | Compression Spring    |
| 13  | Pawl                  |
| 14  | Hammer Mass           |
| 15  | Retaining Spring      |
| 16  | Impact Spring         |
| 17  | Guide Sleeve          |
| 18  | Felt Washer           |
| 19  | Acrylic Window        |
| 20  | Trip Screw            |
| 21  | Lock Nut              |
| 22  | Pin                   |
| 23  | Pawl Spring           |

# Empirical correlations

- **Empirical correlations** interrelating the intact rock parameters:

Table 3.11  $\sigma_c$ - $\sigma_t$  Correlations

| Correlation                      | Reference                    | Comments                                                  |
|----------------------------------|------------------------------|-----------------------------------------------------------|
| $\sigma_c = 10.5\sigma_t + 1.2$  | Hassani et al. (1979)        |                                                           |
| $\sigma_c = 3.6\sigma_t + 15.2$  | Szlavin (1974)               | United Kingdom; 229 tests                                 |
| $\sigma_c = 2.84\sigma_t - 3.34$ | Hobbs (1964)                 | Mudstone, sandstone and limestone                         |
| $\sigma_c = 12.4\sigma_t - 9.0$  | Gunsallus and Kulhawy (1984) | Dolostone, sandstone and limestone from the United States |
| $\sigma_c = 10\sigma_t$          | Broch and Franklin (1972)    |                                                           |

# Empirical correlations

- **Empirical correlations** interrelating the intact rock parameters:

Table 3.12  $\sigma_c - I_{s(50)}$  Correlations

| Correlation                       | Reference                    | Comments                                                             |
|-----------------------------------|------------------------------|----------------------------------------------------------------------|
| $\sigma_c = 24I_{s(50)}$          | Broch and Franklin (1972)    |                                                                      |
| $\sigma_c = 24I_{s(50)}$          | Bieniawski (1975)            | Sandstone, South Africa                                              |
| $\sigma_c = 29I_{s(50)}$          | Hassani et al. (1980)        | Sedimentary rocks, United Kingdom                                    |
| $\sigma_c = 14.5I_{s(50)}$        | Forster (1983)               | Dolerite and sandstone                                               |
| $\sigma_c = 12.5I_{s(50)}$        | Chau and Wong (1996)         | Hong Kong rocks                                                      |
| $\sigma_c = 16I_{s(50)}$          | Read et al. (1980)           | Basalt                                                               |
| $\sigma_c = 20I_{s(50)}$          | Read et al. (1980)           | Sedimentary rocks, Australia                                         |
| $\sigma_c = 23.4I_{s(50)}$        | Singh and Singh (1993)       | Quartzite, India                                                     |
| $\sigma_c = 15.3I_{s(50)} + 16.3$ | D'Andrea et al. (1964)       | Range of rock types                                                  |
| $\sigma_c = 16.5I_{s(50)} + 51.0$ | Gunsallus and Kulhawy (1984) | Dolostone, sandstone and limestone from the United States            |
| $\sigma_c = 9.3I_{s(50)} + 20.04$ | Grasso et al. (1992)         |                                                                      |
| $\sigma_c = 23I_{s(54)} + 13$     | Cargill and Shakoor (1990)   | Mostly from United States and some from Canada; 54-mm-diameter cores |