بسم الله الرحمن الرحيم

Faculty of Science

Geology Department

Rock Mechanics

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Second year students

Main Topics

1- Introduction, Definition

2- Intact rock and rock masses

3- Behavioral classification of rock

4- Stress and strain and deformation behavior of rocks

5- Index Properties of rock system

6- Ground water related rock foundation (Porosity, Permeability, Flow, Hydraulic Gradient, …).

7- Engineering Classifications of rock masses

8- Problematic rocks

- **Difination**:

Mechanics of materials is a branch of engineering that deal with stresses and properties of materials.

Steel & Concrete: homogeneous (same composition throughout), isotropic (same directional properties throughout), Lab. Testing.

Rocks & Soil: inhomomgeneous & anisotropic, both Lab. and field Testing.

- **Difination:**

Rock: (single system, continium, mineral association).

Rock mass: (Multi system, discontinium, Joining „Joints“, one or more type of rocks).

Rock mechanics: a branch of engineering (geotechnology), deals with stresses and mechanical properties of rock and rock mass to understand the mechanical behavior of rocks and rock mass for foundations, tunnels, mining, etc….. (applications in engineering Geology and civil engineering.

- Geological classification of rocks:

* Genetic classification: (Geologist)

Igneous, metamorphic, and sedimentary.

* Behavioral classification: (Civil Engineer & Engineering Geologist)

I- Crystalline texture

II- Clastic texture

III- Very fine-grained rocks

IV- Organic rocks

I. CRYSTALLINE TEXTURE

		Examples
A.	Soluble carbonates and salts	Limestone, dolomite, marble, rock salt, trona, gypsum
B.	Mica or other planar minerals in continuous bands	Mica schist, chlorite schist, graphite schist
C.	Banded silicate minerals without continuous mica sheets	Gneiss
D.	Randomly oriented and distributed silicate minerals of uniform grain size	Granite, diorite, gabbro, syenite
E.	Randomly oriented and distributed silicate minerals in a background of very fine grain and with vugs	Basalt, rhyolite, other volcanic rocks
F.	Highly sheared rocks	Serpentinite, mylonite

Figure 2.1 Photomicrographs of thin sections of rocks, viewed in polarized, transmitted light (courtesy of Professor H. R. Wenk). (*a*) Tightly interlocked fabric of a crystalline rock—diabase (×27).

Figure 2.1 Photomicrographs of thin sections of rocks, viewed in polarized, transmitted light (courtesy of Professor H. R. Wenk). (*b*) Highly anisotropic fabric of a quartz mylonite (× 20).

II. CLASTIC TEXTURE

		Examples
A.	Stably cemented	Silica-cemented sandstone and limonite sandstones
B.	With slightly soluble cement	Calcite-cemented sandstone and conglomerate
C.	With highly soluble cement	Gypsum-cemented sandstones and conglomerates
D.	Incompletely or weakly cemented	Friable sandstones, tuff
E.	Uncemented	Clay-bound sandstones

III. VERY FINE-GRAINED ROCKS

A.	Isotropic, hard rocks	Hornfels, some basalts
B.	Anisotropic on a macro scale but microscopically isotropic hard rocks	Cemented shales, flagstones
C.	Microscopically anisotropic hard rocks	Slate, phyllite
D.	Soft, soillike rocks	Compaction shale, chalk, marl

IV. ORGANIC ROCKS

A. Soft coal — Lignite and bituminous coal

B. Hard coal

C. "Oil shale"

D. Bituminous shale

E. Tar sand

- **Crystalline rocks** (ex. Granite, Diabase, etc…..), hard, Deformation Model: elastic behavior „reversibly“.
- **Soluble carbonate, salts, and fissured rocks**: Deformation Model: plastic behavior „irreversibly“ .
- **Shale, Serpentine, and Mylonite**: cleavage, weakness plans, reducing strength.

Stress and strain

- The unite of force called Newton (N), is defined as the force which gives an acceleration of $1 m/s^2$ to a mass of 1 kg.
- **Stress** (σ) is the force per unit area that exists within a specified plane in a material.

σ= F/A where F= Force (compression or tensile) (N)

A ⟶ (m^2)

σ= N/ m^2 = also known as Pascal (1 N/m^2 = 1 Pa).

- **Stress analysis**:

General three dimentional states of stress

Normal (direct stress)

Shear stress

Three principal stresses

Major principal stress σ1

Intermediate principal stress σ2

Minor principal stress σ3 (σ1 > σ2 > σ3)

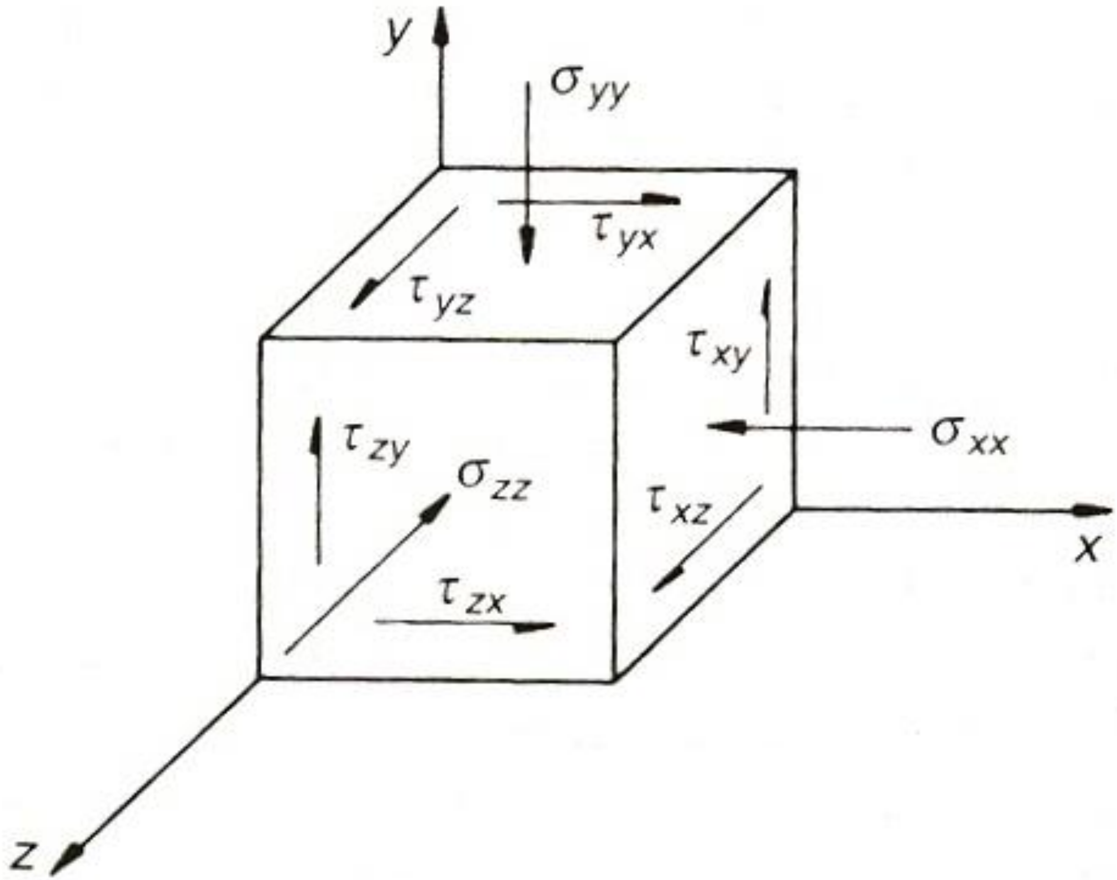

Figure 2.1 *General three-dimensional state of stress. The faces of the cubic element shown are termed the* **positive faces,** *because the outward normals are in the positive directions of* x, *y and z. On the faces not shown (the* **negative**

Strain

Strain: (ε) is a measure of the deformation of a material when a load is applied.

Strain is a ratio of lengths, such as meters per meter. Strain has dimentionless units.

$\varepsilon = \Delta L / L$ where ΔL = difference of Length & L = original Length

$E = \text{stress}/\text{strain} = \sigma/\varepsilon$ (Hooke;s Law)

Within an elastic range, strain is proportional to stress , E= constant known as Young;s modulus or modulus of elasticity. (N/m^2)

- **Deformation behavior of rocks (materials):**

1- Elastic behavior (spring) e.g, Rocks (Granit)

A- Linear

B- Convex

C- Concave

2- Plastic B. (Friction Model)

e.g. Soils (sandstone)

3- Viscous B. (Flow Model): e.g. claystone

Index properties of rock systems:

These index properties to describe the rocks quantitatively, they including:

1- Porosity

2- Density

3- Permeability

4- Durability

5- Sonic velocity

6- Strength

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Index properties of rock systems:

- Water content (moisture content):

The ratio of the mass of water to the mass of rock solids.

$$W = m_w/m_s \cdot 100 \quad (\%)$$

Determination of water content in lab.:

1- Porosity

- Porosity: the relative proportion of solids and voids. The porosity of the rock, indicated by the dimensionless quantity n, is a fraction expressing the proportion of void space to total space in the rock.

$$n = V_p/V_t \cdot 100$$

V_p= the volume of pores in total volume V_t.

Porosity

- There are two types of the porosity:

1- total (absolute) porosity. (all connected and unconnected pores), larger value.

2- net (effective) porosity. (only connected pores), smaller value.

Porosity

* Sedimentary rocks: (pores between grains), ranging from 0 to 90%.

And it depends on both the age and the depth.

* Crystalline rocks: (limestone, evaporites, igneous „1 or 2% and due to weathering progresses it increased to 20% or more“, and metamorphic):

(planar cracks termed fissures).

Porosities of Some Typical Rocks Showing Effects of Age and Depth[a]

Rock	Age	Depth	Porosity (%
Mount Simon sandstone	Cambrian ←	13,000 ft	0.7
Nugget sandstone (Utah)	Jurassic		1.9
Potsdam sandstone	Cambrian ←	Surface	11.0
Pottsville sandstone	Pennsylvanian		2.9
Berea sandstone	Mississippian	0–2000 ft	14.0
Keuper sandstone (England)	Triassic	Surface	22.0
Navajo sandstone	Jurassic	Surface	15.5
sandstone, Montana	Cretaceous	Surface	34.0
Beekmantown dolomite	Ordovician	10,500 ft	0.4
Black River limestone	Ordovician	Surface	0.46
Niagara dolomite	Silurian	Surface	2.9
limestone, Great Britain	Carboniferous	Surface	5.7
chalk, Great Britain	Cretaceous	Surface	28.8
Solenhofen limestone		Surface	4.8
Salem limestone	Mississippian	Surface	13.2
Bedford limestone	Mississippian	Surface	12.0
Bermuda limestone	Recent	Surface	43.0
Shale	Pre-Cambrian	Surface	1.6
Shale, Oklahoma	Pennsylvanian ←	1000 ft	17.0
Shale, Oklahoma	Pennsylvanian	3000 ft	7.0
Shale, Oklahoma	Pennsylvanian ←	5000 ft	4.0
Shale	Cretaceous	600 ft	33.5
Shale	Cretaceous	2500 ft	25.4
Shale	Cretaceous	3500 ft	21.1
Shale	Cretaceous	6100 ft	7.6
Mudstone, Japan	Upper Tertiary	Near surface	22–32
Granite, fresh		Surface	0 to 1
Granite, weathered			1–5
Decomposed granite (Saprolyte)			20.0
Marble			0.3
Marble			1.1
Bedded tuff			40.0
Welded tuff			14.0
Cedar City tonalite			7.0
Frederick diabase			0.1
San Marcos gabbro			0.2

[a] Data selected from Clark (1966) and Brace and Riley (1972).

Figure 2.2 Photomicrographs of thin sections of fissured rocks, photographed in transmitted, polarized light (courtesy of H. R. Wenk). (*a*) Anorthosite with many intracrystalline and some intercrystalline fractures (× 6.5).

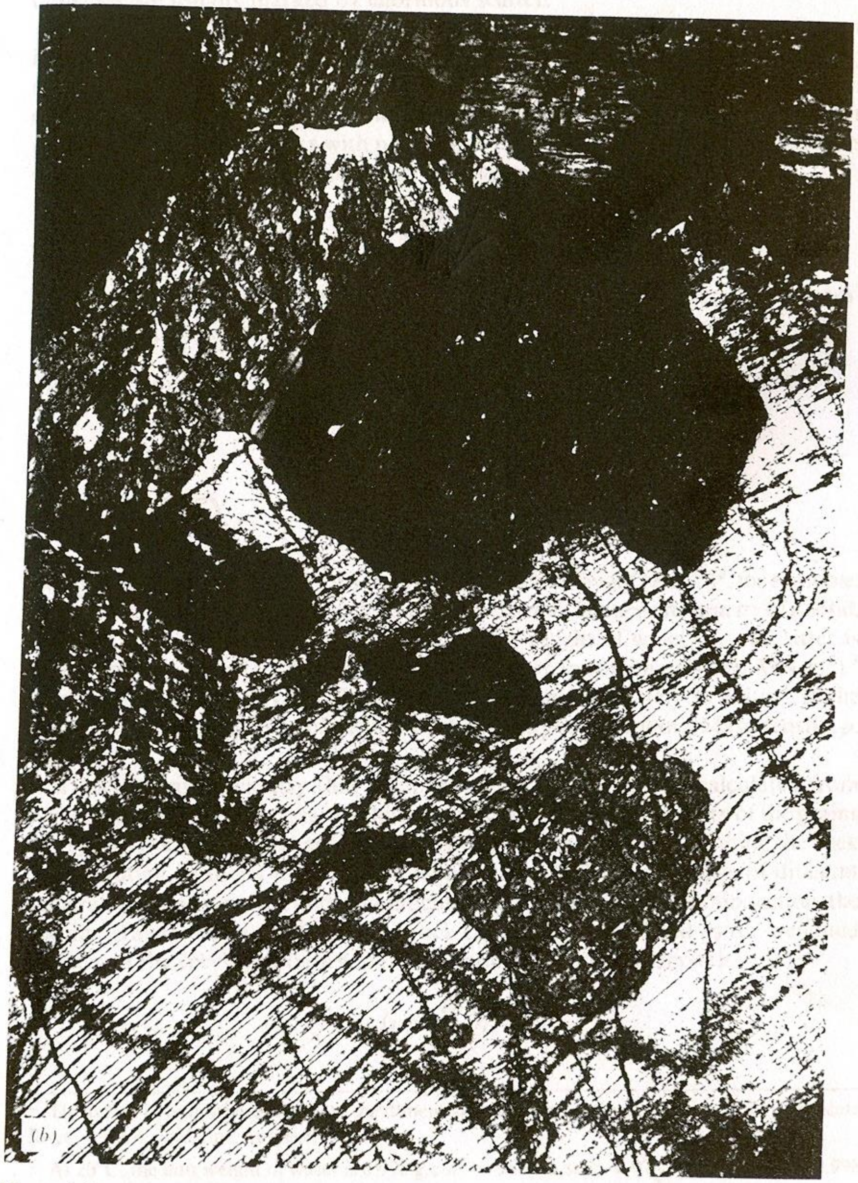


Figure 2.2 Photomicrographs of thin sections of fissured rocks, photographed in transmitted, polarized light (courtesy of H. R. Wenk). (*b*) Gabbro with regular fissures oriented across the cleavage (× 7).

Porosity

* Determination of the porosity:

$$n = W_2 - W_1 / W_2 - W_3 \, . \, 100 \qquad (\%)$$

W_2= mass (water saturated)

W_1= mass (dry)

W_3= mass (in water)

* $n = W_{Hg} \, . \, G/G_{Hg} \, / \, 1 + (W_{Hg} \, . \, G/G_{Hg})$

W_{Hg}= mercury content & G_{Hg}= specific gravity of mercury (13.546), G= specific gravity of rock.

- **Void ratio (e):** the ratio of the volume of voids to the volume of the solids.

The relationships between e & n

$n = e/(1+e)$ & $e = n/(1-n)$

2- Density

- Density (ρ) add information about the mineralogy or grain constituents.

Dry Density = $\rho_d = m_d/V$ (g/cm^3) or (T/m^3)
m_d= dry mass & V= volume.

Wet Density = $\rho_w = m_w/V$ (g/cm^3) or (T/m^3)
m_w= wet mass & V= volume.

$\rho_d = \rho_w / 1+W$ where W= water content

Density

- Unite weight = Density . g

$\gamma = \rho \cdot g$ (KN/m³)

g= gravity acceleration (=9.8 „10“ m/S²).

Specific gravity (Gs)= ratio between unite weight of rock to the unite weight of water

$Gs = \gamma / \gamma_w$

Bulk Density: total density of the rock in the field.

3- Permeability

- Permeability defined as the ability of a rock to allow the passage of fluids into or through it without impairing its structure.

  Permeability of particular material is defined by its coefficient of permeability or hydraulic conductivity.

Permeability

- Darcy's Law : which governs the flow of ground water through soil and rocks.

V =Ki   K=V/i   where Q=VA

Q = kiA   K= coefficient of permeability or hydraulic conductivity (m/s).

V= velocity of water filteration (m/s)

Q= volumetric flowrate of water (m^3/s)

A= the cross-sectional area of the flow-tube

i= hydraulic gradient (the rate of decrease of total head (potential) with distance in the direction of the flow (dh/dx).

Permeability

- 1 Darcy = 10^{-3} cm/s

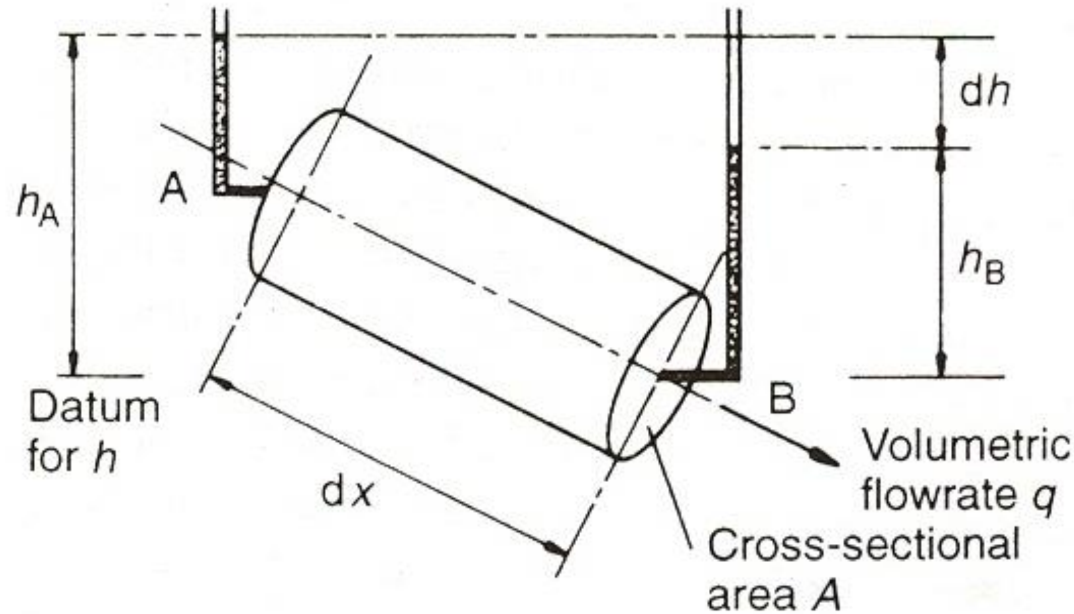
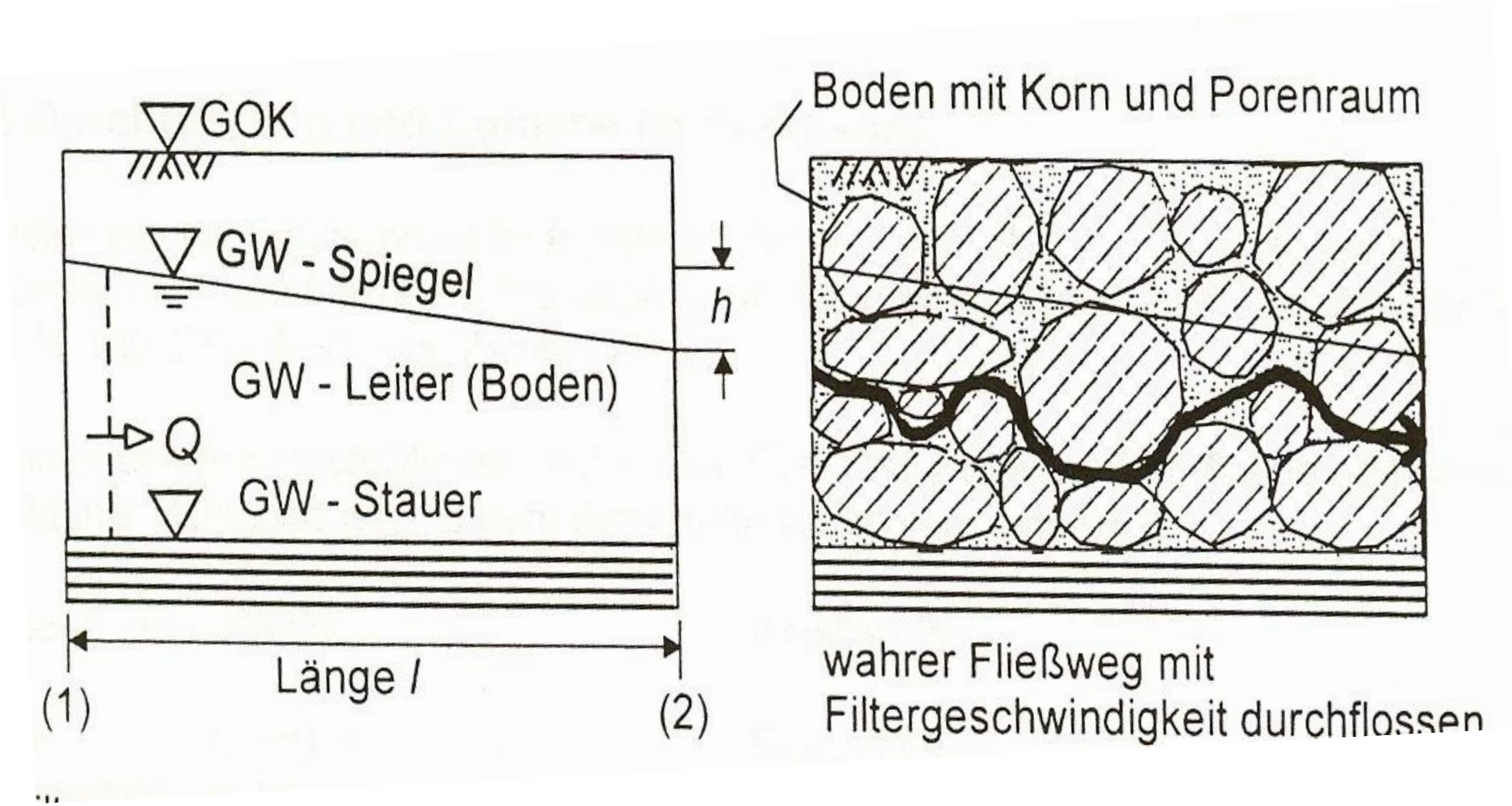


Figure 3.5 *Darcy's Law.*

Permeability



Permeability

Permeabilities of Typical Rocks[a]

	k (cm/s) for Rock With Water (20°C) as Permeant	
	Lab	Field
Sandstone	3×10^{-3} to 8×10^{-8}	1×10^{-3} to 3×10^{-8}
Navajo sandstone	2×10^{-3}	
Berea sandstone	4×10^{-5}	
Greywacke	3.2×10^{-8}	
Shale	10^{-9} to 5×10^{-13}	10^{-8} to 10^{-11}
Pierre shale	5×10^{-12}	2×10^{-9} to 5×10^{-11}
Limestone, dolomite	10^{-5} to 10^{-13}	10^{-3} to 10^{-7}
Salem limestone	2×10^{-6}	
Basalt	10^{-12}	10^{-2} to 10^{-7}
Granite	10^{-7} to 10^{-11}	10^{-4} to 10^{-9}
Schist	10^{-8}	2×10^{-7}
Fissured schist	1×10^{-4} to 3×10^{-4}	

4- Slaking and durability

- Durability of rocks is fundamentally important for all applications.
- Changes in the properties of rocks are produced by exfoliation, hydration, slaking, solution, oxidation, abrasion, and other processes.

Slake durability test (Franklin and Chandra 1972):

Slaking and durability

Slake durability test (Franklin and Chandra 1972):

1-500 g of rock is broken into 10 lumps and located inside a drum (140 mm in diameter and 100 mm long with sieve mesh „2 mm opening“ forming the cylindrical walls)

2- the drum is turned at 20 revoltions per minute in a water bath.

Slaking and durability

3- After 10-minutes of this slow rotation, the percent of rock retained inside the drum, on a dry weight basis, is reported as the slake durability index (Id).

- Liquid limit method (WL): for shale and claystone.
- The rate of slaking was classified in terms of the change in liquidity index (Δ IL) following immersion in water for 2 hours.

Slaking and durability

$\Delta IL = \Delta w / wL - wp$

Δw = the change in water content of the rock or soil after soaking for 2 hours.

WL= water content at liquid limit

Wp= water content at plastic limit.

Description of Rate and Amount of Slaking[a]

Amount of Slaking	Liquid Limit (%)
Very low	<20
Low	20–50
Medium	50–90
High	90–140
Very high	>140

Rate of Slaking	Change in Liquidity Index after Soaking 2 Hours
Slow	<0.75
Fast	0.75–1.25
Very fast	>1.25

[a] After Morgenstern and Eigenbrod (1974).

Gamble's Slake Durability Classification

Group Name	% Retained After One 10-Minute Cycle (Dry Weight Basis)	% Retained After Two 10-Minute Cycles (Dry Weight Basis)
Very high durability	>99	>98
High durability	98–99	95–98
Medium high durability	95–98	85–95
Medium durability	85–95	60–85
Low Durability	60–85	30–60
Very Low Durability	<60	<30

Index properties of rock systems:

These index properties to describe the rocks quantitatively, they including:

1- Porosity

2- Density

3- Permeability

4- Durability

5- Sonic velocity

6- Strength

5- Sonic velocity

- Measurment of the velocity of sound waves in a core specimen is relatively simple and apparatus is available for this purpose.
- The most popular method pulses one end of the rock with a piezoelectric crystal and receives the vibrations with a second crystal at the other end.
- The travel time is determined by measuring the phase difference with an oscilloscope equipped.

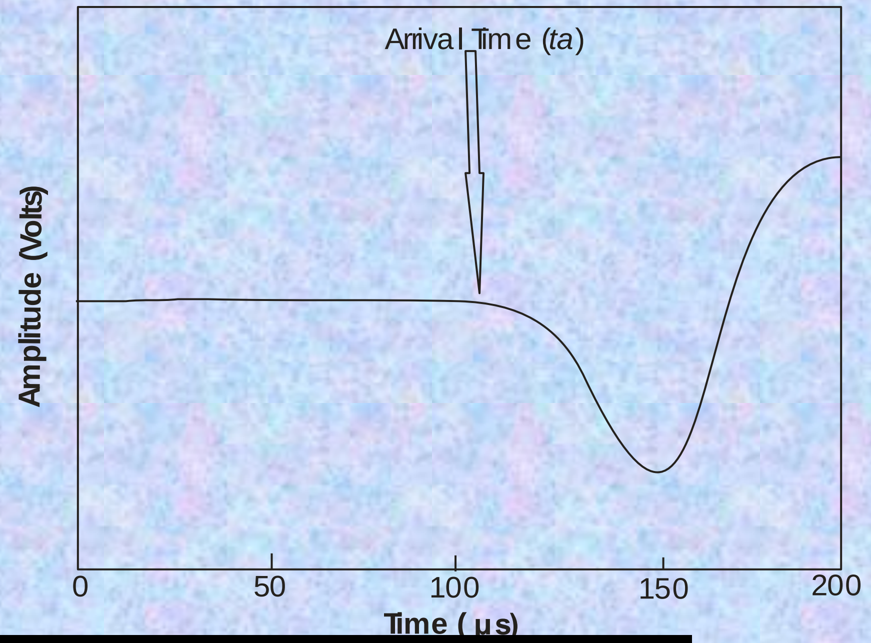
5- Sonic velocity

- Longitudinal (Vl) & transverse (Vs) shear wave velocites.
- The velocity depends exclusively upon their elastic properties and their density.
- The sonic velocity (Vl) can serve to index the degree of fissring within rock specimens.

5- Sonic velocity

Ultrasonic instrument.

Typical waveform.



The velocity of the p-waves was obtained as the quotient of the travel pass “x” (the height of the samples) and the travel time of the P-waves “*ta*” (P-waves velocity “Vp” =x/*ta*) (Yesiller N. et al. 2001).

5- Sonic velocity

- Fourmaintraux (1976):

$1/ VL^* = \sum_i Ci/Vli$

Vl*= velocity of longitudinal waves in rock-forming minerals

Ci= volume proportion of mineral in the rock.

IQ%= (Vl/Vl*).100

IQ%= quality index

5- Sonic velocity

Longitudinal Velocities of Minerals

Mineral	V_l m/s
Quartz	6050
Olivine	8400
Augite	7200
Amphibole	7200
Muscovite	5800
Orthoclase	5800
Plagioclase	6250
Calcite	6600
Dolomite	7500
Magnetite	7400
Gypsum	5200
Epidote	7450
Pyrite	8000

[a] From Fourmaintraux (1976).

Typical Values of V_l* for Rocks

Rock	V_l* m/s
Gabbro	7000
Basalt	6500–7000
Limestone	6000–6500
Dolomite	6500–7000
Sandstone and quartzite	6000
Granitic rocks	5500–6000

[a] From Fourmaintraux (1976).

5- Sonic velocity

- Sonic velocity as an index to degree of fissuring:

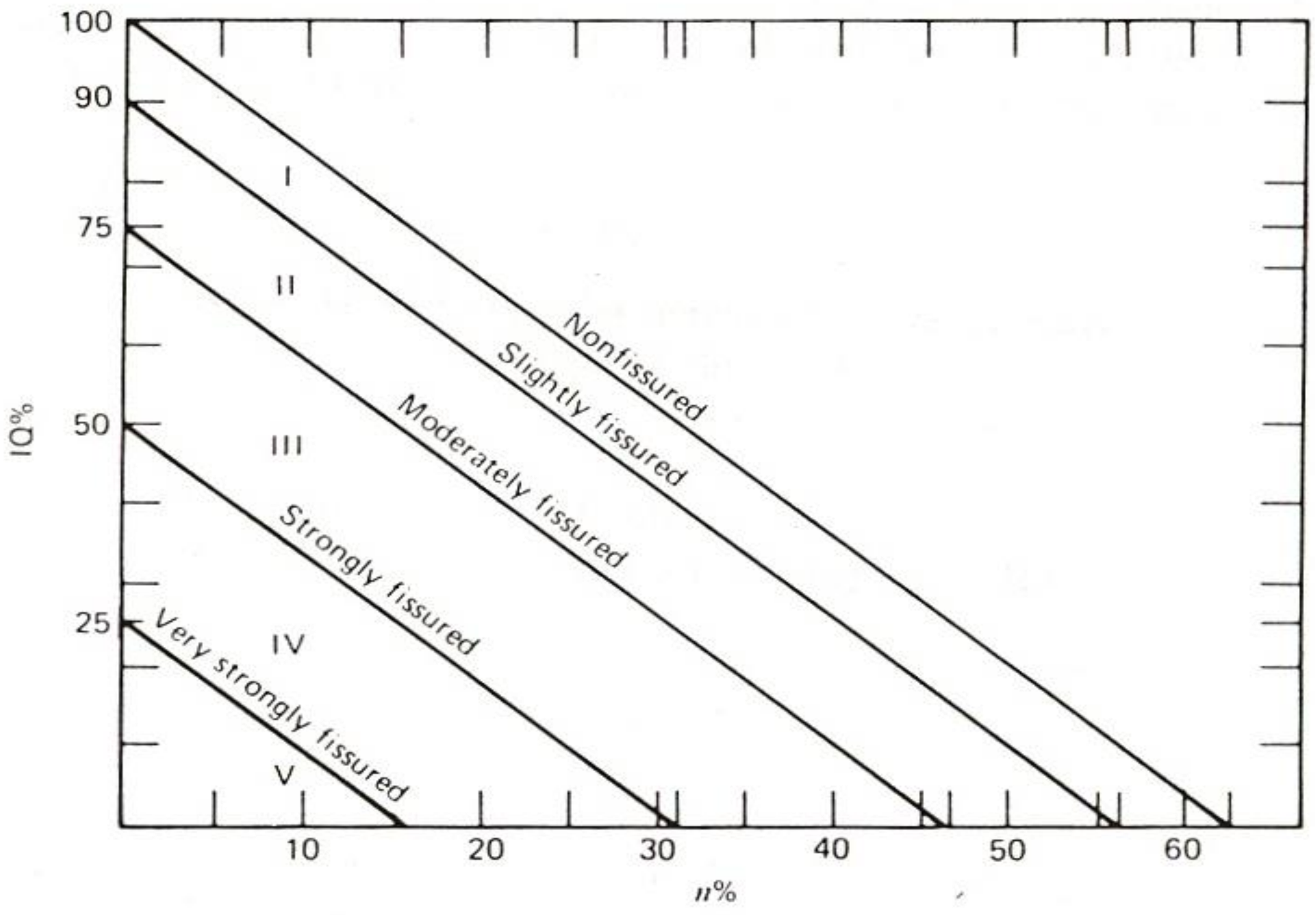


Figure 2.3 Classification scheme for fissuring in rock specimens. [After Fourmaintraux 1976.]

6- Strength

- The most commonly measured rock strength property is the uniaxial compressive strength σ_c (unconfined compressive strength q_u)
- There are several different levels of rock strength to be considered:

i) If suitable core samples and specimen preparation facilities are available, direct measurments of the σ_c can be obtained.

6- Strength

ii) If you are on site you may have the rocks, but no laboratory to carry out the testing. However, the site equipment may include a point load tester.

$Qu = 24. Is_{(50)}$

1- point load test

2- schmidt rebound hammer test

3- unconfined compressive test

1- point load test

- Point load test equipment consists of two types, non-portable laboratory equipment and portable equipment which can be used in the field or laboratory.

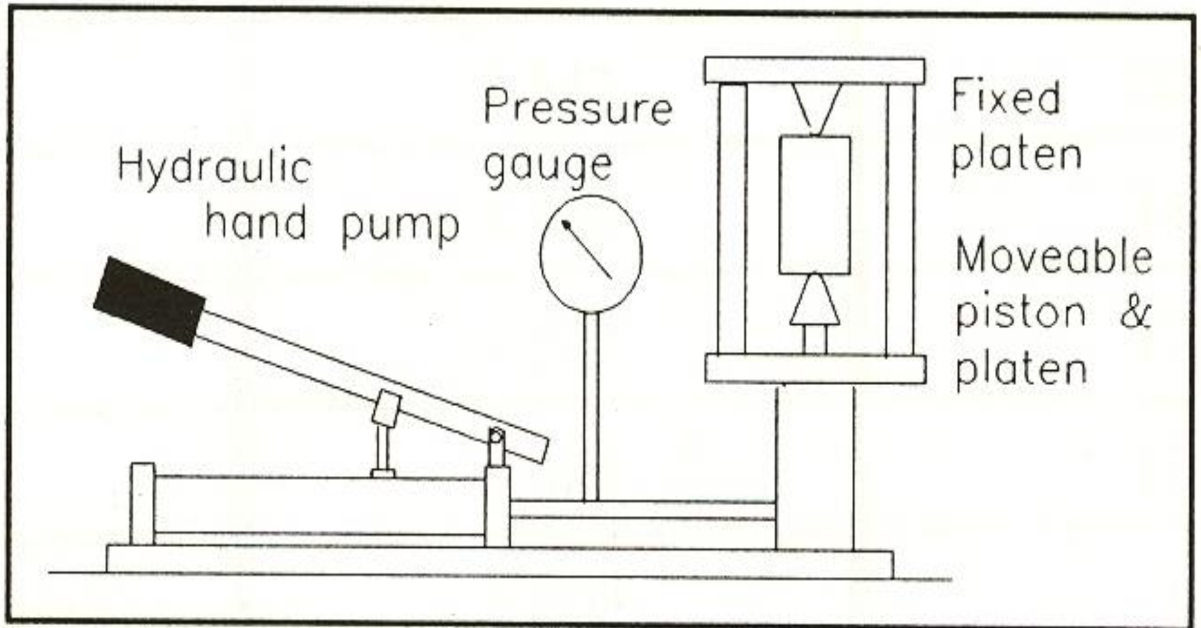
$I_s = P/D^2$

I_s= point load index (for specimen with 50mm diameter)

P= applied load in N

D= distance between points in appropriate units

1- point load test



Category	*Strength, psi*	*Strength, MPa*	I_s
Very high	>32000	>200	>10
High	16000-32000	100-200	4-10
Medium	8000-16000	50-200	2-4
Low	4000-8000	25-50	1-2
Very low	<4000	<25	<1

1- point load test

- Uncorrected point load strength must be corrected to obtain correcter $I_{s\ (50)}$.

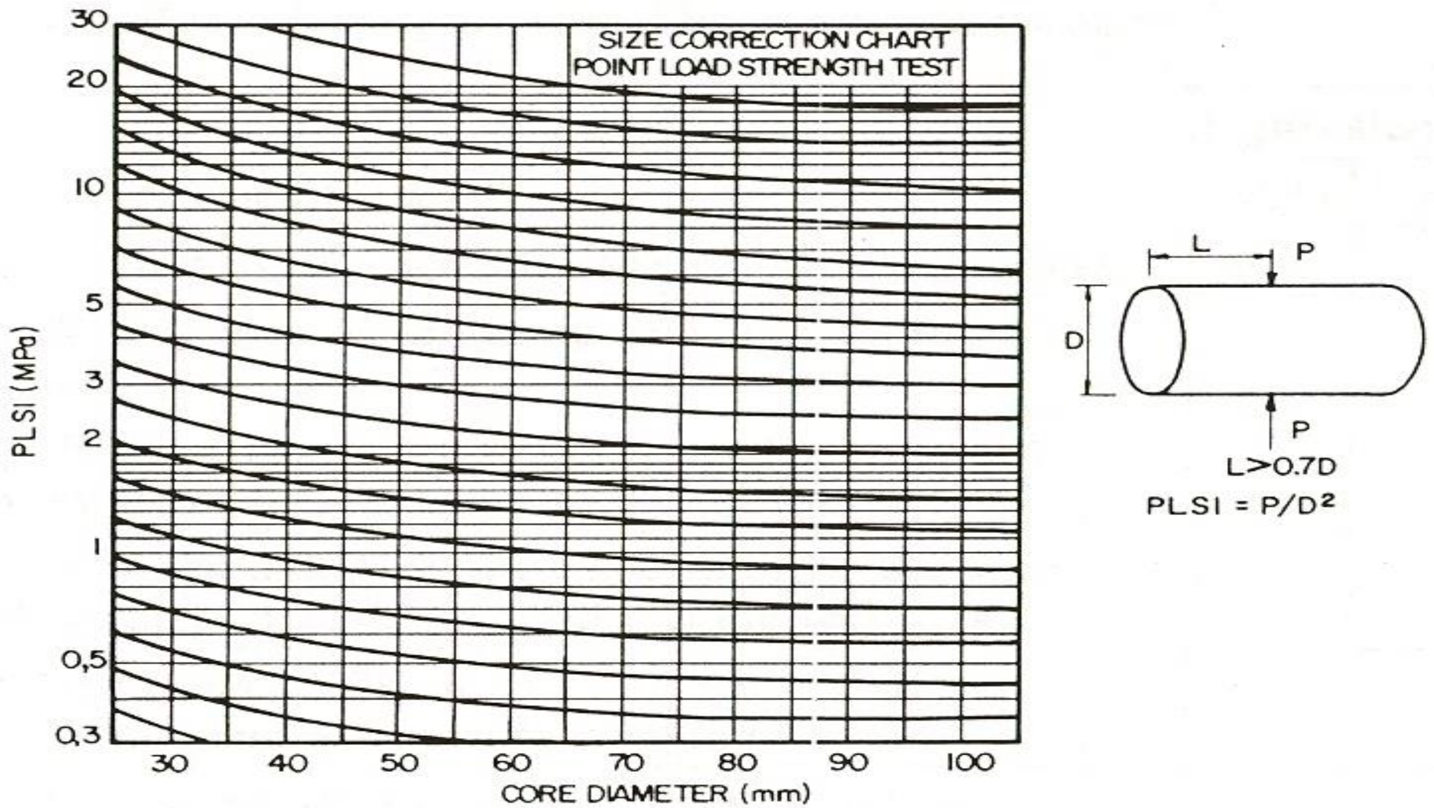


Fig. A1
Point Load Strength Test Size Correction Chart
(Redrawn after Broch and Franklin[14])

2- schmidt rebound hammer test

- The schmidt rebound hammer was designed to standarize both the methodology of hardness testing and the force with which a hammer strikes a rock surface.
- The measured amount of rebound can be correlated with the rock strength in much the same way as with point load data.
- The amount of rebound is actually a measure of the material;s elasticity which is reflected in its hardness

2- schmidt rebound hammer test

Figure 6.2 Photo by D. Zavadil

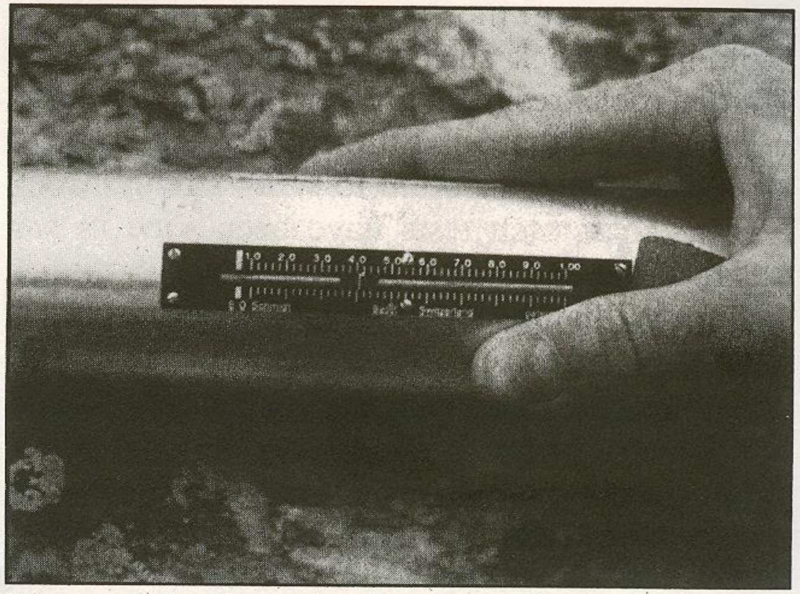


Figure 6.3 Photo by D. Zavadil

2- schmidt rebound hammer test

Rock surface after blow	*Strength, psi*	*Strength, MPa*
No change	>15000	>103
Shallow, rough pit	8000-15000	55-103
Dent or depression	3000-8000	21-55
Cratering with rim	1000-3000	7-21

2- schmidt rebound hammer test

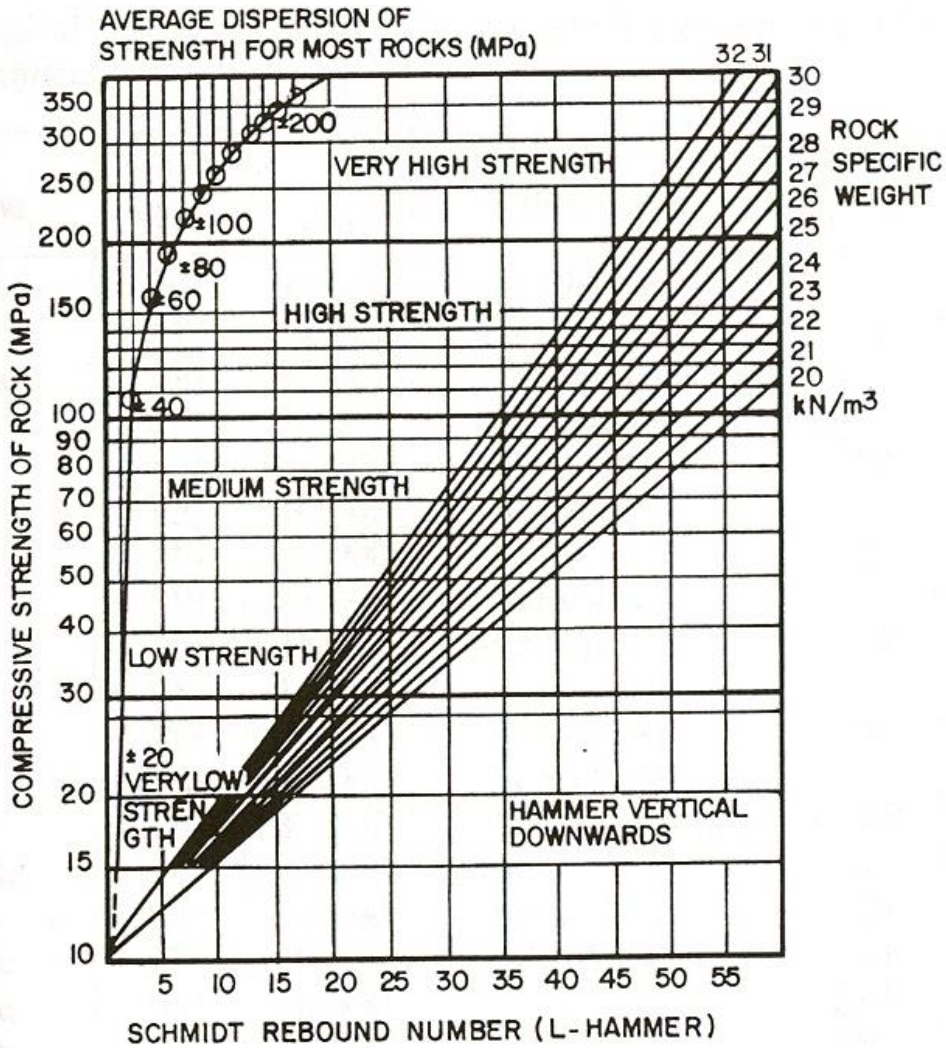


Fig. A2

Correlation between Schmidt Rebound Number (L-Hammer) and σ_c

(Redrawn after Miller[31])

3- unconfined compressive test

- q_u= F/A

q_u= unconfined compressive strength

F= Force (load) at the failure

A= area

3-unconfined compressive test

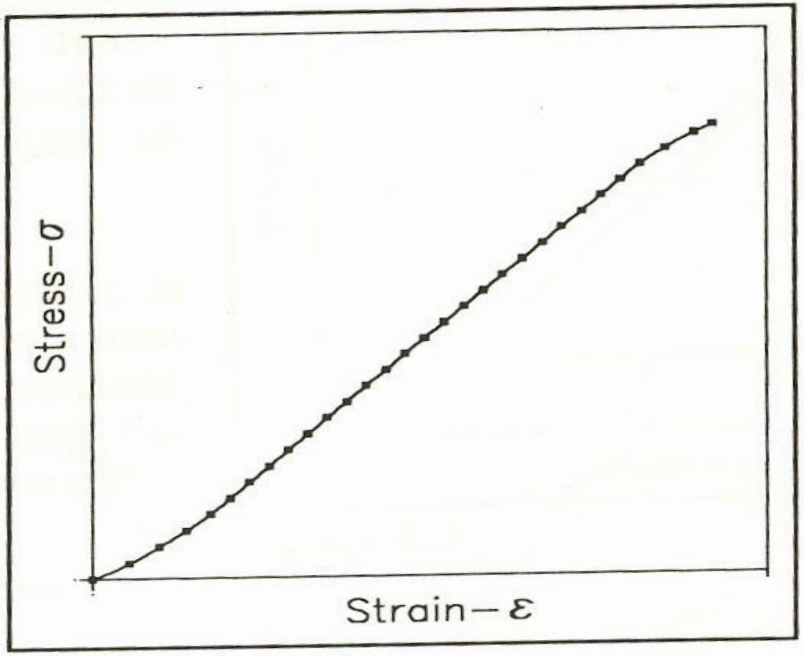
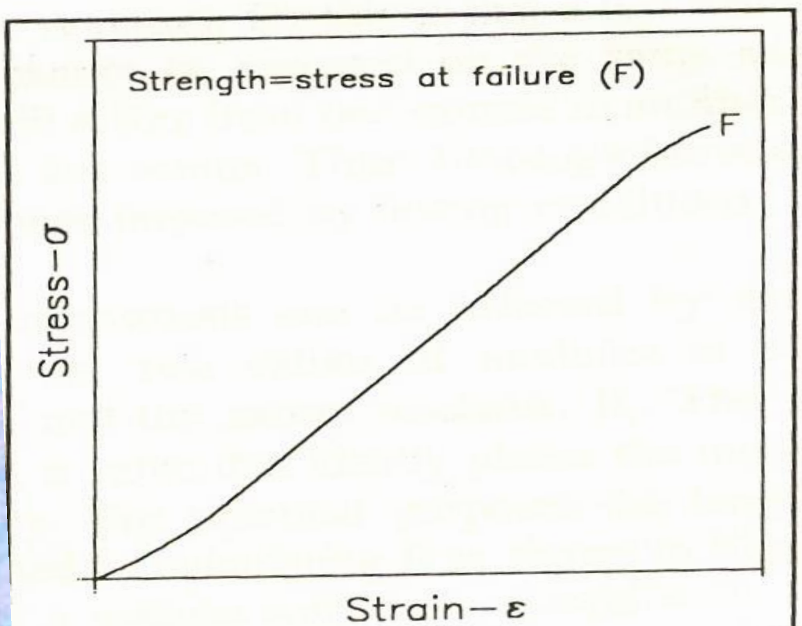


Figure 4.1



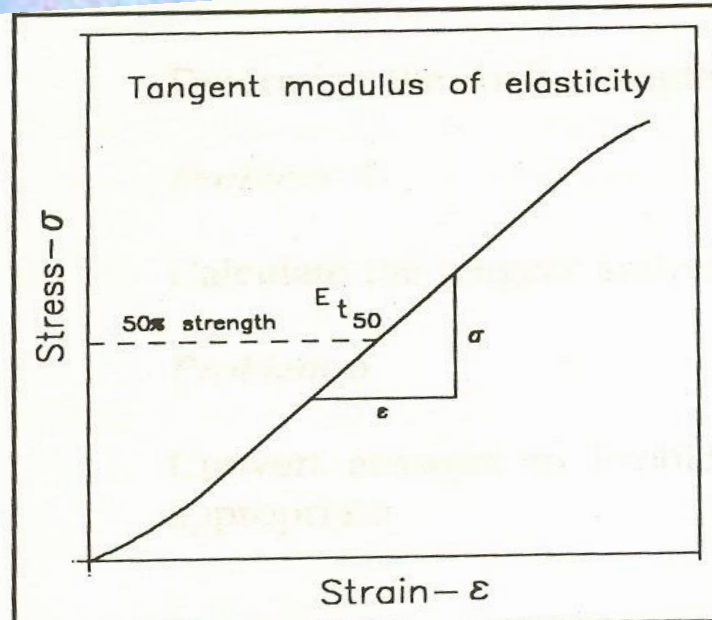


Figure 4.4

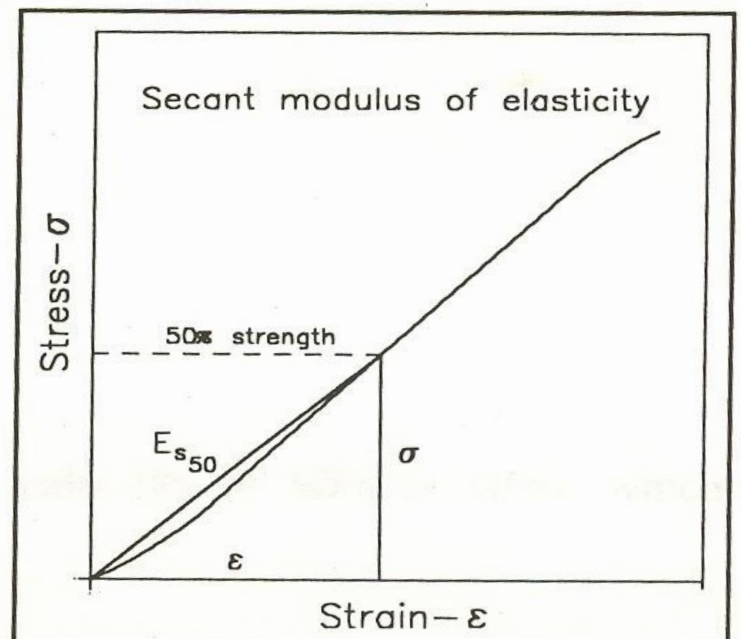


Figure 4.5

Classification of rock masses for engineering purposes

Bieniawski's geomechanics classification system provides a general rock mass rating (RMR) increasing with rock quality from 0 to 100.

It is based upon five universal parameters including: strength of the rock, drill core quality, ground water conditions, joint and fracture spacing, and joint characteristics.

* A sixth parameter (orientation of joints) is entered differently for specific application in tunneling, mining, and foundations.
* Increments of rock mass rating corresponding to each parameter are summed to determine RMR.

1- RMR increments for compressive strength of the rock

TABLE 2.10

Rock Mass Rating Increments for Compressive Strength of the Rock

Point Load Index (MPa)	or	Unconfined Compressive Strength (MPa)	Rating
>8		>200	15
4–8		100–200	12
2–4		50–100	7
1–2		25–50	4
Don't use		10–25	2
Don't use		3–10	1
Don't use		<3	0

2- RMR increments for drill core quality (RQD)

TABLE 2.11

Rock Mass Rating Increments for Drill Core Quality

RQD (%)	Rating
91–100	20
76–90	17
51–75	13
25–50	8
<25	3

- Determination of RQD (rock quality designation) according to Deere (1967):

RQD = sum of length of core-pieces ≥ 10 cm / length of the core * 100 (%)

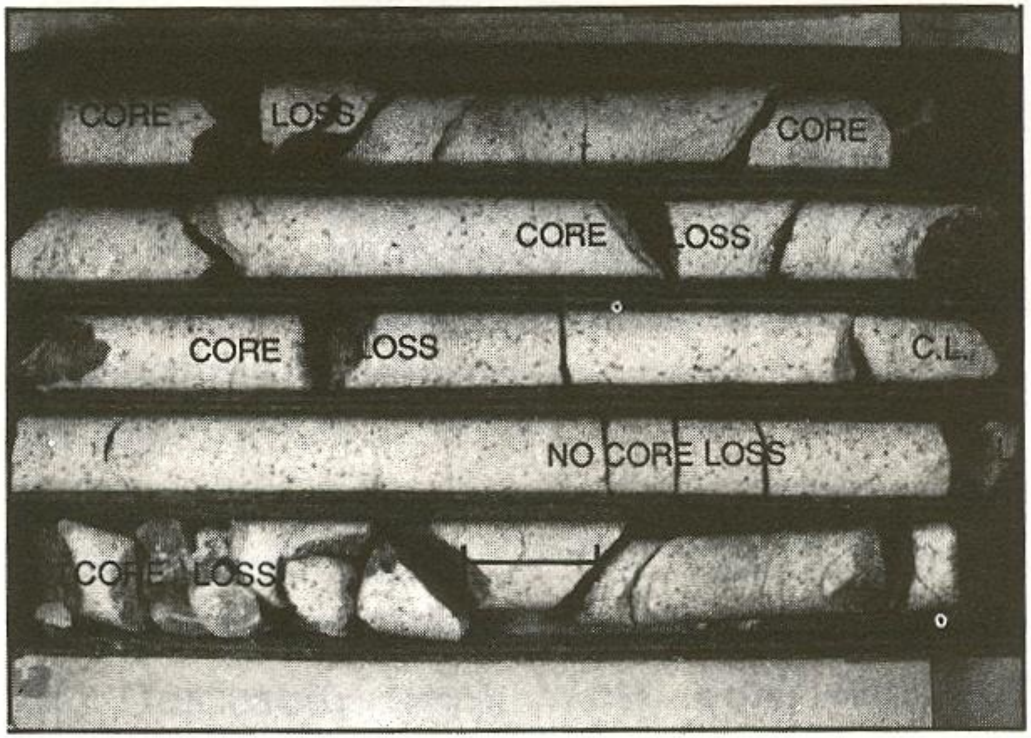


Figure 7.1

Table 7.1

RQD %	ROCK QUALITY	FRACTURE SPACING
0-25	Very poor	Very close
25-50	Poor	Close
50-75	Fair	Moderately wide
75-90	Good	Wide
90-100	Excellent	Very wide

3- RMR increments for spacing of joints of most influential set

TABLE 2.12

Increments of Rock Mass Rating for Spacing of Joints of Most Influential Set

Joint Spacing (meters)	Rating
>3	30
1–3	25
0.3–1	20
0.005 to 0.3	10
<0.005	5

4- RMR increments for joint condition

TABLE 2.13

Rock Mass Rating Increments for Joint Condition

Description	Rating
Very rough surfaces of limited extent; hard wall rock	25
Slightly rough surfaces; aperture less than 1 mm; hard wall rock	20
Slightly rough surfaces; aperture less than 1 mm; soft wall rock	12
Smooth surfaces, OR gouge filling 1–5 mm thick, OR aperture of 1–5 mm; joints extend more than several meters	6
Open joints filled with more than 5 mm of gouge, OR open more than 5 mm; joints extend more than several meters	0

5- RMR increment due to ground water condition

TABLE 2.14

Increments of Rock Mass Rating Due to Ground Water Condition

Inflow per 10 m Tunnel Length (l/min)	OR	Joint Water Pressure Divided by Major Principal Stress	OR	General Condition	Rating
None		0		Completely dry	10
25		0.0–0.2		Moist	7
25–125		0.2–0.5		Water under moderate pressure	4
125		0.5		Severe water problems	0

6- Adjustment in RMR for joint orientations

TABLE 2.15

Adjustment in RMR for Joint Orientations

Assessment of Influence of Orientation on The Work	Rating Increment For Tunnels	Rating Increment For Foundations
Very favorable	0	0
Favorable	–2	–2
Fair	–5	–7
Unfavorable	–10	–15
Very unfavorable	–12	–25

Geomechanics classification of rock masses

TABLE 2.16

Geomechanics Classification of Rock Masses

Class	Description of Rock Mass	RMR Sum of Rating Increments from Tables 2.9–2.14
I	Very good rock	81–100
II	Good rock	61–80
III	Fair rock	41–60
IV	Poor rock	21–40
V	Very poor rock	0–20