1.0 Introduction

1.1. Rock → Geologists definition: all of the earth's crust is made up of:

a. consolidated rock (rock)
b. unconsolidated rock (soil)

distinction is not always clear

shales weathering clays

residual rock

→ Terzaghi: defines soil: "sediments and other unconsolidated accumulations of solid particles produced by the mechanical or chemical disintegration of rock".

→ Civil Engineers: rock: hard and solid formation of earth crust.

→ Contractor (earth moving): rock: material which can't be excavated by conventional mechanical means, but must be excavated by blasting.

→ Emery (1966): rock is a "granular material composed of grains and glue". The "glue" may be ferrogeneous (iron), calcareous (calcium), argillaceous (Al) or silicareous (silica) materials which "cements" the grains.

→ Jumikis (1983): rock: granular, anisotropic heterogeneous substance which occurs naturally and which is composed of grains of varied polycrystalline or noncrystalline (amorphous) materials which are cemented together by a glue (as previous defined) or by a mechanical bond (interlocking of grains) but ultimately by atomic, ionic and molecular bonds within the grains, the glue and at very interface of bonding.

1.2 Rock Mechanics: the theoretical and applied behavior of rock. It is that branch of mechanics concerned with the response of rock to the force fields of its environment.

1.2.1 Brief History of Rock Mechanics

- Pre-historic times: stability of cave roofs
- Stone age: tools and weapons made from rocks

  15,000 BC: First known subsurface excavations

  3,500 BC: (bronze age) – tunnels constructed for ore mining

  2,000 BC: Limestone used by Egyptian to cut bricks.

Ancient Rome & Greece - tunnels constructed for water, underground passage, tombs and military purposes.

18th – 19th century: large tunnels were driven from nines, canals and rail transport.

Last 25 years: engineers and geologists develop the principles of rock mechanics, including Lab & In-situ testing techniques.

1.2.2 Issues in Rock Mechanics (course pack)

Rock strength depends on defects.

Soil fails only in shear
Rock fails by tension

1.2.3 Applications of Rock Mechanics

1. surface structures (buildings, bridges, dams)
2. transportation systems (highways, canals, railways)
3. surface excavations (rock quarries)
4. underground excavation (miners, tunnels, chambers)
5. energy development (geothermal, nuclear, power plants, nuclear waste disposal).

1.2.4 The most important point to remember about rocks…

"That is important in rock mechanics is what is not rock !"

⇒ discontinuities (faults, shears, joints fissures, and microfissures)

The right bank, although not as high, is more likely to fail because of kinematic considerations.

Rocks only move in kinematically favorable directions.

In Lab, you don't include $\rightarrow$ discontinuity
$\rightarrow$ orientation of discontinuity

2.0 Geological Classification of Rocks

Rocks of same class may behave differently.

2.1 Genetic Classification

2.1.1 Igneous: formed by cooling & crystallization of molten silicates (magma)

a) extrusive: (volcanic)
   i) lava flows
   ii) ash deposits
   iii) volcanoes

b) intrusive: (plutonic) large subsurface bodies which cooled and solidify under pressure at great depth.

- Although originally formed underground, intrusive rocks are now widely exposed at the surface, because of earth movements and erosion processes.
- The rate of crystallization controls the rocks that form.

- Igneous rocks can be classified by their texture [size, shape, and arrangement of interlocking mineral grains].

→ a. Granular texture: large mineral grains, from slow cooling (plutonic).

→ b. Aphonitic texture: (volcanic) from rapid cooling. Individual minerals can't be seen without a microscope.

→ c. Glassy texture: (volcanic) from ions disorganized as in a liquid, but frozen in place by quick cooling.

→ d. Porphyritic texture: (volcanic) is a mixture of large mineral grains in an aphanitic or glassy mass.

→ e. Cellular texture: (from lava) very high porosity, like pumice and scoria. Very low unit wt.

- Granular
- Aphanitic
- Glassy
- Color

	Light	Medium	Dark
Color	Light (pink, gray)	Medium (dark gray, red)	Dark (dark green, black)

- Ferromagnesians: $Mg_2 SiO_4$, $Fe_2 SiO_4$
  $(M_g - Fe)_2 SiO_4$

- Feldspars: silicates of aluminum with potassium, sodium or calcium.

- Orthoclase → k

- Plagiodase Na
  (Al Si_3 O_8)
  Ca

- Quartz SiO_2

2.1.2 **Sedimentary Rocks:** covers 75% of the earth's surface

- By origin → a. detrital: material has been worn from the land mass (erosion)

  → b. chemical: deposits precipitated from solution

- Mineral content: clay, quartz, calcite, plus small amounts of other minerals like: dolomite , goethite, hematite, limonite, feldspars, mica, halite and gypsum.

- Classification by texture: → a. clastic: rocks that have been formed from deposits of mineral, rock or shell fragments.

  → b. non-clastic: grains are interlocked.

They become rocks by lithification.

<u>Lithification</u>: conversion of unconsolidated sediments to firm rock by:
→ cementation
→ compaction
→ desiccation, drying out of clays → shales
→ crystallization: new rocks may crystallize within a deposit or existing crystals may increase in size. (Generally in finer sediments).

Origin	**Texture**	**Composition**	**Rock Type**
Detrital	Clastic	Gravel →	Conglomerate, Breccia
		Sand →	Sand stone
		Silt →	Siltstone
		Clay →	Mudstone, shale
Chemical	- clastic	Calcite, $CaCO_3$ →	Limestone
→ organic		Dolomite, Ca Mg (CO_3) →	Dolomite
	- non-clastic	Halite, Na CL →	Salt
		Gypsum Ca SO_4 . $2H_2O$ →	Gypsum
→ Biochemical	- clastic	$CaCO_3$ shells →	Limestone, Ch
		SiO_2 diatoms →	Diatomite
	- non-clastic	Plant remains →	Coal

2.1.3 **Metamorphic Rocks**: rocks that have changed in form or structure.

1. Agents of metamorphism:

   a) Heat: essential agent [10^o-15^oC / km or 1^oC / 100 ft]

   b) Pressure: may produce a closer atomic packing of the elements in a mineral, recrystallization of the mineral or formation of new minerals.

   c) Chemically active fluids: hydrothermal solution percolating from the magma or liquid that is present in the rock.

2. Location of metamorphic rocks:

   a) in mountain ranges
   b) at roots of mountain ranges

   } (due to pressure → heat)

   c) continental shields

3. Texture: → Foliated: minerals arranged in parallel layers of flat or elongated grains. Exhibit cleavage.

   $\sigma_1 > \sigma_3$

   → Unfoliated: don't exhibit cleavage.

   $\sigma_1 \approx \sigma_3$: hydrostatic press.
   Isotropic stress

4. Degree of alteration:

	Low Grade	**Medium Grade**	**High Grade**
Textural change	Slight	Significant	Complete Alteration
Mineral Change	None	Significant	Complete Alteration
≈ T	300^oC	450^oC	650^oC
≈ P	30,000 psi	50,000 psi	70,000 psi
~ Depth	7 miles	13 miles	17 miles

Example of metamorphism:

(1)

σ_i ↓ ↑	σ_{ii} ↓ ↑	σ_{iii} ↓ ↑	σ ↓ ↑	
		250^oC -------------⇒ 300^oC		
Shale Clay	Slate Small Mica Flakes	Phyllite (larger mica flakes)	Schist clearly visible Mica distinct Cleavage	Gneiss (nice) individual grains melts segregated color bonding.

(2) Limestone → Marble
$CaCO_3$

(3) Sandstone → Quartzite
(pores) (no pores)

(silica fills
pore space)

*   Look at boxes of rack samples

* Look at maps to find which rock is where.

3.0 Index Properties of Rocks

Why use them? They are easily obtained and furnish an indirect measure of strength and/or deformability.

3.1 Porosity:

$$h = \frac{V_{pores}}{V_{Total}}$$

generally will decrease with age of sedimentary rock and depth of

- in sed. Rocks: primarily due to intergranular pore space.
- In met. and igneous rocks: porosity due to planes cracks.

Generally porosity of sed. rocks > igneous or metamorphic (if not weathered).

From Table 2.1 Text observe that

0.7 < sand stone < 34.0%

0.3 < limestone < 43.0

1.6 < shale < 50.0

0 < granite < 1.0 if not weathered but up to 20 if weathered.

wide range $\Rightarrow$ mech. properties are not constl.

3.2 **<u>Density</u>:** since rock can be made up of made up of many diff. minerals (not like soil which made up of one or two minerals).

The specific gravity of rock is given by:-

$$G_{s_{rock}} = \sum_{i=1}^{n} Gs_i \; V_i$$

where, Gs_i = sp. gr. of i^{th} mineral.

V_i = vol. % of i^{th} mineral

n = # of minerals

- Dry unit weight = $\gamma_{dry} = Gs_{rock} \cdot \gamma_{water} \cdot\cdot (1 - \eta)$ $\rightarrow$ same as for soil.

Table 2.2 Text
Table compact

3.3 **Permeability**: what would $\frac{k_{field}}{k_{lab}}$ reflect ??

$\frac{k_f}{k_L}$ = high $\Rightarrow$ cracks

$\frac{k_f}{k_L}$ = 1
- no crack
- sample is representative

Table 2.4 Text
- sand stone
- limestone $\Rightarrow$ solution cavities

* high $\frac{k_f}{k_L}$ indicates broken crack (many discontinuities)

<u>Ex.</u> Granite, basalt, schist, crystalline limestone.

<u>From Darcy's Law:</u>

$$q_i = k_i * \frac{dh}{dx_i} Ai$$

- Ai → cross-section for flow
- $\frac{dh}{dx_i}$ → hydraulic gradient
- k_i → hydraulic conductivity
- q_i → Flow rate

$$k = K\ F = K \frac{g_w}{m}$$

- F → fluidity: function of the permeant or fluid.
- m ← viscosity
- K → permeability: function of pore geometry
- k → hydraulic conductivity [coeff. of permeability]

- Lab tests for Permeability:-

1. Constant Head Tests: just as for soils. Read about it in Soil Manual.
2. Radial Flow Test:

(top & bottom are sealed) (out flow)

$$k = \frac{q \ln\left(R_2 / R_1\right)}{2p\ L.\Delta h}$$

crack open — k higher

cracks close — k lower

Thus, $\frac{k_{\inf low}}{k_{outflow}}$ = f (discontinuities)

- Snow (1965), Vaugh (1963)

$$k = \frac{g_w}{6m}\frac{e^3}{S}$$

(g_w: unit wt. if water; m: viscosity)

Only good for 3 mutually perpendicular sets of fractures with parallel walls and identical S and e.

3.4 Point Load Test: easily performed @ a drilling site.

sample fails in tension across the diameter

D = 54 mm diameter

L = 1.5 D

$I_s = \frac{P}{D^2}$ point load index value.

- Table 2.5, text.

- Correlation to uniaxial compressive strength

$q_u = C\ I_s$

<u>Limitations</u>

- Tension (α) compression ??
- Crack $\leftrightarrow \uparrow$??

C	D (mm)
24	54 — Standard (Fig. 1.8) pp.17
17.5	20
19	30
21	40
23	50
24.5	60

See Fig. 1.7 pp,17 course pack.
1.8

3.5 Slaking Durability: test provides an index of rock alterability

Slake Durability Index, I_d = % Rock Retained (dry weight basis)
See Text Table 2.6 for I_2 classification.

3.6 Sonic Velocity:

$$V_p^2 = E / r$$

Where V_p = velocity of longitudinal wave

E = Young's modulus

ρ = mass density

$V_p)_{field}$

$V_p)_{Lab}$

$V_{p, Lab} > V_{p, field}$

- Fourmaentreux (1976): proposed a classification system for fissuring in rock based on wave propagation tests:-

1. Rock is composed of diff. minerals, each possessing a distinct E_1ρ and V_p.

2. Calculate V_ℓ^* that rock would have if there were no pores.

$$\frac{1}{V_\ell^*} = \sum_{i=1}^{n} \frac{C_i}{V_{\ell_i}}$$

Where V_{ℓ_i} = longitudinal propagation velocity of mineral *i*.
C_i = volume % of mineral *i*.

3. Measure actual propagation velocity, V_ℓ

4. Rock quality Index, $I_Q\% = \frac{V_\ell}{V_\ell^*} * 100\%$

See Fig. 2.3 Text.

- For totally intact rocks (no fissures, only pores).

$I_Q = 100 - 1.6\,\eta$, η = porosity as %

top line in Fig. 2.3

3.7 Rock Quality Designation (RQD)

$$RQD = \frac{\Sigma \text{ lengths of core pieces greater than 4" in length}}{\text{total length of rock cored}}$$

neglect crack due to coring

4.0 Failure Mechanisms in Rock

- Tension ← (not in soil if not cemented)
- Shear
- Crushing

4.1 Tension:-

Examples: 1)

2) on slopes

3) topping failure

4) above an excavation flexure

5) buckling of pillars in mined out areas

6) pressure tunnels

7) Tensile failure of a lab specimen

4.2 Shear

1) above openings

2) on slopes

a) o homogeneous, previously intact

b) along pre-existing planes of weakness

3) shear failure in a laboratory rock specimen.

4.3 Crushing or Compression Failure

Examples

1) Crushing of pillars

2) Ballistics

3) Lab

4) Crushing typically occurs under high hydrostatic pressure (i.e. σ_1, σ_3 are very high and σ_1-σ_3 not high)

4.4 Mixed Mode:-

Example: Cracking may be initiated in tension, but may continue in shear along a created failure plane.

5.0 Laboratory Strength Testing

5.1 Unconfining compression test (1880's): the oldest and most frequently used strength test.

q_u : unconfined compressive strength = $\frac{P_{max}}{A}$

Problems: end effects. Friction between rock and end platens keeps rock from expanding laterally.

Frictionless platens or lubrication may be used to decrease friction but may introduce cracks.

- How to insure that cracks will occurs at mid height?

  Best solution for insuring failure through central portion of specimen is to use "sharped" specimens.

* displacement (strain) measured by i) mechanical system - dial gauge
- LVDT's

ii) strain gauges (electrical)

* load (stress) measured by - proving ring (mechanical)
- load cell (electrical) - system gauge

* Ref. Raligh : Exp. Stress analysis

5.2 **Triaxial Testing**:-

Goel: to stimulate in-situ stress conditions where the rocks is subjected to confining pressures, p.

strength of rock = f (p).

s = c + p* tanϕ

See fig. 6.4.1 pp. 18 course pack.

See fig. 4.2.6 pp. 19 course pack.
" " 4.2.8 pp. 19 course pack.