PROPERTIES OF ROCKS AND THEIR APPLICATIONS (ROCK MECHANICS)

By

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1. INTRODUCTION

Rocks in different sizes and shapes have been used in the construction of buildings, in sculpturing and in recording historical events. Rock masses have been supporting large structures such as foundations of buildings and dams, and accommodating tunnels, shafts, underground installations and deep excavations.

Rocks are geological materials. In any construction activity and exploration for resources, understanding of the rock mass response is a prime concern of engineering geologists, geophysicists, civil, mining and petroleum engineers.

The oldest work of the Indian subcontinent was recovered from Mohenjo-Daro and Harappa in the Indus valley. More than 2000 seals containing animal motifs below an inscription are yet to be deciphered. The Harappans could perfectly model human and animal figures. Some examples are as given in Figure 1 and 2.



Figure 1 Steatite seals from Mohenjo-Daro; unicorn and bull with inscriptions (2500 – 1500 BC)



Figure 2 Bearded man's bust in limestone, Mohenjo-Daro (2500 BC)

Knowledge of Soil Mechanics is not adequate to with the problem of rock mass. Rock mechanics as a subject started in 1960. It deals with properties of rocks and the special methodology required for design of rock related components used in engineering schemes. Design in rock is really special due to the following reasons.

1. In rock structure applied loads are less significant than forces deriving from redistribution of initial stresses.

- 2. It needs as much judgment as measurement.
- 3. Geological section of site is important.
- 4. Closely related with/allied with geology and geological energy.

For example, granite can behave in brittle, elastic manner upto confining pressures of hundreds of mega Pascal while carbonate rocks become plastic at moderate pressure and flow like clay. Compacted shales and friable sandstones are weakened by immersion in water. Gypsum and rock salts are inclined to behave plastically at relatively low confining pressures and are highly soluble. Therefore, we need the following in Rock Mechanics.

- 1. Meaningful tests
- 2. Calculations
- 3. Observations

Preparation of a reliable geological map from scanty borehole logs is really a challenging task for Engineering Geology. About 20% of the predictions are wrong in the Himalayan river valley projects. Geology is complex due to faults and folds in the rocks. Shear zones are too thin to be predicted well in the drifts and can never be detected from borehole logs. Bedding planes are likely to change with depth. Any change in design may lead to 30% to100% rise in the cost of construction, besides delay in the target. Therefore, adequate and purposeful geological exploration is a must.

2. THE INDIAN MAINLAND



Figure 3 Physiographic Division of Indian Mainland



Figure 4 Stratigraphic Units of Indian Mainland

The Indian mainland is physiographically divided into the three regions as given below and shown in Figure.

- The Peninsula: Southern part, south of Vindhyanchal regions as the triangular portion
- **The Extra-Peninsula**: The extra-peninsula lines in the extreme north composed of Himalayan Mountains.
- The Indo-Gangetic alluvial plains: These areas lie in between the peninsula and extrapeninsula covering West Bengal, Bihar, UP, UK, Haryana, Punjab and western Rajasthan.

The stratigraphic units of the India mainland are Achaean (the very ancient and covers 2/3 of the peninsula region), Cuddapah, Vindhyan, Paleozoic, Mesozoic, Gondwana, Deccan trap, Tertiary (most recent) and alluvial. At most places, the parent rocks are covered by residual or transported soils.

3. COMPOSITION OF THE EARTH

It has varying density, elasticity and composition as described below and given in Figure. The different components of the Earth are as described below.

Lithosphere: It is the stony part of the earth and in a broader sense includes all the solid materials composing the earth from the surface downwards.

Crust: It is the outermost solid shell of the earth which has varying thickness at different locations. e.g. in ocean: 5 to 10 km; for continents: 30 to 35 km and for mountains: 70 to 100 km. On average the depth of core 40 km below the surface of the Earth, i. e. in mountainous regions 50 to 60 km thick, in continental regions 30 to 40 km thick and in oceanic regions 5 to 19 km thick. The upper crust layer = 2 to 10 km and it consist of sedimentary rocks, and density = 2.2 gm/cc. The middle layer, density = 2.5 gm/cc and it consists of mostly granites, gneiss and other igneous and metamorphic rocks. The lowest layer of the crust has the density around 2.8 - 3.2 gm/cc. This is called basaltic layer and its thickness under continents varies from 25 to 40 km. The lowest basaltic layer mostly lies under ocean and its density is around 3 g/cc.

Approx. radius of the Earth is 6378 km. Silica (SiO_2) is greater than 50% for oceans and greater than 62% for continents.

Mantle: It is the zone that starts after the crust and continues up to a depth of 2900 km. It is made up to extremely basic material called ultra-basic, very rich in iron and magnesium but quite poor in silica. The upper 100 to 150 km of mantle is in plastic state and is responsible for the occurrence of volcanic activity.

Core: The boundary between the mantle and the core is at a depth of about 2900 km below surface. The core extends right up to the center of the earth, at a depth of 6378 km. The liquid like core extends from a depth of 2900 km to about 5060 km and is often termed as outer core. The density varies from outer **Figure 5** The Interior of





core to the top of the inner core. The inner core starts from 4800 km and extends up to 6360 km. It is of unknown nature but is definitely in a solid state and with properties resembling to a metallic body. It has the following components.

Alumina (*Al*₂*O*₃): 13 to 16%

Other components: Iron oxides (Fe_2O_3): 8%, Lime (CaO): 6%, Sodium Oxide: 4%, Magnesium Oxide: 4%, Potassium Oxide: 2.5% and Titanium Oxide: 2%

Mohorovicic discontinuity or M. Discontinuity: The base of the crust has a sharp boundary. The thickness is greater in continents than below sea. This is the lowest limit of crust. Density increases abruptly in this region.

Age of the Earth: There are many theories, based on which, age of the earth has been predicted. The results of some of these theories are the following.

Charles Darwin	:	57 million years
Kelvin	:	20 - 40 million years
Helmmholtz	:	22 million years
Radioactivity	:	2.0 billion years
Radioactivity	:	4.60 billion years

4. MINERALS AND ROCKS

Detailed description of minerals and rocks can be found in any textbook of Engineering Geology. However, brief description of minerals and rocks and related terms are as given below. **Geology**: It is from Greek origin; Geo means earth and Logos means Science. It deals with the forces of nature and how they combine to produce the features visible on the Earth's surface as well as those beneath the ground.

Engineering Geology: It is a field of applied science, in which geological science is used in civil engineering practices. It deals with geological study of the site and location for major engineering projects and availability of materials of required quantity for construction of a particular project. It has wide applications, e.g. Site selection of dams, reservoirs, tunnels, highways, airport, docks and harbors etc.

Geomorphology: It deals with the study of surface features of the earth mainly of land surface.

Mineralogy: It deals with formation, occurrence, properties and uses of minerals, which are basic building units of which crust of Earth is made of such as soils and rocks.

Petrology: It deals with the nature of geographic distribution of rocks on the surface and reasons governing such distributions.

Mineral: A mineral is a substance or chemical compound that is normally crystalline and that has been formed as a result of geological processes. Number of known mineral as of today: 4900 Also two elements are added every year. Number of mineral present in the Earth's crust is 2000.

Only less than 10 minerals account for over 90% of the Earth's crust. Naturally occur as inorganic substances. Minerals have chemical formula. They have definite internal structure i.e. they are crystalline. They have fixed physical properties and are controlled by their composition and structure.

Geological Cycle: Many processes are acting simultaneously. The most important of these processes is being with molten magma, from which earth forming into rocks. Then it continues with rock being broken down into soils and that soils being converted back into rocks.

4.1 Formation and Types of Minerals

- 1. Solidification of Magma
- 2. Sublimation
- 3. Recrystallization
- 4. Evaporation

Types of Mineral: There are two types of clay minerals as described below.

- 1. **Ore-forming minerals**: Sulphides of common elements occurring in rock-forming minerals are classified as ore-forming minerals.
- 2. **Rock forming minerals**: Silicates, oxides and carbonates group of minerals are the most common rock forming minerals.

4.2 Physical, chemical and optical properties: Oxygen and silica mainly contribute to 75% and others are Al, Fe, Ca, Na, K, Mg. **Physical properties are** colour, lusture, form, hardness, cleavages, fracture and tenacity as described below.

Streak: It is the colour of powdered mineral and is more reliable and consistent indicator than the body colour of the mineral.

Lusture: It is the reflection from the mineral surface in ordinary light. It may be metallic, nonmetallic or sub-metallic. It is the appearance of a mineral surface in reflecting light. Minerals with no lusture are described as dull.

Cleavage: The tendency of a mineral to break along a certain definite direction and yield almost a smooth plane is called cleavage. It may be perfect or imperfect e. g. Halite and Galena have perfect cleavage. Many minerals possess a tendency to split in a certain regular direction and yield smooth plane surface called cleavages, i.e. Cleaves can be perfect (for mica), good, distinct and imperfect.

Fracture: Breaking of a mineral in a direction other than that of cleavage is known as fracture. It may be even and uneven. Most minerals show uneven fracture.

Specific Gravity: Sp. Gravity varies from 1 to 20, for clays, it varies from 2.5 to 2.80 and for native platinum it is 21.46. However, for most of the minerals it lies between 2 to 7.

Hardness: It shows the resistance of its surface to abrasion or scratching. We use Moh's hardness scale 1 to 10. Talc : 1; Gypsum : 2; Calcite : 3; Fluorspar : 4; Apatite : 5; Orthoclase : 6; Quartz : 7; Topaz : 8; Corundum : 9 and Diamond : 10

Tenacity: The response of a mineral to hammer or blow to cutting with knife and to bending is described as its tenacity.

Malleability: Due to this, a mineral can be beaten to new shapes e.g. gold. However, most minerals are brittle and get fractured when struck with a hammer.

Properties of Quartz Mineral: Hardness = 7, Formula: SiO_2 , G = 2.65, It has Perfect crystals and are found in all the three types of rocks i.e. Igneous, Sedimentary and Metamorphic rocks.

4.3 Rocks and Their Properties

Formation of Rocks: The Earth's crust called 'Rock' is built up of different mineral aggregates. Rocks may be mono-mineral e.g. marble or poly-mineral e.g. granite. The mineral composition of a rock is almost similar but its chemical composition depends on kinds of constituent minerals. Hence cannot be expressed by formula since the number of different mineral is not constant. Every rock type is a distinguished by its own physical properties like colour, density, mechanical strengths, fusibility etc. Therefore rock is an aggregate of more or less quantitatively or qualitatively constant mineral grains differing from each other in certain texture features, physical properties and in geological conditions in what they are formed.

The rock is formed under certain geological conditions which exert an important control upon the mode of occurrence, nature and relation of its constituent minerals.

By their origin all the rocks fall into three major groups:

- 1. Igneous: Associated with magmatic activities.
- 2. Sedimentary: Associated with exogenous process
- 3. Metamorphic: Formed as a result of transformation of igneous and sedimentary rocks.

Distribution of these rocks is irregular. Lithosphere contains 95% igneous and metamorphic rocks and only 5% of its entire bulk is made up of sedimentary rocks. **Lithosphere** includes crust and a portion of upper mantle which behaves elastically on time scale of thousands of years or more.

Nature of Rock Mass: It is a discontinuous, anisotropic and in-homogeneous naturally occurring prestressed medium. Rock mass is a discontinuous medium due to the presence of fault, joint, shear plane, bedding plane cleavage and schistosity.

Depending upon the ratio of mass considered to the spacing of joints, the rock mass is often treated as continuous for its overall behaviour. Rocks have several defects and discontinuities. Discontinuity is due to the actions of tectonic forces. Therefore, Grouting and other suitable important methods are used.

The influence of joints, their configuration and the structure along them will have to be considered in the analysis and design. Continuum approaches are not applicable in rock mass analysis

As stated above lithosphere is the uppermost shell of the earth crust and only that part of mantle upto which the material exists in a definite solid state. Solid aggregate that makes the crust of the earth is called rock. Due to inherent non-homogeneity of rock masses, there is need for their quantitative classification.

Rock Cycle: Igneous rock is formed first due to the solidification of molten magma / lava and the other types are transformed from it. In due course of time, erosion of the existing igneous rocks takes place and the sediments are deposited in basins which form sedimentary rocks. Further under continued rise in temperature and pressure, the metamorphic rocks melt and give rise to molten magma, which in turn changes into igneous rocks. This cycle is called rock cycle.

Classification of Igneous Rocks

Chemical characteristics of rocks are based on silica (SiO₂) content.

Ultra-basic	:	less than 45% of silica
Basic	:	from 45% to 52% of silica
Intermediate	:	from 52% to 65% of silica
Acid	:	from 65% to 75% of silica

Ultra-basic rocks are heavy and their density varies from 3 to 3.4 gm/cc. Basic rocks are heavy with density between 2.6 to 3.17g/c.c. Basalt and diabases are used as constructional material; chips for concreting, paving stone and stone foundry. For acid rocks, density is around 2.7 g/c. c, e.g. granite – it is the most common rock. Colour of granite depends upon the colour of the feldspar making it white, grey, pink or bloody red.

Important Igneous Rocks: Granite, Diorite, Andesite, Syenite, Gabbro, Dolerite, Basalt, Lamprophyre, Peridotite.

Engineering Importance of Igneous Rocks

- Are typically impervious, hard and strong form. These rocks provide very strong foundation for Civil Engineering projects such as dams and reservoirs.
- Basalts are used in foundation of structures and roads.

Sedimentary rocks

- Formed due to disintegration and subsequent deposition of various products of weathering of igneous and metamorphic and even sedimentary rocks.
- Boulders are widespread among glacial deposits. Boulders are used as construction materials and as paving stones.

- Conglomerate, Breccia, Sandstones, Shales, Mudstone, Siltstone, Limestone
- Chalk- It is the purest form of limestone.
- Breccia, Sandstones, Shales, Mudstone, Siltstone, Limestone, dolostones,
- Coals- organic sedimentary rock
- Ironores, Gypsum, rock salt, chert and Tillite _

Pebbles and Gravels

Size of pebbles	:	10 - 100 mm
Size of gravels	:	2 -10 mm

These are valuable construction materials and are also utilized in road construction. Conglomerates are consolidated rounded pebbles and gravels. Certain types of conglomerates are beautiful facing material.

Clays containing great quantities kaolinite are called greasy clays and those including an admixture of quartz, iron oxide are called lean clays. Lean clays are used for the production of Portland cements. Claystones are massive dehydrated and cemented clay rocks which are not softened when wet.

Metamorphic rocks

These rocks are an important source of building materials. It may be of two types given below. Foliated: slate, schist, phyllite, gneiss, molonite

Non-foliated: quartzite, marble, hornfels.

A combination of processes that lead to alteration of rocks is called metamorphism and the transformed sedimentary and igneous rocks due to metamorphism are called metamorphic rocks. Metamorphic rocks derived from sedimentary one is given a name with prefix "para" e.g. paragness. If it is from igneous variety, the prefix is "ortho" e.g. orthogness.

Examples: shales, phyllites, chlorite schists, guartzites, marble and gneisses

Marble: contains one mineral, calcite. White, fine grained uniform marbles are the best material for sculpture works.

The physical and mechanical properties of rocks are as described below.

1. Physical properties

Density/Sp. Gravity = 2.5 to 2.8. Non-porous and compact rocks have higher density and toughness. Normally rocks have three times the density of water. Pumice rock has density less than that of water. Basalt: 3 g/cm³; granite: 2.7 g/cm³; sandstone: 2.3 g/cm³. High density rocks like massive gabbro, basalt and quartzite are very hard and most suitable for foundation purposes.

Porosity: It varies between 0 and 1.0e. g. for solid granite: 0.01 and for porous sand stone: 0.50

Permeability: It is ability of a material to transmit fluids.

Hardness: It is the measure of resistance to abrasion i.e., resistance to permanent deformation. It is determined by Schmidt rebound hardness number.

Abrasivity: It is resistance to abrasion.

Index properties of Rocks: We rely on a number of basic properties of rocks which reflects variations of structure, fabrics and components. Properties which are relatively easy to measure and valuable in this regard are called index properties of rock as described below.

Porosity: Range: 0-90%, 15% for sand stone. It can be measured in terms of water content after saturation, relative proportion of solids and voids. Its value is 1.2% for igneous rocks.

Density: It depends on mineralogical or grain constituents.

Sonic velocity: It together with petrographic description, evaluates the degree of fissuring.

Permeability: It represents relative interconnection of pores.

Durability: It is tendency for eventual breakdown of components or structures w.r.t rock quality.

Strength: It represents present competency of rock fabric to bind the components together. Density or unit weight or specific weight: If G= 2.6, $\gamma = 26 KN/m^2$ approx.

Mass density =
$$\frac{Density}{g}$$
 e. g. for quartz, G= 2.65

For rocks, $G = \sum_{i=1}^{n} G_i V_i$, Where V_i = volume % of solid part of the rock and G_i be the corresponding specific gravity.

Also, $n = \frac{WG}{1+WG}$, with usual notations.

Relationship between porosity and dry density

 $\gamma_{\rm dry} = G \gamma_{\rm w} (1-n)$

Mode of failure is dictated by the joint system.

The seepage is governed by these discontinuous and the gouge material present.

2. Geo-mechanical properties

Compressive strength/crushing strength is as given below.

Category	Grade	Compressive strength (kN/m ²)
А	Very high, strong	100 - 209
В	High, strong	54 - 109
С	Medium	54 - 109
D	Low	27 – 54
Е	Very low	< 27

4.4 Defects in Rock Mass

Defects are in the form of fractures, cracks and hair cracks, fissures, bedding planes and laminations, stratification, joints, faults, folds and cavities.

- Epeirogenic or continent-building movements
- Orogenic or mountain building movements

The continental building movements are continuous but slow. Due to this, there may be upheaval or subsidence. Deteriorations in such cases may be uniform. The mountain buildings movements are associated with immerse disturbing forces. Such movements are of more severe type, but affect the earth periodically.

4.5 Strike and Dip

Direction of the line along which an inclined bed meets a horizontal plane is known as the strike of the bed. It is denoted as $N(^{\circ})E$, $N(^{\circ})W$, $S(^{\circ})E$, $S(^{\circ})W$. It means a particular angle of deviation in the direction of East or West from North or South direction.

Dip indicates the maximum slope of a particular inclined plane e.g. angle ABC. It is denoted as (°) N, (°)S, (°)SE etc. True dip means the angle made with horizontal by a line which lies in the inclined plane and is perpendicular to the strike. Strike and dips are used to describe joints.



- **5.** Joints: The tensile and compressive stresses, which act within the rock, are produced due to decrease in volume i.e. shrinkage of rock mass. It is due to
 - Drop in temperature or
 - Loss of moisture or
 - Both the above

Any break in rock mass irrespective of its size is called fracture. Minor fractures are called cracks and fissures. Cracks, along which the rock masses have not suffered relative displacement, are known as joints. Joints occur in all types of rocks i.e. I, S and M. in S-rocks, there are two systems of mutually perpendicular joints, both perpendiculars to bedding planes. In igneous rocks, there are three regular joint sets.

- Flat laying joints
- Q joints or cross joints
- S joints or longitudinal joints

Joints seldom occur alone. Generally, a number of more or less parallel joints occur together in the form of joint set. Two or more joint sets together constitute a joint system.

6. References

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