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Review of Mechanical Rock Properties Measurement and Estimation Techniques

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Abstract: At the wellbore, the majority of mechanical rock characteristics are not immediately measured. Therefore, it is crucial to establish these characteristics employing measurable data from well logs and core samples. With this decision, numerous drilling and production difficulties over the well's life might possibly be reduced. These properties are classified into the strength parameters (rock cohesiveness, friction angle, and unconfined compressive strength of the rock) and the elastic parameters (bulk and shear moduli, Poisson's ratio, and Young's modulus). This article includes a complete review of the mechanical rock properties and their impacts on the rocks. Also, the measurement techniques (static and dynamic) of these properties were explained, and the world-wide empirical correlations for different lithologies were inserted in order to determine the static profiles of the mechanical rock properties. Lastly, this study can be used as a reference or guideline for any application related to geomechanics.

Keywords: Unconfined compressive strength, Friction angle, Poisson's ratio, Young's modulus.

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1. Introduction

Rocks generally consist of small grains. Because the solid grains are in contact with one another and may cement together, different materials with distinct forms, sizes, and directions can exist. As a result, rocks are often neither homogenous nor isotropic. Grain and cementing elements together form the skeleton of the rock. The pores between the grains create a porous medium for the rock. The rock material strength is greatly affected by the type and degree of cementing, shape, and overlapping of the grains. However, for practical modeling in rock mechanics, rocks are typically assumed to be homogenous and isotropic [1,2].

The forces exerted by a drill bit, pore pressure, and in-situ stresses are typically applied to the formation rocks. Consequently, knowing the properties of the formation rocks in such circumstances is essential for avoiding deformation and collapse. Constitutive stress-strain relationships are employed for this purpose. Within the elastic and plastic limitations, the relationship between the applied stresses and the deformation of the rock may be extracted. However, mechanical rock properties describe the mechanical behavior of the formation rock when it is subjected to the applied stresses [3].

Understanding the mechanical rock characteristics of subsurface strata is a crucial component for any geomechanical application, including but not limited to analysis of the wellbore stability, hydraulic fracturing, prediction of sand production, reservoir compaction, and subsidence [4]. These characteristics include the rock cohesiveness, friction angle, and unconfined compressive strength of the rock, in addition to the elastic characteristics of the rock, which include bulk and shear moduli, Poisson's ratio, and Young's modulus [5]. These properties are widely used to forecast the far-field stresses (i.e., overburden stress, and maximum and minimal horizontal stresses), assess the possibility of sanding, investigate the issues of wellbore instability, determine the optimum drilling mud weight, and evaluate the compressibility of reservoirs [6].

In general, static and dynamic techniques are used to measure the mechanical characteristics of rocks. Static techniques are frequently used in the lab using specialized test apparatus that includes core samples. This sample is continually put under load until it fails. Finally, stress-strain curves may be used to determine the mechanical rock characteristics. In contrast, the dynamic techniques typically compute the rock mechanical parameters using the compression and shear velocities (Vp and Vs) derived from logs (i.e., based on the correlations that utilize geophysical and well logging data),[7,8].

This study provides a comprehensive review of mechanical rock properties, identifying each property and describing its effects on the formation rocks. It also focuses on the measurement techniques and methods that are utilized to estimate the rock properties.

2. Rock Mechanical Properties

The determination of mechanical rock properties plays a vital role in constructing a complete Mechanical Earth Model (MEM) and maximizing reservoir productivity. Relying on the distortion regime, the mechanical rock properties are classified into linear elastic and rock strength (inelastic) properties [2].

2.1. Elastic Properties

Elasticity is a methodology that generates a linear relation between the imposing force (stress) and resulting deformation (strain), and it governs by Hooke's law (Fig.1). In other words, the theory of elasticity explains the behaviour of formation rocks under loading and unloading conditions. Poisson's ratio (ν), Young's modulus (E), Bulk modulus (K), and Shear modulus (G) are the significant elastic properties [1].

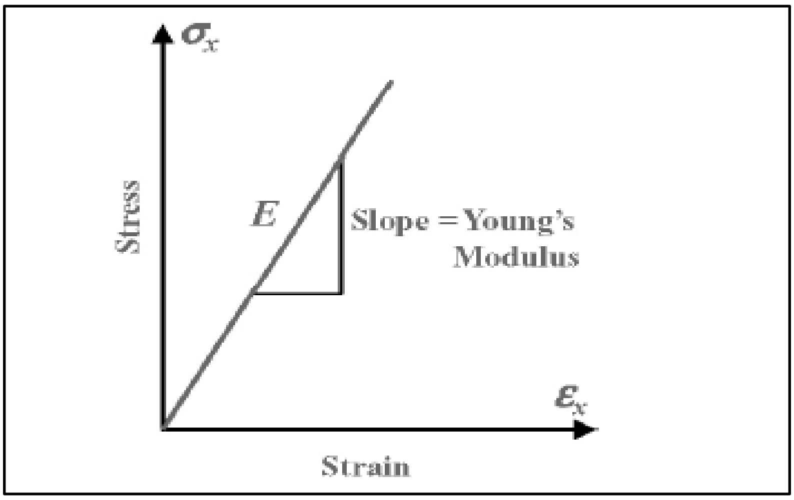

Figure1. Stress and strain diagram [1]

2.1.1. Young's Modulus (E)

Young's modulus, can be computed through the slope of the force-deformation diagram as shown previously in Fig.1. It is a measure of the capability of a material to endure variations in length when the lengthwise compression or tension are applied. It equals the lengthwise stress change divided by longitudinal strain change [8].

$$E = \frac{Axail\ stress}{Axial\ strain} = \frac{\sigma_x}{\varepsilon_x} \tag{1}$$

2.1.2. Poisson's Ratio (v)

In solid mechanics, the Poisson effect measures the deformation (contraction or expansion) of the material in orientations orthogonal to the direction of loading. For the material that stressed over one axis, Poisson's ratio defined as the ratio of the lateral deformation to axial deformation. Axial and transverse deformations (strains) are formulated and depicted in Fig.2 [2].

$$\nu = \frac{Lateral\ strain}{Axial\ strain} = \frac{\varepsilon_l}{\varepsilon_a} \tag{2}$$

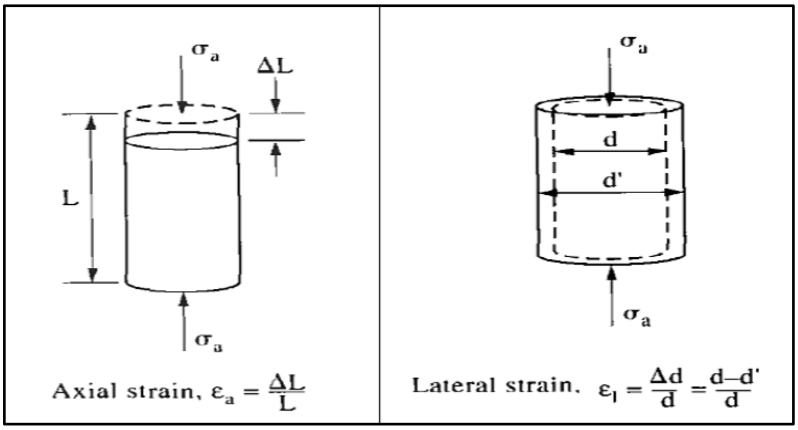

Figure 2. Schematic of the axial and transverse strain **[18]**.

2.1.3. Shear Modulus (G)

The shear modulus, measures the materials' stiffness and arises from generalized Hooke's law. In other words, the modulus of rigidity (shear modulus) is interested in the distortion of a solid body when it subjects a force analogous to one of its faces whilst its opposite surface subjects an opposing force. In one -dimension, the shear modulus can be expressed as the following [1]:

$$G = \frac{Shear\ stress}{Shear\ strain} = \frac{\tau}{\gamma} \tag{3}$$

2.1.4. Bulk Modulus (K)

The bulk modulus measures the capability of a material to withstand alteration in volume when all sides of the material are under compression. In other words, it describes the proportion of applied pressure to the volumetric deformation of a material [9].

2.2. Strength Properties

When significant stresses are subjected to the rock sample, some failure will happen, and this denotes that the shape of the rock changes permanently and probably falls apart. Thus, it's vital to prophesy under which conditions the formation rock possibly fails. However, the highest stress at which the rock sample usually fails is commonly known as the rock strength. Strength of rock specified in terms of compressive strength, tensile strength, and shear strength [1].

2.2.1. Tensile Strength (T_o)

Rocks are failed by tensile when the pore pressure and stresses are equal or larger than rock strength [10]. In other words, when the effective tensile stress overrides the tensile strength of the sample (Fig.3a), the tensile failure will occur and usually splits over one or tiny fracture planes [2].

2.2.2. Shear Strength

Shear strength (also referred to as compressive strength) measures the shear failure when the shear force over some plane in rock (specimen) is sufficiently high. Finally, the fault zone will evolve along the plane of failure, and the relative movement for both sides of the plane will occur as illustrated in Fig.3b [2].

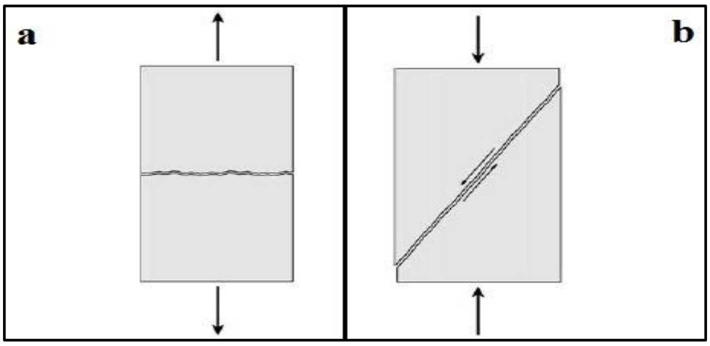

Figure 3. Tensile and shear strength [2].

2.2.3. Cohesion Strength (S_o)

In rock mechanics, cohesion is the strength that presents among the grains of the formation, and it has a direct relation with the level of the consolidation and quality of the cement of the rock [10]. In other words, it is defined as the shear strength of formation rock when the normal stress is not present (equal to zero), [1].

2.2.4. Friction Angle (φ)

Friction angle is an essential property that is utilized to estimate the strength of the rock. The friction angle is a measure of the capability of the rock to sustain shear stress. When a failure occurs due to shear stress, the friction angle (φ) is measured among the normal force and resultant force [1].

3. Rock Mechanical Properties Measurement

Rock mechanical properties are generally measured by utilizing two essential methods known as static and dynamic techniques. The static methods are commonly executed in the laboratory with special test equipment which contains core samples. This sample is continuously subjected to load until a failure happens. Lastly, the mechanical rock parameters can acquire from stress-strain curves. In contrast, the dynamic methods are ordinarily computations of compression and shear velocities (V_p & V_s **)** obtained from logs to determine the rock mechanical parameters. Several studies discovered that the static ways are direct and more practical, while the dynamic ways are straightforward and more continuous. Thus, both well logs and lab experiments techniques are required to measure the rock mechanical parameters [1,7,8].

3.1. Static Methods (Direct)

Lab tests generally consist of straightforward experiments convenient to the rock, where important rock parameters are determined from stress and strain curves. However, various lab tests can be utilized to acquire Young's modulus, rock strength, and other rock mechanical parameters. Hence, the outcomes from lab tests are being used to calibrate the incessant profiles of petrophysical [7,11].

The first type of lab test is the uniaxial compression test; it's the most straightforward and oldest test and a beneficial technique for determining rock properties. This test is usually utilized to determine unconfined compressive strength, Young's modulus and Poisson's ratio. In this test, a cylindrical rock sample is inserted into the loading frame. Then the core sample is subjected to the axial load gradually increase with no confining pressure (equal to zero) until reaching failure point (deformation),[1,2,13-15].

The second type of lab test is the triaxial compressive test; it's most valuable and widely used to determine the mechanical rock properties under various applied stress values. Rock samples are removed from cores and coated with an impermeable plastic jacket. Then, it is placed in a triaxial test apparatus, as shown in Fig.4. In this test, a rock sample undergoes a homogeneous stress state in which the minor principal stresses (σ_3 & σ_2) are of equal value. The axial stress (σ_1) is applied parallel to the longitudinal axis of a circular cylinder core sample, and the minor principal stresses are exerted to the circumference of the core sample via fluid confining pressure. A triaxial compressive test is generally carried out by increasing both axial and confining stresses simultaneously till a specified level of the hydrostatic pressure is reached. Next, the confining stress remains constant, whereas the axial stress increases until failure takes place [1,8,16].

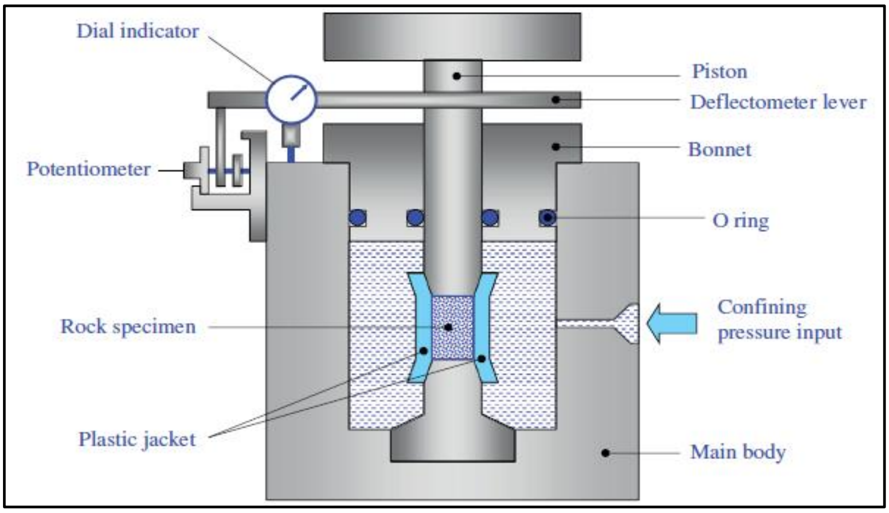

Figure 4. Triaxial compressive test apparatus [1].

The third type of lab test is the Brazilian test, which measures the capability of the rock material to withstand tensile strength. In this test, the specimen preparation and testing procedure are easy. The rock sample shaped to a circular cylinder rod is placed in the Brazilian test apparatus, as shown in Fig.5. Then, the test is carried out by applying a load via two steel plates completely compressed to a cylindrical rock sample. Consequently, tensile stress creates in the center. Eventually, the rock specimen will split into segments at failure [1,12,17-19].

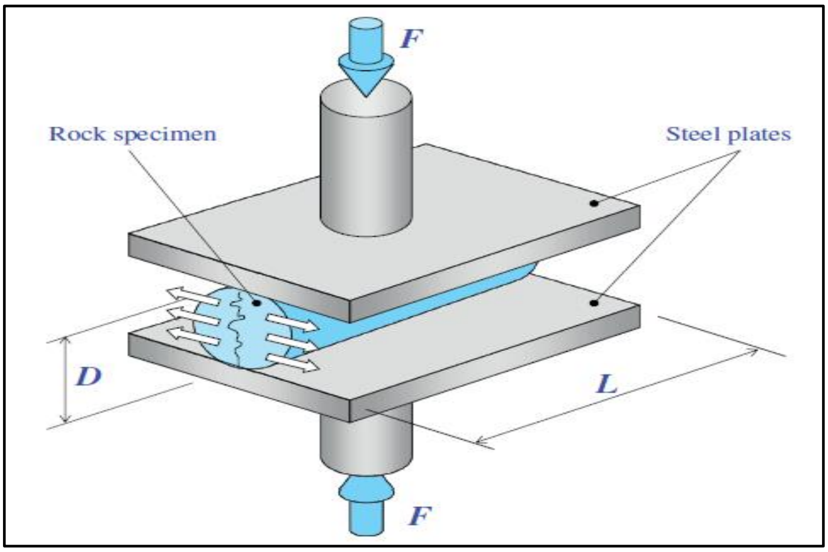

Figure 5. Schematic the Brazilian tension test [1,12].

3.2. Dynamic Methods (Indirect)

Understanding the mechanical rock characteristics of subsurface strata is a crucial component for any geomechanical application, including but not limited to analysis of the wellbore stability, hydraulic fracturing, prediction of sand production, reservoir compaction, and subsidence [5,20-21]. These characteristics include the rock cohesiveness, friction angle, and unconfined compressive strength of the rock, in addition to the elastic characteristics of the rock, which include bulk and shear moduli, Poisson's ratio, and Young's modulus [4,22]. These properties are widely used to forecast the far-field stresses (i.e., overburden stress, and maximum and minimal horizontal stresses), assess the possibility of sanding, investigate the issues of wellbore instability, determine the optimum drilling mud weight, and evaluate the compressibility of reservoirs [6,23].

4. Calculation of Mechanical Rock Properties

The mechanical characteristics of the rock must be continuously recoded for geomechanical applications since they are not easily measured at the wellbore. Rocks' mechanical characteristics vary not just among different rock types but also among various specimens of the same rock. Moreover, the mineral composition, grain structure, and any fissures that may have been induced into the rock all affect the rock's mechanical characteristics [3,24-26]. Static measurement (Lab data points) of the mechanical rock parameters is usually discontinuous along the area of interest. However, several empirical correlations that are available in the literature can be used to achieve this purpose (Table1).

Table 1. Empirical correlations to determine the rock's elastic and strength properties.

Lithology	Equation	Reference
Unconfined Compressive strength (UCS) in MPa		
Different sediment types	$UCS = -3.225\emptyset + 129.54$	Edimann et al. (1998)
Sedimentary, metamorphic, and igneous rocks	$UCS = 0.0642V_p - 117.99$	Sharma & Singh (2008)
Young and weak shales	$UCS = 243.6\ \emptyset^{-0.96}$	Horsrud (2001)
Consolidated and unconsolidated sandstone (fine grained)	$UCS = 1200\exp(-0.036\ \Delta T)$	McNally (1987)
Sedimentary basins	$UCS = 254\ (1 - 2.7\emptyset)^2$	Bradford et al. (1998)
sandstone	$UCS = 3.3348\ E_s^{1.6081}$	Issa & Hadi (2021)
sandstone	$UCS = 2.28 + 4.1089\ E_s$	Bradford et al. (1998)
Internal Friction Angle (φ) in degree		
Different sediment types	$\varphi = -0.7779\emptyset + 41.929$	Edimann et al. (1998)

Sandstone	$\varphi = 57.8 - 105\emptyset$	Weingarten & Perkins (1995)
Shale	$\varphi = 17.134\, e^{0.239V_p}$	Abbas (2020)
Shale	$\varphi = \sin^{-1}((V_p - 1000)/(V_p + 1000))$	Lal (1999)
Static Young's Modulus (E_s)		
Shale	$E_s(Gpa) = 0.2966\, e^{0.6984V_p}$	Abbas (2020)
Shale	$E_s(Gpa) = 0.076\, V_p^{3.23}$	Horsrud (2001)
Igneous and metamorphic rocks	$E_s(Gpa) = 1.263\, E_d - 29.5$	King (1983)
Different sediment types	$E_s(Gpa) = -0.7831\emptyset + 38.878$	Edimann et al. (1998)
Sandstone	$E_s(Mpsi) = 0.0293E_d^2 + 0.4533\, E_d$	Lacy (1997)
Sedimentary rocks	$E_s(Mpsi) = 0.018\, E_d^2 + 0.422\, E_d$	Lacy (1997)
Poisson's Ratio (v) Unitless		
Sandstone	$v = 1.1148\emptyset + 0.1356$	Zhang & Abdelrahman (2015)
Different sediment types	$v = 0.0052\emptyset + 0.0508$	Edimann et al. (1998)
Sandstone	$v = 1.199\, \emptyset^{0.8149}$	Issa & Hadi (2021)
Shale	$v = 0.7621\, e^{-0.353V_p}$	Abbas (2020)

Where: $\emptyset$ is the porosity; V_p is the compression wave velocity; E_d is the dynamic Young's modulus; ΔT is the compression transit time.

5. Conclusions

Researchers that are interested in creating projects that are related to mechanical rock properties should take this study properly. The following points attempt to summarize the conclusions:

- It is crucial to understand the mechanical rock parameters of the subsurface stratum in relation to difficulties with subsidence, such as wellbore stability concerns, sand production evaluation, and fracturing activities.
- Mechanical characteristics of rocks are divided into two categories based on the distortion regime; elastic and rock strength parameters.
- Two fundamental approaches, known as static and dynamic procedures, are often used to measure the mechanical characteristics of rocks.
- The static technique is more practical and it is dependent on the lab tests (Uniaxial, Triaxial, and Brazilian tests), whereas the dynamic technique is more flexible and it is dependent on well logging data.
- There are several empirical equations in the literature based on petrophysical and geophysical log data that can be utilized to construct the static and dynamic profiles of the mechanical rock properties for diverse lithologies.
- The profiles of the dynamic rock mechanical rock properties are larger than the static profiles. Consequently, the dynamic property should be converted to a static property using a suitable correlation.
- In the area of interest, the incessant profile of mechanical rock characteristics gives an accurate indication of the natural variation in the formation stability and strength surrounding the borehole in various formations.

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