

Confined Stress Analysis of Consolidated and Unconsolidated Sandstone Reservoir Core Samples

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Abstract- This research investigates the effects of fluid saturation on the geo-mechanical properties of consolidated and unconsolidated sandstone reservoirs under confined stress conditions. Sandstone formations are critical for hydrocarbon production, but their mechanical behavior is strongly influenced by lithology and pore-fluid interactions. A comparative knowledge gap exists regarding how consolidated and unconsolidated sandstones respond under identical multiphase saturation and stress conditions. This study addresses the gap by experimentally analyzing six core samples obtained from the Niger Delta region of Nigeria. The cores were oven-dried, saturated with water and oil-water mixtures, and subjected to triaxial compression tests at confining pressures of 100 psi and 300 psi. Results revealed marked lithological differences: the consolidated dry core exhibited a Young's modulus of 22,300 psi, yield strength of 34,800 psi, and peak strength of 36,775 psi, failing suddenly in a brittle manner. In contrast, the unconsolidated dry core showed a much lower Young's modulus of 65 psi, yield strength of 2,700 psi, and peak strength of 2,915 psi, with gradual strain-softening failure. Saturation kinetics further demonstrated that unconsolidated cores achieved equilibrium within ~1 hour, whereas consolidated cores required 3-5 hours. Fluid type also influenced behavior: under water saturation, consolidated samples weakened to a peak strength of 23,497 psi, while oil-water saturation improved performance, reaching 29,350 psi. The study advances understanding of lithology-dependent saturation kinetics, multiphase fluid effects, and failure mechanisms under confinement. In conclusion, lithology and saturation state jointly control sandstone geomechanics, with consolidated samples showing higher strength but brittle failure, while unconsolidated samples exhibit lower strength with ductile deformation. This study contributes critical experimental data for refining reservoir geomechanical models and supporting sustainable petroleum production.

Keywords-: Lithological, Consolidated, Unconsolidated, Sandstone, Reservoir, Stress, Analysis.

I. INTRODUCTION

Sandstone reservoirs are among the most significant geological formations for hydrocarbon production, carbon capture and storage (CCS), and geothermal energy extraction (Zhang & Yin, 2022). Their mechanical behavior under subsurface conditions is critical for ensuring wellbore stability, optimizing hydraulic fracturing, and mitigating sand production (Whyte et al., 2025). The geomechanical properties of sandstones vary significantly depending on their consolidation state-ranging from unconsolidated (loosely packed grains with minimal cementation) to consolidated (well-cemented with quartz, calcite, or clay minerals) (Fjaer et al., 2021; Rahman et al., 2021).

Unconsolidated sandstones are particularly prone to deformation under stress due to weak intergranular bonding, whereas consolidated sandstones exhibit higher strength but may still experience brittle failure under high confinement (Wong et al., 2020).

Fluid saturation further complicates the mechanical response of sandstone reservoirs. Water saturation can reduce effective stress through pore pressure buildup and weaken grain contacts via capillary forces, clay swelling, or dissolution of cementing materials (Li et al., 2020). In contrast, oil-water saturation introduces multiphase fluid interactions that influence wettability, interfacial tension, and pore-scale fluid distribution, potentially altering failure mechanisms (Alotaibi & Nasr-El-Din, 2018). Previous studies have demonstrated that water-weakening effects can decrease unconfined compressive strength (UCS) by up to 40% in clay-rich sandstones, while mixed oil-water saturation may either stabilize or destabilize grain contacts depending on wettability conditions (Almrabat & Al-Masry, 2021).

1. Consolidated and Unconsolidated Sandstones

Despite extensive research on sandstone mechanics, there remains a knowledge gap regarding the comparative behavior of consolidated and unconsolidated sandstones under identical saturation and confined stress conditions (Khan et al., 2019). Most existing studies focus on either dry samples or single-

fluid saturation states, neglecting the complex multiphase flow conditions present in actual reservoirs (Wu et al., 2023). Furthermore, recent advances in triaxial testing equipment and digital monitoring techniques (e.g., acoustic emission, micro-CT imaging) now enable more precise characterization of failure modes under realistic reservoir conditions (Zhang et al., 2023). This study aims to address these gaps by systematically investigating the confined stress response of both consolidated and unconsolidated sandstone core samples under three saturation states: dry, water-saturated, and oil-water-saturated. The findings will contribute to improved reservoir management strategies.

Whyte et al. (2025), examined how pore fluid type influences the mechanical response of unconsolidated reservoir rock. Their study compared cores fully saturated with water against those saturated with crude oil, with the aim of understanding the implications of saturation for reservoir stability and injection planning. Using conventional geo-mechanical testing methods, the authors reported that oil-saturated cores exhibited higher stiffness, elastic limits, and peak strength than water-saturated ones. Both saturation states showed ductile failure, but oil-saturated samples sustained greater stress before softening. The study highlighted that pore fluid type is not only important for flow dynamics but also a major control on rock deformation and failure thresholds.

Khan et al. (2019) conducted a comprehensive investigation into the geomechanical properties of unconsolidated sandstones, motivated by the need to address sand production risks in weakly cemented reservoirs. Recognizing that traditional models often fail to predict the deformation mechanisms of such materials accurately, the researchers performed triaxial compression tests across a confining pressure range of 5–30 MPa, integrating strain measurements through LVDTs and digital image correlation (DIC) for precise deformation tracking. Their findings revealed a dominant shear-enhanced compaction mechanism, where grain crushing superseded fracture propagation as the primary failure mode. At lower confinements (5–10 MPa), localized shear bands developed, whereas higher confinements (20–30 MPa) induced distributed grain compaction, evidenced by pronounced plastic deformation in stress-strain curves. Post-failure SEM analysis corroborated these observations, highlighting extensive grain-scale damage. The study concluded that conventional Mohr-Coulomb criteria inadequately capture the strength

characteristics of unconsolidated sandstones at elevated confinements, advocating for modified constitutive models that incorporate grain crushing effects to enhance reservoir simulation accuracy.

Wong et al. (2020) systematically examined the brittle-ductile transition under increasing confinement, addressing a critical knowledge gap in deep reservoir stability assessment. Utilizing a high-pressure triaxial apparatus, the researchers subjected Berea sandstone samples to confining pressures up to 100 MPa while monitoring micro fracturing via acoustic emission (AE) sensors. Their experimental protocol included post-test X-ray CT scanning to visualize internal damage patterns.

The results delineated three distinct deformation regimes: below 30 MPa, samples exhibited classic brittle failure with localized shear fractures; between 30–60 MPa, a transitional regime emerged, characterized by hybrid shear fractures and distributed cracking; above 60 MPa, fully ductile behavior dominated, manifesting as homogeneous cataclastic flow without discrete fracture planes. Zhang and Yin (2022) investigated the coupled effects of pore pressure and confinement on sandstone failure, a critical consideration for fluid-injection scenarios in reservoir engineering. Their experimental design involved saturated sandstone samples tested under varying confining pressures (10–50 MPa) and pore pressures (5–20 MPa), with permeability measurements integrated into the triaxial setup to assess fluid flow changes during deformation. The researchers identified a pore pressure-dependent critical confinement threshold (approximately 1.5 times the pore pressure) beyond which dilatant behavior transitioned to compaction-dominated failure.

Wu et al. (2023) introduced innovative multi-scale monitoring techniques to elucidate fracture propagation dynamics in fluid-saturated sandstones under confinement. Their experimental approach combined synchronized AE monitoring, in-situ X-ray microtomography, and 3D digital volume correlation (DVC) during triaxial loading of water- and oil-saturated samples. The research unveiled two paradigm-shifting findings: first, water-saturated samples exhibited 40% more AE events prior to macroscopic failure compared to dry samples, indicating enhanced subcritical crack growth facilitated by stress corrosion; second, oil saturation generated distinctive fracture patterns with branched, tortuous pathways attributed to viscous damping of crack tips. Time-lapse microtomography captured the progressive development of fracture process zones,

revealing that fluid type significantly influenced fracture network complexity water promoted planar fractures while oil induced dendritic structures. The study's theoretical framework integrated fracture mechanics with poroelasticity to explain fluid-dependent fracture morphologies, offering new insights for hydraulic fracturing design in heterogeneous reservoirs.

Rahman et al. (2021) adopted a comparative experimental approach to evaluate how different cementation types (silica, calcite, and clay) influence the confined strength behavior of sandstones. Using a combination of triaxial testing, nanoindentation, and focused ion beam (FIB)-SEM microscopy, the researchers systematically varied cementation types while controlling for grain size and porosity. Their results established a cementation-dependent strength hierarchy: silica-cemented samples showed the highest peak strength (up to 180 MPa at 50 MPa confinement) and brittle behavior across all pressure ranges; calcite-cemented specimens displayed pressure-sensitive ductility due to cement plasticity; clay-cemented sandstones exhibited the lowest strength and pronounced water-weakening effects. Nanoindentation mapping revealed microscale strength anisotropy aligned with cement distribution patterns, explaining macroscale mechanical variations. The study's practical contribution was a cementation-classification-based predictive model for sandstone strength that outperformed conventional porosity-based correlations by 20% in accuracy when validated against field data.

Almrabat and Al-Masry (2021) addressed the underexplored area of cyclic loading effects on confined sandstone behavior, simulating production-induced stress fluctuations in reservoirs. Their sophisticated experimental protocol involved 50+ triaxial loading-unloading cycles at varying stress amplitudes (10–80% of peak strength) under both dry and water-saturated conditions. Strain accumulation data revealed three characteristic response phases: initial cyclic hardening (cycles 1–15), followed by stable deformation (cycles 16–35), and culminating in accelerated damage accumulation leading to failure.

Zhang et al. (2023) enabled unprecedented resolution in tracking real-time mineral-fluid interactions during deformation. Their work on chemically reactive fluids (CO₂-rich brine) revealed dissolution-precipitation cycles that dynamically altered fracture propagation paths, with implications for CO₂ sequestration integrity. The field

continues evolving toward more sophisticated multiphysics experiments that simultaneously capture mechanical, hydraulic, and chemical coupling effects under realistic reservoir conditions.

Brantut and Baud (2023) made groundbreaking contributions through their design of a novel high-pressure triaxial testing apparatus that represents a significant leap forward in experimental capabilities. This innovative system integrates multiple measurement modalities, enabling simultaneous real-time monitoring of acoustic emissions, volumetric strain, and permeability evolution during deformation of Fontainebleau sandstone samples. The apparatus operates at confining pressures up to 200 MPa, with precision temperature control ($\pm 0.1^\circ\text{C}$) and the ability to maintain constant pore pressure conditions throughout testing. What makes this system particularly remarkable is its capacity to capture transient phenomena during deformation through high-frequency data acquisition (up to 1 MHz sampling rate for acoustic emissions), allowing researchers to detect subtle microstructural changes as they occur. Through this advanced

experimental setup, the team identified and characterized a previously unrecognized "semi-brittle" transitional regime that exists between classical brittle fracture and cataclastic flow..

Liu et al. (2022) developed an innovative experimental protocol that has significantly enhanced our ability to quantify and understand strain localization phenomena in sandstones under confinement. Their groundbreaking approach combines two powerful imaging techniques - digital image correlation (DIC) and micro-computed tomography (μCT) - to capture full-field, three-dimensional strain distributions in Bandera Gray sandstone across a comprehensive range of confining pressures (5-100 MPa).

The experimental setup involves a specially modified triaxial cell that permits continuous μCT scanning during mechanical loading, with DIC patterns applied to the sample surface through a novel micro-spray technique that doesn't interfere with X-ray transmission. Meng et al. (2023) pioneered the application of in-situ neutron diffraction techniques to study stress partitioning in sandstones under triaxial compression. Their innovative experimental approach, conducted at a high-flux neutron source facility, allows direct measurement of intergranular stresses at different crystallographic orientations in Bentheim sandstone during mechanical loading. The experimental setup involves a dedicated deformation rig that

fits within the neutron beamline, capable of applying triaxial stresses while permitting neutron transmission for diffraction measurements. Through careful analysis of diffraction peak shifts, the team demonstrated that stress partitioning among different mineral phases can vary by up to 40% under confinement, with quartz grains consistently bearing disproportionately higher stresses compared to the surrounding clay matrix. This stress partitioning occurs because the stiffer quartz grains (Young's modulus ~95 GPa) carry more load than the compliant clay phases (Young's modulus ~20 GPa), creating localized stress concentrations that ultimately control failure initiation in heterogeneous sandstones.

Dautriat et al. (2023) addressed one of the most persistent challenges in experimental rock mechanics through their comprehensive investigation of size effects in sandstone behavior. Their ambitious study spanned five orders of magnitude in sample size, from miniature 3 mm diameter plugs to large-scale 1.5 m diameter blocks, all carefully cored from the same sandstone unit to ensure material consistency. The experimental program involved coordinated testing at multiple laboratories worldwide, utilizing specially designed loading frames for the largest samples capable of applying 50 MN axial load. Their results revealed three distinct scaling regimes governed by different dominant flaw populations. In small samples (<10 mm), behavior is controlled by grain-scale defects, resulting in high strength variability (COV ~25%). Medium-sized samples (10-100 mm) show transitional behavior where both grain-scale and sample-scale flaws contribute, while large samples (>100 mm) exhibit consistent behavior dominated by sample-scale heterogeneities.

The researchers developed a generalized scaling law incorporating these transitions that successfully predicts strength reduction from laboratory to field scales. Their findings help explain long-standing discrepancies between laboratory measurements and field observations, particularly in hydraulic fracturing operations where the relevant process zone size often exceeds laboratory sample dimensions. The study also demonstrated that conventional size effect theories based on fracture mechanics principles require modification for porous sandstones, where pore collapse mechanisms become increasingly important at larger scales.

Yang et al. (2024) pushed the boundaries of microstructural characterization through their application of focused ion beam-scanning electron microscopy (FIB-SEM) to study deformation

mechanisms in sandstones at the nanoscale. Their innovative approach involved creating a series of microscopic "stress markers" in undeformed samples using FIB milling, which could then be tracked after deformation to quantify local strain fields. The technique achieved remarkable 5 nm spatial resolution in three dimensions, allowing visualization of deformation processes at the crystal lattice scale. Contrary to traditional views, their work demonstrated that even nominally "ductile" compaction in sandstones involves significant intragranular microfracturing at the crystal scale, with quartz grains showing extensive cleavage along specific crystallographic planes. The researchers identified three primary deformation modes:

- Transgranular fracturing in quartz, C
- lay mineral reorientation and kinking, and
- Cement bridge bending and rupture.

Their quantitative analysis revealed that stress concentrations at grain contacts can exceed the macroscopic stress by factors of 3-5, explaining why local failure often precedes bulk yielding. The study also provided the first direct evidence of pressure solution activity at grain contacts under relatively low confinement (10-20 MPa), a mechanism previously assumed to require much higher stresses. These findings have profound implications for micromechanical modeling, demonstrating that continuum approaches may miss critical grain-scale processes that ultimately control macroscopic behavior.

Meyer et al., (2016) explore the influence of varying fluid saturation levels on the mechanical behavior of sedimentary rocks, specifically focusing on sandstone and shale samples. Their study assesses both elastic and plastic deformation responses through a series of uniaxial and triaxial compression tests conducted on saturated and unsaturated rock specimens. Key parameters measured include Young's modulus, peak strength, and post-failure behavior.

Chaloner et al. (2020) examine the impact of fluid saturation on the mechanical properties of granular soils, focusing specifically on how varying saturation levels influence shear strength and

compressibility. The study involved conducting a series of triaxial tests on a variety of granular soil samples, including sand and gravel, under saturation levels of 0%, 25%, 50%, 75%, and 100%. In these tests, they measured parameters such

as effective stress, shear strength, and volumetric changes to assess the impact of different fluid saturation conditions.

The results clearly demonstrated that shear strength decreases as fluid saturation increases, with a particularly sharp decline observed at full saturation. This effect was primarily attributed to the significant reduction in effective stress caused by increased pore pressure at full saturation. As the fluid saturation rises, pore pressures within the soil structure increase, weakening the soil's ability to resist shear forces. They provide critical insights into how fluid saturation affects the mechanical properties of granular soils, emphasizing the implications for construction and earthworks in saturated conditions. Their findings highlight the necessity of considering fluid conditions when planning construction in environments where soils are likely to become saturated.

2. sandstone Formations under Stress

Sandstone formations represent a significant portion of petroleum-bearing formations due to their desirable storage capacity, permeability, and mechanical stability under pressure. This sedimentary lithotype typically consists of sand grains predominantly composed of quartz, with lesser amounts of feldspars, clay, and other sediments, all bound together by a matrix of cement (Rutter & Glover, 2012). The degree of cementation profoundly controls its stiffness, compressibility, resistance to deformation, and eventual structural stability under stress. Consolidated formations exhibit greater stiffness and resistance due to strong grain-to-grain contacts enforced by secondary cement formations, while unconsolidated formations are more prone to grain rotation, rearrangement, and eventual structural collapse under pressure. Stress can be classified into three types: compressional stress, tensional stress, and shear stress (Figure 1.1).

The mechanical response of sandstones under stress cannot be fully explained by their lithologic framework alone; the pore structure, the distribution of pores and throats, the clay content, and the pressure acting upon their grains collectively govern their ability to retain their form under pressure (Jin & Zimmerman, 2015). Furthermore, the degree of consolidation controls their Young's Modulus and compressibility. Higher Young's Moduli typically correlate with greater resistance to deformation, reflecting a more well-cemented grain framework. The influence of stress extends to both microcracks within grains and microstructures within their pores, which

under pressure may close or grow, affecting both stiffness and eventual failure mechanisms (Dewhurst et al., 1998).

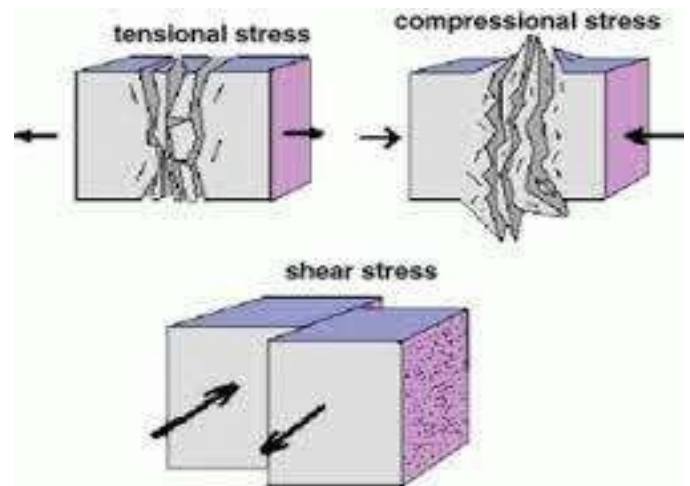


Figure 1.1: diagram showing different types of stress in rock
source: Geologyscience, 2023

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3. Fluid-Saturated Formations under Stress

Fluids within pores (Figure 2.2) profoundly affect the geomechanical response of formations under stress (Takeda et al., 2022; Muqtadir et al., 2018). Water, brine, or oil can fill the porous space, adding a secondary pressure component that dampens or exacerbates the effects of external stress (Jin & Zimmerman, 2015).

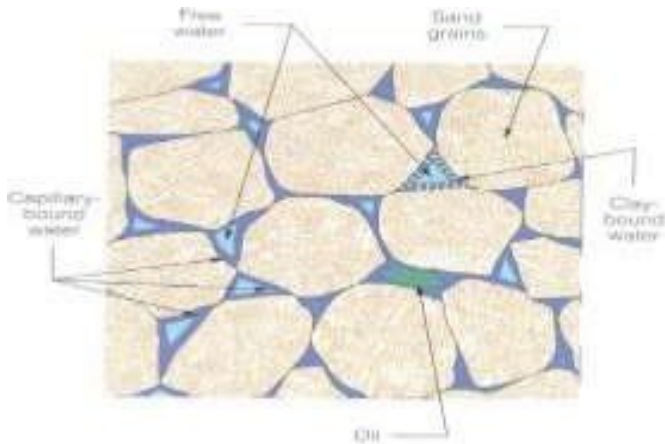


Figure 1.2: Fluid saturation (Drilling Formulas, 2016)

This phenomenon occurs due to pore pressure effects and fluid–solid interactions at the grain contacts (Turner et al., 2019). When formations are saturated with water, for instance, their stiffness typically decreases due to reduced grain-to-grain contacts and an increase in pore pressure (Rutter & Glover, 2012). This weakening can manifest as a lower Young’s Modulus, greater compressibility, and a propensity toward microcracks under stress (Yadav et al., 2020). Furthermore, low salinity water can undermine grain cementation, adding a physico-chemical weakening to the mechanical effects (Takeda et al., 2022). This phenomenon results from electric double-layer effects and disjoining pressure, which undermine grain bonding.

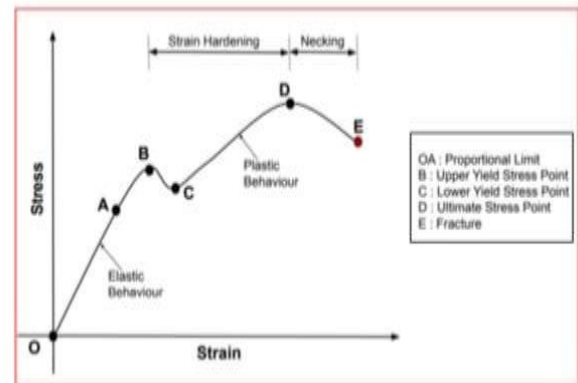
4. Geomechanical Properties and Methods for Their Determination

Geomechanical properties represent a fundamental aspect of geotechnical and petroleum engineering, as they dictate how geological materials such as rocks and soils respond to mechanical stresses, fluid pressures, and environmental changes.

These properties are critical in designing and analyzing structures such as tunnels, dams, foundations, slopes, and hydrocarbon reservoirs, where understanding material behavior under load is essential for ensuring stability and longevity. The most significant geomechanical parameters include elastic modulus (E), Poisson’s ratio (ν), uniaxial compressive strength (UCS), tensile strength, cohesion (c), internal friction angle (ϕ), and permeability (k), each playing a distinct role in governing deformation, failure, and fluid flow characteristics. The elastic modulus, for instance, quantifies a material’s stiffness and its ability to resist deformation, while Poisson’s ratio describes

how a material contracts laterally when subjected to axial compression. Uniaxial compressive strength is a direct measure of a rock’s load-bearing capacity, whereas tensile strength determines its resistance to fracturing under tension, Figure 2.3 stress-strain curve for the Tensile Strength. Cohesion and internal friction angle are key components of shear strength, influencing slope stability and wellbore integrity, while permeability controls fluid migration through porous and fractured media, affecting groundwater flow and hydrocarbon recovery.

Figure 1.3 stress-strain curve. (Senthil 2020)



Given the complexity and variability of geological materials, determining these properties requires a multi-faceted approach involving laboratory experiments, in-situ field testing, and empirical correlations. Laboratory testing provides precise, controlled measurements but may not fully capture large-scale heterogeneity and in-situ stress conditions. Field investigations, including geophysical surveys and borehole logging, offer insights into rock behavior at a larger scale but may lack the resolution of laboratory techniques. Empirical methods, such as rock mass classification systems, bridge the gap by providing estimates based on observable geological features.

5. Key Geomechanical Properties and Their Significance

1. Elastic Modulus (E) and Poisson’s Ratio (ν)

Hooke’s Law states that for materials subjected to tensile stress at relatively low levels, the relationship between stress and strain is proportional. This relationship is characterized by a constant known as the modulus of elasticity, or Young’s modulus E (Equation 2.1).

$$\sigma = E\epsilon \quad (1.1)$$

The elastic modulus (E), also known as Young's modulus, is a fundamental property that describes the relationship between stress and strain within the elastic deformation range of a material. (Equation 2.2).

$$E = \frac{F/A}{\Delta l} \quad (1.2)$$

It is a measure of stiffness, indicating how much a rock or soil will deform under a given load before returning to its original shape upon unloading. Rocks with a high elastic modulus, such as granite or basalt, exhibit minimal deformation under stress, making them suitable for high-load-bearing applications like bridge foundations and dam constructions. Conversely, softer materials like clay or poorly consolidated sandstones have low elastic moduli, leading to greater deformation under the same stress conditions. Poisson's ratio (ν), on the other hand, quantifies the lateral strain response relative to the axial strain when a material is compressed. Most rocks have Poisson's ratios between 0.1 and 0.3, meaning they contract laterally when compressed axially, though some highly fractured or porous rocks may exhibit higher values due to internal void collapse (Jaeger et al., 2007). (Equation 1.3).

$$\nu = \frac{\Delta l}{l} \quad (1.3)$$

These properties are crucial in numerical modeling and finite element analysis, where accurate input parameters are necessary to predict stress distributions around underground excavations, wellbores, and hydraulic fractures. For instance, in petroleum engineering, the elastic modulus and Poisson's ratio are used in wellbore stability models to prevent collapse or excessive deformation during drilling. In civil engineering, these parameters help assess the load-bearing capacity of foundations and the potential for settlement under structural loads. Additionally, seismic wave propagation studies rely on

elastic properties to interpret subsurface structures, as compressional (P-wave) and shear (S-wave) velocities are directly related to the elastic modulus and Poisson's ratio (Fjaer et al., 2008). Thus, understanding these properties is essential not only for material characterization but also for predicting the dynamic behavior of geological formations under various loading conditions.

2. Uniaxial Compressive Strength (UCS) and Tensile Strength

The uniaxial compressive strength (UCS) presented in Figure 2.4 is one of the most widely used parameters in rock mechanics, representing the maximum axial stress a rock sample can withstand before failure under unconfined conditions. It is a critical indicator of rock competence and is used in rock mass classification systems such as the Rock Mass Rating (RMR) and the Q-system. UCS values vary significantly across different rock types, ranging from less than 1 MPa for weak, weathered shales to over 300 MPa for strong, intact igneous rocks like granite and basalt. The UCS is typically determined through laboratory testing, where cylindrical rock samples are subjected to axial loading until failure occurs. However, factors such as sample size, loading rate, and moisture content can influence the results, necessitating standardized testing procedures like those outlined by the International Society for Rock Mechanics (ISRM, 2007).



Figure 2.4: UCS testing machine. (Whyte et al., 2025)

While UCS measures resistance to compressive loads, tensile strength defines a rock's ability to withstand stretching or pulling forces. Since rocks are generally much weaker in tension than in compression, tensile strength is a critical parameter in scenarios where tensile stresses dominate, such as in the roof of underground openings or in hydraulic fracturing operations. The most common method for determining tensile

strength is the Brazilian test, an indirect tensile test where a disc-shaped rock sample is compressed diametrically until it splits along the diameter.

3. Fracture Strength

Fracture strength refers to the stress level at which the rock breaks or fractures. This occurs after the rock has undergone elastic and plastic deformation and reached its ultimate strength. For sandstones, fracture strength is a function of grain cementation, mineralogy, porosity, and existing microcracks. In consolidated formations, where grains are tightly bound by silica or carbonate cement, fracture strength is generally high. Conversely, in unconsolidated formations, the absence of cementation lowers the fracture strength significantly.

Fracturing often propagates along grain boundaries or through pre-existing weaknesses, and its prediction is crucial for reservoir stimulation design (Li et al., 2021). Laboratory-based triaxial testing is commonly used to identify fracture strength by observing the stress level at which a sudden drop in load-bearing capacity occurs (Fjaer et al., 2008).

4. Yield Point

Yield point marks the transition from elastic to plastic behavior. Up to this point, deformation is recoverable, but beyond it, the rock undergoes permanent, irreversible deformation. In sandstone, this point depends not only on mineral composition but also on pore pressure and fluid saturation. Water saturation, for instance, can lower the yield point due to lubrication effects at grain contacts and reduction of frictional resistance (Muqtadir et al., 2018).

The yield point is typically detected from stress–strain curves as the point at which non-linear behavior begins and deviates from the initial linear trend. It is a key criterion in determining safe mud weights during drilling operations to avoid inducing plastic deformation around the wellbore (Zoback, 2010).

5. Elastic Limit

Elastic limit refers to the maximum stress that a material can withstand without undergoing permanent deformation. It is closely related to the yield point but is defined in a stricter physical sense. While the yield point is often approximated from the stress–strain curve, the elastic limit is the last point at which the material still obeys Hooke's law. Exceeding the elastic limit results in permanent changes to the rock structure, including microcrack initiation, grain boundary sliding, or irreversible compaction. For sandstone, especially under fluid-saturated conditions, the elastic

limit can be significantly lowered. This has operational implications in subsidence control and sand production during reservoir depletion (Mahatadi et al., 2020).

6. Cohesion (c) and Internal Friction Angle (ϕ)

The shear strength of geological materials is typically described using the Mohr-Coulomb failure criterion, which incorporates two key parameters: cohesion (c) and internal friction angle (ϕ). Cohesion represents the inherent shear resistance of a material at zero normal stress, arising from chemical bonding, cementation, or electrostatic forces between particles. In contrast, the internal friction angle reflects the frictional resistance between grains or along fracture surfaces, increasing with higher normal stresses. These properties are fundamental in slope stability analysis, where the shear strength of soil or rock determines the factor of safety against sliding. For example, a steep rock slope with low cohesion and friction angle is more prone to failure, whereas a gently inclined slope composed of highly cohesive material is more stable.

7. Permeability (k)

Permeability is a measure of a material's ability to transmit fluids and is governed by the interconnectedness of pore spaces and fractures within the rock matrix. It plays a crucial role in groundwater hydrology, hydrocarbon reservoir engineering, and geoenvironmental applications such as contaminant transport and carbon sequestration.

Permeability is typically expressed in millidarcies (mD) or square meters (m^2) and can range from less than 0.1 mD in tight shales to several darcies in highly porous sandstones or fractured carbonates. The determination of permeability involves laboratory methods such as the constant-head or falling-head permeameter tests for soils and the steady-state or transient pulse decay methods for rocks.

II. METHODS FOR DETERMINING GEOMECHANICAL PROPERTIES

1. Laboratory Testing

Laboratory testing remains the most accurate method for determining geomechanical properties, as it allows for controlled conditions and precise measurements. The uniaxial compression test is the standard procedure for assessing UCS and elastic parameters, where a cylindrical rock sample is loaded axially until failure while strain gauges record deformation. The triaxial compression test (Figure 2.5) extends this by applying confining pressure to simulate in-situ stress conditions, providing data on shear strength and failure envelopes. For tensile strength, the Brazilian test is widely used due to its simplicity, though the direct tensile test offers more accurate results when feasible.



Figure 1.5: Triaxial Equipment (Primetek Instruments & Technology, 2026)

The direct shear test is employed to measure cohesion and friction angle by shearing a rock or soil sample along a predefined plane under varying normal stresses. Advanced techniques such as the hoop test and hollow cylinder test allow for more complex stress path simulations, relevant to wellbore stability and fault reactivation studies (ISRM, 2007). Additionally, specialized equipment like the resonant column apparatus and bender elements can determine dynamic elastic properties by measuring shear

2. Field Techniques

Field techniques, including well testing (e.g., pressure transient analysis) and tracer studies, provide in-situ permeability estimates that account for large-scale heterogeneities. Additionally, geophysical methods like nuclear magnetic resonance (NMR) logging can infer permeability based on pore-size distribution (Bear, 1972). Understanding permeability is essential in reservoir engineering, where it controls hydrocarbon production rates, and in civil engineering, where it affects seepage through dams and embankments. Furthermore, in geothermal energy extraction, high-permeability zones are targeted for efficient heat transfer, while in radioactive waste disposal, low-permeability formations are selected to minimize contaminant migration.

3. Confining Stress and Geo-mechanical Response

Confining stress, or pressure that is evenly distributed from all directions, profoundly controls the geo-mechanical response of formations (Zhou et al., 2020; Mahatadi et al., 2020). An increase in confining pressure typically results in greater stiffness, reduced pore volume, and an upward shift in Young's

Modulus, reflecting the closing of microcracks and pores under compression (Turner et al., 2019). This phenomenon occurs because higher stress drives grains into tighter contacts, thereby strengthening their resistance to further deformation (Rutter & Glover, 2012). Under high confining pressures, saturated formations may respond differently than their dry counterparts due to fluid pressure redistribution within their pores (Muqtadir et al., 2018). This redistribution can produce an additional stiffening or weakening effect, depending on fluid viscosities, surface tension, and wetting properties (Jin & Zimmerman, 2015). The result is a complex geo-mechanical response where both the external pressure and internal fluid pressure govern stiffness and eventual mechanical failure (Yadav et al., 2020).

III. MATERIALS AND METHODS

1. Materials

Unconsolidated and consolidated core samples, triaxial equipment, Saturation cylinder system, electrical weighing balance, tong, crucible, oil-water sample and water sample.

2. Methods

1. Overview of Core Samples.

Six reservoir cores were collected from a core laboratory in Akwa Ibom State, Nigeria's Niger Delta region, sourced from two different reservoirs (unconsolidated and consolidated) and subsequently dried in an oven at 480°F. The core samples are shown in Plate 2.1.



Plate 2.1 Consolidated Core Samp

Core plugs were oven-dried at 480°F until a constant dry weight was obtained. The mass was monitored every 24 hours until the difference between two successive readings was less than 0.01g. The dry mass of each sample was recorded as M_d (g). The dimensions (diameter and length) of the core were measured using a digital vernier caliper. The dimensions, weight, and the pressure wrongful stops due to faulty facial recognition or misidentified hotspots).

Sample Type	Sample No	Depth (ft)	Core plug size (mm)	Dry Mass (g)
	1	7000	71 × 36	118.44
Consolidated	2	7000	71 × 36	118.16
Reservoir Core				
	3	7000	71 × 36	112.68
	A	7800	57 × 37	104.22
Unconsolidated	B	7800	57 × 37	104.33
Reservoir Core				
	C	7800	57 × 37	103.22

3. Core Saturation

The dried cores were immersed in a cylinder of water and water-oil (saturating fluid) at ambient laboratory temperature (27 °C). Care was taken to ensure the cores were fully submerged and free from direct air exposure. At predetermined time intervals (t_i), the samples were carefully removed from the fluid, gently blotted with a moist lint-free cloth to remove excess surface water, and immediately weighed using an analytical balance of ± 0.001 g accuracy. The measured mass at each interval was denoted as $M(t_i)$. After weighing, the core was returned to the fluid for continued saturation.

This process was repeated at short intervals during the initial stages (e.g., 10, 20, 30, 60 minutes ...), until no significant change in weight was observed between successive readings. The final constant mass was recorded as the fully saturated mass, M_s . (Karimaie et al., 2025)

The degree of saturation at any time $S(t)$ was calculated as shown in Equation (2.1): (Karimaie et al., 2025)

$$S(t) = \frac{M(t) - M_d}{M_s - M_d}$$

(2.1)

Where:

- $S(t)$ = saturation level at time t (dimensionless, fraction or %)
- $M(t)$ = mass of core at time t (g)
- M_d = dry mass of core (g)
- M_s = fully saturated mass of core (g)

The adsorption (fluid uptake) rate was determined as the slope of mass change over time, expressed in Equation (3.2): (Kennedy, 2025)

$$R(t) = \frac{M(t_{i+1}) - M(t_i)}{t_{i+1} - t_i}$$

(2.2)

Where $R(t)$ is the average adsorption rate between two time intervals.

Full saturation was considered achieved when the difference between successive mass measurements was less than the balance resolution (± 0.001 g) over two consecutive intervals, indicating equilibrium.

IV. GEO-MECHANICAL ANALYSIS OF DRY CORE AND SATURATED CORE SAMPLES.

1. Confined Compressive Strength (Triaxial) Test

The triaxial system comprised a pressure vessel (triaxial cell), axial loading frame with micrometer or screw-driven actuator, load cell (capacity ≥ 50 kN and resolution ≤ 0.01 kN), axial displacement transducer (dial gauge or LVDT, resolution ≤ 0.001 mm), and a confining pressure system using hydraulic oil or de-aired water with a calibrated pressure gauge or transducer

(resolution ≤ 5 kPa). The procedure was repeated for the saturated samples. The data obtained from the load and deflection readings were later used to calculate stress-strain relationships, strength parameters, and elastic properties of the core samples under the different confining stresses (ASTM, 2020; ISRM, 2007). Plate 2 shows the image of the core samples after the confined stress test.



Plate 2- Image of the core samples after the confined stress test systematic monitoring of recruitment performance and facilitate more informed HR decisions.

2. Determination of Geo-Mechanical Parameters

1. Data Processing

The experimental dataset obtained from the triaxial tests was subjected to systematic computational workflows to derive the required geo-mechanical parameters. The recorded parameters included axial load (P , in kN), axial displacement (ΔL , in mm), confining pressure (σ_3 , in MPa).

A. Axial Strain

Axial strain represents the relative deformation of a rock specimen in the axial direction under load. It is defined as the change in length divided by the original length of the specimen

(Ulusay & Hudson, 2007). The governing equation is in Equation 2.3.

$$\epsilon = \frac{\Delta L}{L_0}$$

(2.3)

a L_0

Where ϵ is the axial strain (dimensionless), ΔL is the measured axial displacement (mm), and L_0 is the original sample length (mm).

B. Cross-Sectional Area Correction

Since the specimen deforms during loading, the instantaneous cross-sectional area was corrected to account for lateral expansion. Following the approach proposed by Zhang et al. (2021), the corrected area is expressed in Equation 2.4 as:

$$A = \frac{A_0}{1 - \epsilon_a}$$

(2.4)

Where A is the corrected area (mm^2) and A_0 is the initial area (mm^2). This correction ensures that stress values are not underestimated as the specimen undergoes axial shortening.

C. Axial Stress

Axial stress quantifies the force per unit area applied along the axis of the specimen. Using the corrected area, the axial stress was computed according to ASTM D7012-14 standards in Equation 2.5:

$$\sigma = \frac{P}{A}$$

(2.5)

Where σ is the axial stress (MPa), P is the applied load (kN), and A is the corrected area (mm^2).

D. Deviatoric Stress

The deviatoric stress, which drives plastic deformation and failure in rocks, is defined as the difference between the axial

and confining stresses as expressed in Equation 2.6 (Li et al., 2022):

$$q = \sigma_1 - \sigma_3 \quad (2.6)$$

Where q is the deviatoric stress (MPa) and σ_3 is the confining pressure (MPa).

2. Geomechanical Property Derivation and Analysis

After obtaining the fundamental stress-strain relations, several mechanical properties were derived to characterize rock behavior.

A. Young's Modulus Determination

Young's modulus (E) describes the rock's stiffness and is defined as the ratio of stress to strain within the elastic region (Chen et al., 2023). It was determined from the slope of the linear portion of the stress-strain curve, typically between 30–70% of peak strength with Equation 2.7:

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

$$(2.7)$$

Where $\Delta \sigma$ is the stress increment and $\Delta \epsilon$ is the corresponding axial strain increment.

B. Elastic Limit Determination

The elastic limit (also called proportional limit) marks the end of linear elastic behavior. It was determined using the 0.01% strain offset method according to ASTM E111-17: The corresponding stress at this offset point on the stress-strain curve defines the elastic limit.

C. Yield Point Determination

The yield point, representing the onset of permanent deformation, was identified using the 0.2% offset method as per ASTM E8/E8M-21: Here, a line parallel to the elastic modulus is drawn from 0.2% strain, and its intersection with the experimental stress-strain curve defines the yield stress.

D. Peak Strength Identification

The peak strength was defined as the maximum sustainable deviatoric stress reached by the rock specimen before failure (Zhang & Yin, 2020):

E. Brittle-Ductile Classification

Post-peak deformation behavior was used to classify samples as brittle, transitional, or ductile. The classification employed the brittleness index (BI) proposed by Rahimzadeh et al. (2023) as in Equation 2.8:

$$BI = \frac{q_{\text{peak}} - q_{\text{residual}}}{q_{\text{peak}}} \times 100\% \quad (2.8)$$

Where q_{peak} is the peak deviatoric stress and q_{residual} is the residual stress after failure. Samples with $BI > 20\%$ were categorized as brittle, those with $5\% < BI < 20\%$ as transitional, and $BI < 5\%$ as ductile.

V. RESULTS AND DISCUSSION.

1. Discussion of Saturation Behavior

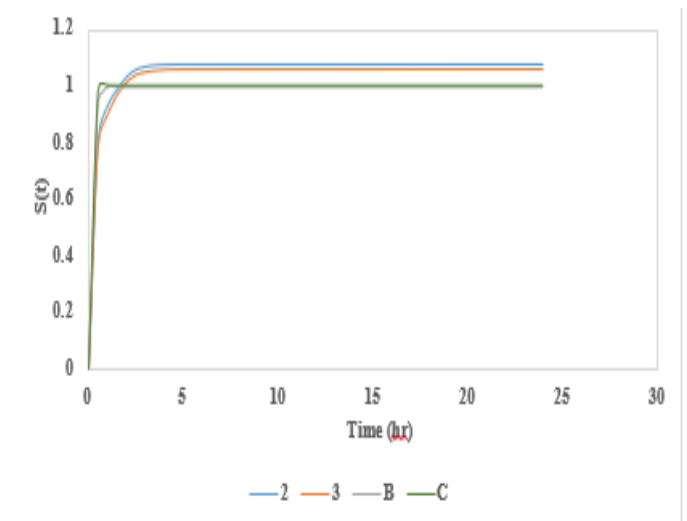


Fig 3.1a: The degree of saturation at any time $S(t)$

A clear distinction emerged between consolidated and unconsolidated cores. The unconsolidated samples (B and C) achieved near-complete saturation within the first hour. In the oil–water system (Sample B), saturation rose to approximately 95% at 0.5 hours and reached equilibrium by 1.0

hour, while the water-only system (Sample C) surpassed 99% at 0.5 hours and was fully saturated by 1.0 hour. This rapid imbibition can be attributed to the higher permeability and larger pore throats of unconsolidated materials, which promote faster fluid migration with minimal capillary resistance.

Conversely, consolidated samples (2 and 3) exhibited slower saturation kinetics, requiring up to 3–5 hours to reach equilibrium. Sample 2 (oil–water system) recorded ~82% saturation at 0.5 hours and ~99% by 2.0 hours, whereas Sample 3 (water only) achieved ~80% saturation at 0.5 hours and ~98% by 2.0 hours. These slower uptake rates reflect the tighter pore networks, reduced permeability, and higher tortuosity of consolidated rocks, which hinder fluid transport. A behavior consistent with the findings of Dullien (1992) on the influence of compaction and cementation on pore accessibility.

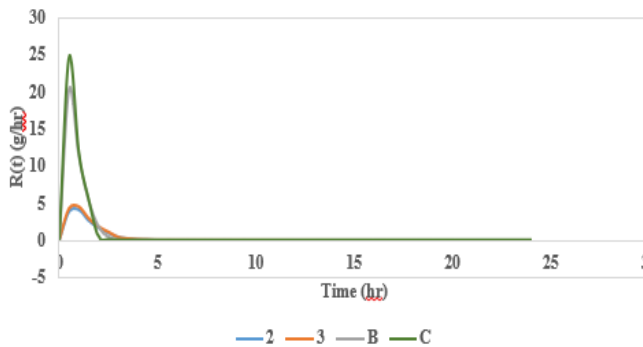


Fig 3.1b: The adsorption (fluid uptake) rate $R(t)$

The adsorption rate data further reinforce these observations. At 0.5 hours, unconsolidated samples exhibited the highest uptake rates, ranging between 20–25 g/hr, consistent with their rapid saturation. In contrast, consolidated samples showed much lower uptake rates of 3.9–4.3 g/hr during the same interval. From 1.0 hour onward, the rates in unconsolidated samples approached

zero, indicating early equilibrium, whereas consolidated samples continued to imbibe fluid, though at progressively lower rates, until approximately 3.0 hours. This behavior reflects the diminishing capillary pressure gradients as pore spaces fill, which is a fundamental feature of imbibition dynamics in porous systems.

2. Stress-Strain relationship of the Dry Core Samples

The consolidated dry reservoir core (Sample 1) displayed a clear brittle response, as shown in Figure 4.2a. At the early stage of loading, the specimen exhibited a steep linear stress increase with strain, reflecting the elastic region, and this was associated with a relatively high stiffness given by a Young's Modulus of 22,300 psi. The material sustained load up to an

elastic limit of 19,925 psi, after which deviation from linearity was observed. Beyond this point, permanent deformation began, and the specimen reached a yield strength of 34,800 psi.

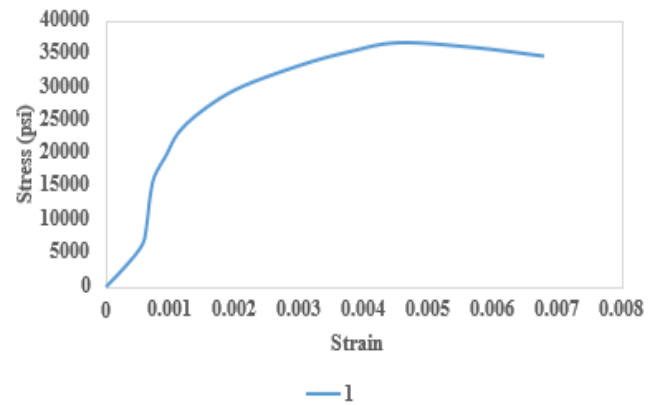


Fig 3.2a: Stress-Strain diagram for sample 1

The unconsolidated dry reservoir core (Sample A) demonstrated a much weaker and less stiff response, as depicted in Figure 3.2b. The stress–strain curve rose less steeply in the elastic region, corresponding to a very low Young's Modulus of only 65 psi. The specimen sustained stress up to an elastic limit of 540 psi, followed by yielding at 2,700 psi. The peak strength attained was 2,915 psi, which is more than an order of magnitude lower than the consolidated sample

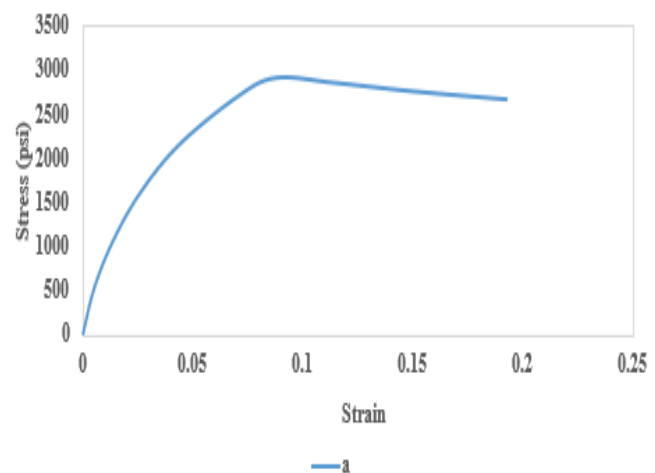


Fig 3.2b: Stress-Strain diagram for sample 1

The consolidated specimen exhibited more than 300 times greater stiffness and over ten times higher peak strength than the unconsolidated specimen. However, the mode of failure differed significantly: while the consolidated core failed suddenly in a catastrophic brittle fracture, the unconsolidated core failed gradually through strain-softening. In practical terms, these results suggest that consolidated formations, though strong, can fail abruptly under excessive stress, whereas unconsolidated formations, though weak, deform progressively and are prone to sand production and compaction.

Table 3.1. Table of Young Modulus, Elastic Limit, Offset Yield Points, Peak Strength and Failure Type for Sample 1 and A

Samples	Young's	Elastic	Yield	Peak	Failure Type
Property	-----	Limit	Strength	Strength	
	(E) (kpsi)	(psi)	(psi)	(psi)	
1	22300	19,925	34,800	36,775	Brittle Fracture(Sudden, catastrophic)
A	65	540	2700	2915	Brittle (Strain-Softening)

3.Stress-Strain relationship for saturated core samples

Stress-Strain analysis for Saturated Consolidated Core Samples (2 and 3)

The stress-strain response of samples 2 and 3 shown in Figure 3.3 plotted from the values in Table A2 and A3 of Appendix A reveals marked differences in their mechanical behavioural despite a broadly similar initial elastic regime. Both curves begin with a well-defined linear segment, from which the Young's modulus values were derived. Table 3.1 shows the derived geo-mechanical properties. Sample 2 exhibits a modulus of 10,400, while sample 3 records a slightly lower value of 9,100. This difference of approximately 14% indicates that sample 2 is mechanically stiffer, offering greater resistance to deformation under applied stress. Interestingly, the elastic limit for both specimens is almost identical, with values of 13,185 and 13,375 respectively.

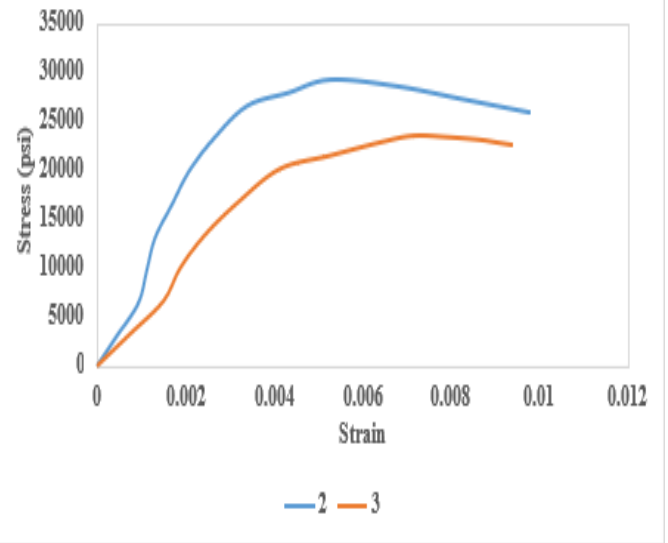


Fig 4.3: Stress-Strain diagram for sample 2 and 3

Beyond the elastic limit, the two samples diverge significantly in their stress-strain paths. Sample 2 demonstrates higher yield and peak strengths, attaining values of 28,300 psi and 29,350 psi respectively, compared to 22,500 psi and 23,497 psi for sample 3. These differences, amounting to roughly 25–26%, highlight that sample 2 can sustain substantially greater loads before experiencing irreversible plastic deformation and eventual failure. Mechanistically, this outcome may be attributed to stronger intergranular bonding, lower porosity, or a lower pore pressure within sample 2, all of which would enhance its ability to withstand higher stresses

VI. CONCLUSION

This study investigated the effects of fluid saturation on the geomechanical properties of consolidated and unconsolidated sandstone reservoirs under confined stress conditions. The research objectives were successfully achieved, and the key findings are concluded as follows:

- Core sample preparation and saturation behavior were successfully achieved. The results showed that unconsolidated cores saturated much faster (within ~1 hour) due to higher permeability, while consolidated cores required up to 3-5 hours to reach equilibrium. Fluid type also played a role: water generally achieved slightly higher final saturation, whereas oil-water systems promoted faster early imbibition in consolidated cores.

- Geo-mechanical properties of dry cores revealed clear lithological differences.
- Consolidated sandstones exhibited higher stiffness, elastic limits, yield points, and peak strengths compared to unconsolidated sandstones, reflecting the influence of cementation and compaction. Conversely, unconsolidated samples showed lower resistance to deformation and higher susceptibility to ductile failure.
- Geo-mechanical behavior of saturated cores demonstrated that fluid type significantly influences rock strength. Water saturation consistently weakened both lithologies by reducing cohesion and enhancing ductile deformation, while oil–water saturation enhanced stiffness and delayed failure, especially in consolidated cores. This confirms the critical role of pore-fluid interactions in modifying rock mechanical response.
- Comparison between consolidated and unconsolidated formations established that consolidation strongly governs strength and deformation modes. Consolidated sandstones retained higher strength even under water saturation, while unconsolidated samples rapidly lost strength under the same conditions. Oil–water saturation, however, improved mechanical stability in both lithologies, although the effect was more pronounced in consolidated cores

2. Recommendations

- Industry practitioners can incorporate the experimentally derived geomechanical parameters into predictive models, improving accuracy in production forecasting, enhanced oil recovery (EOR) planning, and reservoir compaction assessment.
- Drilling operations in consolidated reservoirs should anticipate sudden brittle failure, and adequate mud weight programs should be designed to prevent collapse. In unconsolidated reservoirs, sand control techniques such as gravel packing or chemical consolidation should be prioritized to manage progressive grain failure.
- The experimentally derived geomechanical parameters (elastic modulus, yield point, peak strength, and failure type) should be incorporated into numerical reservoir models to improve the accuracy of production forecasts, compaction predictions, and fracture propagation analyses.
- Future studies should extend beyond two sandstone types to include carbonates, shales, and mixed lithology,

thereby providing a more comprehensive understanding of fluid–rock interactions.

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