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The experimental methods and elastic properties of shale bedding planes materials state-of-the-art review

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ABSTRACT

The identification of physical properties and fracture behavior of shale or hydrocarbon materials has grown to have substantial importance in the last four decades to industry and investigators alike due to its importance in unconventional oil and gas resources. This interest deviates from shale being a transversely isotropic material formed by bedding layers with different orientations and isotropic properties. In this paper, the experimental setup and the mechanical properties of shale materials have been reviewed. The investigator shows that the properties of shale are not unique, and it is highly dependent on, volume, loading type, and geolocation. Furthermore, the investigator utilized different experimental setup methods to identify the elastic properties of shale and the most common methods are Transducers Strain Detection, Strain gauges, Ultrasonic, and Digital image correlation that is shown in detail.

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1. Introduction

The investigating and testing of the mechanical properties of shale materials are an interesting topic for the last four decades by researchers. The most interest has been in regions rich with organic shales like the Midwest of America, Canada, Australia, China, Russia, and a few countries in Europe. Oil and gas extraction enhancement is the primary goal from a mechanical engineering standpoint. The enhancement of shale and porous rock will increase the injection and storage of CO₂ into the ground, one of the safest technologies currently used. However, a full understanding and information on transversely-isotropic material, as shown in Fig.1, and to understand its

mechanical properties and fracture behavior, different experimental and numerical simulation setups were used. The utilization of fracture mechanics to determine mechanical properties, which is the scope of this article, applies linear elastic fracture theory as a base for analytical solutions and is a common technique for many investigators. Fig.2 is an SEM image showing the sedimentary rock containing at least 30% of clay which is known as shale, and its properties are dependent on microstructural

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Figure 1: Example of Shale core [2]

features, intra-granular porosity, anisotropy degree, petrophysical characteristic, mineralogy, thermal history, organic content, location, depth, and so on. of the porous rock and shale are needed [1]. In general, there are no unique parameters for shale.



Figure 2. Typical of microstructure of sedimentary rock (shale)

Experimentally, different setups were used to understand shale behavior such as Large-scale simulation, acoustic wave operating, stress wave propagation, Digital image correlation, and three-point bending experimental apparatuses. Most of these experimental setups are carried out on two bedding orientations relative to the loading direction, longitudinal, and transverse directions. However, the result shows different shale responses and properties, as shown in Table 1. In Table 1, for example, Gautam tests the shale using Transducer strain detection and transverse isotropy. The result is dependent on the global data and shows that the elastic modulus is the same in compressive and tension, and the inelastic modulus in the longitudinal direction is larger than the elastic modulus in the transverse direction. In addition, Ye used line data information from the TSD, SG, DIC, and BM. He found that the elastic modulus with a longitudinal direction under tensile load is smaller than the elastic modulus

along the transverse direction under compressive load. For the same materials, there are different results as shown in Table 1.

Table 1 shows that the shale is transverse-isotropy is the isotropic material response in one plane and different in the other plane, while bi-modulus materials refer to the elastic modulus in tension being different from compression. Furthermore, shale has distributed micro or macro cracks at different locations and orientations, as shown in Fig.2. In this work, the experimental method of shale materials is covered, then fracture mechanics data is listed following the summary and the general notes. [2]

Table 1. Transverse-isotropy shale response and the experimental method

Author	TSD	SG	US	DIC	BM	TI	Data	Result
Gautam [3]	✓	✗	✗	✗	✗	✓	Global	$E_{ll}^t > E_{tt}^t$
Hakala [4]	✓	✓	✗	✗	✗	✓	Global	$E_{ll}^t > E_{tt}^t$
Wong [5]	✓	✗	✓	✗	✗	✓	Global	E_{ult}, E_{st}
Ye [6]	✓	✓	✗	✓	✓	✗	Line	$E_{ll}^t < E_{tt}^c$
Ming [7]	✗	✓	✗	✗	✗	✓	Point	$E_{ll}^t > E_{tt}^t$
Shant. [8]	✗	✓	✗	✓	✗	✓	Line	$E_{ll}^c > E_{tt}^t$
Segam. [9]	✗	✗	✗	✓	✗	✓	Local	$E_{ll}^c > E_{tt}^t$

Where: ✓ mean the author used this method, and ✗ mean not.

TSD: Transducers Strain Detection

SG: Strain gauges

US: Ultrasonic

DIC: Digital Image Correlation

BM: Bi-Modulus

TI: Transverse isotropy

2. The experimental methods

As shown in Fig. 3, there are many examples of experimental setups that are used to investigate the physical properties (mechanical properties) of shale. The standard specimen geometry for shale and rock is circular or cylindrical, and the load is an indirect tensile test or direct compressive test. However, the method to measure the deformation and strain will vary based on the chosen method, as described in the following references [5], [10], [7], and [8].

Luo et al., 2018, studied anisotropic shale bedding planes. The research aims to understand the crack extension, the effect on the bedding planes, and the effects of anisotropy of shale regarding fracture toughness and crack extension characteristics. The authors mentioned that the crack behavior and fracture on the shale could alter based on pressure change brought from the SEM and did not discuss the effect of hydraulic liquid on the fracture properties. This hydraulic liquid would create a realistic simulation of shale fracture in field situations. In addition, only the theoretical stress field was investigated, and Mode-II fracture was claimed to be negligible on account of the stress concentration factor. [11]. Chalivendra et al., 2009, Studied predictive simulations for dynamic fracture along weakened planes that were challenging and lacked fitting parameters for accurate results. The group aimed to compare predictive data generated from experiments with published data and numerical simulations. They used a modified Hopkinson bar setup with photoelastic experiments on a notched face specimen to obtain controlled loading fracture crack propagation. An inverse problem of cohesive zone modeling is used to obtain Mode-I cohesive zone laws. The authors found that both the experiments and the numerical simulations result in comparable crack

initiation times and create similar crack tip velocities with a difference of less than 6%. The results confirm that the detailed shape of the non-linear cohesive zone law does not have a significant influence on the numerical results [12].

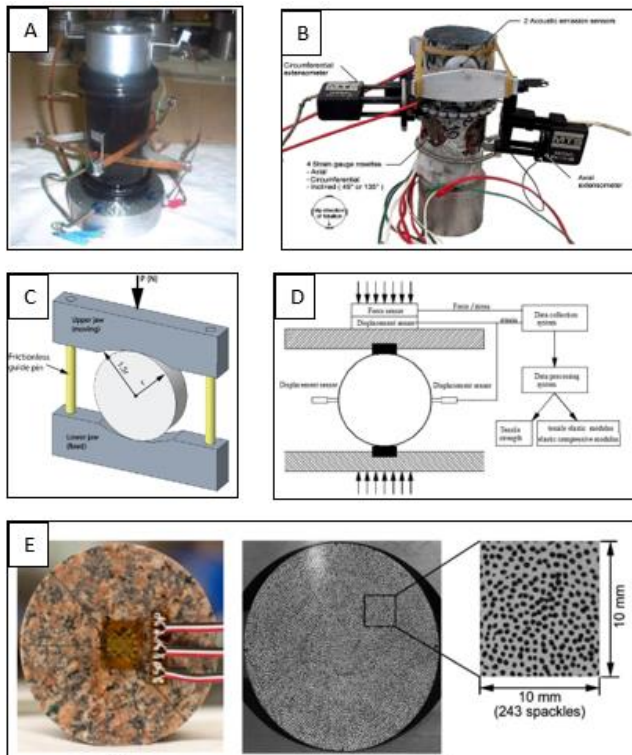


Figure 3. Examples of experimental setups that are used to investigate the mechanical properties and fracture toughness of shale: A) Wong setup [5], B) Hakala setup [10], C) Brazilian Disk, D) Ming setup [7], Shantonu setup [8]

[13]

Tan, 2018, studied the layer's influences on coal technical behavior in subversive environments such as coal or rock bursts. The author conducted this research using eight specimens and numerical models of dynamic SHPB using micro parameters of pre-load coal with different sheet angles to study the effects of bedding angles on failure patterns. Three impact velocities of 4, 8, and 12 m/s were used to analyze the dynamic of coal-holding bedding planes under different loads. The results indicated that the existence of bedding planes leads to the degradation of the mechanical properties, and their weakened effect significantly depends on the bedding angle between the bedding planes and load direction. The bedding angle was changed from zero to ninety degrees in 15-degree increments. The result shows that the strength first decreased and later increased as the angle increased. The specimen became most vulnerable when the bedding angle was thirty or forty-five degrees. Also, energy characteristics combined with ultimate failure patterns showed that the maximum accumulated energy and failure intensity has a positive relationship with the strength of the specimen. When bedding planes were parallel or perpendicular to the loading direction, specimens absorbed more energy and expended more aggressive failure with an increased number of cracks. However, bedding planes with 30 or 45 degrees reduced the specimen's ability to store strain energy to the lowest, with fewer cracks observed after failure. The

numerical and experimental results show a 26.73% error in the failure strain. However, the other mechanical properties were accurate. Jian et al., 2020, focused on studying the effects of bedding structures on the acoustic characteristics of shales at operating frequencies of acoustic logging, and an acoustic transmission apparatus is used to determine acoustic wave propagation characteristics in shale with various bedding angles. A numerical model based on the viscoelastic properties of shale is used to estimate the density, the effects of the angle, and the thickness of bedding planes on the acoustic characteristics of shale at operating frequencies of acoustic logging. It was shown that the bending angle is the primary feature when observing the shale bedding structure and significantly affects acoustic wave propagation. The amplitude increased as the wave velocity increased the bedding angle. The wave velocity decreased as the bedding density and thickness increased when the acoustic waves were transferred across the shale numerical model. Significant reflection and refraction of the acoustic waves propagate through shale resulting in energy loss [14]. Daehnke, 1999, used experimental and theoretical approaches to develop a full simulation model to understand the behavior of rocks sufficiently. This work is essential to underground and open-cast mining operations. Three-dimensional, PMMA, cube-type laboratory experiments are loaded with explosives and dynamically tested. Photoelastic and high-speed imaging techniques are used to examine fracture evolution [15].

The interaction between stress waves and a crack was reviewed by Williams, 2009 [16]. The publishers mention that it is crucial to understand the dynamic fracture of engineering materials and its initiation and propagation of cracks subjected to elastic, plastic, or shock waves. Elastic stress waves theory of elastodynamics is utilized to better understand the dynamic fracture of engineering materials as the initiation and propagation of cracks that are subjected to elastic, plastic, or shock waves. Multiple topics are reviewed and related to the elastic stress wave. This paper contained multiple experimental methods that used a disc for loading a half-plane crack with a tensile pulse. The response of a crack under plane strain loading using a plate-impact setup. Also, the effects of dilatational (longitudinal) and transverse (shear) waves interacting with a crack were analyzed. They did not mention the effects of weakened planes between the stress waves and cracks. Meier et al, 2015, [17] point out that 75% of wells are drilled from sedimentary basins worldwide in the research. However, there are instability issues from borehole drilling that are not entirely understood. The solidity of wells drilled into bedded shapes. For example, shale depends on the direction between the bedding and the hole axis. The risk of borehole insecurities increases significantly if the borehole is drilled sub-similar to sheet. Thick-walled cavity cylinder experiments with differing orientations of bedding planes are used to analyze the structure of stress-induced borehole escapes in Posidonia shale. The samples were loaded iso-statically until the creation of breakouts. The onset of borehole breakout improvement was determined through acoustic emission activity, strain measurements, ultrasonic velocities, and amplitudes. As the bedding plane inclination angle changed from perpendicular to parallel to the borehole axis, the critical pressure for breakout initiation decreased from 151 MPa by nearly 65%. Shale bedding structure showed an anisotropy in elasticity and strength that resulted in a change in the strength that overshadowed the integrity of the thick-walled hollow cylinders. The initial failure was the result of slip along bedding planes. The initial failure was an early point for more severe breakouts forming either as shear or buckling failure. Kramarov et al., 2020, found that hydraulic fracturing is dependent on the height and width of the fracture and the major component of controlling the fracture size is the use of the formation fracture

toughness[18]. Berea Sandstone and Manco's semi-circular curve test (SCB) and digital image correlation (DIC) are utilized at varying notch orientations concerning the bedding planes. Full-field displacements determine the fracture process zone and Williams' series answer to obtain critical stress intensity factors. Essential parameters for calculating fracture toughness using DIC translations depend on the area of importance (AOI), the field of view (FOV), and the number of phrases of result (N). Values for FPZ and fracture toughness are reported and show to be in good standing. Aliha et al., 2012, studied shale fracture under indirect tensile load to better understand mixed-mode fracture toughness on brittle materials such as marble. The fracture toughness describes the resistance of rock materials against crack propagation. Two separate mixed-mode fracture experiments were utilized on Harsin marble. One was the Brazilian disc, and the other was the semi-circular bend specimens, and a range of pure Mode-I to pure Mode-II fracture toughness a fracture envelope was developed. The results show that the major takeaway from these experiments is that fracture toughness depends on geometry and loading. Generalized equations which account for geometry and loading are the best ways to fracture toughness. This is proven with the experimental results of the BD and SCB experiments [19].

3. The outline fracture data

There are considerably more numerical and theoretical studies than there are laboratory experiments for crack tip interactions within the load. The investigator found that the most common discussions included

- However, there is a disparity in results. The primary cause for this is the bedding planes' thickness, voids, and geographical characteristics of shale. Fracture toughness yields the best results when a generalized equation considering loading and geometry is utilized. Most researchers include a discussion about fracture process zone (FPZ). The results exhibited brittle fracture in the shale, and the fracture strength was strongly dependent on the bedding plane inclination angle.
- Crack propagation started along the bedding plane when the bedding plane inclination angle was high such as angles greater than 60 degrees. However, angles at and below 30 degrees showed that cracks penetrated the matrix. Higher fracture toughness was reported with a lower bedding plane inclination angle.
- The stress field around the crack tip was analyzed theoretically and an equation was derived. A criterion for determining whether a crack extends along the bedding plane was developed by differentiating the characters in the strengths of the shale bedding and the matrix.
- The crack tip stress field is determined by three major factors: the stress intensity factor and the elastic constants, and the bedding plane inclination angle.
- Most of the work discusses Mode-I of fracture and does not discuss the effects of angles for Mode-I and Mode-II fracture and process zone on the rock specimens [20].
- The fracture process zone was not mentioned throughout in rock specimen studies. The discussion was based on a global scale and not regarding fracture toughness.
- The CTOD and the development of the cohesive zone model are not discussed in detail in most works. However, most discuss the importance of the fracture process zone regarding sandstone and shale. The fracture process zone is a vital characteristic of brittle material because it

characterizes its liability of fracture toughness. The Brazilian disc and semi-circular bend specimens Harsin marble specimens are common specimens' geometries to determine the mixed-mode fracture toughness and fracture envelope. However, most were interested in isotropic material and did not look at the shale's weakened planes.

- The shale can be tested under torsional stress wave using the spiral crack and investigate the mixed mode fracture under low and high loading rates, [21-22]

4. Summary

Numerous experimental techniques have been used to investigate the fracture mechanics of shale using global or far-field load and deformation data or local and deformation data. The most common are Transducers Strain Detection, Strain gauges, Ultrasonic, and Digital Image Correlation. Unfortunately, in all these methods the weak plane behavior and effect on the fracture have not been considered. However, the shale is fractured and fragmented in three dimensions depending on the direction of the weak plane.

Some researchers focus on the weak plane but use numerical simulation with no experimental test. In a dynamic case, the numerical model of an SHPB is utilized to investigate micro parameters of pre-stressed rock specimens with different bedding angles to study the effects of bedding angles on failure patterns such as elastic strain energy. The acoustic logging that characterizes shale's bedding structure at various angles was also used but is not related to the weak plane. Up to today, there are a few points that need to be covered by the researcher in detail as follows:

- Use the Cohesive zone laws along the weakened planes. extend acoustic wave interactions between the bedding planes and characterize the strength of the bedding planes and the fracture.
- There have been reviews such as Williams's A Concise review on the interactions between stress waves and cracks. However, this review does not consider the effect on weakened planes and stress waves along the weakened, cracked body.
- . There is a large potential for the exploration of energy dissipation regarding bedding planes.
- Crack-load interactions along weakened planes have the potential for development.
- Stress wave interactions are mainly explored using photoelastic techniques and have not been looked at with modern and developing techniques such as DIC.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

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