Transversely isotropic mechanical properties of water-bearing shale: An experimental investigation

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Abstract: This study investigated the transversely isotropic properties of water-bearing shale by performing laboratory experiments on shale specimens with different bedding angles of 0°, 45°, and 90° under different saturation conditions. X-ray diffraction, P-wave velocity, and water absorption tests reveal that the studied shale features low porosity and brittleness. During uniaxial compression tests, transversely isotropic and axial apparent moduli degrade linearly with increasing saturation degree, but the former shows more significant changes than the latter. The Poisson’s ratio in the direction perpendicular to the bedding plane decreases with increasing saturation degree, whereas that in the parallel direction shows the opposite behavior. Weak transverse isotropy is observed on the uniaxial compression strength of air-dried specimens. As the saturation degree is increased, strengths corresponding to different bedding angles degrade linearly, and the transverse isotropic strength is weakened. Despite the significant degradation of strength, the brittle failure patterns and the fraction of dissipated energy density of the specimens do not change with saturation degree.

1 Introduction
Shale rocks, which are abundant in Southwest China, have distinct characteristics of water susceptibility and transverse isotropy. Researchers have extensively investigated the transversely isotropic mechanical properties of shale. Hiroki[¹, ²] systematically studied gas shale from different locations in America to understand the factors controlling the elastic properties and static strengths of shale rocks. Analysis of the mineralogical characteristics, elastic moduli, and inferred uniaxial compression strengths of different shale rocks revealed close links of the content of clayey minerals with the elastic deformation properties and static strengths of shale. The static elastic modulus was suggested as an indicator of the transversely isotropic properties of shale rocks, and a two-element model was further proposed to explain how the
layered soft and hard materials control the transversely isotropic properties of shale. Zhang[3] also considered the microstructures of shale as a type of homogenized two-part structure, and they further explored the influences of the orientation of embedded particles on the macroscopic transversely isotropic properties of shale rocks. Bennett[4] conducted nanoindentation and focused ion beam–scanning electron microscopic tests at multiple scales to investigate the anisotropic mechanical properties of Woodford shale. Results revealed the predominant minerals and basic microscale structure of the studied shale. In addition, distinctive differences were found between the indent depth of clayey and brittle minerals, thereby providing a microscopic perspective for studies on the transverse isotropy of organic-rich shale rocks.

Shale, similar to other sedimentary rocks, is water susceptible. Studies have been conducted from different views to investigate the influence of absorbed water on the mechanical and other physical properties of shale[5, 6]. Pane[7] performed multistage triaxial compression tests on shale samples, monitored the P- and S-waves throughout the process, and calculated transversely isotropic elastic parameters. The experimental results revealed the significant susceptibility of ultrasonic velocity on the changes in differential stress, and the transverse isotropy of the studied shale rock was estimated. Meng[8] conducted a series of quasi static uniaxial and triaxial compression tests on shales reserved under different saturation conditions to understand the influence of fluid immersion on the failure modes of shale. Transient failure along a main shearing surface was observed on dry specimens, whereas distributed progressive cracking failure was observed on saturated ones. Chen[9] investigated the mode-I fracture toughness and fracture growth properties of different shale rocks saturated by water and suggested that clay-rich shale shows a significant susceptibility on water immersion and that subcritical failure enhanced by water immersion could greatly increase brittle failure in clay-rich shale.

These studies focused on clayey minerals inside shale rocks. The weakening effect of water works by changing the structures and properties of clayey materials, and significant water susceptibility has been observed on clay-rich shales[10]. However, the relationship between water content and the mechanical properties of shale rocks containing a low fraction of clayey minerals remains to be established. Accordingly, the present study aimed to investigate the influence of water content on the transversely isotropic properties of shale rock with a low content of clayey minerals.

2 Laboratory Experiments

2.1 Sample Preparation and Experimental Design
Shale of Longmaxi Formation from Chongqing was chosen as the studied shale in this paper. Cylindrical specimens with different bedding angles of 0°, 45°, and 90° were retrieved from one block and then weighed, and the P-wave velocity in the axial direction was measured to check the discreteness of samples and avoid its influence on experiment results. Four groups of air-dried specimens with the above mentioned bedding angles were saturated for 0, 2, 18, and 36 h in a vacuum saturation machine, whose vacuum pressure was maintained at −0.1 MPa, to obtain specimens with different degrees of water saturation. Another three specimens (1 for 0°, 1 for 45°, and 1 for 90°) were first dried in the oven and then saturated for 1 week to investigate the behavior of water absorption of the studied shale. After preparing each group of specimens, they were immediately taken to measure their masses and then
conduct uniaxial compression tests with a constant strain rate of $5 \times 10^{-6} \text{s}^{-1}$. Deformations of specimens were measured with strain gauges and axial linear variable differential transformer.

2.2 Mineralogical and Physical Properties of Studied Shale

The density of the air-dried shale sample ranges from 2.57 g/cm$^3$ to 2.66 g/cm$^3$, and the average value is 2.65 g/cm$^3$. X-ray diffraction (XRD) tests reveal that the predominant minerals in the studied shale are quartz (51.9%) and albite (20.3%), along with small amounts of calcite, muscovite, potassium feldspar, and other materials. Clayey minerals mainly composed of illite and illite-montmorillonite take a mass fraction of 6.3%, indicating the significant brittle characteristic of the studied shale rock.

The results of water absorption experiments are shown in Figure 1. After 7 days of saturation, the average rate of water absorption $r_{\text{abs}}$ decreases quickly in the first 15 h and then decreases at a relatively low rate. When the saturation time reaches 144 h, all the tested specimens become saturated. Accordingly, the curve of saturation degree $S_w$ increases sharply from 0% to 80% in the first 15 h and then reaches a relatively steady state. During the entire process, the final water absorption mass of the tested specimens ranges from 5.9 g to 6.3 g. Thus, the average effective porosity is determined as 3.08%, which indicates that the studied shale has a dense structure and a low permeability.

The P-wave velocity of the specimens was tested before and after water absorption before mechanical tests. The average P-wave velocities of the air-dried specimens with bedding angles of 0°, 45°, and 90° are 4543, 4180, and 4689 m/s, respectively. As shown in Figure 2, after water immersion, the P-wave velocity of the specimens with different bedding angles increases to different extents. For example, the maximum velocity increment for the specimen with a bedding angle of 45° is 859 m/s (20.6%), and that for the specimen with a bedding angle of 90° is 427 m/s (9.1%). This observation suggests a transversely isotropic characteristic of shale that the absorbed water mainly enhances the ultrasonic wave conductivity in the direction perpendicular to the bedding plane.

**Figure 1.** Relationship between saturation degree $S_w$, water absorption rate $r_{\text{abs}}$, and saturation time.

**Figure 2.** P-wave velocity of specimens with different bedding angles and saturation degree $S_w$. 
2.3 Methods of Parameter Measurement

According to the elasticity theory of transversely isotropic materials, the elastic deformation behavior of transversely isotropic rocks under a certain stress state can be described by five independent elasticity parameters and the intersection angle $\theta$ between the loading and normal directions of the transverse isotropy plane[11].

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{yz} \\
\gamma_{zx} \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\
a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\
a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\
a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\
a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\
a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yz} \\
\tau_{zx} \\
\tau_{xy}
\end{bmatrix}
\]  

(1)

Under uniaxial compression condition, stress components vanish except for $\sigma_y$. Thus, from Eq. (1), the following equations can be acquired:

\[
\varepsilon_x = a_{12}\sigma_y, \quad \varepsilon_y = a_{22}\sigma_y, \quad \varepsilon_z = a_{32}\sigma_y
\]  

(2)

where

\[
\begin{align*}
a_{12} &= -\frac{v'}{E'} \sin^2 \theta - \frac{v'}{E'} \cos^2 \theta + \frac{\sin^2 \theta}{4} \left(1 + \frac{1}{E} - \frac{1}{E'} - \frac{1}{G'} \right) \\
a_{22} &= \frac{\sin^2 \theta}{E} + \frac{\cos^2 \theta}{E'} + \frac{\sin^2 \theta}{4} \left(1 - \frac{1}{G} - \frac{1}{E'} \right) \\
a_{32} &= -\frac{v'}{E'} \cos^2 \theta - \frac{v'}{E} \sin^2 \theta
\end{align*}
\]  

(3)

$E$, $v$ and $E'$, $v'$ are the elastic moduli and Poisson’s ratios in the parallel and perpendicular directions to the transversely isotropic plane, and $G'$ is the shearing modulus in the perpendicular direction to the transversely isotropic plane.

According to Eqs. (2) and (3), all transversely isotropic elastic parameters can be calculated by measuring the axial stress, axial strain, and the lateral strain of the specimens with bedding plane perpendicular, parallel, and inclined to the uniaxial loading direction, as shown in Figure 3. For detailed information about the calculation methods, refer to Jung-Woo’s work[12].

![Figure 3](image_url)

Figure 3. Scheme for measuring the transversely isotropic deformation with strain gauges, marked as
coarse cross lines.

3 Results and Discussion

3.1 Influence of Sw on the Elastic Properties of Shale
Influences of water immersion on the transversely isotropic elastic parameters and axial apparent Young’s moduli $E_{ap}$ of the specimens were analyzed. As depicted by Figure 4(a), both $E_{ap}$ for different bedding angles and transversely isotropic moduli of $E$, $E'$ and $G'$ degrade as $S_w$ increases. As $S_w$ increases from 39% to approximately 90%, $E$ decreases from 30.00 GPa to 12.36 GPa, and the degradation ratio is approximately 58.8%; $E'$ decreases from 26.76 GPa to 12.95 GPa, and the degradation ratio is approximately 51.6%; meanwhile, $G'$ decreases from 34.13 GPa to 21.82 GPa, and the degradation ratio is approximately 36.1%. $E_{ap}$ corresponding to bedding angles of 0°, 45°, and 90° degrade by 53.6%, 36.2%, and 43.2%, respectively. The transversely isotropic elastic parameters and the axial apparent Young’s modulus degrade after saturation, but compared with $E_{ap}$, larger changes are observed on $E$, $E'$ and $G'$ during the experiment. Figure 4(b) depicts the changes of parameters $\nu$ and $\nu'$ as $S_w$ increases. As $S_w$ increases, $\nu'$ shows a descending trend, whereas $\nu$ shows an ascending trend.

\[E' \quad E \quad G'\]

\[0^\circ \quad 45^\circ \quad 90^\circ\]

Figure 4. Relationships between elastic parameters and saturation degree $S_w$. (a) Relationships between elastic moduli and $S_w$, where points represent the testing values and fitting lines describe how parameters change with $S_w$, (b) relationships between transversely isotropic Poisson’s ratios and $S_w$.

3.2 Influences of $S_w$ on Uniaxial Compression Strength and Failure Characteristics of Shale
The average uniaxial compression strength (UCS) of specimens with different bedding angles and $S_w$ are plotted in Figure 5. The UCSs of the air-dried specimens show weak transverse isotropy, and the ratio of the maximum to the minimum UCS is approximately 1.13, which is lower than the recommended threshold of weak transverse isotropy [13]. As $S_w$ increases, UCS decreases in an approximately linear law. For different bedding angles, the decreasing trend of UCS does not show great distinction. For a
constant $S_w$, UCS shows small differences as the bedding angle changes, and the transverse isotropy of UCS almost vanishes when the specimens are completely saturated.

Figure 5. Relationships between the average uniaxial compression strength (UCS) and saturation degree of specimens, where points mean experimental values and solid lines mean fitting trend.

Typical failure patterns of specimens with different bedding angles and $S_w$ are shown in Figure 6. All the tested specimens behave brittle failure patterns. The specimens with a bedding angle of 90° present a splitting failure, and the specimens with bedding angles of 0° and 45° present a compounded splitting-shearing failure. Although the increment of $S_w$ is significant, the absorbed water does not significantly change the microstructure of the specimens because of the low clayey mineral content and low porosity of the studied shale. Thus, limited influence is triggered on the failure modes of the water-bearing specimens.

During the experiment, an interesting phenomenon was observed on the failure pattern of specimens with a bedding angle of 45°. As shown in Figure 6, specimens with bedding angles of 45° do not slide along the bedding planes when failed, which is contrary to the failure pattern usually observed on transversely isotropic rocks[14]. Instead, a predominant shear failure surface forms across the bedding planes at an either large or small intersection angle, whereas several secondary cracks initiate from the main failure surface, which is similar to the typical uniaxial failure pattern of some isotropic brittle rocks[15, 16]. This phenomenon results from the high quartz content and low clayey mineral content of the study shale, which significantly reduce the weakening effect of the bedding planes. To elucidate this phenomenon, future studies should perform a micro investigation on the characteristics of particle structures and bonds.
Figure 6. Failure patterns of specimens in uniaxial compression tests. Numbers on the pictures indicate the duration of water immersion, (a) bedding angles of 0°, (b) 45°, and (c) 90°.

3.3 Influence of Sw on the Energy Evolution Behavior of Shale

By assuming that during uniaxial loading, for any rock element, all the absorbed energy transforms into elastic strain energy and surface energy consumed during fracturing. As shown in Figure 7, the energy function in unit volume of a loaded specimen during pre-peak loading of uniaxial compression can be expressed as

\[ U = U^e + U^d \]  \hfill (4)

\[ U^e = \frac{1}{2} \sigma \varepsilon \approx \frac{\sigma^2}{2E_{ap}} \]  \hfill (5)

where \( U \) is the total input energy in unit volume, or input energy density, \( U^e \) is the elastic strain energy density, \( U^d \) is the consumed energy during fracturing in unit volume or dissipated energy density, and \( \varepsilon \) is the axial elastic strain of the unit.

The evolution of \( U^d \) during the pre-peak stage of different specimens was calculated using Eqs. (4) and (5). Figure 8 depicts the relationship between the rate of \( \frac{U^d}{U_f} \) and \( S_w \), where \( U^d \) and \( U_f \) are the dissipated and input energy densities corresponding to the peak point of stress–strain curve. Despite the increase in \( S_w \), \( \frac{U^d}{U_f} \) corresponding to different bedding angles fluctuates within a narrow range from 0.091 to 0.163, which may also explain why the failure patterns of the specimens with different \( S_w \) do not change significantly. However, \( \frac{U^d}{U_f} \) varies distinctly as the bedding angle changes. For example, the average \( \frac{U^d}{U_f} \) corresponding to 0°, 45°, and 90° are 0.151, 0.117, and
0.136, respectively, which shows a slight transversely isotropic characteristic.

![Figure 7](image1.png)  
**Figure 7.** Sketch of the dissipated energy density $U_d$ and elastic strain energy density $U_e$ of a uniaxial compression test.

![Figure 8](image2.png)  
**Figure 8.** Relationship between the ratio of dissipated energy density and total input energy density at peak point and $S_w$.

4 Conclusion

Laboratory experiments were conducted on water-bearing shale specimens with bedding angles of $0^\circ$, $45^\circ$, and $90^\circ$ to investigate the influence of water immersion on the transversely isotropic mechanical properties of the studied rock. XRD analyses reveal that the studied shale mainly consists of brittle minerals such as quartz and albite. The low content of clayey minerals causes the significant brittle characteristic of the rock. The porosity of the studied shale was determined to be approximately 3%.

The P-wave velocity of specimens was tested, with a minimum average value of 4180 m/s for $45^\circ$ and a maximum average value of 4689 m/s for $90^\circ$, indicating the dense structure, and transverse isotropy of the studied shale rock.

Air-dried specimens of each bedding angle were divided into four subgroups and saturated for 0, 1, 18, and 36 h. The saturation degree $S_w$ was measured, and then uniaxial compression tests were conducted on these water-bearing specimens. Transversely isotropic elastic parameters $E$, $E'$, $\nu$, $\nu'$ and $G'$ as well as axial apparent Young’s moduli $E_{ap}$ were determined. Experimental results show that $E$, $E'$ and $G'$ degrade at different decreasing rates as $S_w$ increases, indicating the transversely isotropic weakening effect of water immersion on the elastic deformation properties of shale. $E_{ap}$ for different bedding angles also degrade similarly but with smaller changes on value. As $S_w$ increases, $\nu$ increases while $\nu'$ decreases.

UCSs for all the investigated bedding angles degrade significantly as $S_w$ increases. Although the UCSs of the air-dried specimens show weak transverse isotropy, when the specimens approximately reach saturation, the transverse isotropy of UCS seems to vanish. This result indicates that the increase in saturation degree weakens the transverse isotropy of the studied shale. However, as $S_w$ increases, no obvious change is observed on the failure patterns and the fraction of dissipated energy density at the failure point of the specimens with different bedding angles.

The observed experimental results may provide valuable information on the transversely isotropic
mechanical properties of water-bearing shale for researchers interested in related fields.

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