

Article

Long-Term Anisotropic Mechanical Characterization of Layered Shale—An Experimental Study for the BaoKang Tunnel of the Zhengwan Railway, China

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Abstract: With the further implementation and development of the Western Development Strategy, studying the mechanical behavior and deformation characteristics of deep-buried tunnels in layered hard rock under high ground stress conditions holds considerable engineering significance. To study the mechanical properties and long-term deformation and failure characteristics of different bedding stratified rocks, this research employed an MTS815 electro-hydraulic servo rock testing system and a French TOP rheometer. Triaxial compression tests, rheological property tests, and long-term cyclic and unloading tests were conducted on shale samples under varying confining pressures and bedding angles. The results indicate that (1) under triaxial compression, shale demonstrates pronounced anisotropic behavior. When the confining pressure is constant, the peak strength of the rock sample exhibits a “U”-shaped variation with the bedding angle (its minimum value at 60°). For a fixed bedding angle, the peak strength of the rock sample progressively increases as the confining pressure rises. (2) The mode of shale failure varies with the angle: at 0°, shale exhibits conjugate shear failure; at 30°, shear slip failure along the bedding is controlled by the bedding weak plane; at 60° and 90°, failure occurs through the bedding. (3) During the creep process of layered shale, brittle failure characteristics are evident, with microcracks within the sample gradually failing at stress concentration points. The decelerated and stable creep stages are prominent; while the accelerated creep stage is less noticeable, the creep rate increases with increasing stress level. (4) Under low confining pressure, the peak strength during cyclic loading and unloading creep processes is lower than that of conventional triaxial tests when the bedding plane dip angles are 0° and 30°, which is the opposite at 60° and 90°. (5) In the cyclic loading and unloading process, Poisson’s ratio gradually increases, whereas the elastic modulus, shear modulus, and bulk modulus gradually decrease.

Keywords: rock mechanics of layered shale; hard rock; anisotropy; mechanical properties; failure modes



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1. Introduction

Shale is a prevalent engineering rock primarily formed through the deposition and subsequent compaction of clay under specific pressure and temperature conditions. It exhibits a complex composition characterized by thin laminae or layered joints. This structural

feature results in distinct strength and deformation characteristics when observed in parallel, perpendicular, or diagonal orientations, indicating significant anisotropy. Therefore, investigating its mechanical properties and long-term deformation and damage behavior is of considerable importance for practical engineering applications.

The study of shale engineering properties has garnered significant attention from scholars due to its critical role in engineering construction. Substantial research achievements have been made to date. Historically, studies primarily focused on macroscopic damage modes using conventional triaxial testing and rheological testing methodologies. In the 1960s, L.S.G [1,2] initiated theoretical analysis of this special structural rock body based on elastoplastic mechanics, introducing the concept of anisotropy in the mechanical properties of layered rock bodies. Deng et al. [3] conducted Brazilian disk splitting tests on layered sandstones with varying bedding angles, revealing remarkable anisotropic tensile strength characteristics. Cho et al. [4] investigated the anisotropic characteristics of shale through uniaxial compression and Brazilian splitting tests, demonstrating significant deformation and anisotropic strength in the tested rock samples. If anisotropic properties are not considered, substantial errors may occur in engineering practice.

Niandou et al. [5,6] examined the microstructure, mechanical properties, and anisotropy of various types of shales via mechanical tests and scanning electron microscopy (SEM), finding that shales exhibit pronounced anisotropic plastic deformation and that their damage behavior is largely dependent on constraint pressure and loading direction. Amadei [7] analyzed the anisotropic characteristics of layered rock bodies from the stress–strain relationship, concluding that rock anisotropy decreases with increasing confinement. Chen [8] explored the relationship between the strain rate and anisotropic mechanical characteristics of shale, showing that anisotropic mechanical characteristics weaken with increasing strain rate. Through uniaxial and triaxial compression tests conducted on rock samples, the relationship between confining pressure and anisotropic characteristics, as well as the influence of bedding angle on rock mechanical properties and failure modes, was systematically analyzed. The results indicate that with increasing confining pressure, the differences in strength and deformation parameters among rock samples with varying bedding angles gradually diminish, leading to a weakening of anisotropic characteristics [9–13]. Zhao et al. [14,15] found through uniaxial compressive strength tests on layered sandstone that the strength of rock samples was lowest when the weak surface of the bedding was at a 30° angle to the principal stress. Mao et al. [16,17] analyzed the anisotropy of the compressive and tensile strengths of slate through compressive and tensile tests, summarizing relevant damage modes. Huang [18] determined the modulus of elasticity, peak strength, and residual strength of rock specimens and their variation rules with the inclination angle β of the layers, analyzing the peak damage pattern of the specimens. Meng et al. [19] systematically investigated the effects of varying bedding angles (β values) and confining pressures (σ_3 values) on layered rock masses. They further highlighted that when the bedding angle is 45°, the distribution and morphology of cracks exhibit significant changes. Zhang et al. [20] analyzed the anisotropy of stress, strain, elastic modulus, and Poisson's ratio of shale. Zhao [21] compared the deformation and damage characteristics of granite specimens under high confining pressure cyclic loading and unloading versus conventional triaxial tests, finding that peak strength and crack damage stress increase linearly with confining pressure, while modulus of elasticity and crack initiation stress initially increase and then decrease with confining pressure, and Poisson's ratio initially increases and then remains constant or decreases with confining pressure. Hu et al. [22] found that Young's modulus and tensile strength of layered sandstone are significantly influenced by confining pressure and loading–unloading cycles, with both parameters affected by confining pressure and loading angle. Li [23] introduced the concept of the anisotropy

index, derived the theoretical formula for equivalent elastic deformation parameters of anisotropic-layered structural rock, quantitatively analyzed the anisotropic characteristics of rock deformation, and systematically discussed the influence laws of single-set structural surface geo-metric parameters and stress environment on rock body anisotropy.

Cruden [24] systematically characterized through static compression tests, including unloading cycles, the anisotropy of the material structure. It was concluded that the failure behavior of shale is highly dependent on confining pressure and loading direction. Lu et al. [25] conducted cyclic loading and unloading tests using models made of similar materials. They found that as the load increased incrementally, both the strain value and the elastic recovery strain exhibited an upward trend. The application of the load altered the original stress state of the surrounding rock, leading to stress concentration. Long-term cyclic loading and unloading induced creep in the surrounding rock, thereby promoting the initiation and propagation of fractures. Zhang et al. [26] performed triaxial compression and triaxial creep tests under varying stress levels and concluded that stress and holding time significantly influence creep characteristics. Under low stress and long-term loading conditions, mudstone exhibits pronounced steady-state creep and accelerated creep failure. Furthermore, the onset time of accelerated creep decreases exponentially with increasing stress. They also investigated the strength degradation and accelerated creep characteristics of mudstone, proposing that the internal creep damage variable of mudstone can be described by an exponential function.

In summary, the majority of existing studies have focused on the anisotropic mechanical properties of various rock types, including their deformation parameters and the location of weak bedding planes. However, there is a relative paucity of research concerning the long-term mechanical properties and damage characteristics of layered shale under varying bedding inclination angles. Additionally, limited attention has been paid to the time-dependent damage behavior of shale in practical engineering contexts. This study addresses this gap by investigating layered shale at different bedding angles through triaxial tests, staged loading creep tests, and cyclic loading–unloading creep tests. Our findings elucidate the mechanical behavior of rock under different confining pressures and bedding inclination angles, as well as provide insights into the long-term deformation characteristics and damage evolution laws of layered shale.

2. Methodology

2.1. Test Preparation

The shale samples utilized in this study were collected from the Baokang Tunnel of the Zhengwan Railway. The rock type is slightly weathered shale with well-defined bedding planes. To ensure the representativeness and consistency of the samples, all the rock samples were taken from the same rock mass, and the variable-angle rotary table was used for precision processing, and four groups of standard cylindrical specimens with diameters of 50 mm × 100 mm with laminar inclination angles of 0°, 30°, 60°, and 90° were prepared. As illustrated in Figure 1, the 0° angle corresponds to transversely isotropic samples, while the 90° angle represents samples perpendicular to the transversely isotropic orientation. During sample preparation, the angle between the cutting surface and the bedding plane was precisely controlled to strictly adhere to the design specifications (with a tolerance of ±2° to ±5°). To validate the accuracy of the samples, an ultrasonic thickness gauge was employed to measure all the specimens. The precision of the bedding angles was confirmed by analyzing variations in the propagation speed of ultrasonic waves in different directions, and any samples that failed to meet the criteria or exhibited significant surface defects were discarded. To further ensure data reliability, 10~20% of the samples were randomly selected for re-inspection, during which the angle verification and integrity

checks were repeated. Additionally, the height, diameter, surface flatness, density, and wave velocity of the samples were measured, and only those with closely clustered physical properties, such as wave velocity and density, were chosen for subsequent testing.

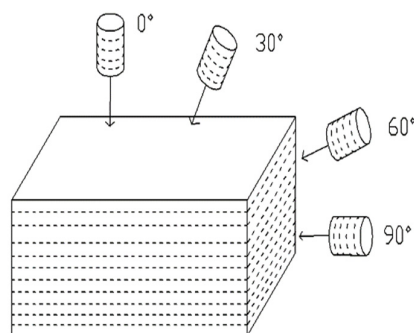


Figure 1. Schematic diagram of shale directional coring.

According to the wave velocity test, when the dip angle of the bedding plane is 0° , the average longitudinal wave velocity of the samples taken is the lowest, with a value of 4993 m/s. With the increase in the dip angle of the bedding, the longitudinal wave velocity increases gradually. When the dip angle of the bedding is 90° , the average longitudinal wave velocity of the samples taken is 5514 m/s, which indicates that this shale has obvious anisotropic characteristics. At the same time, electron microscope scanning (SEM) tests were carried out on shale samples with different bedding angles, and the SEM directions were parallel bedding direction, oblique intersecting bedding direction, and perpendicular bedding direction.

As can be seen from Figures 2–4 in the direction of parallel beddings, shapes of various sizes of striped fractures are visible, with more debris material attached to the crystals, and tiny pores can be seen locally, but the area of pore linkage is relatively small, and the structural mineral particles are arranged more tightly. In the direction of oblique intersecting bedding, the fracture is broken along the bedding surface, forming along-crystal damage, the fracture is broken along the bedding surface, the shape is stepped, and the development of microscopic pores and cleavage is obvious. In the vertical bedding direction, vertical strip-like fracture can be seen. In the microscopic test, the three directions of the specimen are damaged along the direction of the bedding surface; the bedding structure is obviously different, with significant anisotropic characteristics, which also leads to the different mechanical properties of the specimen at different angles at the macroscopic level.

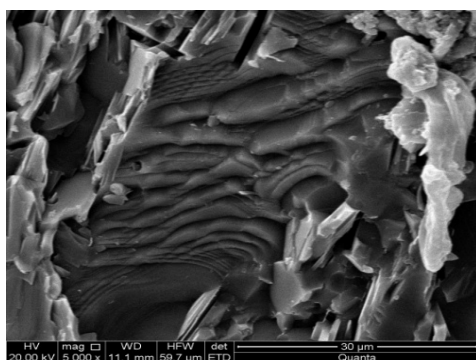


Figure 2. SEM photograph of laminated shale with parallel lamination direction.

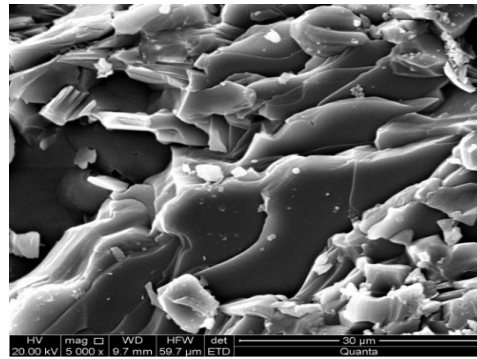


Figure 3. SEM photograph of diagonally cross-laminated directionally laminated shales.

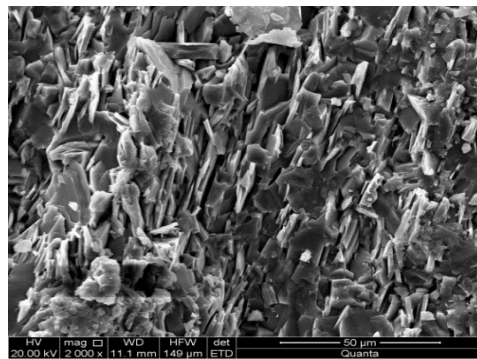


Figure 4. SEM photograph of vertically laminated shale in the direction of vertical lamination.

2.2. Mechanical Test Program

The prepared specimens with bedding angles of 0°, 30°, 60°, and 90° were subjected to triaxial compression tests, graded loading creep tests, and cyclic loading and unloading creep tests. The triaxial compression tests were conducted on an MTS815 testing machine, the test equipment is shown in Figure 5, while the graded loading creep and cyclic loading and unloading creep tests were performed on a French rheometer at the Institute of Geotechnical Mechanics, Chinese Academy of Sciences.



Figure 5. MTS815 pressure testing system.

During triaxial compression and creep tests, cylindrical shale specimens measuring 50 × 100 mm (drilled at angles of 0°, 30°, 60°, and 90°) were employed, with the laboratory environment temperature maintained at a constant of 20 °C. The testing procedure was divided into two stages: Initially, axial stress was applied at a rate of 10 bar/min until hydrostatic pressure was achieved, followed by the simultaneous application of confining pressure to 10 MPa (with both loading rates set at 10 bar/min). Once the confining pressure stabilized, axial deviatoric stress ($\sigma_1 - \sigma_3$) was incrementally applied at the same rate until

specimen failure occurred. For cyclic loading and unloading creep tests, a stepwise loading approach was adopted. First, the specified confining pressure and axial load were applied, and the deviatoric stress was loaded to a stable state under displacement control mode (set as 80% of the average triaxial compressive strength under 10 MPa confining pressure, serving as the damage strength threshold). Subsequently, 15 loading and unloading cycles were performed during the stable rheological phase of each load level (with intervals of 12–14 h and loading/unloading rates of 10 bar/min). Each load level was sustained for a creep observation period of 10–12 h. After completing 15 cycles and achieving creep stability, the next load level was applied until specimen failure.

3. Results and Discussion

3.1. Anisotropic Mechanical Characterization of Layered Shales

3.1.1. Mechanical Characterization of Triaxial Tests

The triaxial compressive stress–strain curves of layered shale under different confining pressure conditions are presented in Figures 6–9, from which the following observations can be made:

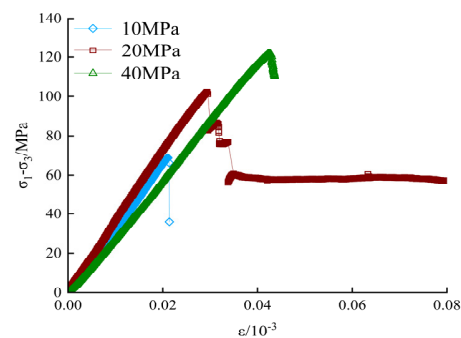


Figure 6. Triaxial compression characteristic curve of 0° shale.

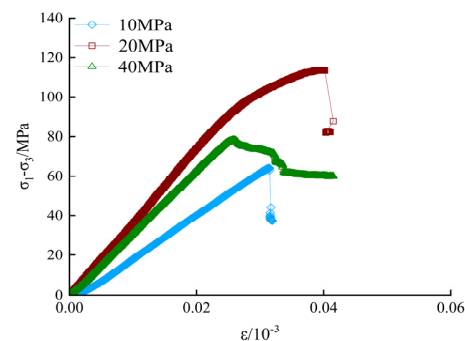


Figure 7. Triaxial compression characteristic curve of 30° shale.

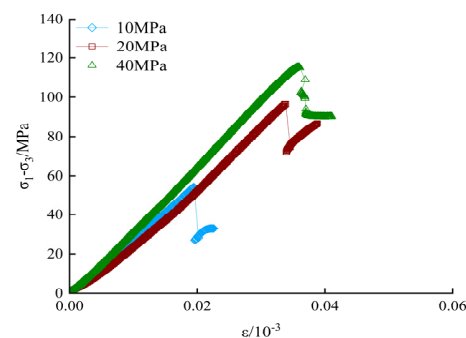


Figure 8. Triaxial compression characteristic curve of 60° shale.

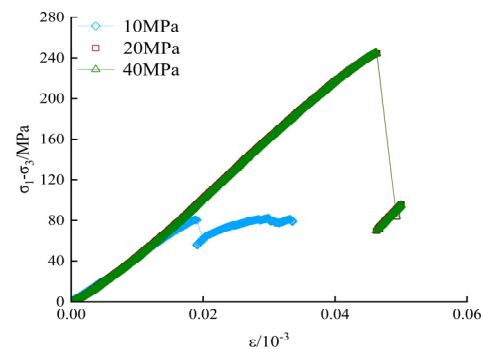


Figure 9. Triaxial compression characteristic curve of 90° shale.

(1). Rock samples with varying bedding angles and under different confining pressures have undergone four distinct stages: compaction, elasticity, yielding, and failure.

(2). In the compaction stage, initial microcracks within the rock gradually close as stress increases, resulting in an upward concave trend in the stress–strain curve. During the elastic phase, the stress–strain curve exhibits linear behavior as deviatoric stress increases, and the inflection point of volumetric strain corresponds to the cracking stress of the respective rock sample. In the yielding stage, internal cracks begin to propagate stably, leading to a gradual transition from expansion to compression. The axial stress–strain curve starts to flatten, with a significant decrease in slope, indicating the onset of plastic deformation and yielding. In the failure stage, rock samples exhibit pronounced brittleness, characterized by a sudden drop in deviatoric stress and abrupt specimen failure. However, with increasing confining pressure, brittle damage transitions to ductile damage, and residual strength increases.

From Figures 10 and 11, it can be observed that as the bedding inclination angle increases, the peak strength of the rock samples at failure exhibits a U-shaped trend, initially decreasing and then increasing. Additionally, with increasing confining pressure, the corresponding peak strength of the rock samples at failure also increases. When the confining pressure is 40 MPa, the peak strengths of the 30° and 60° rock samples are lower. This may be attributed to the internal porous structure of the samples or disturbances introduced during the drilling process, leading to microcracks along the weak bedding surfaces. Consequently, these factors result in lower wave velocities during wave velocity tests. Therefore, when failure occurs along the weak bedding surface, the peak strength of the rock samples is reduced.

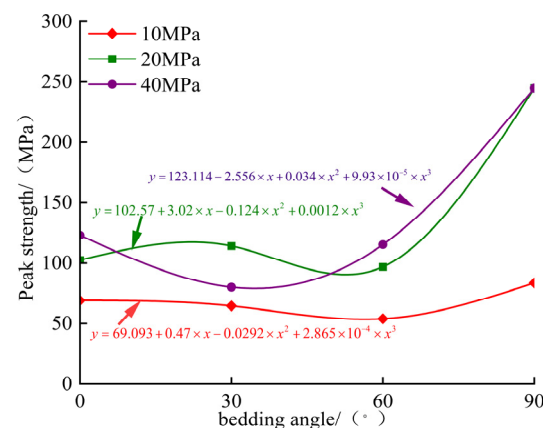


Figure 10. Triaxial strength profiles of shale with different layered dip angles.

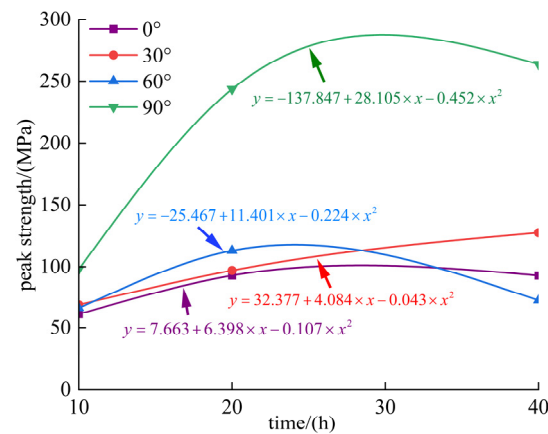


Figure 11. Triaxial peak strength profiles of shale with different enclosing pressures.

As can be observed from Figures 12 and 13:

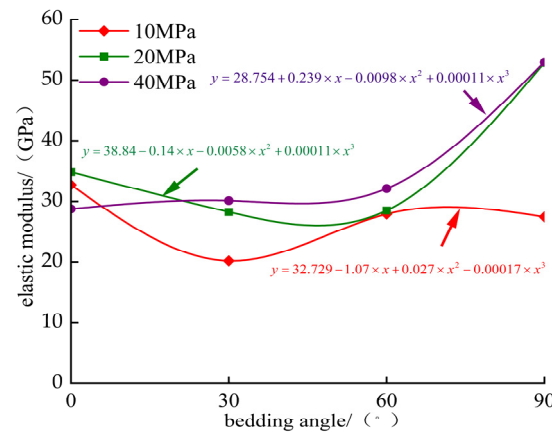


Figure 12. Elasticity modulus of shale with different laminar inclinations.

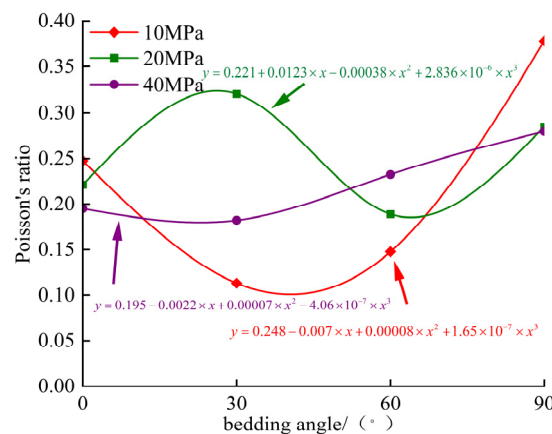


Figure 13. Poisson's ratio diagram of shale with different laminated dip angles.

(1). Under low confining pressure conditions, due to the inherent brittleness of hard rock and the limited development of internal voids, the rock samples remain relatively intact as a whole. Consequently, the compaction stage is not pronounced, leading to poor compaction effects. Therefore, the change in elastic modulus follows a similar trend to that of peak strength, showing a U-shaped trend of first increasing and then decreasing. As confining pressure increases, the elastic modulus of shale with different bedding angles generally shows an increasing trend, primarily due to the densification effect of confining

pressure on the rock samples during loading. Specifically, at 20 MPa confining pressure, the elastic modulus of the rock samples first decreases and then increases with the increase in the bedding angle. At 40 MPa confining pressure, the elastic modulus gradually increases with the increase in the bedding angle. When the bedding angle is 0° , the weak bedding surface is perpendicular to the direction of partial stress, resulting in better compression during the compaction stage and larger axial compressive deformation, which leads to a smaller elastic modulus. When the bedding angle is 90° , the weak bedding surface is parallel to the direction of partial stress, resulting in smaller axial compressive deformation and a larger elastic modulus. The magnitude of the elastic modulus changes significantly when confining pressure increases from 10 MPa to 20 MPa, but the change becomes relatively smaller when confining pressure increases from 20 MPa to 40 MPa. This indicates that the increase in confining pressure has a more significant effect on the elastic modulus under low confining pressure conditions, while its influence gradually diminishes under high confining pressure conditions.

(2). With the increase in the bedding angle, Poisson's ratio of the rock samples exhibits a U-shaped curve, initially decreasing and then increasing, indicating that the bedding angle has a substantial influence on Poisson's ratio. Overall, under different confining pressure conditions, Poisson's ratio reaches its maximum value when the bedding angle is 90° . The magnitude of Poisson's ratio varies significantly when confining pressure increases from 10 MPa to 20 MPa, but the variation becomes relatively smaller when confining pressure increases from 20 MPa to 40 MPa. Notably, at 20 MPa confining pressure and a bedding angle of 30° , Poisson's ratio of the rock samples is unusually high for two reasons: Firstly, the brittle destructive characteristics of hard rock lead to dispersion in peak strength at failure. Secondly, potential installation faults in annular hoops or annular transducers during testing may result in an overestimated Poisson's ratio.

3.1.2. Damage Characteristics of Triaxial Test

The macroscopic damage characteristics of triaxial compression tests on shale specimens with different bedding inclinations under various confining pressure conditions are illustrated in Figures 14–16. These figures reveal that the primary damage mode of the shale specimens is shear damage, which can be categorized into three types, exhibiting strong anisotropy. Specifically, at a bedding angle of 0° , the damage is characterized by conjugate shear. At a bedding angle of 30° , the damage is primarily shear slip along the bedding, controlled by the weak bedding surface. At bedding angles of 60° and 90° , damage occurs through the bedding.

Damage surfaces generally follow the weak bedding planes. As confining pressure increases, the damage surfaces of the rock samples become more complete, and the brittle damage properties weaken. Under 40 MPa confining pressure, fewer fine branch cracks are observed, whereas under 10 MPa, the development of fine branch cracks at the specimen ends is clearly visible.

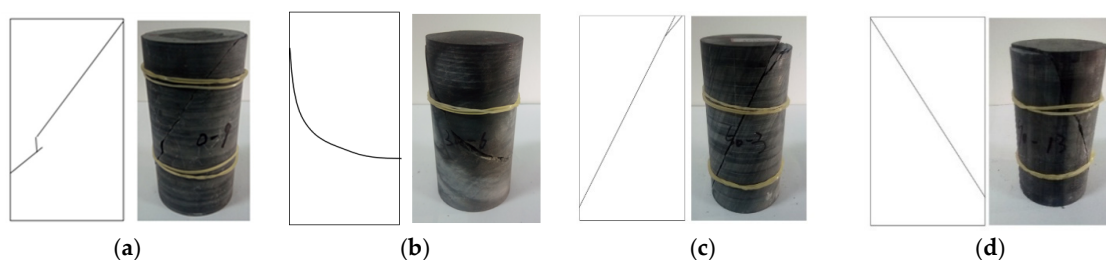


Figure 14. Failure characteristics of shale under 10 Mpa confining pressure. (a) 0° shale; (b) 30° shale; (c) 60° shale; (d) 90° shale.

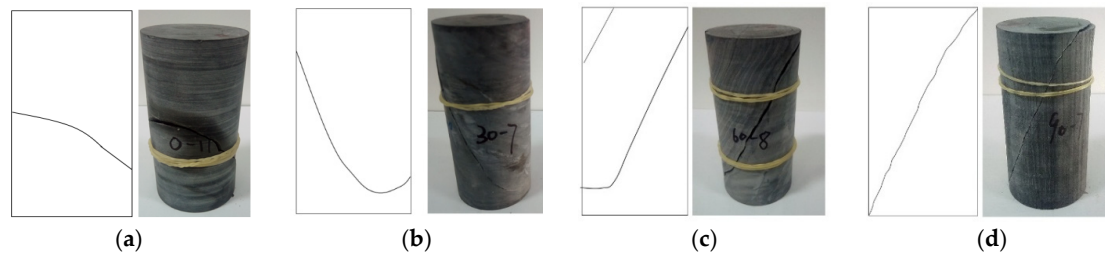


Figure 15. Failure characteristics of shale under 20 Mpa confining pressure. (a) 0° shale; (b) 30° shale; (c) 60° shale; (d) 90° shale.

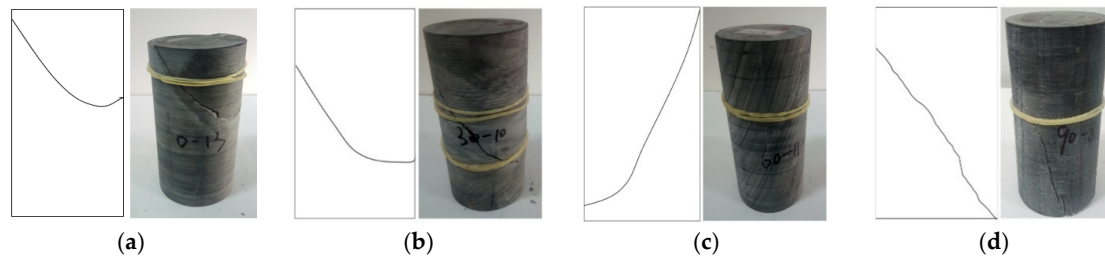


Figure 16. Failure characteristics of shale under 40 Mpa confining pressure. (a) 0° shale; (b) 30° shale; (c) 60° shale; (d) 90° shale.

3.2. Creep Characterization

3.2.1. Test Methods

Given that the peak strength of shale specimens with a bedding angle of 60° is the lowest under triaxial compression, a creep test was conducted on shale specimens with a bedding angle of 60° for research and discussion. In this test, the confining pressure was maintained at a constant of 10 MPa, while the axial deviatoric stresses were set to 20 MPa, 50 MPa, and 80 MPa, respectively. The loading rate for both the axial deviatoric stress and confining pressure was 10 bar/min. The specific test parameters for the rock samples are summarized in Table 1.

Table 1. Physical properties of rock samples.

Rock Sample Number	Peripheral Pressure (MPa)	Wave Velocity (m/s)	Compressive Strength (MPa)
60-10	10	5647.46	66.16

3.2.2. Creep Characterization Analysis

As can be seen from Figures 17 and 18, according to the creep characteristics of rock, creep is generally divided into three stages, namely decelerating creep stage, steady creep stage, and accelerated creep stage. In the decelerating creep stage, although the load is more stable, there is the strain to keep the growth trend at a decreasing rate; in the steady creep stage, the strain is increasingly growing, but the growth rate is more stable; and in the accelerated creep stage, the strain continues to increase over time, and the rate of enhancement becomes faster until the destruction of the shale occurs, leading to the phenomenon of the creep curve warping head. From Figure 18, it can be seen that when the bias stress is 20 MPa and 50 MPa, the characteristics of the accelerated creep stage of the shale with a bedding dip angle of 60° are not obvious. This is because the shale damage shows obvious brittle damage characteristics, and the microscopic cracks inside the specimen appear to expand gradually under the influence of stress concentration and

fatigue. When the bias stress is 80 MPa, the microscopic crack size increases continuously, and when the crack size reaches a critical level, the specimen is suddenly damaged.

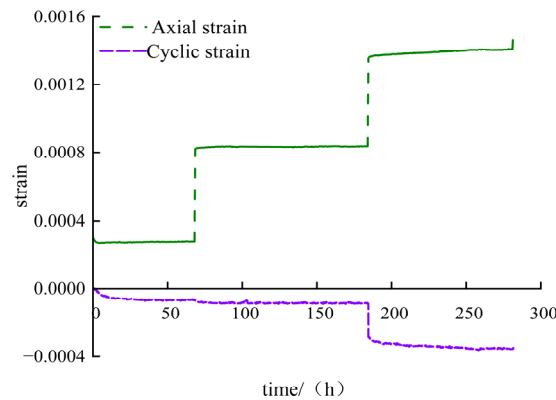


Figure 17. Rheological strain characteristics of 60° shale.

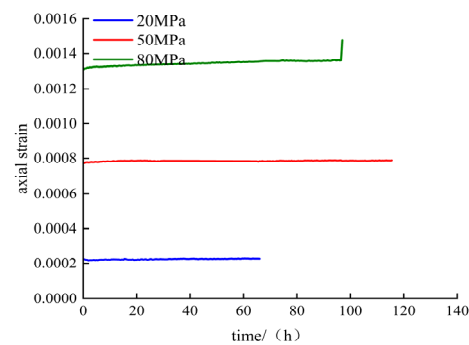


Figure 18. Axial strain under different confining pressure conditions in 60° shale.

As illustrated in Figure 19, the axial strain of shale increases with the applied stress. The deformation in the strain–time curve can be divided into two distinct components: (1) A sudden increase in axial strain due to transient strain that occurs during the loading process as a result of increasing deviatoric stress. (2) Creep strain that develops due to specimen deformation under a stable stress state.

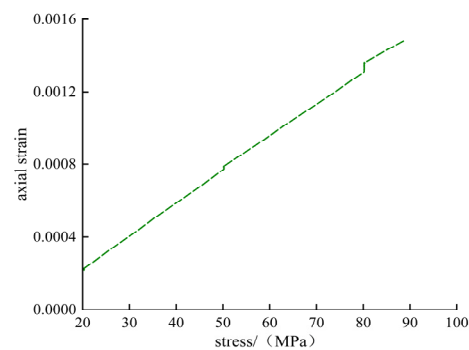


Figure 19. Axial strain under different stress conditions in 60° shale.

3.2.3. Effect of Instantaneous Elastic Strain

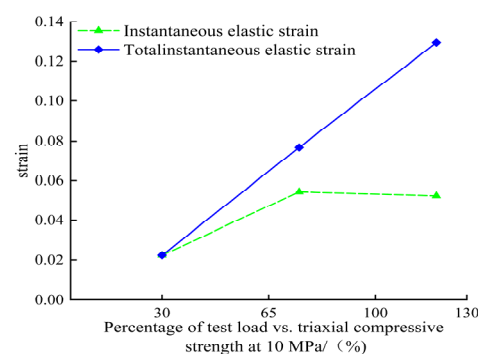
Table 2 shows the statistics of the instantaneous elastic strain, creep strain, and total strain at each loading level.

Table 2. Percentage of creep strain versus instantaneous elastic strain.

Load and Unload Times/h	Bias Stress/MPa	Prompt Elasticity Strains/ 10^{-2}	Creep Strains/ 10^{-2}	Total Strain/ 10^{-2}	Creep Strain/Total Strain/%
66	20	0.022	0.0003	0.0228	1.48
115	50	0.055	0.0015	0.0559	2.72
97.5	80	0.052	0.0052	0.0577	9.07

According to the data presented in the table, during the first loading stage, the axial deviatoric stress increased from 0 MPa to 20 MPa, resulting in a total strain of 0.000228. Of this, the creep strain was 0.000003 (1.48% of the total strain), and the instantaneous elastic strain was 0.00022. During the second loading stage, the axial deviatoric stress increased from 20 MPa to 50 MPa, where the stress was held constant for 115 h. The total strain produced was 0.000559, of which the creep strain was 0.000015 (2.72% of the total strain), and the instantaneous elastic strain was 0.000544232. In the third loading stage, the axial deviatoric stress was increased from 50 MPa to 80 MPa, with the stress held constant for 97.5 h. The total strain produced was 0.000577, of which the creep strain was 0.000052 (9.07% of the total strain), and the transient elastic strain was 0.00052. It can be observed that the proportion of creep strain increases progressively across the loading stages, accounting for 1.48%, 2.72%, and 9.07% of the total strain, respectively. This indicates that as the level of axial deviatoric stress increases, creep becomes more pronounced.

The axial deviatoric stresses applied to the specimens were 30%, 75%, and 120% of the triaxial peak compressive strength (under 10 MPa confining pressure). As shown in Figure 20, under low-stress conditions, the instantaneous elastic strain of the 60° bedding angle rock samples is higher because slip shear damage along the bedding surface results in larger shear displacements. Under high-stress conditions, the instantaneous modulus of elasticity of the specimen becomes more stable, leading to a stabilization of the instantaneous elastic strain; thus, the increase in total instantaneous strain also tends to stabilize.

**Figure 20.** Creep bias stress intensity ratio versus elastic strain.

3.2.4. Analysis of Factors Affecting Creep Rate

The creep rate versus stress relationship is shown in Table 3.

Table 3. Creep rate versus stress.

Stresses/MPa	Creep Rate/ 10^{-5}
20	0.511
50	1.304
80	5.333

The creep rate versus stress curve is shown in Figure 21.

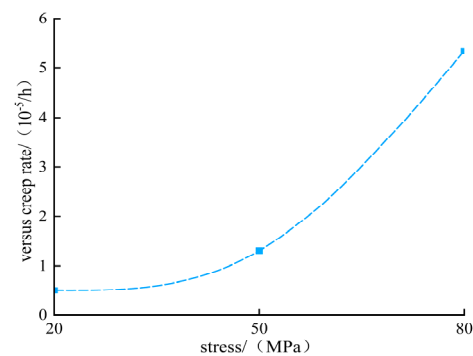


Figure 21. Stress level versus creep rate.

The creep rate, which serves as a critical parameter for assessing rock creep failure, exhibits an exponential relationship with stress [26]. Using the stress function $v = A + Be^{Rs}$ for regression, the corresponding curve function equation is given by $v = 0.2161e^{0.0391\sigma}$, conforming with the exponential stress dependence. As illustrated in the figure, as the stress level increases, the creep rate also increases gradually. This phenomenon can be attributed to the accelerated crack propagation within the specimen as the stress level rises, leading to a higher creep rate. Specifically, when the bedding angle of the rock sample is 60° , the creep rate increases significantly due to the angle being close to the potential failure plane of the rock. Therefore, the stress conditions have a pronounced influence on the creep rate.

3.3. Study of Long-Term Strength and Parameters of Layered Shale

3.3.1. Analysis of Mechanical Properties Under Cyclic Loading and Unloading

As illustrated in Figure 22, a hysteresis loop is formed during each cyclic loading and unloading process. In each stable creep stage, 15 hysteresis loops are generated corresponding to 15 cycles of loading and unloading until the specimen fails. The area of each hysteresis loop increases with the number of loading and unloading cycles, and the convexity of the hysteresis loops becomes more pronounced as the axial deviatoric stress increases. This phenomenon can be attributed to the cumulative increase in irreversible plastic deformation within the specimen during each loading and unloading cycle, which intensifies with higher levels of bias stress.

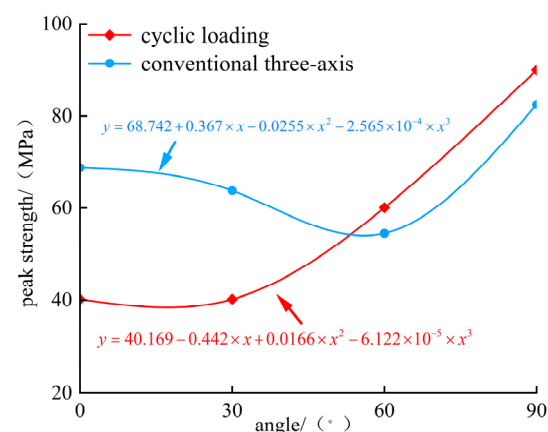


Figure 22. Cyclic loading and unloading versus conventional triaxial test peak strengths for shale with different bedding inclinations.

Comparing the peak strength of cyclic loading and unloading with that of conventional triaxial tests (Figure 9), it can be observed that for bedding inclination angles of 0° and 30° , the peak strength in conventional triaxial tests is higher than that in cyclic loading and unloading. Conversely, for bedding inclination angles of 60° and 90° , the peak strength in cyclic loading and unloading is higher than that in conventional triaxial tests. This difference can be attributed to the relative orientation between the weak bedding surface and the direction of axial deviatoric stress. For samples with bedding angles of 0° and 30° , the large angular difference exacerbates crack propagation and the formation of new cracks during the loading and unloading cycles, leading to a lower peak strength compared to conventional triaxial tests. In contrast, for samples with bedding angles of 60° and 90° , the smaller angular difference results in the better closure of microfractures, which enhances the peak strength beyond that observed in conventional triaxial tests.

3.3.2. Analysis of Cyclic Loading and Unloading Failure Characteristics

The macroscopic damage morphology of shale specimens with different bedding angles after cyclic unloading is illustrated in Figure 23. It can be observed that the cracks in the rock samples are more extensively developed during the cyclic unloading process. The damage pattern resembles that observed under triaxial conditions, characterized by shear damage along the weak bedding surfaces, with the damage planes primarily oriented at angles between 30° and 45° .

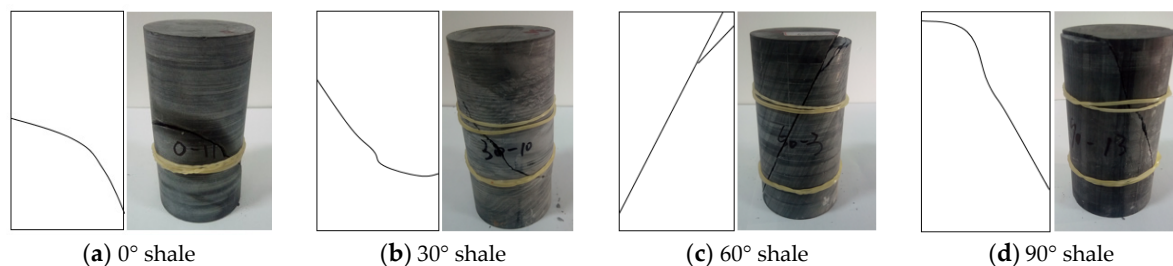


Figure 23. Cyclic loading and unloading damage characteristics of shale samples with different angles. (a) 0° shale; (b) 30° shale; (c) 60° shale; (d) 90° shale.

3.3.3. Analysis of the Evolution of Creep Parameters Under Cyclic Loading and Unloading

Since the long-term creep properties of 60° specimens have already been analyzed, this section does not discuss the 60° rock samples further. As illustrated in Figures 24–26, Poisson's ratio curves of shale specimens with different bedding inclinations exhibit a gradual increasing trend after each cyclic loading. This is because the axial deviatoric stress remains constant during the loading process, while the cyclic strain gradually increases. Upon applying the next level of load, Poisson's ratio suddenly decreases due to intensified axial strain deformation and a higher deformation rate compared to the cyclic strain following the increase in bias stress. Subsequently, during each subsequent loading stage, Poisson's ratio shows a slow increasing trend. Under the same confining pressure conditions, Poisson's ratio of rock samples with different bedding angles exhibits a U-shaped curve, initially decreasing and then increasing. This pattern is consistent with that observed in conventional triaxial tests under 10 MPa confining pressure. It was found that Poisson's ratio in cyclic loading and unloading tests is larger than that in conventional triaxial tests, attributed to the accumulation of internal damage within the rock samples due to the repetitive nature of the cyclic loading and unloading process. Regarding the modulus of elasticity, it tends to decrease slowly during the loading and unloading process. When the next level of load is applied, the modulus of elasticity suddenly increases due to the increase in bias stress, followed by a slow decreasing trend during each subsequent loading stage. The

shear modulus curve also shows a gradual decreasing trend, with sudden increases upon applying the next level of load, followed by a slow decreasing trend in each subsequent loading stage. The volumetric modulus curve exhibits a gradual decreasing trend; when the next level of load is applied, there is little change in the volumetric modulus, which then continues to show a slow decreasing trend during each subsequent loading stage.

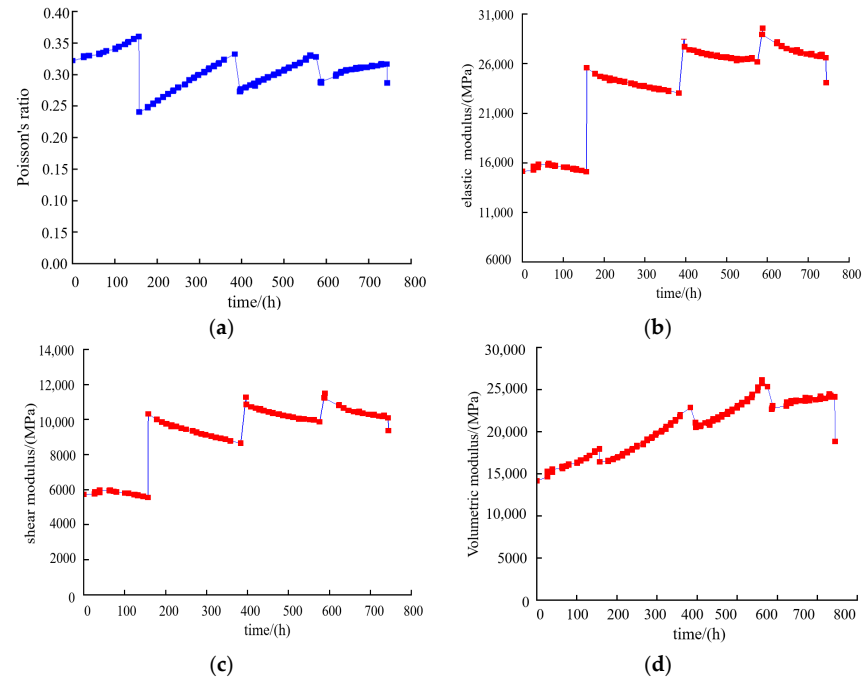


Figure 24. Mechanical parameter curve of 0° shale damage under 10 MPa confining pressure. (a) Poisson's ratio change rule. (b) Modulus of elasticity change rule. (c) Shear modulus change rule. (d) Volume modulus change rule.

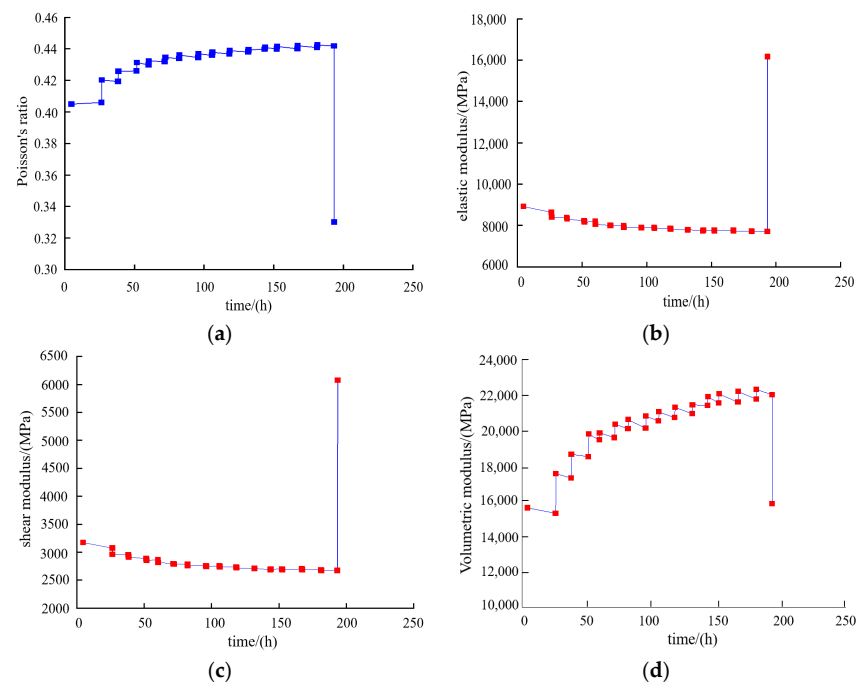


Figure 25. Curves of damage mechanical parameters of 30° shale under 10 MPa confining pressure condition. (a) Poisson's ratio change rule. (b) Modulus of elasticity change rule. (c) Shear modulus change rule. (d) Volume modulus change rule.

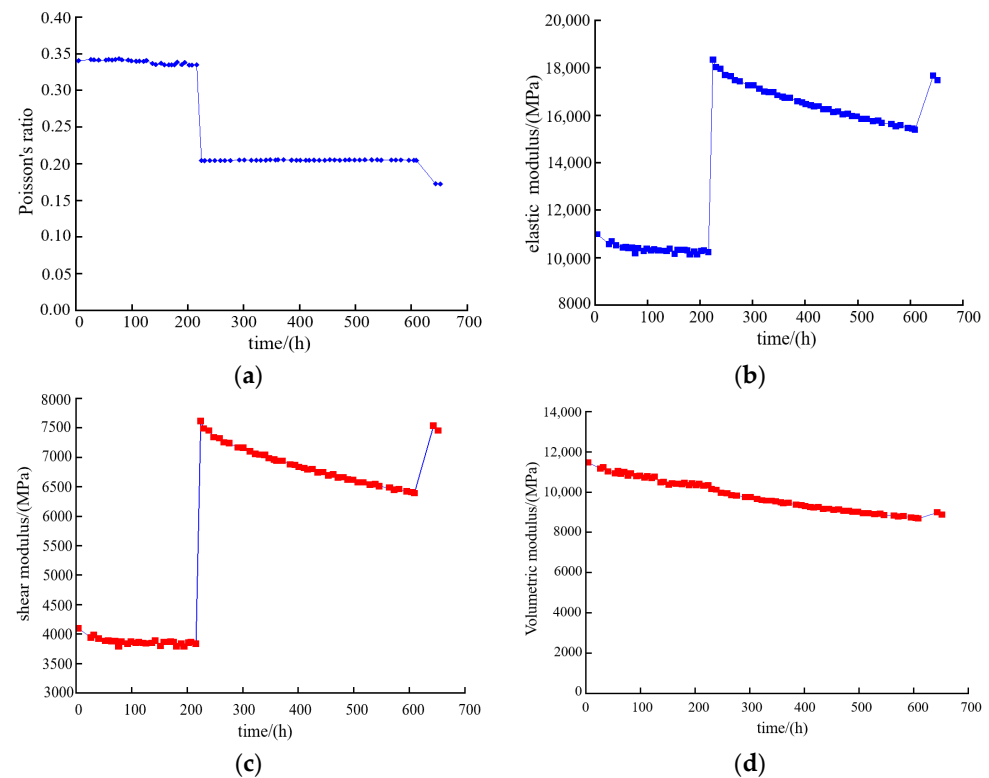


Figure 26. Mechanical parameters of 90° shale damage under 10 MPa confining pressure condition. (a) Poisson's ratio change rule. (b) Modulus of elasticity change rule. (c) Shear modulus change rule. (d) Volume modulus change rule.

4. Conclusions

To investigate the mechanical properties and long-term deformation behavior of layered shale with varying bedding inclinations, triaxial tests, graded loading creep tests, and cyclic loading and unloading creep tests were conducted on shale specimens with bedding angles of 0°, 30°, 60°, and 90°. Through the investigation of the mechanical behavior of rock samples under varying confining pressures and bedding dip angles, the experimental results provide valuable insights for the support design of deep-buried tunnels surrounding rock. Based on these findings, the following conclusions are drawn:

(1) Through laboratory tests on rock samples with varying bedding inclination angles and different confining pressures, the results indicate that shale anisotropy in the study area is relatively pronounced. The strength variation with inclination angle exhibits a “U”-shaped trend and conforms to the progressive failure mechanism observed during graded loading creep tests and cyclic loading and unloading creep tests.

(2) The damage patterns of shale specimens with different bedding surface inclinations also vary: for 0° inclination, the damage is characterized by conjugate shear failure; for 30° inclination, the damage primarily involves shear slip along the weak bedding planes; and for 60° and 90° inclinations, the damage manifests as shear failure through the bedding surfaces.

(3) In the rheological tests of shale specimens with a 60° bedding surface inclination, the ratio of creep strain increases progressively compared to previous loading levels, reaching 2.72% and 9.07%, respectively. These results indicate that creep becomes more pronounced as the axial deviatoric stress level increases. Additionally, a stress function $v = A + Be^{Rs}$ was used for regression, and the corresponding curve functional equation was obtained as $v = 0.2161e^{0.0391\sigma}$.

(4) During cyclic loading and unloading creep tests, Poisson's ratio exhibits a gradual increasing trend, while the elastic modulus, shear modulus, and bulk modulus show a gradual decreasing trend.

Limitations: This study planned to statistically analyze the standard deviation of the sample groups with different lamina angles (0° , 30° , 60° , 90°) and loading conditions and assess the significance of the differences between the groups using a one-way ANOVA parametric test, with $p < 0.05$ as the threshold of significance. Due to the difficult and expensive preparation of the experimental material, the sample size was only $n = 2$ per group, which is significantly lower than the minimum sample size required for statistical tests ($n \geq 15$ per group is required to ensure 80% test efficacy if detecting moderate effect sizes). Therefore, this study was unable to assess the statistical significance of the differences between groups through the hypothesis test described above and was only able to provide descriptive statistical results to reflect the data trends. The results exhibit substantial variability, making it challenging to capture the overall characteristics, which introduces limitations in terms of reliability. Additionally, the conclusion is drawn from a limited sample size, which compromises its representativeness and generalizability.

As shown in Table 4, under a confining pressure of 10 MPa, the mean peak load of the samples with a 0° bedding angle is 60.98 MPa (SD = 4.21), which is 38% lower than that of the 90° samples (98.04 MPa, SD = 22.19). However, due to the small sample size in each group ($n = 2$), this difference only indicates a numerical trend and cannot be confirmed as a true effect through statistical tests. The high variability of the data in each group (e.g., the SD of the 90° group reaches 49.75%) suggests that the results may be influenced by random errors. Future research should increase the sample size and adopt methods such as random grouping to control confounding factors so as to enhance the reliability and universality of the conclusions.

Table 4. Statistical analysis of standard deviations of sample groups under different bedding angles and loading conditions.

Laminae Angles/ $^\circ$	Loading Conditions Confining Pressure/MPa			Sample Size of per Group/n	Mean Value of Peak Intensity/MPa			Standard Deviation		
0°	10 MPa	20 MPa	40 MPa	2	60.98	92.97	121.39	4.21	31.64	0.60
30°				2	68.96	97.03	127.63	43.74	31.98	13.32
60°				2	66.17	113.07	72.66	16.60	23.35	3.13
90°				2	98.04	243.6	263.74	22.19	85.09	49.75

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