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Analysis of the Mechanical Anisotropic Properties of Shale

Hongyu Bai*

School of Green Mining and Engineering, Liaoning Petrochemical University, Fushun, Liaoning 113001, China

*Corresponding Author

Abstract

Shale is an important rock in oil and gas exploration and development. Its mechanical properties directly affect the safety and efficiency of oil and gas extraction. Due to the special internal structure, complex mineral composition and bedding structure of shale, the relationship between different stress directions and the bedding plane significantly influences its mechanical behavior. Therefore, this study aims to explore this influence law. In the research, shale specimens with different bedding angles were designed. Through uniaxial compression tests, the relationships between stress changes and deformation of the specimens, the ability to resist elastic deformation, and the maximum bearing strength under unidirectional pressure were analyzed. The results show that the stress - deformation changes of all specimens went through four stages: initial pore closure, elastic deformation, yield stage approaching the ultimate strength, and final failure stage. The ability to resist elastic deformation shows a "V - shaped" pattern of first decreasing and then increasing with the increase of the bedding angle, and it is the strongest when the bedding angle is 90°. The maximum bearing strength under unidirectional pressure shows a "U - shaped" pattern. The strength is the highest when the bedding angle is 0° and 90°, and the lowest when it is 60°. The maximum value is approximately six times the minimum value. This study indicates that there are significant differences in the mechanical properties of shale in different directions. This variance is related to the bedding structure of shale, the distribution of internal minerals, and the development of micro - fractures. The research findings can provide a reference for engineering practices such as ensuring the stability of the drilling wellbore and reservoir stimulation during the process of oil and gas extraction.

Keywords

Shale, Anisotropy, Stress - Strain, Compressive Strength, Elastic Modulus.

1. Introduction

As a typical sedimentary rock, shale is not only an important caprock for conventional oil and gas reservoirs but also the core target reservoir rock for current global shale - gas exploration and development. Its mechanical properties, such as strength, deformation modulus, and failure characteristics, are key factors determining the stability of the drilling wellbore, the propagation pattern of hydraulic - fracturing cracks, and the effect of reservoir stimulation, which are directly related to the safe and efficient exploitation of oil and gas resources [1]. However, as a complex porous medium, shale has a complex mineral composition and well - developed bedding structure, showing strong heterogeneity and anisotropy [2]. This unique structural feature makes its mechanical behavior significantly different from that of homogeneous rocks, and its mechanical parameters highly depend on the spatial relationship between the stress - loading direction and the bedding plane [3].

Against this backdrop, conducting systematic uniaxial compression tests on shale holds great theoretical significance and engineering value. By designing specimens with different bedding orientations for testing, the anisotropic laws of its mechanical properties can be systematically revealed [4].

2. Mechanical Properties

2.1. Variation Law of the Stress - Strain Relationship Curve

By statistically processing the obtained experimental data, the stress - strain curves of shale specimens with different bedding angles in the uniaxial compression test, as shown in the figure, can be obtained. The shapes of the stress - strain curves during the loading process are basically the same, all experiencing the compaction stage, elastic stage, yield stage, and failure stage [5].

(1) Fracture Compaction Stage: The axial pressure starts to increase from 0 MPa. As the stress increases, the strain increases rapidly. The pre - existing micro - pores and fractures within the rock gradually close under the load, and the rock is compacted, showing early non - recoverable non - linear deformation.

(2) Elastic Deformation Stage: As the axial pressure increases further, the rock enters the elastic deformation stage. The stress - strain curve gradually becomes steeper and is basically in a linear relationship, with the corresponding elastic modulus gradually increasing.

(3) Yield Stage: Before reaching the peak strength, the corresponding stress is called the yield limit. At this time, the external force received by the specimen gradually reaches the limit it can bear. In this stage, the micro - fractures of the rock expand rapidly and new cracks are generated. The strain rate increases rapidly, and the stress reaches its peak value.

(4) Post - peak Failure Stage: When the axial stress reaches the peak strength, the internal structure of the rock is damaged. The fractures develop rapidly, intersect and combine with each other to form a macroscopic fracture surface. The specimen is completely destroyed and loses its bearing capacity.

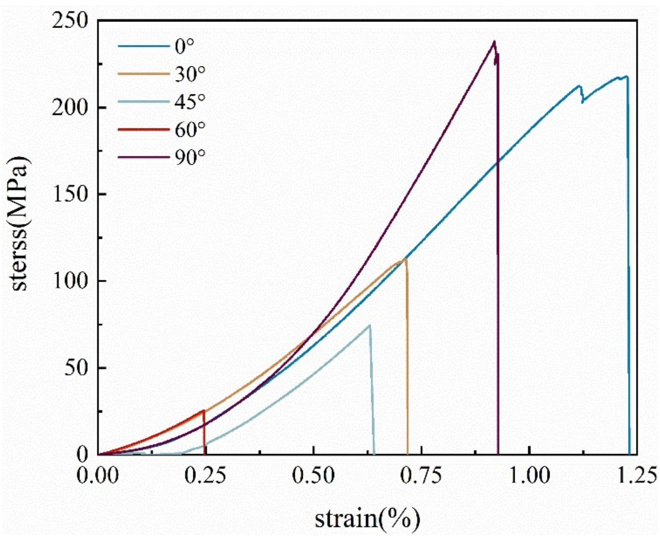

Figure 1. Stress - Strain Curve relationship

2.2. Variation Law of Elastic Modulus

As can be seen from the figure, the elastic modulus is the largest at 90°, which is 36.63 GPa. Next is 0°, with a value of 27.26 GPa, followed by 30° and 45°. It is the smallest at 60°, which is 11.08 GPa. As the bedding angle increases, the elastic modulus of the rock sample generally shows a V - shaped curve of first decreasing and then increasing.

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There are mainly two reasons for this. On the one hand, the bedding weak - plane structure is relatively loose with developed pores. In the initial stage of loading, the bedding weak - plane will undergo large axial compaction deformation. Therefore, when the principal stress is parallel to the bedding plane, the bedding plane is in a tensile deformation state, and the specimen has obvious lateral expansion, resulting in a relatively large elastic modulus [6]. On the other hand, as can be seen from the X - ray diffraction and optical microscope analysis tests conducted in this paper, the shale mineral content and the development of micro - fractures vary greatly at different bedding - plane angles. These differences lead to the anisotropy of the elastic modulus [7].

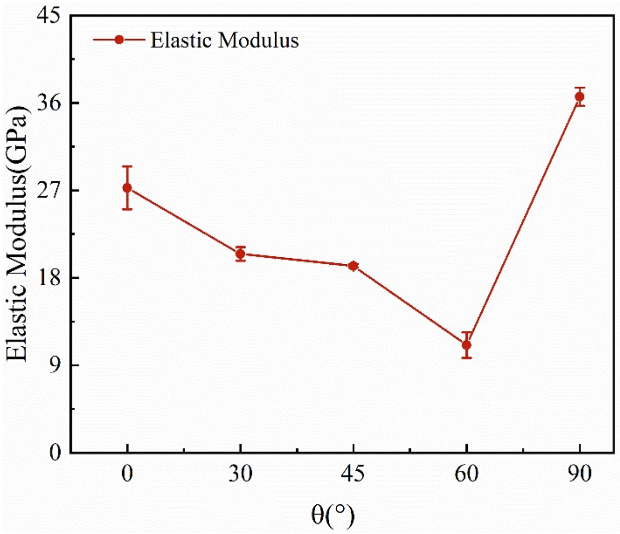

Figure 2. Elastic Modulus

2.3. Variation Law of Uniaxial Compressive Strength

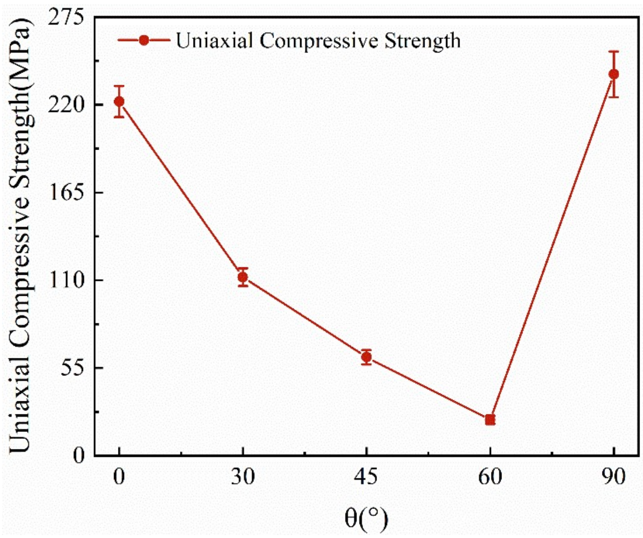

Figure 3. Uniaxial Compressive Strength

As can be seen from the figure, with the increase of the bedding angle, the strength curve of shale approximately shows a U - shaped variation pattern with high values at both ends and a low value in the middle. That is, as the angle increases, the uniaxial compressive strength of shale first gradually decreases and then gradually increases. The maximum values are obtained when the angle is near 0° and 90°. When the angle is near 60°, the compressive strength reaches the minimum value, and the maximum value is almost six times the minimum value. When the

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angle ranges from 30° to 60°, the change in compressive strength is slow, while at other angles, the change is rapid. All these indicate that layered shale has strong anisotropy [8].

The significant strength anisotropy of layered shale is closely related to its failure mode. When the angle is near 60°, the failure type is shear - slip failure along the bedding weak - plane. The compressive strength depends on the bedding weak - plane, so its value is the lowest, reflecting the shear - slip resistance of the rock mass structural plane and the structural body [9]. When the angle is near 90°, the failure type is split - type layered shear failure through the bedding plane. The strength depends on the shale rock itself, reflecting the compressive capacity of the rock itself, so the compressive strength is the highest.

3. Conclusion

In this study, uniaxial compression tests were carried out on shale specimens with different bedding angles to systematically explore the influence of bedding orientation on the mechanical properties of shale. The main conclusions are as follows:

(1) The stress - strain changes during the uniaxial compression of shale are consistent. All specimens go through four stages in sequence: fracture compaction, elastic deformation, yield, and post - peak failure. The deformation characteristics of each stage are directly related to the evolution process of internal pore closure, micro - fracture development, and macroscopic fracture in shale.

(2) The bedding angle has a significant impact on the ability of shale to resist elastic deformation. The elastic modulus of shale shows a "V - shaped" pattern of first decreasing and then increasing with the increase of the bedding angle. The elastic modulus is the largest (36.63 GPa) at 90°, the smallest (11.08 GPa) at 60°, and the second - largest (27.26 GPa) at 0°. This difference is mainly due to the loose structure and pore development of the bedding weak - plane, as well as the heterogeneity of shale mineral composition and micro - fracture distribution at different bedding angles.

(3) The uniaxial compressive strength of shale shows a "U - shaped" pattern with the change of the bedding angle. The strength is the highest near 0° and 90°, and the lowest near 60°. The maximum value is approximately six times the minimum value. The strength changes gently in the range of 30° - 60°, and changes rapidly in other angle ranges. The strength difference is directly related to the failure mode. Near 60°, the failure is mainly shear - slip failure along the bedding weak - plane, and the strength is controlled by the bedding weak - plane. Near 90°, the failure is mainly split - type shear failure through the bedding plane, and the strength is determined by the properties of the shale itself.

(4) The study confirms that the mechanical properties of shale are strongly anisotropic. The bedding structure is the core factor leading to the directional dependence of its elastic modulus, compressive strength, and failure mode. The research results can provide a scientific basis for the evaluation of drilling wellbore stability, the optimization of hydraulic fracturing schemes, and the prediction of reservoir stimulation effects in oil and gas exploitation projects. It also lays a foundation for further in - depth research on the micro - mechanisms of shale anisotropy.

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