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Study on the Splitting Mechanical Properties of Asymmetric Large Deformation Surrounding Rock Mass in Deep Underground Engineering

Shuguo Zhang, Ling Dai, Xiaohu Yuan, and Yongbiao Lai

China State Construction Railway Investment &Engineering Group Ltd, Beijing 102600, China

Abstract

The mechanical properties of carbonaceous slate will weaken under the interaction of water-rock and natural weathering after tunnel construction, which will lead to the instability failure of deep underground engineering such as tunnel and slope. Therefore, the carbonaceous slate in the Muzhailing tunnel of Gansu Province was taken as the research object, and the Brazilian splitting test was carried out on the natural weathered samples (after processing, the samples were placed under normal temperature ventilation for 90 days) to analyze the effect of different bedding angles on the force-displacement characteristics and failure modes of the carbonaceous slate. The results show that the force-displacement curves of carbonaceous slate under different bedding angles have an approximate variation trend, and the vertical displacement and peak load increase gradually with the increase of inclination angle. The experimental data shows great discretization due to the influence of micro-cracks, water-rock interaction and natural weathering. In terms of the failure mode of carbonaceous slate, tensile fracture or tensile shear failure occurs along the bedding plane when the bedding angle is close to 0°. When the bedding angle is close to 90°, tensile fracture, shear fracture or compression fracture occur. The failure state also presents asymmetrical distribution and some differences due to the comprehensive effects of mineral matrix, bedding, defects, water-rock and weathering.

Keywords

Deep Underground Engineering; Large Deformation; Brazil Splitting; Weathering; Failure Mode.

1. Introduction

Carbonaceous slate is a kind of soft surrounding rock with plate structure and poor stability. In the process of excavation of carbonaceous slate underground engineering under high in-situ stress environment, it often shows the characteristics of large deformation, fast deformation rate and long duration [1-2]. Meanwhile, the mechanical properties of carbonaceous slate are related to the angle of the structural plane, and the shear failure and slip failure along the bedding plane are easy to occur after the structural plane is stressed. Therefore, the basic experimental research on the mechanical properties of carbonaceous slate from different bedding angles has engineering application significance for the underground engineering construction of carbonaceous slate and similar geological conditions.

At present, it is difficult to use the direct tensile method to test the compressive strength of rock in the sample preparation and tensile test. However, as a means to test the tensile strength of rock, the Brazilian splitting test has been widely used in rock engineering test due to its relatively simple sample preparation and test process. Since the Brazilian splitting test was proposed, scholars at

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domestic and abroad have carried out a large number of theoretical and experimental studies on layered rock mass through the Brazilian splitting test. Dan et al. [3] conducted the Brazilian splitting test with inclination intervals of 15° for four rock samples, including gneisses, combining the angle between the sample axis, the structural plane, the loading direction and the angle of structural plane. Nezhad et al. [4] conducted the Brazilian splitting test and finite element simulation on shale, and studied the effects of bedding and matrix on tensile strength and fracture toughness. Khanlari et al. [5] conducted the Brazilian splitting test on layered sandstone and analyzed the influence of bedding angle on tensile strength, failure mode and fracture length. Tavallali et al. [6] analyzed the influence of bedding angle on the failure mode of disc through Brazilian splitting test. Tan Xin et al. [7] conducted the Brazilian splitting experiments and discrete element numerical simulation studies on gneiss and explained the mechanism of splitting failure modes. Wang et al. [8] and Hou Peng et al. [9] conducted the Brazilian splitting test on shale and believed that the tensile strength and failure mode anisotropy of shale under different bedding angles were significant, and explored the variation rule of acoustic emission energy in the process of deformation and failure.

To sum up, taking carbonaceous slate from the Muzhailing Tunnel as the research object in this paper, and conducting the Brazilian splitting test with different bedding angles on the natural weathered carbonaceous slate to study the effects of bedding angles on force-displacement characteristics and failure modes of carbonaceous slate, which hope to provide solid theory and application foundation for engineering practice.

2. Brazilian Splitting Test

2.1 Processing Equipment

The processing equipment used in this test mainly include vertical drilling machine, American GCTS/RLS-100 rock cutting machine and SHW-WOY double face grinding machine, as shown in Figure 1.

(a) Vertical drilling machine **(b)** Rock cutting machine **(c)** Double face grinding machine

Figure 1. Rock sample processing equipment

2.2 Sample Preparation Process

After obtaining enough complete rock blocks in Min County, Gansu Province, the outer layer of the whole rock is waxed, and then the rock sample is wrapped with plastic wrap for sealing. After being sealed and transported to the test processing plant, it is inspected in strict accordance with the requirements. The external packaging wooden frame of the rock block is complete, the internal carton is complete, the plastic wrap is complete, and the integrity of the rock block is free from defects. As a special slate, carbonaceous slate is rich in clay minerals and is easily affected by water-rock contact and weathering exposed to the air. Therefore, in order to study the mechanical properties of weathered rock samples, after the rock sample arrives at the processing plant, it shall be weathered for 90 days

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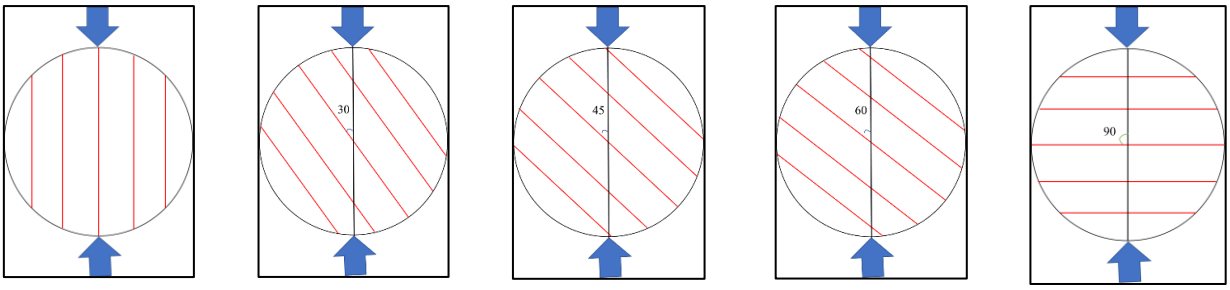
before drilling the core. In strict accordance with the standard [10], the sample end face parallelism is ±0.02mm, which meets the test requirements.

2.3 Test equipment and Test Plan

The Brazilian splitting test was also carried out on RMT-150B rock mechanics test system. The stroke controlled loading mode was adopted, and the stroke rate was 0.010mm/s, which was loaded until the sample was completely damaged. The vertical force of the sample is tested by 100kN force sensor, the vertical deformation of the carbonaceous slate sample is measured by 5mm displacement sensor, and the transverse deformation of the carbonaceous slate sample is measured by two 2.5mm displacement sensors. The Brazilian splitting test loading system is shown in Figure 2. The carbonaceous slate natural weathering sample takes into account the discreteness caused by the interaction of water-rock in the air and the influence of weathering, two samples were taken in each group.

Figure 2. Brazilian split rock sample and test process

The disc perpendicular to the transverse isotropic plane has a bedding plane, and the angle α between the bedding plane and the loading direction is set as the bedding angle, as shown in Figure 3. Based on the English initials, the Brazilian split samples are named according to the angle between the loading direction and the bedding plane as 0°, 30°, 45°, 60°, 90°, such as B1, B2, B3, B4, B5.



B1 B2 B3 B4 B5

Figure 3. Schematic diagram of Brazilian disc sample

3. Test Results and Analysis

3.1 Influence of Bedding Angle on Force-displacement Characteristics of Carbonaceous Slate

The typical force-displacement curves of the natural weathering carbonaceous slate samples are shown in Figure 4. The samples selected under different bedding states are B1, B2, B3, B4, and B5. With the increase of axial displacement, the force-displacement curve of carbonaceous slate has a certain similarity, and the force-displacement relationship has experienced three stages: compaction, linear elasticity and failure drop.

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For the vertical displacement, the vertical displacement of the carbonaceous slate Brazilian split B1 group is about 0.322mm~0.379mm when it is in splitting failure. It can be seen that the vertical displacement of the 90° bedding samples in each group is the smallest. The main reason is that the sample only produces tensile failure along the weak bedding plane after compacting the micro-cracks. According to the typical test results, the vertical displacements of the samples in groups B2, B3, and B4 were 0.723~0.926mm, 0.801~0.965mm, and 0.901~1.005mm respectively. It can be seen that the displacement of inclined bedding with bedding angles of 30°, 45° and 60° increases gradually with the increase of inclination Angle, which is mainly related to the sliding shear failure of the sample along the bedding. The vertical displacement of samples in group B5 is about 1.277-1.565mm, and the larger vertical displacement is caused by micro-cracks and the compaction between bedding.

For the peak load, the peak loads of the samples in groups B1, B2, B3, B4 and B5 are 0.872~1.108kN, 1.1586~1.406kN, 1.276~2.420kN, 1.472~3.178kN, 3.148~3.238kN respectively. Specifically, when the bedding angles are 30°, 45°, and 60°, the peak load is discrete due to the influence of micro-cracks, water-rock interaction and 90-days natural weathering effect. The results of group B1 samples are consistent because tensile failure along the bedding plane. Meanwhile, it also shows that the mechanical properties of cementation between bedding planes are relatively close. Comparing with the real-time carbonaceous slate samples, it can be seen that the splitting failure displacement of each group of weathered carbonaceous slate samples increases a lot. In addition, the load by the natural weathering sample decreases sharply, but the bedding angle still has a significant effect on it.

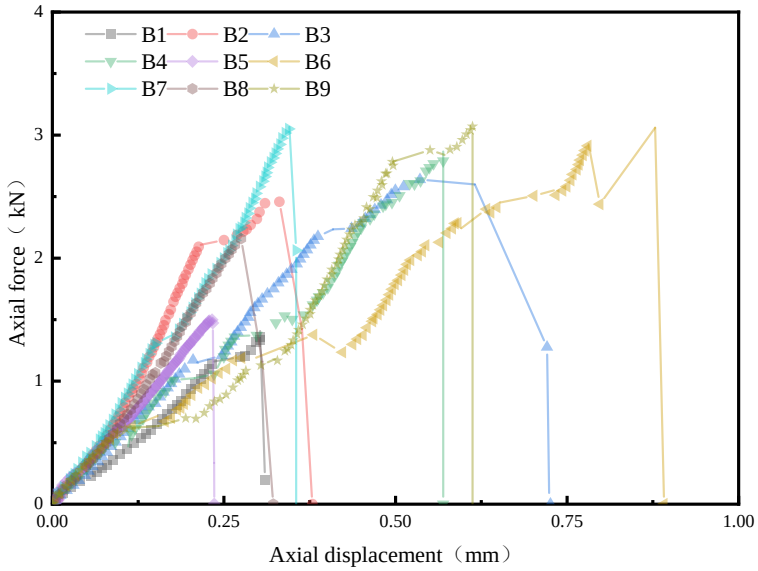

Figure 4. Force-displacement curve

3.2 Influence of Bedding Angle on Failure Mode of Carbonaceous Slate

In the Brazilian splitting test, for the complete rock samples without bedding structure, the disc first cracks from the two loading ends, and then the crack penetrates through the center of the disc to form a vertical through crack. The existence of bedding will cause its deformation and failure to be jointly affected by the tensile and shear strength of the matrix and the tensile and shear strength of the bedding. Therefore, the transverse isotropy of the deformation of carbonaceous slate will make the tensile crack deviate from the center of the disc and produce non central crack, which complicates the failure mode of carbonaceous slate.

In order to better understand the common influence relationship between natural weathering and bedding angle, the final failure mode of Brazilian splitting test of carbonaceous slate natural weathering sample is analyzed here, as shown in Figure 5. The splitting generally presents a nearly symmetrical failure mode along the loading axis, and the cracking path also extends along the

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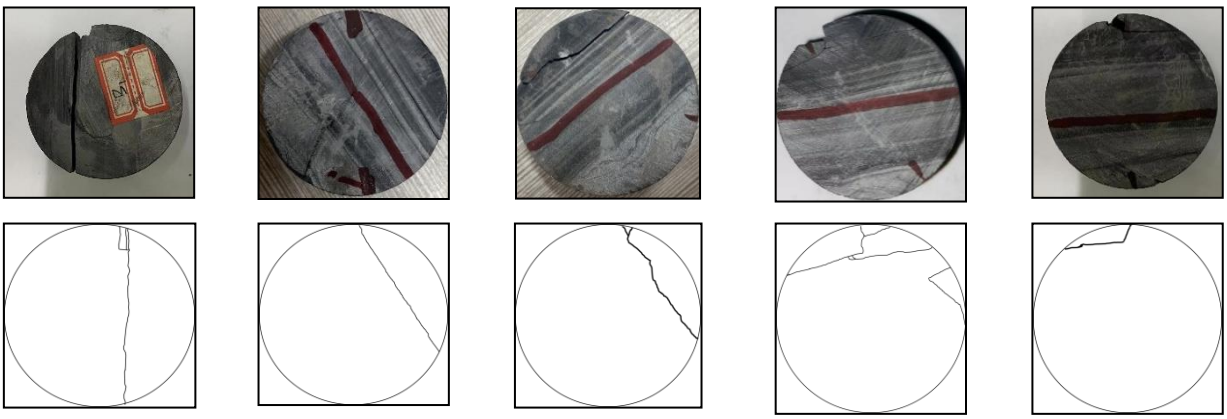
diameter direction to the two loading ends. Meanwhile, the end of the sample in contact with the two loading ends has the phenomenon of shear fracture. To sum up, the failure modes of carbonaceous slate samples can be divided into the following three types:

(1) The ultimate load is generally small when the bedding angle is 0 °. Because the fracture of the horizontal tensile stress sample originates from a certain position of the center line of the disc and divides the disc into two parts by splitting and tensile failure along the bedding, the tensile strength measured in this group of test can generally be regarded as the tensile strength between the bedding planes of carbonaceous slate.

(2) When the bedding angles are 30°~60°, shear or partial path shear failure occurs along the bedding, and the fracture path deviates from the center line of the vertical sample. If the bedding angle is large, such as B2 (30°) and B3 (45°), the crack is easy to develop straight along the bedding under the effect of shear. If the bedding angle is small, such as B4 (60°) sample, the crack no longer develops straight along the bedding, but there are both slip between bedding and tensile shear failure in the longitudinal direction of slate mineral matrix, which is usually in the form of tortuous arc failure.

(3) When the bedding angle is 90°, the bedding has a toughening effect on the sample, that is, a large ultimate load will lead to splitting failure. Specifically, the vertical main crack develops through the center line of the sample and perpendicular to the bedding plane, crushing or compression failure will occur at both ends in contact with the loading equipment. Meanwhile, the tensile stress in the middle of the sample is affected by the bedding, which leads to transverse secondary tensile cracks that penetrate through the bedding and destroy the mineral particles in the matrix, thereby also producing a complex failure mode of multi-lamellar bedding cracking. The tensile strength measured by this group of test can be regarded as the tensile strength of the carbonaceous slate mineral matrix. Therefore, the anisotropy of the natural weathered sample not only affects its tensile strength, but also its failure morphology. Comparing with the instant sample, it can be seen that the natural sample has more obvious damage along the bedding, more cracks, and more changes in form.

The specific performance is as follows: when the bedding angle approaches 0°, the sample is prone to tensile cracking or tensile shear failure along the bedding plane; when the bedding angle approaches 90°, tensile failure, shear failure or compression failure occur in the mineral matrix of the sample. Due to the combined effect of water-rock and 90 days natural weathering on the natural weathering sample in this test, the splitting failure mode is actually a combination of mineral matrix, bedding, defects, and water-rock and weathering effects. The failure states of each group show asymmetric distribution and show certain differences.



B1 B2 B3 B4 B5

Figure 5. Typical failure modes of Brazilian splitting

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4. Conclusion

Through Brazil splitting test on natural weathering samples of layered carbonaceous slate, the mechanical properties of carbonaceous slate under different bedding angles are studied. The conclusions are as follows:

(1) In Brazilian splitting test, with the increase of axial displacement, the forms of force-displacement curves of carbonaceous slate with different bedding angles are similar, and the force-displacement relationship has roughly experienced three stages: compaction, near linear elasticity and failure drop.

(2) By observing the force-displacement curve, it can be concluded that the vertical load and peak load gradually increase with the inclination angle, but the test data show great discreteness due to the influence of micro-crack, water rock interaction and natural weathering effect.

(3) The failure modes of carbonaceous slate can be divided into three categories: when the bedding angle is 0°, the sample is prone to tensile crack or tensile shear failure along the bedding plane; When the bedding angle is 30°~60°, the sample is sheared along the layer or part of the path; When the bedding angle is 90°, the sample is prone to tensile crack, shear or compression failure.

(4) The force-displacement characteristics and failure modes of carbonaceous slate are affected by water rock interaction and natural weathering effect. The failure modes of carbonaceous slate are asymmetric and different.

References

[1] Y Liu, X J Wu, Z Q Liu, et al. Discussion of and Solutions for the Large Deformation Mechanism of a Tunnel in Carbonaceous Slate [J]. Modern Tunnelling Technology, 2014, 51(06):19-24.

[2] X X Guo, A L Zhu, W P Wang, et al. Large deformation characteristics and mechanism analysis of high-stress carbonaceous slate tunnel [J]. Hazard Control in Tunnelling and Underground Engineering, 2021, 3(04):29-39.

[3] Dan D Q, Konietzky H, Herbst M. Brazilian tensile strength tests on some anisotropic rocks[J]. International Journal of Rock Mechanics and Mining Sciences, 2013, 58:1-7.

[4] Mohaddeseh, Mousavi, Nezhad et al. Experimental Study and Numerical Modeling of Fracture Propagation in Shale Rocks During Brazilian Disk Test[J]. Rock Mechanics and Rock Engineering, 2018, 51(6): 1755-1775.

[5] Khanlari G, Rafiei B, Abdilor Y. An Experimental Investigation of the Brazilian Tensile Strength and Failure Patterns of Laminated Sandstones[J]. Rock Mechanics and Rock Engineering, 2015, 48(2): 843-852.

[6] Tavallali A, Vervoort A. Effect of layer orientation on the failure of layered sandstone under Brazilian test conditions[J]. International Journal of Rock Mechanics and Mining Sciences, 2010, 47(2): 313-322.

[7] X Tan, Konietzky H. Brazilian split tests and numerical simulation by discrete element method for heterogeneous gneiss with bedding structure[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(5):938-946.

[8] J Wang, L Z Xie, H P Xie, et al. Effect of layer orientation on acoustic emission characteristics of an isotropic shale in Brazilian tests[J]. Journal of Natiral Gas Science and Engineering, 2016, 36:1120-1129.

[9] P Hou, F Gao, Y G Yang, et al. Effect of bedding plane direction on acoustic emission characteristics of shale in Brazilian tests[J]. Rock and Soil Mechanics,2016,37(6):1603-1612.

[10] National Standards Writing Group of the People's Republic of China. GB/T23561-2009 Methods for Determining the Physical and Mechanical Properties of Coal and Rock[S]. Beijing: Standards Press of China, 2009.