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Research paper

Study on strength characteristics and permeability of chlorite schist during triaxial compression permeability

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Abstract: In order to grasp the strength characteristics and permeability of chlorite schist, the triaxial compression permeability test of chlorite schist was carried out by using a rock triaxial servo testing machine equipped with seepage device. Based on the test results, the failure strength, initial permeability and permeability development of rock samples under different confining pressure and different pore water pressure are compared, and the failure types of rock samples under triaxial compression permeability and their influence on permeability are analyzed. The results show that the increase of confining pressure is conducive to the improvement of failure strength of chlorite schist, and the increase of pore water pressure reduces the failure strength, which is related to the inhibition of crack development in rock samples by confining pressure and the promotion of crack expansion by pore water pressure. The mechanical deformation of chlorite schist in triaxial compression permeability process has experienced initial compaction stage, linear elastic stage and crack stable propagation to failure stage. As a consequence, permeability shows three trends of decline, stable development and rise, which is closely related to the development of the internal structure of rock samples at each stage. During the failure of triaxial compression permeability, there is a local compression zone in chlorite schist, and the rising rate slows down due to the influence of the compression zone.

Keywords: chlorite schist, strength characteristics, permeability, triaxial compression, compression band

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1. Introduction

With the continuous development of human beings to the depth in the process of underground engineering development and construction, especially the mining depth of underground mineral resources has reached more than 1000 meters, the engineering problems encountered are becoming more and more complex and have great particularity compared with surface engineering. The seepage and stress caused by engineering excavation are the key factors affecting coal mine safety production, and the water gushing caused by high underground water pressure is the potential danger of mining activities [1–4]. Among them, the serious deformation and damage of roadway (tunnel), especially the prominent phenomenon of floor heave is a more common engineering problem. Professor Jing Laiwang used the floor anchor drilling machine to drill holes in the project site, and found that there was a large amount of free groundwater inside the floor, and the groundwater pressure was on the high side, and the groundwater would gush out immediately when the drill bit was pulled out after the floor drilling was over. It can be concluded that the existence of groundwater aggravates the damage to the floor. In addition, in the process of roadway (tunnel) excavation, the surrounding rock must be affected by the construction load to produce initial damage, which is manifested in the initiation of micro-cracks in the rock. It is the existence of these microcracks that provide an obvious seepage channel for groundwater. The seepage of high-pressure groundwater in the rock exerts an area force load on the surface of the micro-crack to form a splitting force, which accelerates the expansion and penetration of the micro-crack, resulting in the reduction of the resistance of groundwater infiltration into the rock, and then accelerates the infiltration rate of groundwater and the propagation speed of crack. Crack growth increases the permeability coefficient and the rate of groundwater infiltration is accelerated again. This is a vicious circle process, in which the interaction between seepage field and stress field is called seepage-stress coupling [5]. This makes the process of rock infiltration, deformation and failure extremely complicated, and influence of coupling damage becomes more important, so that it is very necessary to study it.

Taking chlorite schist as an example, compared with sedimentary rock and magmatic rock, the operation of sampling and processing is very difficult, so the research on the properties of chlorite schist is relatively weak. Chen Yi [6] examined the material composition and microstructure of the chlorite shale, as well as the physical and mechanical parameters and morphology of uniaxial compression failure. Yu Dehai [7] carried out conventional triaxial compression tests on chlorite schist under dry and saturated conditions respectively, and discussed the effect of water on the strength and deformation characteristics of rock samples. Zhou Hui [8] soaked chlorite schist in NaCl solution and distilled water respectively. After reaching saturation, uniaxial and conventional triaxial compressive strength tests were carried out, and the strength was compared with that of chlorite schist in dry state. Because the composition of this kind of rock is complex, the mineral composition is diverse, and the water stability is poor, it is easy to affect the roadway stability under the condition of floor flooding [9]. However, the existing research is mainly aimed at the saturated chlorite schist, in the actual loading process, there is no direct contact between pore water and chlorite schist, and there is no coupling effect of seepage field and stress field, which is obviously different from the actual working conditions. Zhao et al [10] and Du et al [11] used TAW-2000 to conduct triaxial compression permeability tests on limestone and sandstone, respectively, to clarify the sensitivity of the specimen to confining pressure, water pressure difference and effective stress, and pointed out that due to the decrease of effective minimum principal stress, the lateral deformation of the specimen was activated, thus weakening the strength and deformation modulus of rock. Liu et al. [12] carried out a series of triaxial creep tests on granite under three different pore pressures, revealed the effect of pore pressure on creep evolution, and studied the correlation between permeability and volumetric strain during creep. Chen et al [13] considered sandstone as a research object and conducted triaxial permeability tests under the conditions of confinement pressure coupling and interstitial pressure difference. The results show that the stress-strain curve, failure shape and permeability evolution curve of sandstone specimens are significantly affected by confining pressure, but have little effect on pore pressure difference. Other scholars have also proved that the use of TAW-2000 and its matching sealing measures can effectively prevent the outflow of water from the heat-shrinkable tube and the edge of the sample, and the heat-shrinkable tube and upper and lower head provide good sealing performance, and will not interfere with the infiltration of pore water along the rock sample.

During the construction and operation of underground engineering, rocks are inevitably subjected to stress-seepage coupling because of the existence of ground stress and groundwater. For this complex coupling situation, chlorite schist has not been studied in the existing literatures. Therefore, in order to study the strength and permeability evolution characteristics of chlorite schist during the construction and operation of underground engineering, a real loading state is simulated in this paper. By using the rock servo triaxial testing machine with seepage device, pore water pressure can be applied to rock sample simultaneously during triaxial loading process, thus realizing the coupling of stress field and seepage field. Based on this, mechanical properties, permeability evolution, and failure characteristics of chlorite schist are studied. The results of this study provide an experimental basis and theoretical foundation for the design and construction of such underground engineering in chlorite schist.

2. Experiment scheme

The test sample is chlorite schist, and the results of XRD analysis are shown in Figure 1. The rock sample is composed of Muscovite, orthoclase, magnesium chlorite, plagioclase and quartz, and the corresponding composition is 42.3%, 14.8%, 14.2%, 12.1%, 11.6%. The average uniaxial compressive strength of these rock samples is 30.73 MPa, and the softening coefficient is 0.82. To simulate the stress environment of the deep ground, the containment pressure was set at 10 MPa, 15 MPa and 20 MPa respectively during the triaxial compression test.

TAW-2000 rock servo test system is adopted, which has axial pressure system, confining pressure system and pore water pressure system, and the full digital servo controller imported from DOLI Company of Germany is used as the control core, which can realize

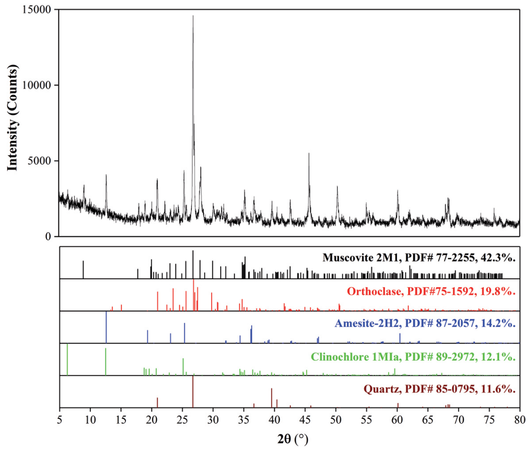


Fig. 1. XRD analysis results of rock samples

uniaxial loading, triaxial loading and triaxial compression osmotic loading [14]. As illustrated in Figure 2, the test equipment is capable of meeting the requirements of this test. In the triaxial compression permeability test, the axial load of 1 kN is applied to ensure that the specimen is in close contact with the upper and lower head, and then the confining pressure is applied laterally, and the pore water pressure is applied by the pore flow channel connected by the upper end of the specimen, and the lower end of the specimen is connected with atmospheric pressure, thus forming a pore water pressure difference to facilitate the seepage of pore water in the rock sample. It should be noted that in order to ensure that the heat-shrinkable rubber sleeve is not broken by pore water pressure, the pore water pressure must be less than the confining pressure value, and combined with the underground water pressure of the floor of the roadway (tunnel) project, the pore water pressure is set to 2.5 MPa and 5 MPa during the test. Therefore, six groups of tests are carried out with the combination of confining pressure and pore water pressure. Using A10B2.5 as an example, this indicates that the containment pressure applied in this group is 10 MPa and the pore

Fig. 2. TAW-2000 rock servo test system

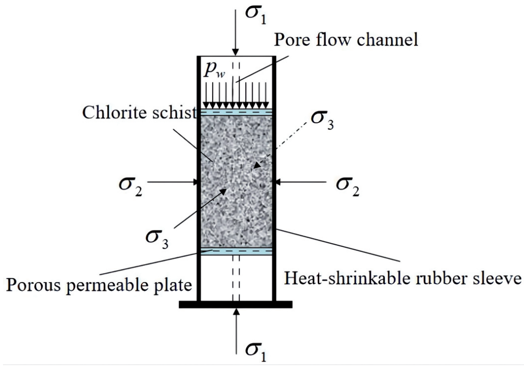


Fig. 3. Schematic diagram of triaxial compression permeability of chlorite schist

water pressure is 2.5 MPa, and so on. At the same time, the strain of the rock sample under pressure of infiltration by triaxial compression is shown in Figure 3. Before formal loading, the axial load 1 kN is kept stable for 30 minutes when both confining pressure and pore water pressure reach the experimental design value, and then the axial load is controlled by 35 N·s^{-1} until the specimen is destroyed.

3. Results and analysis

3.1. Triaxial permeability strength

The failure strength of chlorite schist under triaxial compression under different pore water pressure combinations is shown in Figure 4. Under the action of pore water pressure 2.5 MPa, the failure strength of rock samples under confining pressure is generally higher than that of pore water pressure 5.0 MPa. However, the internal pore structure is closely related to the performance change [15, 16]. The analysis shows that pore water can exert

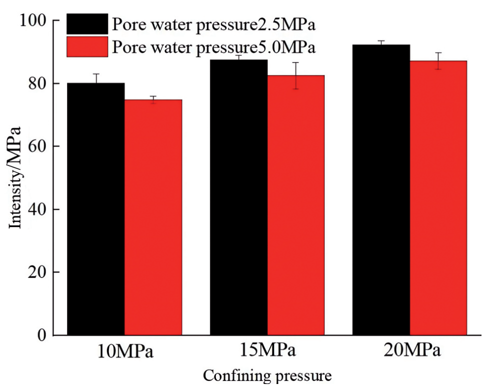


Fig. 4. Failure strength of chlorite schist in triaxial compression permeability state

splitting force on the crack tip to promote the further crack propagation [17]. The more the number of internal cracks in the rock sample, the more severe the propagation degree, the less conducive to the stability of the rock sample. At the same time, according to the theory of damage mechanics, it is known that there is a direct relationship between crack development and damage in rock samples. It is generally believed that the higher the crack development degree, the greater the damage degree [18]. Therefore, under the same stress state, when the pore water pressure is 5.0 MPa, the damage degree of rock sample is obviously higher than that of 2.5 MPa, which makes the strength of rock sample lower during failure. Further study found that with the increase of confining pressure, the difference of failure strength caused by pore water pressure difference gradually weakened. When the containment pressure was 10 MPa, 15 MPa and 20 MPa, the fracture toughness under a different pore pressure was 6.66%, 5.70% and 5.56%, respectively. Due to the high confining pressure applied in this test, the initial crack compaction in the rock sample is high, so that the malignant effect of the coupling of seepage field and stress field caused by pore water is relatively reduced [19]. In addition, when the confining pressure reaches 15 MPa, the internal crack compaction effect of the rock sample is remarkable, and the threshold is reached at this time, that is, the number of cracks that can be compacted inside the rock sample after the threshold is close to zero. Therefore the influence of the seepage movement of pore water inside the crack is also reduced, even if the confining pressure continues to increase, the influence on it is also very weak. Therefore, the difference in fracture toughness due to the difference in pore water pressure is similar when the containment pressure is 15 MPa and 20 MPa.

It can also be found from Figure 4 that when the pore water pressure is the same, the failure strength of rock samples increases positively with the increase of confining pressure, and the average failure degree increases by 9.77% and 15.79% when the confining pressure increases from 10 MPa to 15 MPa and 20 MPa. The analysis shows that the internal crack of the rock sample tends to be closed under the confining pressure, and the splitting force exerted by the pore water seepage must be greater than the compaction effect caused by the confining pressure in order to make the crack further propagate [20]. Consequently, with the increase in containment pressure, the greater the resistance to crack propagation in the same stress state, so that the fracture toughness is greatly enhanced. Through comparative analysis, it can be found that the positive effect of confining pressure on the failure strength of chlorite schist under triaxial compression is greater than the negative effect caused by pore water pressure. This is because the development of fracture strength of rock samples is closely related to the degree of internal crack propagation [21]. The effects of containment pressure and pore water pressure on crack propagation differ greatly. The effect of containment pressure on crack closure is more important than that of crack expansion due to pore water pressure.

3.2. Stress-permeability evolution

The chlorite schist is always in the coupling state of seepage field and stress field in the triaxial compression infiltration process, and the permeability of rock samples in different stress stages will show different trends due to the development of its internal microstructure.

Referring to the relevant literature, it is found that the pore water seepage velocity is small in the triaxial compression test, and it can be assumed that the pore water seepage accords with Darcy's law in the process of stress and strain [22, 23]. Therefore, according to the real-time fluid flow changes recorded by TAW-2000 rock servo test system during loading, the permeability values of each test point are calculated by Darcy's law, as shown in the following formula.

$$k = \frac{\mu L V}{A P_w \Delta t} \tag{3.1}$$

in the above formula, k is the permeability, m^2; A is the cross-sectional area of fluid passing through the specimen, m^2; P_w is pore water pressure, Pa; L is the height of the specimen, m; V is the flow rate of fluid through the specimen, m^3; μ is the coefficient of viscosity, At room temperature μ is equal to 1.005×10^{-3} Pa·s.

At an axial load of 1 kN, the permeability of the rock sample is referred to as initial permeability. According to the permeability change law of the loading process, the permeability change of the entire stress-strain process is summarized in three steps, as shown in Table 1. The initial permeability may indirectly reflect the internal pore water infiltration canal at the initial loading stage of the rock samples. by comparison, it is found that when the confining pressure is 10 MPa and pore water pressure is 5 MPa, the initial permeability of rock sample is the highest, followed by confining pressure 10 MPa pore water pressure 2.5 MPa, the difference of initial permeability between the two groups of test rock samples is 60.51%. The analysis shows that the pore water pressure of A10B2.5 group is twice as low as that of A10B5 group, and the seepage movement of pore water in rock samples largely depends on the value of pore water pressure, and pore water pressure provides power source [24]. Especially in the initial state, the internal structure of the rock sample has not changed greatly due to the external force, and the influence on the development of permeability is not prominent, so the initial permeability depends largely on the rock sample itself and the confining pressure and pore water pressure. By further comparison, it is found that the initial permeability decreases obviously with the increase of confining pressure, although the initial permeability of the test group with high pore water pressure is higher

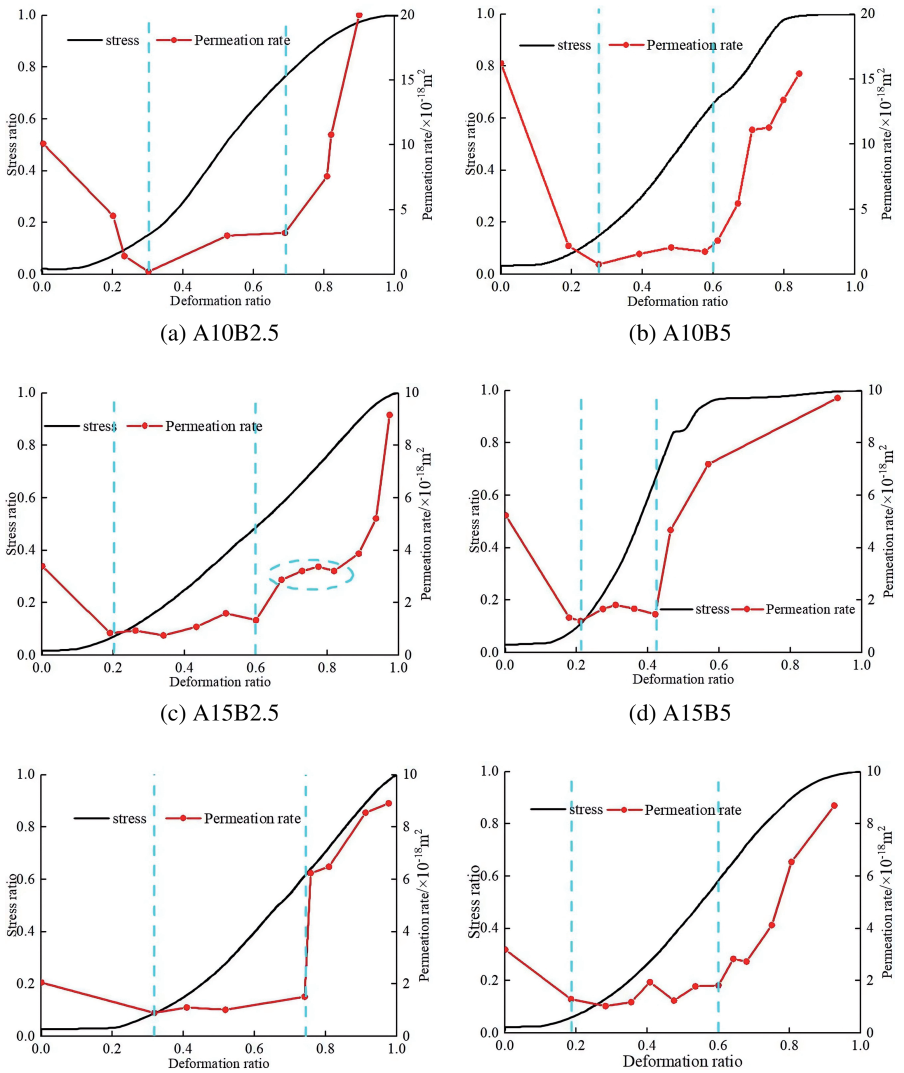
Table 1. Permeability evolution characteristics of triaxial compression permeability process

Group	Initial permeability/ $\times 10^{-18}$m^2	Permeability decline section/ $\times^{-18}$m^2	Stable development stage of permeability/ $\times 10^{-18}$m^2	Permeability rising section/ $\times 10^{-18}$m^2
A10B2.5	10.10	10.10÷0.22	3.00÷3.21	7.58÷20.03
A10B5	16.21	16.21÷0.76	1.57÷1.75	2.59÷15.43
A15B2.5	3.40	3.40÷0.85	0.94÷1.34	2.88÷9.16
A15B5	5.24	5.24÷1.21	1.66÷1.47	4.68÷9.72
A20B2.5	2.06	2.06÷0.89	0.89÷1.52	6.24÷8.91
A20B5	3.19	3.19÷1.29	1.03÷1.82	2.84÷8.70

under the same confining pressure. However, it is still inferior to the initial permeability of rock samples with two different combinations of pore water pressure under low containment pressure. The axial load officially begins to load until the rock sample is destroyed, and the permeability goes through the decline stage, the stable development stage and the rising stage in turn. The average decrease in the permeability of the six groups of tested rock samples was 76.9%, and the maximum decrease was 97.82%, and the largest decrease occurred in the A10B2.5 group, and it was found that the decrease in the permeability of the A10B5 group also reached 95.31%, which was considered to be related to the low confining pressure of the two groups of rock samples. In the stable development stage, the permeability fluctuates slightly, but compared with the descending section and the rising stage, it can still be considered that its development trend tends to be stable. The average increase in permeability in the rising phase is 205.81%, with a maximum increase of 495.75%.

The stress-strain curve and stress permeability curve of chlorite schist during triaxial compression are shown in Figure 5. From the stress-strain curve, it can be seen that the triaxial compression osmotic loading process of rock samples has experienced the initial compaction stage, that is, with the continuous increase of deformation, the increase of stress is very small, and the permeability shows a downward trend. This is because there are more micropores and microfissures in the rock samples in the initial stage than in the subsequent loading stages [25]. This kind of microfissures do not have the ability to bear external forces, but can be deformed. therefore, at the beginning of axial loading, this kind of micropore microfissures are compacted and deformed, which reduces the seepage channel of pore water in the rock sample and leads to the decrease of permeability. When the rock sample enters the linear elastic stage, the number of micropores and microcracks that can be compacted inside the rock sample is close to zero, and there will be no new cracks in the rock sample in the online elastic stage, so the permeability development in this stage is relatively stable. There is a very small fluctuation in the development of local permeability, which is related to the different internal compactness of rock samples and the number of micro-defects [26]. As a result, there is a weak change in the water flow into the rock sample, and on the whole, the permeability at this stage can be approximately a fixed value. After the rock sample enters the stage of stable crack growth, the stress and strain no longer increase linearly in the process of triaxial compression osmotic loading, and with the increase of stress, the internal new crack begins to develop, and the higher the stress ratio, the greater the degree of crack development. especially under the coupling action of seepage field and stress field, this adverse effect will be further amplified. Therefore, the seepage channel of pore water in the rock sample increases, the infiltration rate of pore water accelerates, the degree of crack propagation is also deepened, and the permeability is greatly developed.

According to the above analysis, the corresponding relationship between permeability evolution and stress development in the triaxial compression permeability process of chlorite schist is pointed out, and it has been verified in six groups of tests. therefore, a conceptual model is proposed to describe the permeability evolution and corresponding mechanical behavior of chlorite schist in each stage of triaxial compression loading process, as shown in Figure 6. The permeability evolution stage I and II can be approximately regarded as



(a) A10B2.5 (b) A10B5

(c) A15B2.5 (d) A15B5

(e) A20B2.5 (f) A20B5

Fig. 5. Stress-strain curve and stress permeability curve of chlorite schist during triaxial compression permeability

the standard uniform deformation stage, when the mechanical properties of chlorite schist are relatively stable as a whole, and the mechanical behavior can still be explained by the classical strength theory and can also be described by linear elastic constitutive model. The permeability evolution stage III can be regarded as the local deformation stage. With the further increase of deformation, the mechanical behavior of chlorite schist changes greatly, so it is no longer suitable to be described by linear elastic constitutive model.

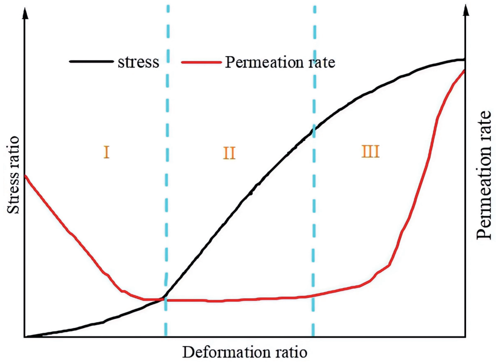


Fig. 6. Permeability evolution model of chlorite schist

3.3. Formation of compression zone and its effect on permeability

The compression zone is a kind of local deformation structure, which is flat and is usually approximately perpendicular to the maximum principal stress. There is no shear deformation in the compression zone, which is mainly due to the defects of notches and cracks. The particles in the compression zone are broken and pore compression. The particles outside the compression zone are basically not broken [27]. Correspondingly, there is another deformation structure called high-angle shear band, which is 45°÷85° with the maximum principal stress [28]. At present, the domestic research on compression zone is mainly focused on sandstone and shale, but rarely on chlorite schist. In the process of triaxial compression osmotic loading, it is found that there is a local compression zone in the failure characteristics of chlorite schist. Fig. 7 clearly shows two representative failure patterns of rock samples in this test, in which the A15B2.5 group rock samples basically show a mixed failure structure of compression zone and high-angle shear zone, while the other groups of rock samples show a high-angle shear zone failure structure. In the process of triaxial compression and infiltration, the primary pores in the chlorite schist are compacted, the local skeleton particles are crushed, and the fine particles fill the internal

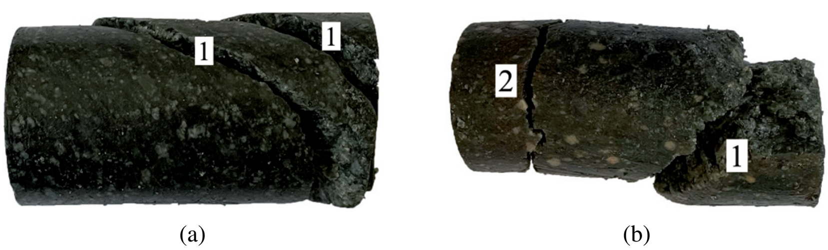


Fig. 7. Different failure characteristics of rock samples; (a) Deformation structure of high angle shear band, (b) Mixed failure structure of compression band and high angle shear band; 1 – high angle shear failure, 2 – compression band failure

seepage channel of the rock sample, thus forming a local compression zone [29, 30], which blocks the pore water seepage, so there is still a stable development trend in the early stage of permeability development in the third stage of Figure 6c, with little fluctuation up and down. However, with the continuous increase of axial load, the number of new cracks in the rock sample continues to increase, the crack connectivity increases, and a local macroscopic crack is formed, which finally leads to a rapid increase in permeability.

4. Conclusions

The main results are as follows:

1. The triaxial compression permeability test of chlorite schist is carried out for the first time, and the failure strength trend of chlorite schist under different confining pressure and pore water pressure is clarified, and the macroscopic failure strength is analyzed from the point of view of the change of internal structure of rock samples. The compaction effect of confining pressure on crack is greater than that of pore water pressure on crack expansion, so the failure strength of rock samples depends more on confining pressure.
2. The permeability of chlorite schist under triaxial compression has gone through three stages, namely, decreasing stage, stable development stage and rising stage, and the corresponding stress and deformation state of rock samples is initial compaction-linear elasticity-crack stable development to macroscopic crack formation. According to the corresponding relationship between seepage rate evolution and stress, a conceptual analysis model is proposed.
3. The phenomenon of local compression zone exists in the triaxial compression permeability process of chlorite schist, and the appearance of compression zone leads to the decrease of permeability, so that the early stage of permeability rise is not prominent. only when the crack propagation effect caused by shear failure is greater than that of the compaction zone, can the permeability develop rapidly.

In this study, the real loading state of chlorite schist was simulated and the performance evolution under the coupling effect of triaxial stress and water seepage was obtained. However, the practical engineering environment is complex and variable, for example, the rocks are often subject to repeated erosion by groundwater. Therefore, triaxial compression permeability tests should be carried out for chlorite schist after dry-wet effects to study the evolution of its properties.

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