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Study on the fracture mode of low permeability shale under different confining pressures

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Abstract: Rock fracture is a complicated none quilibrium and nonlinear evolution process. There are important theoretical significance and engineering value for the research on fracture process of rock and soil engineering materials, to reveal the material failure process of nonlinear macroscopic mechanical behavior, evaluation of rock and rock engineering safe state to understand the stability of rock and soil engineering structure and take reasonable nursing measures. And the cracks can reflect directly the failure process of rock in the quantitative research on fracture. We usually need to choose a rupture criterion to determine rock modes under the action of force, such as the crack formation time and the direction of crack. Structural fracture often not appears as the single patterns. there is a crack, a conjugate shear fractures, and mix the two shear fracture. Therefore, actual research focus on criterion of tension fractures and shear fracture. In this paper, based on the analysis of the rock stress state, the fracture behavior of rock is analyzed from the theory of the Coulomb failure criterion and the Griffith fracture criterion. Then four different layers of silty mudstone were selected to carry out three axial compressive rock mechanics experiments. The fracture characteristics of rock under different confining pressures were studied. Finally, based on the stress strain test data, the fracture parameters of rock (cohesive force, internal friction angle) are calculated by using MATLAB software.

Keywords: - *crack; fracture;coulomb's criterion; griffith criterion*

I. INTRODUCTION

Study of solid materials in the external loads and the environment, the evolution of defects in material and lead to the whole process of the material failure or damage, is the mechanics and material scientists for the long-term struggle interdisciplinary proposition [1]. Because the material damage caused by the accident until today in twenty-first Century to be too numerous to enumerate, although, in many areas of science and technology has made brilliant achievements, but understanding the failure mechanism of brittle and quasi brittle materials people's is quite superficial, and failed to establish a relatively complete and systematic description of the mathematics, to predict the failure of materials and the structure of the mechanical model is still lack of reasonable and effective. Study on failure process of rock and soil engineering materials, macroscopic nonlinear mechanical behavior of the rupture process reveal the material, safety assessment of rock and rock engineering, the stability of geotechnical engineering structure and adopt reasonable supporting measures, it has important theoretical significance and engineering value.

The strength of rock with the change of stress state has long been paid attention to, many scholars put forward a variety of strength criterion. In 1977, it was proposed that the first strength criterion, in 1900, put forward the Moore criterion, until the later Griffith criterion, also promoted the development of fracture mechanics. Later scholars put forward more rock strength criterion to describe and judge the ultimate bearing capacity of rock, such as various stress strength criterion or strain strength criterion, etc.. All these strength theories are used to introduce a limit stress as a criterion to judge the failure (failure). Therefore, the study of failure is usually the study of functional failure, i.e., the state of the study. The traditional geotechnical engineering strength analysis and strength design theory will be treated as homogeneous materials, with elastic theory and classical elastic-plastic theory, stress and deformation analysis of rock and soil materials, with a series of strength theory to the analysis of materials could reach its ultimate bearing capacity, in order to determine whether the material is in safe working condition.

In the appearance of the Griffith fracture theory in 1920, it was realized that only the strength theory was not enough, and the effect of the internal defect (damage) and the damage accumulation of the load on the performance of the components must be considered. The defects in the component can lead to the appearance of stress concentration, which causes the crack propagation to form the fracture surface, which causes the failure of the component. The determination of the whole stress-strain curve of rock has changed people's engineering design concept, and it has changed from the traditional strength (state) design to the process design. Later, the damage mechanics, internal defects and damage of materials under fatigue load caused by the gradual deterioration of components, has not only stay in the state of failure (failure), but has already begun to study [2] rupture process.

Failure is the loss of cohesive force in one part of the material under certain stress conditions, which causes the existing crack to expand, or the new crack in the material's weak position. This paper studies the rupture process of the rock (Failure Process) refers to the rocks in a certain environment and under stress conditions, crack initiation and expansion and start the whole process through until gradually lose the bearing capacity. Usually the strength theory and stress state analysis are only part of the failure process.

Since Cook (1965) found that the stress-strain curve of the whole rock, people began a lot of experimental research on the fracture process of rock. A number of studies have indicated that the failure of the rock occurs at a point after the peak load, not at the point of peak strength. The rupture is no longer seen as a state, but rather a process, a process known as the deterioration of the material [2]. So far, a lot of research about the rock fracture is still in use of the traditional strength theory. In mining engineering, such as mining, slope, drilling and blasting, especially in deep mining of coal mine production, and often encounter "rock burst" and "coal explosion" phenomenon of rock burst. This phenomenon not only seriously damage the underground engineering structure, but also threaten the safety of the production personnel. But just here, the traditional failure criterion is invalid. On the other hand, it is more important to predict and prevent the instability of a lot of underground structures than simply studying the strength limit. Therefore, many of the same issues related to mining damage in geotechnical engineering, people are concerned about not only the peak strength, bearing capacity and rupture after rupture of precursory information is also an important problem of rock mechanics are concerned. Study of rock failure is only a state of rupture process, not simply seek to put forward such as Mohr--Coulomb kind of rock under the condition of laboratory overall failure strength criterion according to, because it is not applicable to the load deformation and fracture process research. The study of the rupture process often appears to be more important than the destruction of the study itself [2]. In this paper, the fracture modes of rock under different confining pressures are studied by experiments.

II. GENERAL CRITERIA AND FAILURE MODES OF ROCK FRACTURE

In order to determine the direction of rupture and rupture of rock under stress, it is often necessary to select a certain fracture criterion in order to determine the formation mechanism and distribution law of fracture. When the rock is more in the direction of stress, the rock burst can be expressed by the [9] $\sigma_1 = f(\sigma_2, \sigma_3)$. This relationship is called the fracture criterion, and its geometric expression is a surface, called the fracture surface or the failure surface. The most widely used in rock mechanics is the Coulomb's and Griffith's principle.

1, Coulumb- Mohr criterion

Coulumb believes that the critical condition of the material damage is a section of the shear stress is equal to the plane of cohesion (single shear strength) and the internal friction force generated by the positive stress. Rock failure is a shear failure; rock resistance is composed of two parts (cohesion, internal friction); strength criterion form linear model:

$$\tau = c + \sigma \tan \phi \qquad (1)$$

τ in equation(1) is critical shear stress, σ is the effective normal stress which is affected by the pore pressure of the fluid is considered, c and ϕ are the material constants, which denote internal cohesion and internal friction angle. The cohesive force c is the shear strength (Pa) of the σ =0, and $u = \tan \phi$ is defined as the internal friction coefficient.

We can obtained from figure 1:

$$2\theta = 90^0 + \phi \qquad (2)$$

Direction of failure face:

$$\theta = 45^{0} + \frac{\phi}{2} \tag{3}$$

$$BD = \frac{\sigma_1 - \sigma_3}{2} \tag{4}$$

$$BD = AB \cdot \sin\phi = (c \cdot \cot\phi + \sigma_3 + \frac{\sigma_1 - \sigma_3}{2}) \sin\phi \tag{5}$$

$$\sigma_1 = 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} + \frac{1+\sin\phi}{1-\sin\phi}\sigma_3 \tag{6}$$

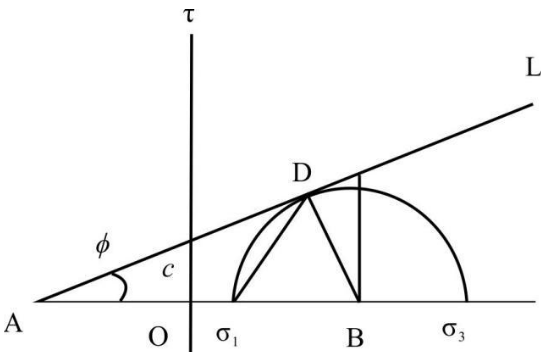


Fig. 1 stress circle of Coulomb criterion

The Coulomb criterion is only applicable to the shear crack, not to be used in the tensile failure, and the tensile breaking line is indicated in the figure. On the left side of the line, the cut line will not work, because the rock will break up first. It is considered that the internal friction coefficient is constant during the deformation of the same kind of rock, and the value is the value of the initial confining pressure of μ=0.6-0.8. It can be seen from the figure that the larger the internal friction coefficient is, the smaller the cohesive force is, the smaller the shearing force is. The internal friction angle less than 45 degrees, under low normal stress, shear rupture (mainly shear rupture), and shear fracture line is always toward the negative direction of principal stress axis σ , which is toward the direction of the tensile stress tilt, internal friction coefficient is larger, to the direction of the tensile stress and the greater the degree of tilt. Therefore, the greater the internal friction coefficient of the rock, in the shear deformation process, the volume becomes larger, called the shear expansion zone. In this way, the larger the internal friction coefficient is, the smaller the cohesive force is, the easier the rock is sliding between each other, and the volume expansion of the shearing process.

The relationship between the normal stress and the shear force acting on the plane is related to the properties of the material when the shear failure occurs along a plane. It is considered that the internal friction angle of the material is not a constant, and the general expression of the fracture line is:

$$\tau_n = f(\sigma_n) \tag{7}$$

When the confining pressure is not too large, the envelope of the brittle rock is generally straight line in the pressure zone. In this special case, the Mohr principle is consistent with the Coulomb rule. It is an experimental criterion. Equation(7) represents a curve, the curve is through the experiment, under different conditions to get different Mohr circle, draw the Mohr envelope, represents the Mohr criteria. The failure surface is determined by the vertical moire envelope.

2、Griffith (Griffith) criteria

The modern strength theory that real material internal defects, these defects lead to the internal stress concentration, the actual strength of the material is much lower than the theoretical strength.

The basic assumption of the Griffith criterion (view) for objects within the random distribution of many cracks; all fractures are open, and through independent; fracture section is flat ellipse; in any state of stress, the crack tip tensile stress concentration, resulting in cracks along a side to further expand; the final are in essence the tensile stress caused by rock failure.

According to Griffith's theory of strength, the fracture condition of rock under plane stress condition is [10,11]:

When $\sigma_1 + 3\sigma_3 > 0$, the failure criterion was:

$$\sigma_t = \frac{(\sigma_3 - \sigma_1)^2}{8(\sigma_3 + \sigma_1)} \quad (8a)$$

$$\cos 2\beta = \frac{(\sigma_1 - \sigma_3)}{2(\sigma_3 + \sigma_1)} \quad (8b)$$

When $\sigma_1 + 3\sigma_3 < 0$, the failure criterion was:

$$\sigma_3 = -\sigma_t \quad (9a)$$

$$\sin 2\theta = 0 \quad (9b)$$

Where σ_t is the rock tensile strength under uniaxial tensile test; β is the angle between the long axis of the elliptic crack and the principal compressive stress axis σ_1, the rupture angle $\theta = \beta$.

If a new fracture occurs, the direction of the new crack should point to the normal direction of the elliptical crack boundary. The angle ψ is between the long axis of the new crack and the original crack, according to Eqs.(8) and (9) can be obtained respectively,

$$\psi = -2\beta \quad (10)$$

$$\psi = 0 \quad (11)$$

Eq.(10) shows the angle between the new crack and the original elliptic crack long axis is 2β for $\sigma_1 + 3\sigma_3 > 0$, The negative sign implies the new cracks direction is in the principal compressive stress axis rotation clockwise direction, Eq(11) shows that the new crack extends along the original elliptical crack.

Griffith fracture criterion from microscopic mechanism of deduced by strict fine drawn, with a strong theoretical foundation, is the classical theory of fracture mechanics. But it is in tension fracture as the premise, the maximum tensile stress theory is actually an equivalent, only suitable for the tensile rupture.

Griffith shows not only the strength curve of rock compressive strength is 8 times the tensile strength, reflect the reality of the rock; also proved that in any rock stress state is due to stretch induced damage; but only for brittle rock, and was closed on fracture pressure, shear strength increase is not enough to explain the high Wai under the pressure, inconsistent with the actual.

2 Fracture mode of rock

Rock fracture form[12] is divided into three types (Fig. 2): The tensile failure, the shear failure, the tensile-shear mixed failure. The tensile failure is uniaxial tensile, splitting, caused by tensile stress, when tensile stress reaches or exceeds the tensile strength of the rock, then along vertical stretching direction, which is the minimum principal stress fracture stress axis, fracture criteria satisfy Griffith tensile fracture criterion $\sigma_3 = -\sigma_t$, the corresponding stress state for point A in Fig. 2, no shear stress, rupture mode is splitting. Shear failure is only caused by shear stress, when the stress reaches or exceeds the shear strength of rock, the shear rupture happens along the σ_1 and σ_3 oblique surface. The rupture criteria meet the Coulomb failure criterion $\tau = c + \sigma \tan\phi$. the stress state is the corresponding BC segment in the figure, and the fracture surface is a single shear plane. the tensile-shear mixed failure is caused by the tensile and the shear stress, and the fracture criterion satisfies the Griffith fracture criterion: $\frac{(\sigma_1 - \sigma_3)^2}{\sigma_1 + \sigma_3} = 8\sigma_t$. The stress state in the diagram corresponds to the AB segment, and the fracture mode is the conjugate shear joint.

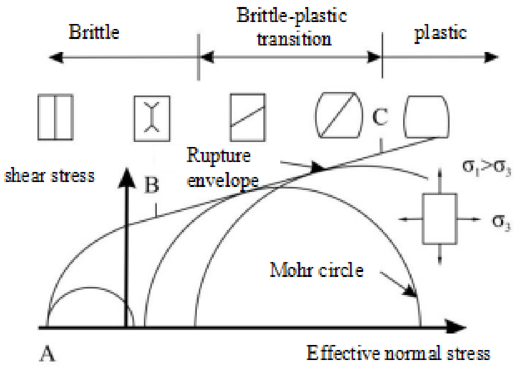


Fig.2 Brittle ductile transition diagram

SIBSON H. (1996) derived from the theory of a variety of ways to rupture the conditions: when $\sigma_1 - \sigma_3 < 4\sigma_t$, The tensile failure occurred; when $4\sigma_t < \sigma_1 - \sigma_3 < 6\sigma_t$, the tensile-shear mixed failure happened; when $6\sigma_t < \sigma_1 - \sigma_3$, the shear rupture occurred.

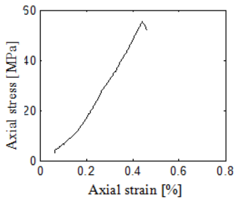
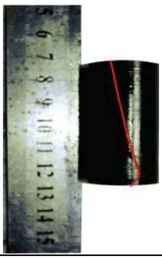
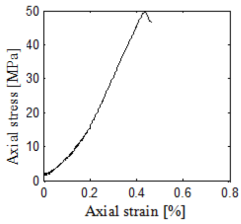
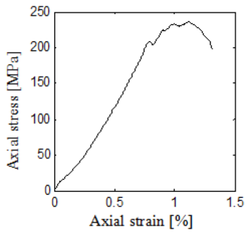
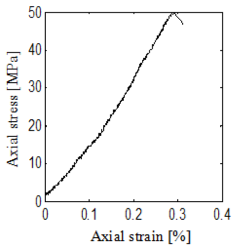
III. ROCK MECHANICS EXPERIMENT

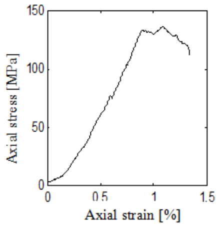
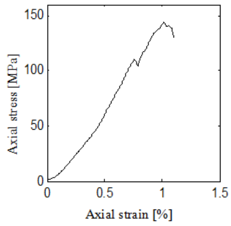
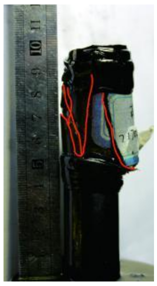
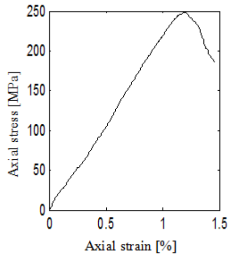
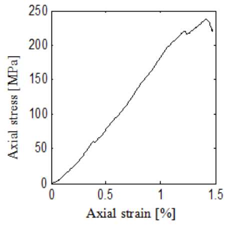
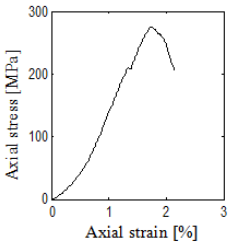
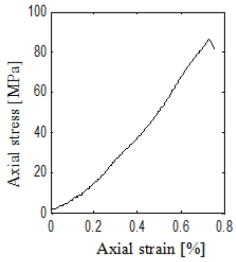
Since Karman Von.'s first three axis pressure test in 1911, the conventional three axis pressure test of rock has been developed greatly. For many years, the three axis pressure test of rock has been the main means to understand the mechanical properties of rock under complex stress state, and it is also the main experimental basis for establishing the strength theory. The strength envelope of Moore's Coulomb strength theory is drawn from the results of the conventional three axis pressure test. In the actual rock engineering, especially in the underground rock and soil engineering, the rock is generally in the three direction stress state. In addition, the rock and metal in the mechanical properties of an important difference is that the rock on the sensitivity of the hydrostatic pressure. Therefore, the three axis pressure test is of great significance for the study of the deformation and failure process of rock. Conventional three axis test makes people realize that the influence of confining pressure on the deformation and fracture of rock, the intermediate principal stress and the minimum principal stress are equal in the conventional three axis pressure test.

As shown in figure 3. This set of equipment is divided into seven parts, respectively: door type rigid system host, oil source, pressure loading system, self balanced pressure chamber, control cabinet, control cabinet, computer, experiment of axial pressure limiting 2000KN, confining pressure and pore pressure of 100MPa, 100MP, the control precision is 0.005 MPa, the highest temperature 200 C. The maximum measuring range of axial deformation is 0-5mm, the maximum measuring range of radial deformation is 0-2.5mm, and the control precision is 0.002mm. This paper designed three axial compression experiments, samples were taken from Daqing oilfield, according to the International Association of rock mechanics of rock uniaxial compression test standard [13], samples were processed into cylindrical body diameter of 25mm and height of 50 mm, with 0.005mm/s constant strain rate compression experiment.

Figure 4 describes fracture and stress strain curve for four kinds .of rock samples, where the porosity of 1.1% samples Y-78-N1, the confining pressure 5MPa, 10PMa, 15PMa; the porosity of 1.5% samplesY-78-N2 , the confining pressure:10MPa, 20MPa; the porosity 3.5% sample Y-391-N27 the confining pressure: 12MPa, 20MPa, 30MPa, 40MPa; the porosity 3.3% sample Y-391-N28, the confining pressure: 6.4MPa, 50MPa, 51MPa.

Fig.3 TAW-2000 microcomputer control electro hydraulic servo rock three axis testing machine system

Number	height [mm]	diameter [mm]	Confining pressure [Mpa]	Sample before the experiment	Sample After the experiment	Stress -strain curve
Y-78-n1	50	25	5			
	50	25	15			
	50	25	30			
Y-78-n2	50	25	10			

	51	25	20			
	50	25	12			
Y-391-n 27	52	25	20			
	50	25	30			
	50	25	40			
Y-391-n 28	50	25	6.4			

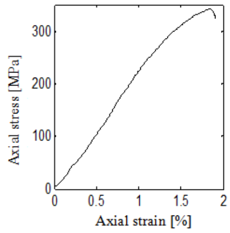
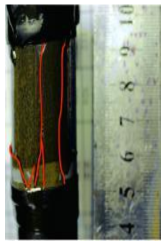
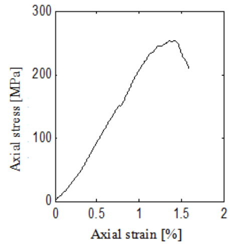
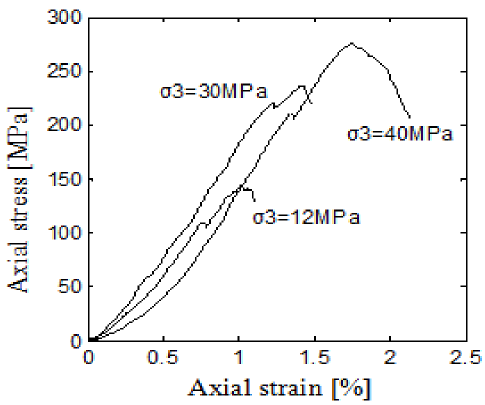
	50	25	50			
	52	25	51			

Fig. 4 pattern of rock fracture and stress strain curve

According to fig. 4 of five groups of rock specimens under different confining pressure rock rupture, we analyze by group, for Y-78-N1 in the confining pressure of 5MPa two crack, a crack in 15MPa under confining pressure, there are 3 cracks in 30MPa under confining pressure, rock fracture and serious, because the greater the confining pressure, stress fractures should be more decentralized, more intensive and more serious fragmentation, and under the confining pressure of 15MPa is only a crack, this set of data may rock mineral distribution and the other two groups have great difference. The Y-78-N2 has many cracks under the confining pressure of 10MPa, and the edge of the phenomenon of rupture under the confining pressure of 20MPa, the crack is more dispersed, showed that the stress dispersion, the rock sample body multiple distribution of weak surface, once there is stress, it is easy to rupture. For Y-78-N4 in the loading confining pressure 10MPa, the occurrence of the obvious splitting phenomenon. As for the Y-391-N27 and Y-391-N28 groups, with the increase of confining pressure, the cracks in rock samples from the central office to the edge gradually extended, shows that the increasing of confining pressure and stress dispersion, and more rock in weak surface, wide crack propagation. In short samples under confining pressure under the condition of small, single (nearly split crack and the direction of the maximum principal stress at a small angle), with the increase of confining pressure, the emergence of multiple cracks, and edge fragmentation phenomenon.

IV. EXPERIMENTAL DATA ANALYSIS

According to the experimental data of Y-391-N27, Y-78-N1, Y-78-N2, make Y-391-N28 rock samples under different confining pressure stress and strain curve, and according to the stress-strain curve, make the stress circle, respectively, as shown in Fig. 6-9.



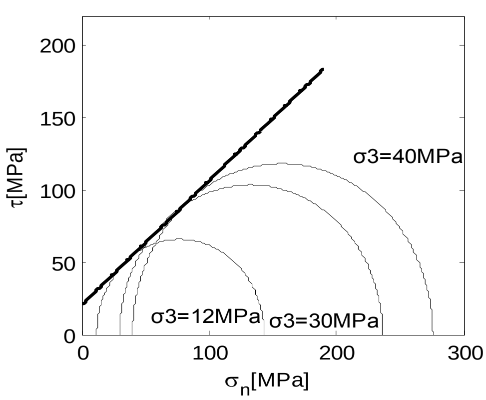


Fig.6 Stress and strain curves of Y-391-N27 under different confining pressures and stress circle

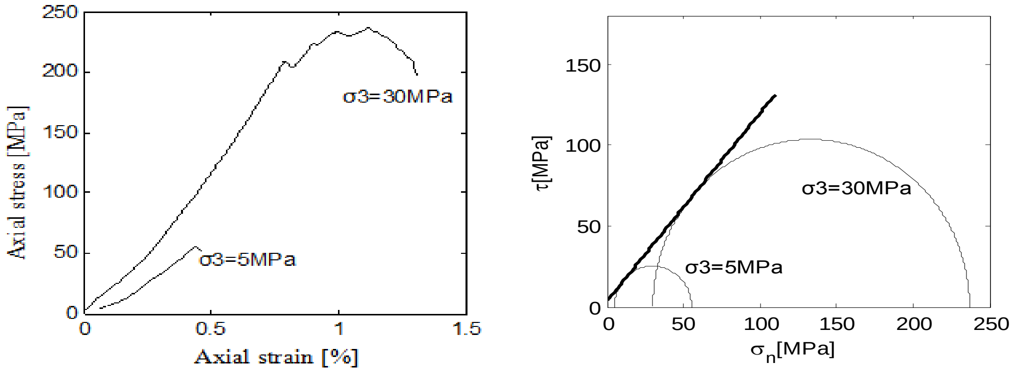


Fig.7 Stress and strain curves of Y-78-N1 under different confining pressures and stress circle

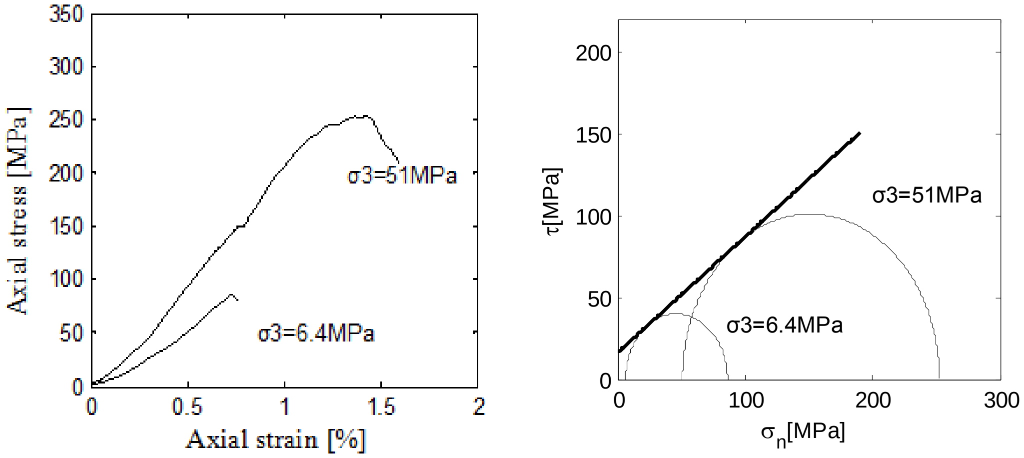


Fig.8 Stress and strain curves of Y-78-N2 under different confining pressures and stress circle

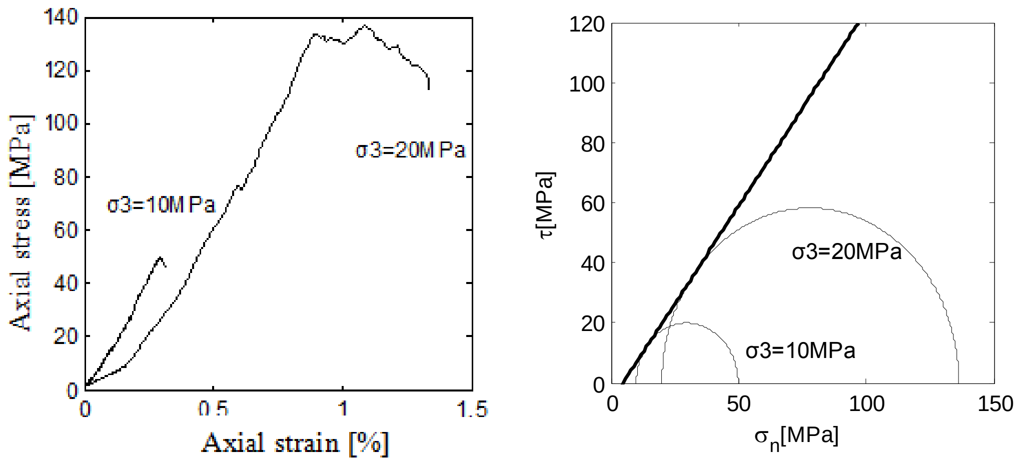


Fig.9 Stress and strain curves of Y-391-N28 under different confining pressures and stress circle

According to the experimental results of rock mechanics, through the MATLAB program, the more stress circle is drawn, and the moire fracture envelope is obtained. Were Y-391-N27 group internal friction coefficient k=0.8589, the internal friction angle of =40.6578 degrees, the rupture angle of [14] $\theta = 45^{\circ} - \phi / 2$ =24.6711 degrees; group Y-78-N1 samples of rock friction coefficient k=1.1616, the internal friction angle of ϕ =49.2757 degrees, the rupture angle of $\theta = 45^{\circ} - \phi / 2$ =20.36215 degrees; Y-78-N2 group internal friction coefficient k=1.3007, internal friction angle ϕ = 52.446 degrees, the rupture angle of $\theta = 45^\circ - \phi / 2$ =18.776 degrees; the Y-391-N28 group the friction coefficient of k=0.7067, the internal friction angle of ϕ =35.2476 degrees, degrees rupture angle $\theta = 45^\circ - \phi / 2$ =27.3762 . Through theoretical analysis, the rock fracture angle is about 20 degrees, which is close to the split, which is consistent with the actual fracture mode.

V. CONCLUSION

Rock fracture and fracture research has always been the frontier of rock mechanics, and it is also an indispensable theoretical basis for mining, energy, water conservancy, transportation, earthquake and other engineering fields. Study on rock fracture and fragmentation is the study of the failure process, which can reflect the failure process of rock crack is the most direct, quantitative research on fracture, usually need to use the criterion to determine certain rocks in stress cracking under the action of the forming time and fracture direction.

Firstly, using stress analysis of circular said the rock stress state, using a Mohr Coulomb failure criterion and Griffith criterion, from the theoretical analysis of rock fracture behavior, and the rock is divided into three modes: tension fracture, shear fracture and tension shear mixed cracking.

Four groups of different layers of silty mudstone and then select the source in Daqing Exploration Institute, three to carry out uniaxial compression experiments of rock mechanics under different confining pressure, the failure mode and stress strain curves of different confining rock. Based on the stress-strain data, using MATLAB software to calculate the cohesion and the internal friction angle of rock rupture, angle of rupture parameters, from the theoretical analysis of the rock fracture surface orientation, and with the actual rock rupture mode comparison. The main results show that the confining pressure under the condition of small samples, a single near cleavage crack (crack and the direction of the maximum principal stress at a small angle), with the increase of confining pressure, the emergence of multiple cracks, and edge fragmentation phenomenon; through theoretical calculation, the rupture angle of silty mudstone in about 20 degrees, close to splitting, consistent with the actual failure mode of brittle rocks.

VI. ACKNOWLEDGEMENTS

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