Experimental study on confining pressure effect of hard rock indirect tensile test and mechanical mechanism.

Fangsheng Su\textsuperscript{1,2}, Pengzhi Pan\textsuperscript{1}

\textsuperscript{1} State Key Laboratory of Geomechanics and Geomechanical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China
\textsuperscript{2} University of Chinese Academy of Sciences, Beijing 100049, China

Abstract. In order to study how the different loading conditions and confining pressures affect the style of rock fracture, an improved Brazilian disk device was firstly used to do same experiments. Several rules were obtained through the experiments with the marble and sandstone. Firstly, the peak stress and vertical strain were increased with the addition of confining pressure. However, the change of angle between pre-set crack and loading direction has little effect on the peak strength. Secondly, scanning electronic microscopy results demonstrated that the fracture morphology of rock influenced by confining pressure. With the low confining pressure, the proportion of tension zone in the specimen is bigger than shear zone and it changed when the confining pressure increased to a high level. Thirdly, the fracture toughness of rock is changed as confining pressure grows.

1. Introduction
With the development of large-scale deep rock masses engineering, various types of rock failures in the excavation of underground works are attracting more and more attention. Most of the damages in the rock mass are tensile failures. However, when the depth increased, the high geostress maybe also cause pure shear damage to the rock mass. Therefore, it is of great significance to study the failure mode of rock mass under complex ground stress. Since 1978, the International Society of Rock Mechanics (ISRM) recommended the Brazilian disk test as an indirect method to test the tensile strength of rocks. This method has been used for nearly 40 years. Many scholars have improved the method from different perspectives: theory, experiment, and numerical simulation. The test is easy to operate because of the simple load conditions. It is the most critical basic theoretical research, which makes it possible to improve on the basis of it, and study more complex failure modes and mechanisms of materials based on it [1-6]. One of the important directions is to use the disk test to determine the fracture toughness of rock. The rock fracture toughness is an important parameter to characterize the rock's resistance to crack propagation and is the main factor that determines the crack propagation in deep rock mass. In 1982, Atkinson [7] proposed a theoretical formula for testing rock fracture toughness using disk specimens. Then for the shear fracture toughness, the International Society for Rock Mechanics recommends the following specimens for testing fracture toughness: herringbone notched short round bar specimens and three-point curved round bar specimens (recommended in 1988), herringbone Slotted Brazilian disc specimens and semi-circular bending specimens (recommended in 1995) have continued to be refined by researchers. Zhang et al. [8] used a disk with holes of different shapes to measure the open fracture toughness of marble, and used the finite element method to determine the fracture toughness calculation formulas for different hole and slot specimens, and took different forms. The open model was analysed. Xu J G et al. [9] proposed an
analytical solution to the stress intensity factor of the Brazilian disk with the confining pressure and the concentrated load acted together from the perspective of fracture mechanics. The correctness of the analytical solution was verified by numerical methods. There is still lack of experimental verification. Cui Z D et al. [10] conducted preliminary V-notch grooving on argillaceous sandstones and tested the fracture toughness of type I. Xu Y et al. [11] simulated the complex fracture process of cut herringbone in the disk rock samples. Wang Q Z et al. [5] used the platform Brazilian disk specimen to study the elastic modulus and tension strength, and fracture toughness of the brittle rock through theoretical, experimental and numerical methods. It is easier to obtain the fracture toughness of type I than the fracture toughness of type II from the experimental point of view, because the tensile strength of rock mass is much lower than its compressive strength. When the tensile stress and shear stress of the crack tip coexist, the energy required to produce tensile failure of rock is much lower than that of shearing. Many researchers want to produce pure shear damage and most of the pure shears by making pure shear conditions, including loading methods or controlling the development of cracks in specimens to cause them to be destroyed, but the nature of shear should be under complex stress conditions, the specimen itself produce a pure shear failure mode.

The Brazilian disk test device was modified to add a device that can apply a stable confining pressure to the sample, thereby suppressing the tensile stress at the tip of the sample. The test can simulate the failure process of the surrounding rock under deep ground and explore the damage characteristics and mechanical mechanism of rocks and similar materials under complex loads based on the fracture mechanics, fracture morphology and other methods.

2. Test Equipment and Sample Properties

A Brazil disc test system considering the confining pressure effect was invented for the test. The servo control system was used to control the loading of confining pressure and axial pressure. The device changes the mode of loading exerted on the sample in the existing Brazilian disc splitting test device. The system is provided with a spring positioning device, a sealing device, and a self-balancing device also equipped with an oil filling port and an exhaust port, etc. The liquid inside the box forms a stable confining pressure. After the sample is placed in the box, the sample is fixed by the spring positioning device, which facilitates the control of the loading of the sample. The schematic diagram of the test system and the sample mechanical model is shown in figure 1. The length of the prefabricated crack is 2a, the angle between the crack direction and the axial loading direction is $\beta$, and the sample is affected by the confining pressure p and the axial pressure P during the test.

T2b marble, low-brittle sandstone and similar materials were used to carry out the test. The specimen was processed into a disc shape with diameter of 50mm and thickness of 25mm. The rock blocks with weak surfaces are avoided to ensure the integrity of the samples. In addition, the accuracy, straightness and verticality of the specimens are in conformity with the “Rock Test Regulations for Water Conservancy and Hydropower Engineering” (SL264-2001). The conventional elastic constants of the samples used were: T2b marble: elastic modulus $E=30.5 \text{ GPa}$, Poisson’s ratio $\nu=0.3$, internal
friction angle 30°, cohesion force 39 MPa, uniaxial compressive strength 120 MPa; low brittle sandstone: the internal friction angle is 15°, the cohesion force is 7.4 MPa, and the uniaxial compressive strength is 15 MPa. The ratio of the length of the pre-crack in the middle of sample to the length of the sample does not exceed 0.3. The test loading rates were set to force rate: 0.50 KN/s and confining pressure rate: 0.200 MPa/s. The samples were divided into different groups under the confining pressure of 4-28 MPa, and the angle between the pre-crack direction and the axial loading direction was 15° to 90° (at intervals of 15°).

3. Analysis of test results

3.1. Analysis of confining pressure and included angle effect of fracture process of rock

Firstly, the Brazilian splitting tests were carried out for marble and sandstone specimens with pre-existing crack angles of 30° and 45° under different confining pressures. The marble load-displacement curve is shown in figure 2.

The confining pressure improves the rock properties. The elastic modulus of the rock increased significantly with the increased confining pressure. Prefabricated fissures are compacted under confining pressure, and the tendency of their extension and expansion is inhibited. However, as the axial load continues to increase, the stress concentration at the loading point is significant, and eventually it expands toward the pre-existing crack tip, finally forming a continuity crack.

The change of the angle of the pre-fabricated crack also affected the peak strength of the rock sample. When the confining pressure is 16-24 MPa, the effect of the crack with \( \beta = 45° \) on the rock sample is less than the crack effect of \( \beta = 30° \). In fracture mechanics, \( \beta = 30° \) is closer to the analytic solution of pure shear failure. Rock under high confining pressure is more prone to pure shear damage and its tension failure trend is inhibited. However, its high energy requirements cannot be achieved in the test. So in its accumulation of energy process, the failure occurred resulting lower strength. The peak strength is higher and the deformation is smaller than the latter. When the confining pressure is smaller, the impact on the high-strength marble is smaller, and the micro-cracks inside the rock sample are not effectively suppressed. Therefore, under a small confining pressure, the rock fracture mainly depends on the rock sample itself.

Similarly, the peak load of sandstone increased with the increase of confining pressure, and the corresponding deformation of peak value decreased. This shows that even slight changes of the crack tip will lead to rock failure under the high confining pressure. The monolithic failure, unlike marble, has multiple stages of frictional steps that can increase the overall deformation of the specimen. Figure 3 shows the typical load-displacement curve for various pre-crack angles. The peak load of T2b
marble sample does not change significantly with the increase of the included angle $\beta$, but the peak load of the low-brittle sandstone fluctuates obviously.

![Figure 3. Load-displacement curve of sandstone with $\beta$=30°/45° under different confining pressure](image)

![Figure 4. Load-displacement curves of marble and sandstone with different included angle](image)

Then the Brazilian splitting tests were carried out for marble and sandstone specimens with different pre-existing crack angles (15°~90°). The marble and sandstone load-displacement curve shown in figure 4.

Because the uniaxial strength of T2b marble sample is high (about 120MPa) than sandstone, the angle change will not fundamentally change the failure mode of the rock sample under the confining pressure 24MPa. The peak load value of each angle is close to each other. The curve of each stage is basically similar. The sample will show a certain relative ductile failure under the effect of high confining pressure after the peak value, and the peak stress will not appear vertical drop as in figure 4(a). In contrast, the peak load of sandstone is significantly affected by the angle $\beta$. The low-brittle sandstone does not show fluctuations such as marble in the loading process. The reason is that the strength of marble is higher than sandstone. The bond strength between minerals is more significant than sandstone. Small internal fractures compacted under the high confining pressure. The secondary contact of the rupture surface can continue to provide support for the bearing of the rock samples. Therefore, there are more steps before the marble peak, and the sandstone mineral particles are much weaker. There is no effect of re-contacting between particles.
3.2. Analysis of rock sample fracture scanning electron microscope

According to the fracture surface topography, microstructure of the rock damage fracture surface contains a wealth of information. It is composed of the external load driven crack extension and the rock micro crack structures, which is closely related to rock properties and loading conditions.

As can be seen in the figure 5, the relatively smooth surface area and the saw tooth area are obviously distributed. The more smooth surface area is the destructive form of tensile failure, while the saw tooth area is the destructive pattern based on the shear action.

![Figure 5. Scanning electron microscope (*100) of marble under different confining pressure](image)

Due to the effect of confining pressure, the damage of rock presents an internal mechanism of brittle transition from brittle to ductility. The fluctuation of the step gradually decreased along the increased confining pressure. In the post-peak stage, the rock failure surface of fracture saw tooth area steps formed bite friction against the rock failure process. So at this time the damage of the rock showed the characteristics of certain ductility.

3.3. Analysis of rock sample fracture toughness

The formula [12] to calculate the fracture toughness as shown:

\[ N_I = 1 - 4 \sin^2 \beta + 4 \sin^2 \beta (1 - 4 \cos^2 \beta) \left( \frac{a}{R} \right)^2 \]

\[ N_{II} = \left[ 2 + (8 \cos^2 \beta - 5) \left( \frac{a}{R} \right)^2 \right] \sin 2\beta \]

\[ K_{II} = \frac{P \sqrt{a}}{\sqrt{\pi R B}} N_{II} \]

KI diminished and KII presents exponential growth along with the increase of confining pressure (shown in figure 6). Under the condition of the increasing confining pressure, rock internal tiny pores and cracks cannot be well connected and extended leading to sample damaged. Rock properties are enhanced obviously.
When $\beta=0^\circ$ or $90^\circ$, specimens produced pure tensile damage. The pre-crack has no guiding effect on the specimens. When $\beta=30^\circ$, $45^\circ$, $60^\circ$, or $75^\circ$, specimens produced mixed tensile and shear damage. When $\beta=30^\circ$, rock fracture toughness reached maximum value, which mostly approached to the pure shear state. The resistance of the specimens to the pure shear weakened and the fracture toughness value decreased continuously with the decreased $\beta$ value.

4. Conclusions
The confining pressure improves the rock properties. The elastic modulus and peak strength of the rock increased significantly with the increased confining pressure. The change of the angle of the prefabricated crack also affected the peak strength of the rock sample.

Rock failure mode changed because of confining pressure. Electron microscope scanning results demonstrate that rock occur tensile failure transfer to tensile and shear mixing damage. The fracture surface has both scratch and steps of the snap.

$K_{I}$ diminished and $K_{II}$ presents exponential growth along with the increase of confining pressure in the test.

Acknowledgements
The authors sincerely acknowledge the financial support by the State Key Research Development Program of China (Grant No. 2017YFC0804203), Key Research Program of Frontier Sciences, Chinese Academy of Sciences (QYZDB-SSW-DQC029) and International Cooperation Project of Chinese Academy of Sciences (Grant No. 115242KYSB20160017).

References
[1] You M Q, Su C D, 2004. Experimental study on split test with flattened disk and tensile strength of rock. J. Chinese Journal of Rock Mechanics and Engineering.18 pp 3106-3112
[2] Guo X, Wang X B, Bai X Y, Wang C W, Qi D L 2017. Numerical simulation of effects of loading types and tensile strength on Brazilian disk test by use of a continuum-discontinuum method. J. Rock and Soil Mechanics.01 pp 214-220
[3] Gong F Q, Li X B, Zhao J 2010. Analytical algorithm to estimate tensile modulus in Brazilian disk splitting tests. J. Chinese Journal of Rock Mechanics and Engineering.05 pp 881-891
[4] Zhang J W, Jin X D, Yuan R P, Li Y L 2016. Three-dimensional stress distribution and failure process of disc specimens in Brazilian test. J. Mining &Safety Engineering.05 pp 873-879
[5] Wang Q Z, Jia X M 2002. Determination of elastic modulus, tensile strength and fracture toughness of brittle rocks by using flattened Brazilian disk specimen—Part1: Analytical and numerical results. Chinese Journal of Rock Mechanics and Engineering.02 pp1285-1289
[6] Huang Y G, Wang L G, Chen J R, Zhang J H 2015. Theoretical analysis of flattened Brazilian splitting test for determining tensile strength of rocks J. Rock and Soil Mechanics.03 pp 739-748

[7] Atkinson C, Smelser R Z, Sanchz J 1982. Combined mode fracture via the cracked Brazilian disk. Int J. Fracture Mechanics, 18 pp 279-291

[8] Zhang S, Wang Q Z 2009. Determination of rock fracture toughness by split test using five types of disc specimens. J. Rock and Soil Mechanics.01 pp 12-18

[9] Xu J G, Hua W, Dong S M 2014. Numerical analysis of effects of confining pressure in the stress intensity factors for Brazilian disk. Chinese Journal of solid mechanics S1 pp 147-152

[10] Cui Z D, Liu D A, An G M, Zhou M, Li Z Q 2010. Research for determining mode I rock fracture toughness KIC using cracked chevron notched Brazilian disc specimen. J. Rock and Soil Mechanics.09 pp 2743-2748

[11] Xu Y, Dai F, Xu N W, Wei M D 2015. Numerical analysis of mixed mode progressive rock fracture mechanism of cracked chevron notched Brazilian disc specimens. Chinese Journal of Geotechnical Engineering.12 pp 2189-2197

[12] AL-Shayea N A, Khan K, Abduljauwad S N 2000. Effects of confining pressure and temperature on mixed-mode (I-II) fracture toughness of a limestone rock. Int J. Rock Mechanics and Mining Sciences.37 pp 629-643