Thermo-hydro-mechanical coupling Triaxial Test Method for Rock with Fracture and Its Application

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ABSTRACT: All kinds of fracture discontinuities in granitic host rock of high level radioactive waste (HLW) repository not only degrade the engineering characteristics of rock mass, but also constitute potential groundwater seepage channels and nuclide migration channels. During repository operation, the expansion and evolution law of host rock fractures under the coupling effect of radiation heat, groundwater and stress field is of great significance for the long-term safety assessment of the repository. In this context, a triaxial test method suitable for rock with single fracture under the condition of thermo-hydro-mechanical (THM) coupling is proposed, which solves the problem that the rock sample with fracture as initial defect is easy to be destroyed due to the changes of complex test conditions such as temperature, hydraulic pressure, confining pressure and axial load.

Keywords: repository host rock, thermo-hydro-mechanical coupling, triaxial test, crack propagation.

1 INTRODUCTION

The host rock of the potential site area (Beishan area, Gansu Province) for China's HLW repository belongs to granitoid, which has the advantages of high strength and low permeability. However, various fractures may deteriorate the engineering characteristics of host rock, and also constitute potential groundwater seepage and nuclide migration channels. During the operation of the repository, the near-field host rock will be in a complex THM coupling environment. Its mechanical and hydraulic characteristics directly affect the long-term safety performance of the repository.

For the test research of mechanical and hydraulic characteristics of host rock in multi field coupling environment, the key lies in the smooth development of mechanical tests under complex conditions, as well as the real-time acquisition and accurate characterization of the evolution of sample microstructure. In situ test in Underground Research Laboratory (URL) can obtain the real response of rock mass (Rutqvist et al. 2008 and Souley et al. 2001), but the cost is too high. The laboratory test conducted by simulating the multi field coupling environment is an effective method.

For example, the hydraulic mechanical coupling test was used to study the influence of rock stress state and damage evolution on its permeability (Chen et al. 2014), and the crack growth rule (Zhao et al. 2019). The hydrothermal coupling test was used to study the influence of temperature on permeability (Li et al. 2014 and Suzuki et al. 1998) and the influence of fissure flow on temperature field (Wu et al. 2020). The influence of temperature on rock mechanical properties (Yoon et al. 2011 & Park et al. 2019), permeability properties (Yang et al. 2017) and fracture propagation (Yang et al. 2020) was studied through preheating treatment. However, the true THM coupling triaxial test is mostly applicable to intact rock samples (Zhang et al. 2020). The THM coupling test technique for rock samples with intermittent crack is not yet mature. In addition, it is difficult to obtain the fracture growth rule and the full stress-strain curve of rock samples under multi field coupling conditions.

In this context, the THM coupling triaxial test method suitable for rock sample with single fracture was proposed in this paper, which solved the problem that cracked rock samples are easy to be damaged due to the existence of initial defects during the THM coupling triaxial test. The method was successfully applied to study the triaxial mechanical properties of Beishan granite under the THM coupling condition.

2 PREPARATION OF ROCK SAMPLE WITH SINGLE FRACTURE

For the THM coupling triaxial test, the existence of the fracture as an initial defect is easy to lead to the external silicone oil and the internal seepage water to break through the heat shrink tube around the rock sample under the action of confining pressure and internal water pressure, thus damaging the seal and directly leading to the rock sample damage.

2.1 Processing of rock samples with single fracture

In order to make the hydraulic pressure directly act on the internal fracture of the rock sample in the test, so as to deeply study the hydraulic and mechanical characteristics, as well as the crack propagation law of the rock sample with fracture under the multi field coupling conditions, a radial through hole with a diameter of 1mm was drilled in the middle of the intact cylinder rock sample by the water jet technique. Then, from the center of the inlet end of the rock sample, an axial hole was drilled to the middle and connect with the radial through hole. Finally, the wire cutting technique was used to process the fracture through the radial through-hole, as shown in Figure 1. Therefore, the axial half-through hole acts as the seepage channel, so that the hydraulic pressure can directly act on the prefabricated fracture.

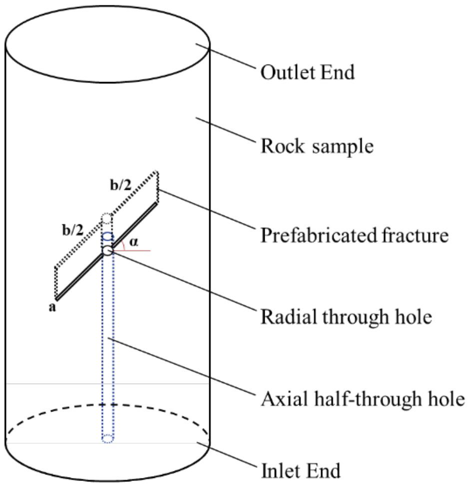

Figure 1. Schematic diagram of the rock sample with fracture.

2.2 *Sealing of fractured rock sample*

The sealing of the prefabricated fracture and the sealing of the end of the heat shrink tube are combined to achieve the sealing of the rock sample in the whole process of the THM coupling triaxial test. A thin layer of quick drying cement and waterproof silica gel material are used to cover the surface of the prefabricated fracture. The solidified cement has appropriate strength to prevent the heat shrinkable tube from falling into the prefabricated fracture under confining pressure and thus breaking. It can also withstand the hydraulic pressure inside the fracture. The waterproof silica gel further prevents the seepage pressure fluid inside the fracture from seeping through the prefabricated fracture during the test. Since the quick drying cement and waterproof silica gel material are not filled inside the fracture, their impact on rock strength can be ignored.

When installing the surface sealed rock sample on the seepage indenter, it is sealed by the combination of heat shrinkable tube, self-adhesive tape, hoop and iron wire, as shown in Figure 2, to ensure that the external silicone oil and the internal high-pressure penetrant does not penetrate the heat shrinkable tube during the test. The filter screen membrane between the rock sample and the seepage indenter can prevent the rock debris generated by the rock sample damage from entering the seepage indenter to block the seepage pipe.

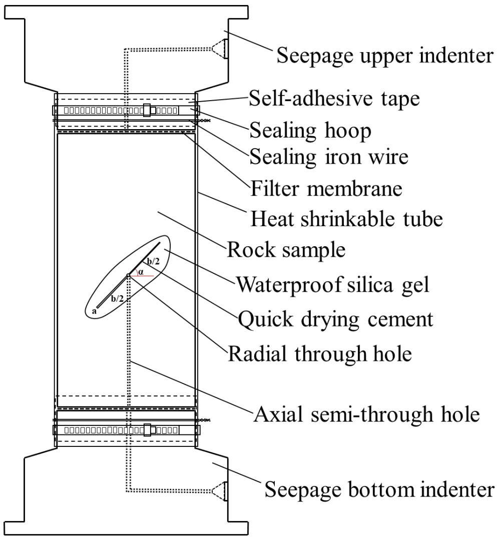

Figure 2. Sealing diagram of rock sample with single fracture for THM coupling triaxial test.

3 THM COUPLING TRIAXIAL TEST METHOD FOR ROCK WITH FRACTURE

For rock samples with fracture, the loading and unloading of test conditions (confining pressure, hydraulic pressure, temperature, axial pressure) are also easy to lead to accidental damage of rock samples. In addition, the rock sample is always in the closed environment of triaxial chamber during the test, so it is difficult to observe the crack propagation process.

3.1 *Operation process of the THM coupling triaxial test*

Firstly, the processed fractured rock sample shall be saturated to avoid water absorption of unsaturated rock sample affecting subsequent permeability measurement. After sealing the saturated rock sample and installing it in the center of the chassis of the triaxial test device, the axial and circumferential deformation extensometers are installed. After preloading with an axial force of 1 kN, the gas in the seepage pipe should be completely discharged, and then connect it with the seepage indenter to form the seepage path. Temperature sensors are arranged at the upper, middle and lower positions of the rock sample.

After the installation of rock samples, the predetermined confining pressure, initial hydraulic pressure, temperature and test hydraulic pressure shall be loaded successively. First, load the confining pressure to the predetermined value, and simultaneously apply an initial osmotic water pressure less than the confining pressure at both ends of the rock sample, which not only supplements the water loss during sample preparation and installation, but also prevents the water liquefaction when the temperature of the triaxial chamber exceeds 100 °C. After the sample is re-saturated, keep the confining pressure and hydraulic pressure stable, heat the triaxial chamber to the predetermined temperature and keep it for at least 1h, and finally simultaneously apply the predetermined test hydraulic pressure at both ends of the rock sample.

After the confining pressure, temperature and hydraulic pressure are stable, the axial load is applied by force control at the rate of 0.5~1 kN/s. When the axial stress reaches the predetermined level, the loading will be stopped. By controlling the water pressure at both ends of the rock sample, the seepage will be formed under the pressure difference, and the permeability will be measured to indirectly characterize the water passing capacity, that is, the connection of the internal micro-fracture of the rock sample under different stress levels. For brittle hard rock that may undergo severe damage, when the circumferential deformation rate of the rock sample is monitored to be accelerated, that is, close to the peak strength, the axial loading control mode can be switched to the circumferential deformation control to obtain the post-peak stress-strain curve, during which the appropriate time is selected to measure the permeability according to the shape of the stress-strain curve.

At the end of the test, in order to ensure that the rock sample will not be damaged twice and protect the sealing system, first unload the axial pressure to a lower level (determined according to the hydraulic pressure), and then unload the hydraulic pressure with the protection of the original confining pressure. Stop the servo control of temperature and confining pressure, so that the triaxial chamber and internal silicone oil will naturally cool. The confining pressure will slowly drop at the same time. When the temperature drops to room temperature, unload the confining pressure and the axial stress to 0 MPa in turn to take out the rock sample, and the test was completed.

3.2 Application of THM coupling triaxial test method

The intact granite on the shallow surface near the BS33 borehole in Beishan, Gansu Province, the potential site area for HLW repository in China, was selected to be processed into cylindrical standard samples with a diameter of 50 mm and a height of 100 mm. A fracture with a width of 0.5 mm, an inclination of 45 °, and a length of 2 cm is prefabricated on it. The THM coupling triaxial test was carried out on the fractured granitic samples according to the test method mentioned above. Firstly, a predetermined confining pressure of 20 MPa and an initial osmotic water pressure of 1 MPa at both ends of the rock sample were loaded and kept stable. Then the triaxial chamber was heated to the predetermined temperature of 60℃. After the temperature stabilizes for 1 hour, a test hydraulic pressure of 5 MPa was simultaneously applied at both ends of the sample. Subsequently, axial loading began. During the axial loading process, the permeability of the rock sample was measured at different axial stress levels. After obtaining the peak strength, unload the axial force step by step, and measure the permeability repeatedly at the stress level where the permeability was measured at the loading stage, and compare the permeability at the same stress level after the peak damage.

The typical stress-strain curve is similar to that of the intact rock sample, as shown in Figure 3. The permeability change law is basically consistent with the stage characteristics of the stress-strain curve. The micro-cracks gradually compact and close in the initial loading section, resulting in the gradual decrease of permeability, reaching the lowest at 66% of the peak strength. Then it began to rise, with the initiation of new cracks and the expansion of existing cracks in the plastic deformation section, the permeability increased significantly. In the unloading section, the opening cracks gradually closes, and the permeability decreases. However, due to the irreversible damage caused by the crack initiation in the loading stage, the permeability of the unloading section is higher than that of the same stress level in the loading stage.

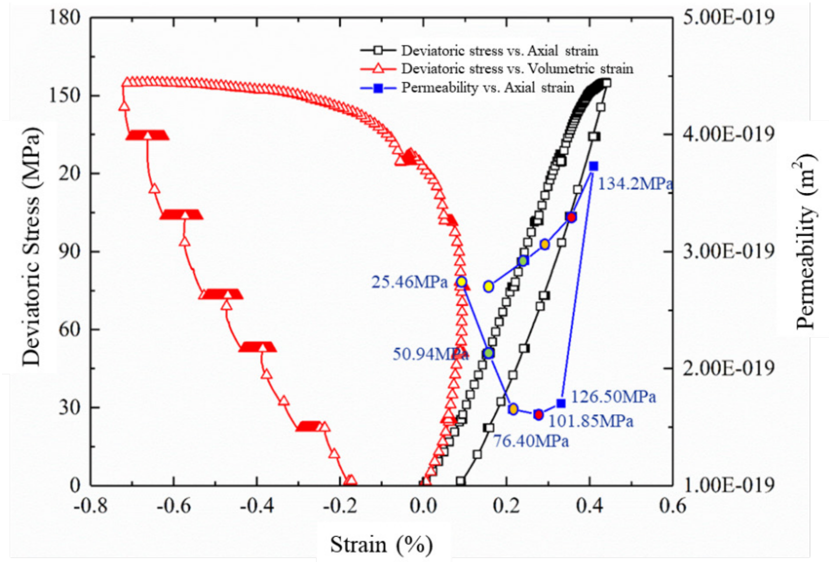

Figure 3. Permeability variation of rock sample during test (confining pressure 20MPa, 60℃, hydraulic pressure 5MPa).

4 CONCLUSION

The processing and sealing technique of rock samples proposed in this paper can prefabricate fracture with controllable length, width and inclination on natural rock samples, and has little damage to rock samples. It solves the water and oil leakage problems that are easy to occur under the THM coupling condition. Therefore, it can truly reflect the mechanical and hydraulic characteristics, as well as the deformation and failure mechanism of fractured rock under the THM coupling condition.

The THM coupling triaxial test method proposed solves the problem that rock samples with fracture are easy to be destroyed under complex loading and unloading of THM conditions, and effectively improves the success rate of the test. This method has been successfully applied to the study of the mechanical and hydraulic characteristics of Beishan granite under the THM coupling conditions. On the basis of conducting systematic research on Beishan granite with standard artificial fracture, the test method proposed in this article will be used for the granite containing natural fracture to further study the effects of roughness, weathering, and infilling on the characteristics of THM coupling of the rock, which will provide key parameters for the long-term safety assessment and engineering design and construction of the repository.

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