Experimental study on the failure behaviour of granite with single fracture under THM coupling condition

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Abstract: During the operation of the high-level radioactive waste (HLW) repository, the expansion and evolution law of surrounding rock fractures under the coupling effect of radiation heat, groundwater and stress field is of great significance for the long-term safety evaluation 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. This method allows the hydraulic pressure to act directly in the fracture, and 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. Subsequently, the granite in Beishan, the preferred pre-selected area of HLW repository in China, was processed into rock sample with single fracture, and triaxial tests were carried out under the condition of THM coupling. The acoustic emission (AE) technology, permeability measurement and CT scanning technology are applied jointly to characterize the internal cracks of rock samples and the propagation law. On this basis, the THM coupling effects on the mechanical properties and failure behaviour of granite with single fracture were mainly studied, which provides basis for long-term safety evaluation and engineering design of HLW repository.

1. Introduction
The host rock in the preferred pre-selected area of HLW geological repository in China (Beishan area in Gansu Province) is granitic rock, which has the advantages of high strength and low permeability. However, various fractures and discontinuities in host rock may degrade the engineering characteristics of the rock mass, and also constitute a potential channel for groundwater seepage and nuclide migration. During the operation of the repository, the surrounding rock of the waste package will be in a complex multi-field coupling environment of radiation heat, groundwater and in-situ stress, and its hydraulic and mechanical characteristics directly affect the long-term safety performance of the repository.

For the host rock of the repository, the key to obtain its strength and deformation characteristics and internal crack propagation law under the combined action of temperature, hydraulic pressure and stress level is the mechanical test under complex conditions and the real-time acquisition and accurate characterization of the microstructure evolution of the rock sample. Although the real response of rock mass can be obtained by in-situ test [1,2], the cost is too high. It is an effective means to study the permeability and mechanical properties, crack propagation and failure law of fractured rock by...
simulating multi field coupling environment in laboratory. For example, the influence of stress state and damage evolution of rock on its permeability [3,4], as well as the crack propagation law [5] were studied through hydro mechanical coupling test, the influence of temperature on permeability [6-7] and the influence of fracture flow on temperature field [8] were studied by hydro thermal coupling test, the influence of temperature on rock mechanical properties [9], permeability properties [10] and fracture propagation failure [11] were studied by preheating treatment. On the other hand, the real sense of thermo-hydro-mechanical (THM) coupling triaxial test is mostly applicable to intact rock samples [12], rock samples with closed joint [13], or rock samples with through fractures [14]. Under the condition of multi field coupling, it is difficult to obtain the fracture propagation law and the full stress-strain curve due to the immature THM coupling testing technology of rock samples with fractures.

Starting from the breakthrough of fractured rock sample preparation technology, this paper proposed a set of THM coupling triaxial test method for rock with fracture, which solves the problem that the rock sample with fracture is easy to be destroyed due to the existence of initial defects during complex thermo-hydro-mechanical loading and unloading. The method is successfully applied to study the triaxial mechanical properties of Beishan granite under the THM coupling condition. Combined with acoustic emission (AE), CT scanning and other micro structure observation techniques, the propagation law of cracks in rock sample is comprehensively characterized, and the influence mechanism of crack propagation on mechanical and permeability properties of rock samples is revealed.

2. THM coupling triaxial test method for granite with single fracture

2.1. Preparation and sealing of fractured granite
In order to make the water pressure directly act inside the fracture of rock samples and study the propagation law of cracks under the THM coupling condition, the wire cutting technology combined with the water jet technology was used to process the single fracture in the middle of natural intact rock samples. With the help of the water jet, a hole was drilled from the center of rock sample’s end face to connect with the central fracture to form the seepage channel, as shown in figure 1.

For the rock sample in the THM coupling triaxial test, the external confining pressure and internal hydraulic pressure are easy to break through the heat shrinkable tube at the prefabricated fracture as an initial defect, which leads to the failure of the rock sample. Therefore, quick drying cement combined with waterproof silica gel is used to seal the surface of the prefabricated fracture. The joint sealing between the rock sample and the seepage indenter was realized by a combined sealing system including heat shrinkable tube, self-adhesive tape, sealing hoop and iron wire (figure 1), so as to prevent the external pressure oil to seep in and the internal high-pressure liquid to seep out during the test.
2.2. Process control of THM coupling triaxial test

The sealed rock sample and seepage indenters are first installed on the bottom plate of the triaxial test apparatus (figure 2), and then the axial and circumferential extensometers are installed. With the protection of preloading axial force of 1kN, the gas in the seepage tube is discharged. Temperature sensors are arranged at the upper, middle and lower positions of the rock sample to measure and feed back the ambient temperature of the rock sample, and the heating power is adjusted accordingly.

According to the test plan, after loading the confining pressure to the predetermined value, an initial water pressure lower than the confining pressure is simultaneously applied at both ends of the rock sample to re-saturate it, which can also prevent water vaporization when the triaxial chamber temperature is too high. After the rock sample no longer absorbs water, start heating the chamber and maintain the predetermined temperature for 1 hour. Subsequently, a predetermined test water pressure is simultaneously applied to both ends of the rock sample. The water pressure at the inlet end can directly act on the interior of the prefabricated fracture through the axial semi-through hole to study
the direct influence of the water pressure on its expansion. When the multi-field coupling environment is stable, the axial loading can be started. At the end of the test, in order to ensure that the rock sample does not undergo secondary damage and adversely affect the observation of its failure mode, the axial pressure should be unloaded to a lower level, and at the same time, ensure that the water pressure does not lift the upper end. Then unload the water pressure to 0 MPa under the protection of confining pressure, stop the servo control of temperature and confining pressure, so that the triaxial chamber and the internal silicone oil are naturally cooled to room temperature. During the cooling process, the confining pressure gradually decreases. When the temperature drops to room temperature, the confining pressure is unloaded to 0 MPa, then the axial pressure is completely unloaded and the rock sample can be taken out for subsequent observation.

During the test, on the one hand, acoustic emission (AE) monitoring synchronized with axial loading is used to record the initiation and propagation of rock sample cracks, on the other hand, the permeability is used to indirectly reflect the water passing capacity of the rock sample, that is, to overall characterize the cracks quantity and connectivity in the rock sample. After the test, CT scan and reconstruction can be performed on the rock sample to obtain the spatial distribution of internal micro-cracks, and the difference of crack morphology under different test conditions can be compared and analyzed, so that the THM coupling effect mechanism of micro-crack propagation can be revealed.

3. THM coupling triaxial test of Beishan granite

The research object is the granite in Beishan area, Gansu Province, the preferred pre-selected area for HLW geological disposal in China. The shallow intact granite near borehole BS33 in Beishan area was processed into a cylindrical rock samples with a diameter of 50 mm and a height of 100 mm. A fracture with a width of 0.5 mm, an inclination angle of 45°, and a length of 2 cm was prefabricated on it. The granite sample with single fracture was then obtained.

The test confining pressure, hydraulic pressure and temperature were determined according to the site characteristics of Beishan such as in-situ stress, regional groundwater and the requirements of HLW repository. The above test conditions are combined and the test is carried out in accordance with the THM coupling triaxial test method described in section 2. The specific test plan and results are shown in table 1. In addition to the AE monitoring throughout the test, when loaded to different stress levels, the water pressure at the inlet end and outlet end of the rock sample was controlled to form seepage under the action of the pressure difference between the two ends, and the current permeability of the rock sample was measured. After reaching the peak strength, the axial force was unloaded step by step, and the permeability was repeatedly measured at the stress level of permeability measurement during the loading stage. The permeability changes under the same stress level before and after the failure were compared.

| Confining pressure (MPa) | Temperature (°C) | Initial water pressure (MPa) | Test water pressure at inlet (MPa) | Shear strength (MPa) |
|-------------------------|------------------|------------------------------|----------------------------------|---------------------|
| 20                      | 30               | 0.5                          | 3                                | 182.96              |
|                         |                  | 0.5                          | 5                                | 171.61              |
|                         | 60               | 0.5                          | 3                                | 172.25              |
|                         |                  | 0.5                          | 5                                | 175.08              |
|                         | 90               | 0.5                          | 3                                | 184.07              |
| 15                      | 30               | 1.5                          | 4                                | 169.13              |
|                         |                  | 0.5                          | 3                                | 162.08              |
Influence of THM coupling condition on mechanical properties of granite with single fracture

4.1. Analysis of typical test results

The typical stress-strain curve of fractured granite in THM coupling triaxial test is shown in figure 3. Although there is no obvious compaction stage, the elastic and plastic deformation stage can still be distinguished. The change of permeability is basically consistent with the section characteristics of the stress-strain curve. The permeability of rock sample in the elastic stage of initial loading decreases with the gradual compaction and closure of micro-cracks, and then increases significantly in the plastic deformation stage with the initiation of new cracks and the propagation of existing cracks. After the peak strength, with the release of the axial pressure during unloading, the water-passing capacity of the rock sample is enhanced. Due to the irreversible damage caused by the crack initiation in the plastic deformation stage before the peak, the permeability in the unloading stage is higher than that in the loading stage under the same stress level.

![Figure 3](image.png)

**Figure 3.** Stress-strain curve and permeability variation of rock sample with single fracture during THM coupling triaxial test

The accumulative AE hits number curve (figure 4) also reveals the same crack propagation law. There is almost no AE signal in the elastic stage. When the axial loading is stopped to measure the permeability, both the axial strain and the AE hits number increase slightly. After entering the plastic deformation stage, the AE hits number increases obviously, and it increases sharply near the peak strength, indicating that the internal micro-cracks penetrate through to form macro-cracks.
4.2. **Influence of hydraulic pressure on strength and deformation characteristics**

Under the confining pressure of 20 MPa, both of the test results under 30 °C and 60 °C show that the brittleness of fractured rock sample is weakened and the ductility is enhanced under the action of hydraulic pressure, and the strengthening effect is more obvious when the hydraulic pressure difference between the two ends of the rock sample is greater (figure 5). The increase in hydraulic pressure difference not only causes the peak strength of the fractured granite to decrease, but also the deviator stress vs. axial strain curve no longer has obvious compaction stage, and the elastic modulus decreases to varying degrees. On the one hand, the presence of water in granite cracks softens the mineral particles and intergranular fillings, and reduces the ability of rock to resist tensile cracking. In addition, if the hydraulic pressure forms stress concentration at the crack tip, it will also promote the propagation of existing cracks.
4.3. Influence of hydraulic pressure on fracture propagation and failure characteristics

When the confining pressure is 15 MPa and temperature is 60 °C, the permeability vs. axial strain curves of rock samples under different hydraulic pressures (figure 6) show that the permeability of the rock sample with single fracture increased with the hydraulic pressure increasing if other conditions are same.

When other conditions are the same, the greater the osmotic pressure difference is, the greater the permeability of fractured rock sample is. Even if the hydraulic pressure difference is the same, the permeability of the single fractured rock sample in the test with a larger initial hydraulic pressure is relatively greater throughout the test, and the increase in permeability is greater after entering the plastic deformation stage.

Figure 7 is the CT scanning reconstruction image of the rock sample after the test with the test water pressure of 3MPa and 5MPa respectively. It can be seen that the number and scale of cracks formed during rock sample failure are larger when the test water pressure is 5 MPa. That is to say, in the THM coupling triaxial test of rock sample with single fracture, the larger hydraulic pressure difference is helpful to the crack propagation, thereby accelerating the seepage. Furthermore, the internal water pressure in the new cracks promotes continuous crack propagation. Under the action of this positive mutual feedback, a larger hydraulic pressure difference leads to larger fracture with straight shape, better connectivity and higher permeability after failure.
5. Conclusions

The proposed processing and sealing technique for rock samples with single fracture, as well as the THM coupling triaxial test method which incorporates the acquisition and characterization of the fracture structure, effectively solves the problem that the rock sample with prefabricated fracture is easy to be destroyed under the complex loading and unloading conditions in the THM coupling triaxial test.

This method has been applied to the THM coupling triaxial tests of Beishan granite with a single prefabricated fracture, and the following conclusions are drawn.
(1) Under THM coupling conditions, the effects of confining pressure, hydraulic pressure and temperature on the mechanical properties of granite sample with single fracture decrease in order. Under higher confining pressure, the internal crack propagation of the rock sample is restricted, the permeability is lower, and the strength increases correspondingly.

(2) The seepage and fracture expansion promote each other under higher hydraulic pressure difference, resulting in a decrease in the strength, a greater permeability, a larger size and straight fracture, together with better connectivity of the rock sample.

(3) The effect of hydraulic pressure difference, especially the temperature on the permeability of the rock sample and the expansion of fractures will be weakened under the constraint of higher confining pressure.

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