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# Experimental Study of Thermal-Hydro-Mechanical Behavior of Gneiss Under True Triaxial Compression

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## Abstract

The thermal-hydro-mechanical (THM) coupling behavior of metamorphic rocks under a true triaxial stress state is a key issue in the field of deep underground engineering. However, no such research has been reported so far due to the lack of test equipment. This paper conducts THM-coupled true triaxial compression experiments on gneiss taken from a deep tunnel in Tibet, China, using a self-developed hard rock THM-coupled true triaxial test system. The effects of temperature and water pressure on the strength and water permeability under true triaxial compression conditions were revealed. The evolution of water permeability with deviatoric stress was examined, and the relationship between the variation of water permeability and failure mode changes was discussed. It was found that high temperatures can lead to significant strength deterioration and increased permeability of gneiss. A temperature of 60°C can cause the strength to decrease by 28% and the water permeability to increase by about an order of magnitude. The increase in the number of secondary shear failure surfaces induced by high water pressure and temperature contributes to the increase in water permeability in the post-peak stage. The research results serve as an important reference for understanding the THM coupling behavior of rocks under complex stress paths.

## Keywords

Deep tunnel, Gneiss, THM properties, True triaxial compression

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# 1 Introduction

Deep tunnels in western China often pass through metamorphic rock formations. In the complex geomechanical environment, where high geothermal temperatures, high geostress, high water pressure, and metamorphic rocks coexist, the construction of these tunnels faces threats such as rock bursts, large deformations, and sudden water gushing. Therefore, the thermo-hydro-mechanical (THM) behavior of metamorphic rocks under coupled conditions has garnered significant attention.

Studies on the THM behavior of metamorphic rocks have focused on understanding the effects of temperature, pressure, and water pressure on rock properties. For instance, high-temperature true triaxial compression tests have explored the influence of temperature on the strength of gneiss, showing that increasing temperature reduces rock strength and enhances microcrack development (Zhou et al., 2024). Triaxial compression tests have also studied the effects of temperature and pressure on the permeability of amphibolite and gneiss, revealing that high temperatures lead to crack formation, which increases permeability (Zharikov et al., 2003). Additionally, triaxial compression tests have explored the hydro-mechanical coupling behavior of transverse isotropic gneiss, demonstrating that rock structure and stress conditions significantly influence its mechanical properties and permeability (Mateo and Marie, 2020). Recently, some papers have reviewed past scientific advances in the THM behavior of rocks and highlighted that coupled THM processes are a promising direction for future research (Chin-Fu Tsang, 2024).

Previous studies underscore the complex and critical role of THM interactions in understanding rock behavior in deep engineering contexts. It is particularly noteworthy that in deep underground engineering, rocks are subjected to a true triaxial stress state ($\sigma_1 > \sigma_2 > \sigma_3$). However, to date, no studies have analyzed the THM properties of rocks under a true triaxial stress state.

In this study, true triaxial compression tests coupled with thermal-hydro-mechanical effects were conducted on gneiss extracted from a deep tunnel in Tibet, China. The influence of temperature and water pressure on strength and water permeability was investigated. Additionally, the evolution of water permeability during the deviatoric stress loading process was examined. Finally, the variations in water permeability were discussed in relation to changes in failure modes.

# 2 Material and test methods

## 2.1 Material

The gneiss shown in Fig. 1 was collected from a deep-buried tunnel in western China. The original rock blocks used to prepare the samples were located at a depth of approximately 1,000 meters below the surface. According to the recommendations of the International Society for Rock Mechanics (ISRM), specimens with a height of 100 mm and a width and length of 50 mm were prepared. Each specimen was cut using a diamond wire saw and polished at both ends, with tolerances for end surface flatness and perpendicularity of ±0.01 mm and ±0.02 mm, respectively.

The gneiss samples are primarily composed of quartz, feldspar, mica, titanite, carbonate, and opaque minerals, with the remaining portion consisting of other minerals. The grain size of the samples ranges from 0.15 to 2 mm. The density of the tested samples ranges from 2.66 to 2.76 g/cm³.

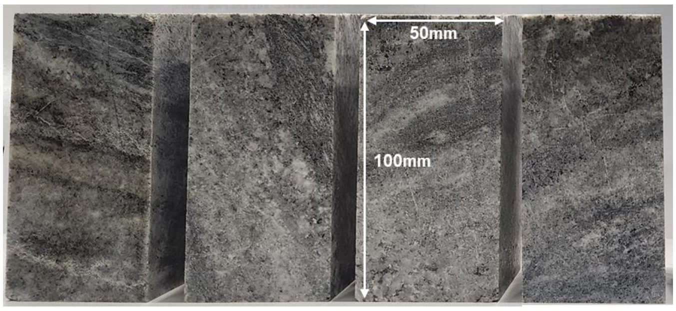



Fig. 1 Gneiss samples

## 2.2 Experimental apparatus

The testing system depicted in Fig. 2 was utilized to examine the THMcoupling behavior of gneiss under true triaxial stress. This system was developed at the Key Laboratory of the Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, China. It comprises five main modules: the true triaxial stress loading module, temperature loading module, seepage module, deformation monitoring module, and data processing module. Detailed information about the experimental system can be found in our published paper (Wang et al. 2022). Here, we provide a brief overview of the critical aspects of this testing system.

The THMcoupling true triaxial testing system shown in Fig. 2 applies the maximum and intermediate principal stresses through a rigid loading frame, with a maximum capacity of 2000 kN and an accuracy of 0.1 kN. The minimum principal stress is applied servo-hydraulically, with a maximum capacity of 70 MPa and an accuracy of 0.1 MPa. The system can achieve a maximum temperature of 250°C and a maximum water pressure of 70 MPa, with accuracies of 0.1°C and 0.1 MPa, respectively. Deformation in the principal stress directions is measured using LVDTs, with a range of ±2.5 mm and an accuracy of 1 μm.

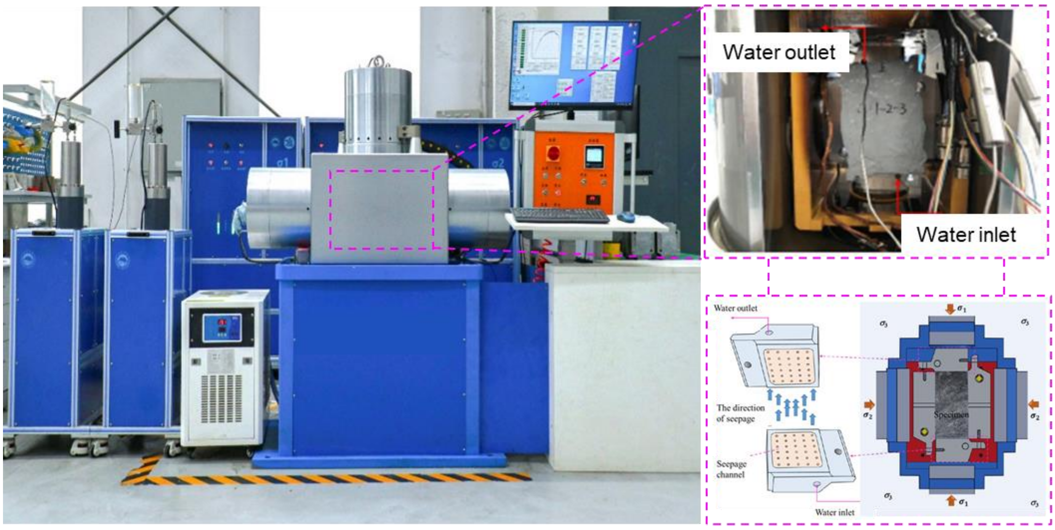



Fig. 2 Schematic of a THM coupled true triaxial testing system for hard rock, modified from Wang et al. (2022).

## 2.3 Experimental scheme and procedures

Geological exploration shows that the geo-stress is about 30 MPa at a depth of 1000 meters in the area where the rock blocks are collected. Therefore, in the THM coupling true triaxial tests, an intermediate principal stress of 25 MPa and a minimum principal stress of 5 MPa was used to simulate the in-situ stress enviornment.

Engineering practice indicates that water seepage is often encountered during the excavation of the studied tunnel, with water pressure generally ranging from 1 MPa to 3 MPa. Thus, representative water pressures of 1 MPa and 3 MPa were used in the THM coupling true triaxial tests. Furthermore, two representative temperatures of 25°C and 60°C were selected to investigate the effect of temperature on the strength and seepage behavior. Among these, 60°C is one of the most representative rock temperatures for the studied tunnel. The experimental scheme is summarized in Table 1.

Table 1. The experimental scheme

| No. | Temperature (°C) | Water pressure (MPa) | Intermediate principal stress (MPa) | Minimum principal stress (MPa) |
|---|---|---|---|---|
| 1 | 25 | 1 | 25 | 5 |
| 2 | 25 | 3 | 25 | 5 |
| 3 | 60 | 1 | 25 | 5 |
| 4 | 60 | 3 | 25 | 5 |

In the present study, Darcy's law was used to determine the water permeability  of gneiss (Wyckoff et al. 1933; Zhu and Wong 1997; Liu and Shao 2017), and the specific expression is as follows:

$$K=\frac{\mu q L}{A(P_{\text{up}}\text{-}P_{\text{down}})}$$

Where $K$ Water permeability ($m^2$)

$\mu$ Viscosity coefficient of the fluid (Pa·s)

$q$ Volume of water flowing through the sample per unit time ($m^3/s$).

$L$ Water flow length (m), which is the height of the sample;

$A$ Cross-sectional area of the seepage sample ($m^2$);

$P_{up}$ Water pressure upstream of the sample (pa);

$P_{down}$ Water pressure downstream of the sample (pa).

A THM coupling true triaxial compression test involves five main loading stages: the hydrostatic stress loading stage, the temperature loading stage, the biaxial stress loading stage, the water pressure loading stage, and the deviator stress loading stage. The specifics of each loading stage are outlined below:

(i) Hydrostatic Stress Loading Stage: Hydrostatic pressure is applied at a constant rate of 0.2 MPa/s until it reaches 5 MPa. After the deformation stabilizes, the process proceeds to the next stage.
(ii) Temperature Loading Stage: The temperature is increased to a selected value and maintained for 2 hours to ensure a uniform temperature field is formed in the specimen. This stage simulates the thermal conditions experienced in deep buried tunnels.
(iii) Biaxial Stress Loading Stage: The minimum principal stress is maintained at 5 MPa, while the maximum principal stress and the intermediate principal stress are simultaneously loaded to 25 MPa at a constant rate of 0.5 MPa/s.
(iv) Water Pressure Loading Stage: Water pressure is applied to a given value (e.g., 1 MPa) at a constant rate of 0.1 MPa/s.
(v) Deviator Stress Loading Stage: The maximum principal stress is monotonically loaded at an initial constant rate of 0.5 MPa/s while and are kept constant. When the deviatoric stress reaches the damage stress is loaded at a fixed strain rate of .During this stage, water permeability is monitored in real-time.

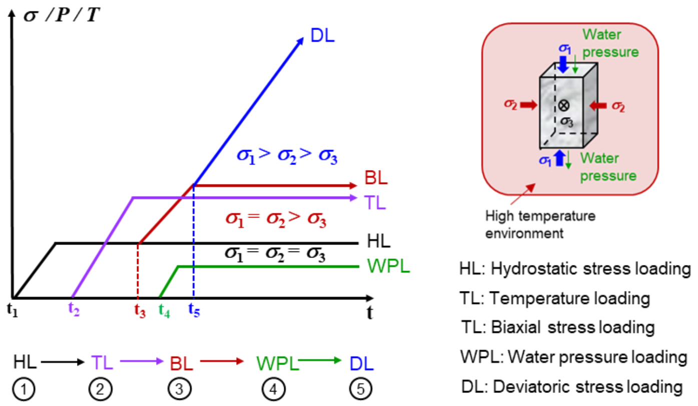



Fig. 3 Laoding path in the THM coupled true triaxial compression test

# 3 Results and analysis

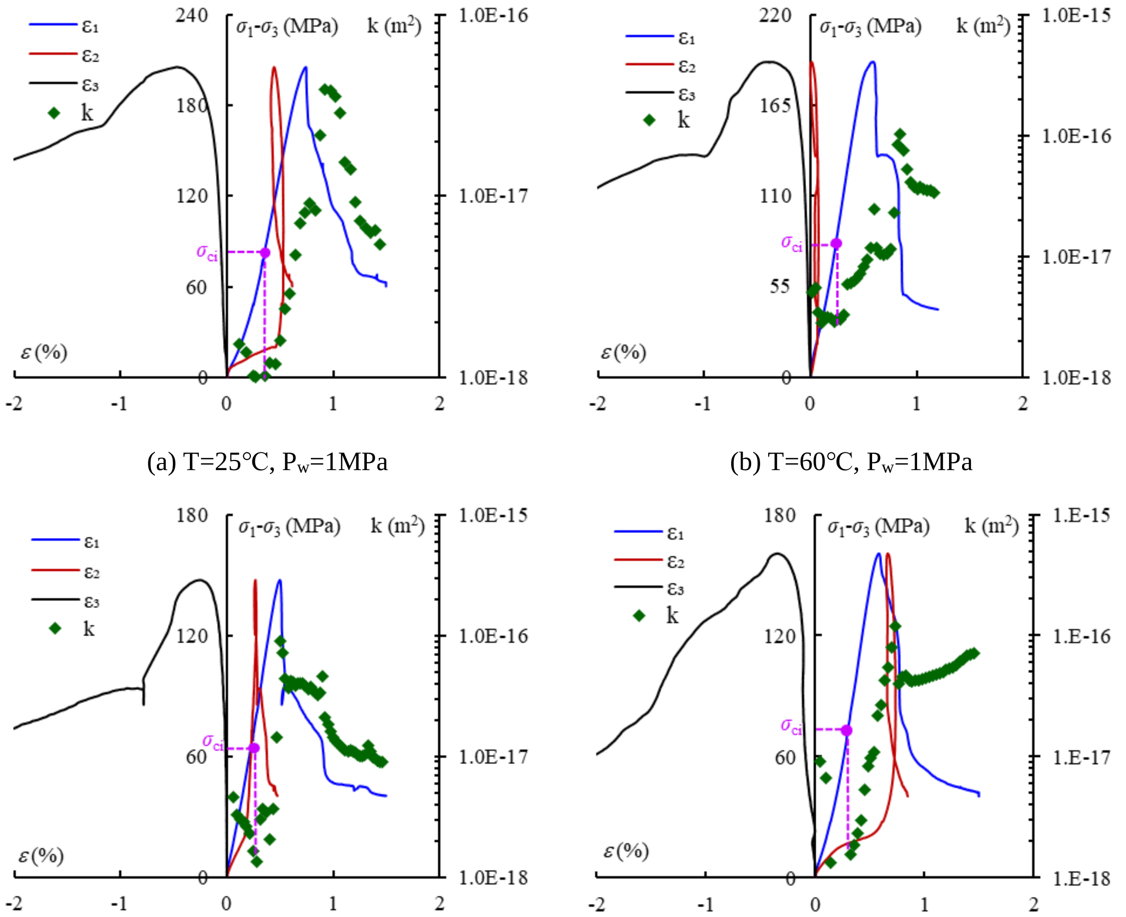
## 3.1 Experimental results

The results of THM coupling true triaxial experiments on gneiss at different temperatures and different water pressures are given in Fig.4. These experimental results were measured at $\sigma_2$=25MPa and $\sigma_3$=5MPa. In each figure, we present the stress-strain relationships and the evolution of water permeability with deviatoric stress. Here, $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ represent the strain in the directions of the maximum principal stress, intermediate principal stress, and minimum principal stress, respectively. $\sigma_1$-$\sigma_3$ represents the deviatoric stress.

Fig.4 illustrates the evolution of water permeability in gneiss during the entire deviatoric stress loading process in THM coupled true triaxial compression tests. Under experimental conditions, the water permeability of gneiss ranges from $10^{-18}$ to $10^{-15}$ m². When temperature, stress level, and water pressure are constant, water permeability is governed by deviatoric stress. When the deviatoric stress is below the initiation stress, an increase in deviatoric stress closes the initial pore cracks in the gneiss, leading to a decrease in water permeability. Conversely, when the deviatoric stress exceeds the initiation stress, secondary cracks develop within the rock, creating channels for seepage, which results in an increase in water permeability. Therefore, in the pre-peak stage, the water permeability of gneiss first decreases and then increases with rising deviatoric stress.

In the post-peak stage, cracks within the rock coalesce to form a macroscopic shear failure surface, resulting in the maximum water permeability appearing in this stage. Furthermore, Figure 4 indicates that in the post-peak stage, water permeability exhibits two distinct evolutionary patterns with changes in deviatoric stress. One pattern shows an initial increase followed by a decrease as deviatoric stress decreases (Fig.4 (a)-(c)), while the other pattern shows an initial increase, followed by a decrease, and finally another increase as deviatoric stress decreases (Fig.4 (d)). Thus, the water permeability are evidently influenced by the deviatoric stress in THM coupled true triaxial compression tests.

From Fig.4, it is evident that under thermo-hydro-mechanical coupled true triaxial compression, both temperature and water pressure significantly influence the strength and permeability of the gneiss. A detailed analysis will be provided in the following sections.




(a) T=25°C, $P_w$=1MPa

(b) T=60°C, $P_w$=1MPa

(c) T=25°C, $P_w$ =3MPa

(d) T=60°C, $P_w$ =3MPa

Fig.4 Results of true triaxial tests with THM coupling at $\sigma_2$=25MPa and $\sigma_3$=5MPa

## 3.2 Effect of temperature and water pressure on strength

Figure 5 presents the true triaxial compressive strength of gneiss under varying water pressures and temperatures. At 1 MPa water pressure, the strengths are 205.4 MPa at 25°C and 147.6 MPa at 60°C. At 3 MPa water pressure, the strengths are 191.3 MPa at 25°C and 161.1 MPa at 60°C. Thus, one can calculate that there is a 28.2% and 15.6% reduction in strength at 1 MPa and 3 MPa water pressures, respectively, with the temperature increasing from 25°C to 60°C. Therefore, under thermo-hydro-mechanical coupled true triaxial compression conditions, elevated temperatures significantly degrade the strength of gneiss.

The influence of water pressure on the true triaxial compressive strength of gneiss under thermo-hydro-mechanical coupling was also analyzed based on the results shown in Figure 5. It is evident that the strength does not exhibit a consistent trend with changes in water pressure. For instance, at 25°C, when the water pressure increased from 1 MPa to 3 MPa, the strength decreased from 205.4 MPa to 191.3 MPa. Conversely, at 60°C, an increase in water pressure from 1 MPa to 3 MPa resulted in an increase in strength from 147.6 MPa to 161.1 MPa. Therefore, based on the current results, it is challenging to definitively determine the effect of water pressure on the true triaxial compressive strength of gneiss. This inconsistency may be attributed to the heterogeneity of the gneiss or the relatively low range of water pressure variation.

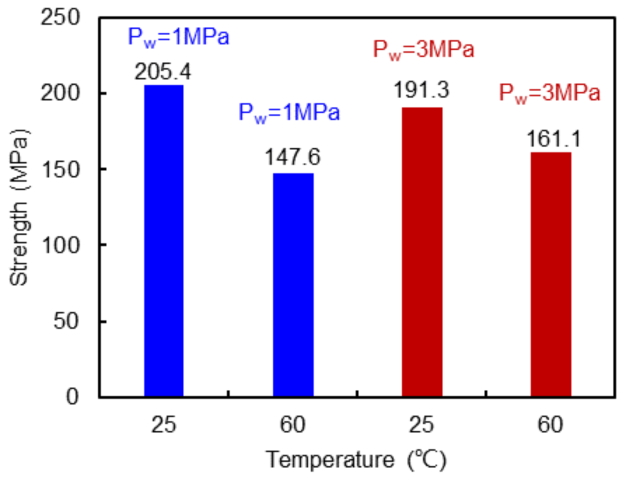



Figure 5. Variation of strength with temperature under different water pressures

## 3.3 Effect of temperature and water pressure on permeability

The maximum and minimum water permeability of the gneiss under each experimental condition were determined according to Fig.4, and the effects of temperature and water pressure were subsequently analyzed. Fig.6 shows the variation of maximum water permeability with temperature at different water pressures. It can be seen that, at a water pressure of 1 MPa, the maximum water permeability increases from $3.86\times10^{-17}$ m² to $9.0\times10^{-17}$ m² as the temperature rises from 25°C to 60°C. At a water pressure of 3 MPa, this permeability increases from $10.1\times10^{-17}$ m² to $12.0\times10^{-17}$ m² over the same temperature range. Regarding the effect of water pressure, the results at temperatures of 25°C and 60°C both demonstrate that the maximum water permeability increases with increasing water pressure. Therefore, under thermal-hydro-mechanical coupled true triaxial compression, the maximum water permeability of gneiss increases with increasing temperature and water pressure.

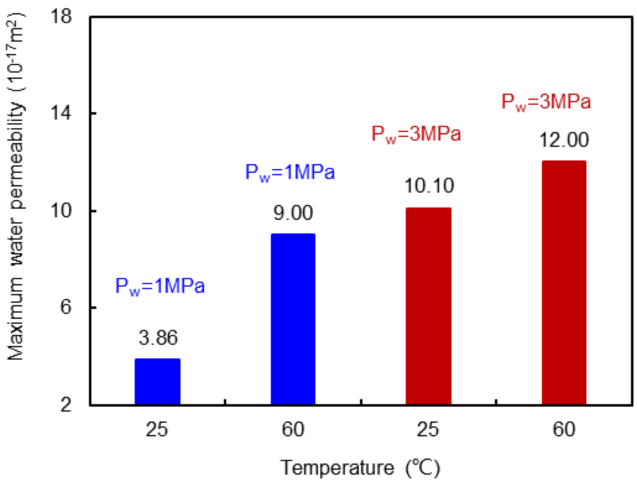



Fig.6. Variation of maximum water permeability with temperature under different water pressures

Fig. 7 illustrates the change of minimum water permeability with temperature at different water pressures. In Fig. 7, the minimum water permeability increases with the increasing in water pressure.

However, it fluctuates with changes in temperature. Thus, it seems that the temperature have no obvious influence on the minimum water permeability.

Fig.4 demonstrates that water permeability is at its minimum during the pre-peak stage and at its maximum during the post-peak stage. Thus, the variation of the maximum and minimum water permeability shown in Figures 6 and 7 indicates that under thermo-hydraulic-mechanical coupled true triaxial compression, the effects of temperature and water pressure on water permeability are more pronounced in the post-peak stage compared to the pre-peak stage.

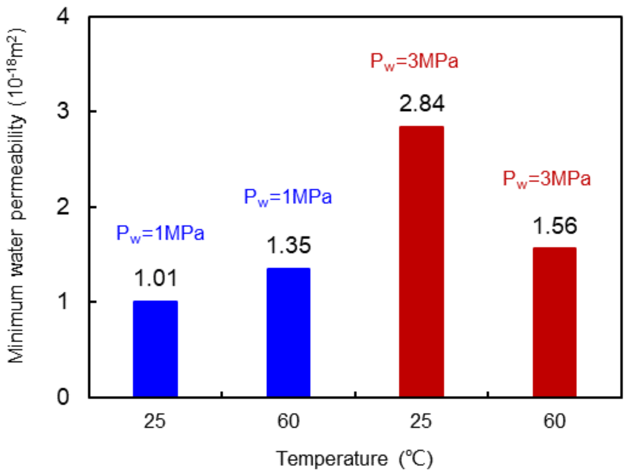
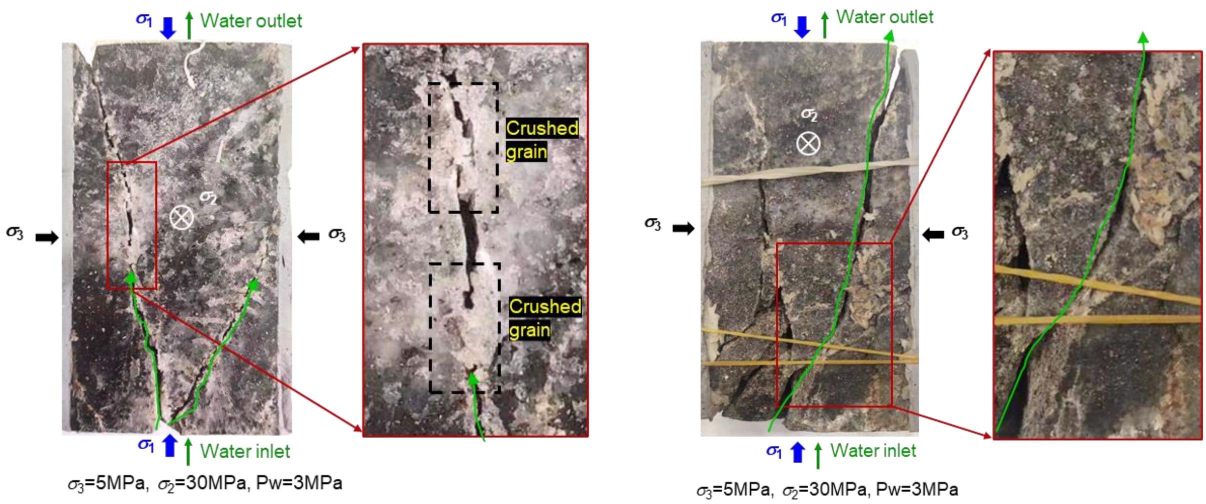



Fig. 7. Variation of minimum water permeability with temperature under different water pressures

## 3.4 Water permeability evolution in the post-peak stage

Macroscopic cracks within rocks serve as channels for fluid flow. Therefore, the failure mode of rocks is closely related to water permeability in the post-peak stage. As shown in Figure 8, under thermo-hydro-mechanical coupled true triaxial compression, gneiss primarily undergoes V-shaped shear failure. When the water pressure is 3 MPa and the temperature is 25°C, a significant amount of mineral particles fill the shear slip surfaces, inhibiting fluid flow within the sample. Consequently, a decrease in water permeability, as shown in Figures 4(a)-(c), is observed in the post-peak stage. However, at a water pressure of 3 MPa and a temperature of 60°C, multiple secondary shear failure surfaces develop near the main shear failure surface. Clearly, the increase in the number of failure surfaces creates additional seepage channels. As a result, a continuous increase in water permeability, as shown in Figure 4(d), is observed in the post-peak stage. Furthermore, higher water pressure and temperature can promote the formation of interconnected shear failure surfaces in the gneiss. Hence, water permeability increases with both water pressure and temperature.




(a) *T*=25℃ (b) *T*=60℃

Figure 8 Typical failure of gneiss under thermo-hydro-mechanical coupled true triaxial compression

# 4 Conclusion

Thermal-hydro-mechanical coupled true triaxial compression tests were conducted on gneiss. Based on the obtained experimental data, the following conclusions can be drawn:

(1) Elevated temperatures significantly degrade the strength while increasing the water permeability of gneiss in thermo-hydro-mechanical coupled true triaxial compression tests. Under the experimental conditions, a temperature of 60°C can cause the strength to decrease by 28% and the water permeability to increase by about an order of magnitude.
(2) In the pre-peak stage, water permeability first decreases and then increases with rising deviatoric stress. In the post-peak stage, water permeability shows two patterns: one with an initial increase followed by a decrease, and the other with an initial increase, followed by a decrease, and finally another increase.
(3) The increase in the number of secondary shear failure surfaces induced by high water pressure and temperature contributes to the increase in water permeability in the post-peak stage. Mineral particles detaching from the matrix due to shear slip can block fluid flow, causing a reduction in water permeability in the post-peak stage.

These findings help in understanding the behavior of rocks under complex stress conditions, which is crucial for the design and stability of deep tunnels. Future research should focus on studying the creep behavior of gneiss under thermal-hydro-mechanical coupling to better predict long-term deformation.

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