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Experimental study of seepage characteristics of single rock fracture based on stress states and stress history

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Abstract: Through seepage tests under different loading and unloading confining pressures and different hydraulic gradients , the authors studied the effects of stress states and stress history on fracture permeability evolution for single granite fracture and sandstone fracture. The results show that there exists a linear relationship between the seepage discharge and osmotic pressure in sandstone fissure under each level of confining pressure. With the increasing in the confining pressure , the permeability of the fracture decreases , but the decreasing rate is changing. During the unloading process , the fracture seepage velocity cannot be fully recovered to the size of the loading process. Therefore , in the unloading process of the confining pressure , the recovery of fracture permeability shows obvious hysteresis effects. The flow rate of the fracture remains unchanged during five cycles of loading and unloading processes of the confining pressure. In each cycle , the evolution character of the flow rate with the confining pressure remains unchanged. These experiments show that the seepage characteristics of sandstone and granite fractures are not the same under the same stress state.

Key words: rock single fracture; rock seepage; stress states; stress history

1 Introduction

Understanding the evolution of rock seepage characteristics with stress state is important in study of rock mechanics and rock engineering (Zhi *et al.* , 2012) , such as in the geological burial of nuclear waste , CO₂ geological sequestration , and exploitation of oil and geothermal resources (Zeng *et al.* , 2012) . In naturally fractured rock masses , permeability of rock is mainly contributed by fracture seepage. The spatial distribution and interconnectivity of fractures , as well as the properties of fluid flow through a single fracture , essentially determine the overall permeability and flow distribution of rock masses (Ju *et al.* , 2013) . Thus , an accurate knowledge and description

of the behavior of fluid flow and the interaction mechanism of stress and fluid flow are of great significance to solving these engineering problems (Xiong *et al.* , 2009) .

Since Snow (1968) proposed cube theorem , the relationship between stress states [normal stress (Shen *et al.* , 2010) , shear stress (Xu & Xie , 2009) , and complex stress (Hou *et al.* , 2011)] and the properties of fluid flow through a single fracture has been studied. However , the literature reveals that no mature theory explains the relationship between stress and single fracture seepage. Nonetheless , the relationship between stress history and single fracture seepage has also been studied (Brace *et al.* , 1968) . However , the study of the relationship between frac-

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ture seepage characteristics and stress state is still in the exploratory stage (Yang *et al.* , 2013) . To improve the exploration in this field ,the relationship between stress and single fracture flow is studied in the present work.

In this study ,we first introduce test methods ,including sample preparation , test equipment , and test processes. Secondly ,laboratory experimental data are used to study the relationship among the seepage characteristics of rock fracture and stress states , stress history , and lithology. Finally , the conclusions of this experimental study are summarized , and suggestions for future research are proposed.

2 Laboratory experiment scheme

2.1 Preparation of rock sample

Two types of lithology are chosen: sandstone and

granite. The mineral composition and quality percent content of the sandstone are as follows: quartz ,54% -59%; alkaline feldspar , 12%-17%; plagioclase , 13%-17%; and others 7%-18%. The mineral composition and quality percent content of the granite are as follows: quartz ,51%-56%; alkaline feldspar ,17%-22%; plagioclase ,21%-27%; and others 1%-3%. All the rock samples measure $\phi 50 \text{ mm} \times H100 \text{ mm}$.

A straight smooth fracture is first cut through each sample in the direction parallel to the axis of the sample (Fig. 1) .

2.2 Laboratory experiment

The experiments in this study are carried out on the fracture flow simulation system , which was developed by the deep geothermal and hot dry rock research team of Jilin University. The main parameters of this experiment system are as follows: confining pre-

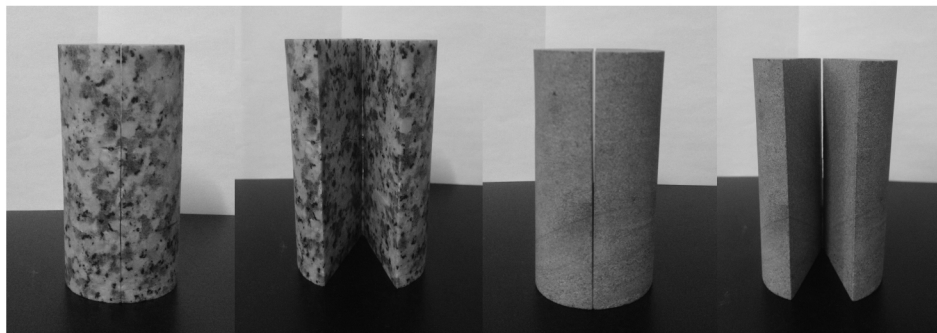


Fig. 1 Rock samples

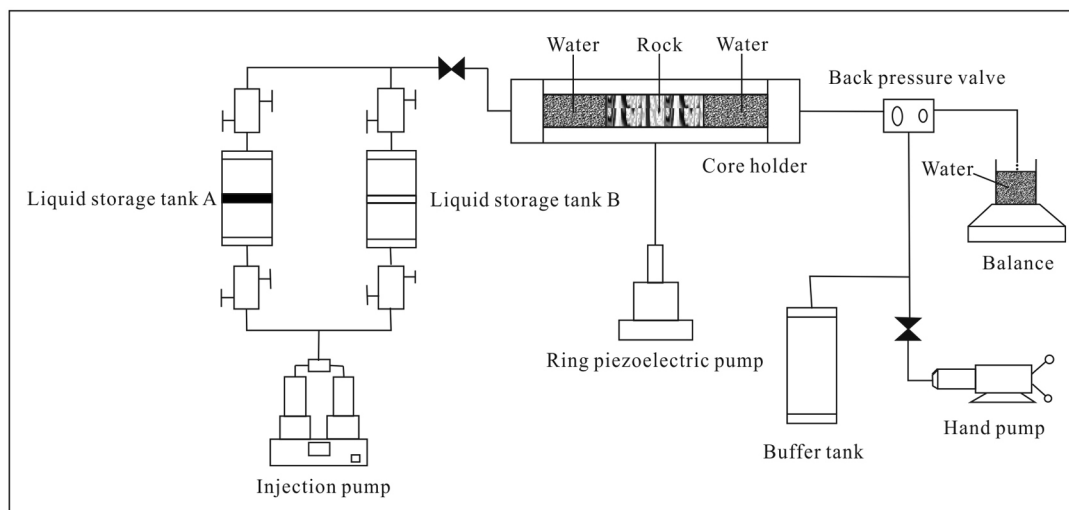


Fig. 2 Structure diagram of rock fracture seepage test system

ssure ,0-40 MPa; osmotic pressure ,0-50 MPa; and temperature ,0-200°C. The diameter of the test sample is required to be around 50 mm , and the height can range from 100 mm to 140 mm. All flow pipelines of the system are made of stainless steel to avoid the corrosion effects of high temperature and pressure environments on the system. An illustrative diagram of the experiment system is shown in Fig. 2.

Working fluids are injected into the rock fracture with an injection pump. Different levels of confining pressure can be applied to the rock sample.

2.3 Experimental procedure

2.3.1 Test under different stress conditions

The artificially made rock sample is first placed into the experiment system. Fracture flow rates are tested while the confining pressure and osmotic pressure are maintained at 5 MPa and 1 MPa , respectively. At the same level of confining pressure , osmotic pressure is gradually increased to the ultimate value of 70% of the confining pressure. Thereafter , the confining pressure is increased to 10 , 15 , 20 , 25 , and 30 MPa. The experiments are repeated as mentioned above , under different confining pressures.

2.3.2 Test under different stress histories

The artificially made rock sample is first placed into the experiment system. The fracture flow rates are tested while the confining pressure and osmotic pressure are maintained at 5 and 1 MPa , respectively. Gradually , the confining pressure is increased to 10 , 15 , 20 , 25 , and 30 MPa , and the evolution of the fracture flow rates is recorded. Thereafter , the confining pressure is gradually decreased to 25 , 20 , 15 , 10 , and 5 MPa , and the evolution of the fracture flow rates is recorded. The loading and unloading processes are repeated in five cycles.

3 Results of laboratory experiment

3.1 Relationship between stress state and fracture seepage flow

As shown in Fig. 3 , there exists a linear relationship between the seepage discharge and osmotic pressure in sandstone fissure under each level of confining

pressure. With the increase in the confining pressure , the permeability of the fracture decreases , and the decreasing rate changes. As shown in Fig. 4 , the fracture seepage flow rate with the increase in confining pressure decreases rapidly at the stage with low confining pressure (10-20 MPa) . When the confining pressure is increased from 25 MPa to 30 MPa , the flow rate of the fracture under different osmotic pressures is slowly decreased and stabilized at 0.18-0.35 mL/min.

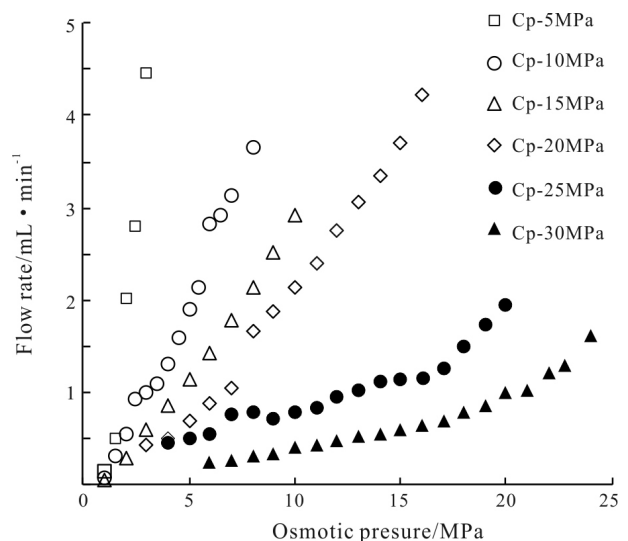


Fig. 3 Relationship between osmotic pressure and flow rate of sandstone fracture

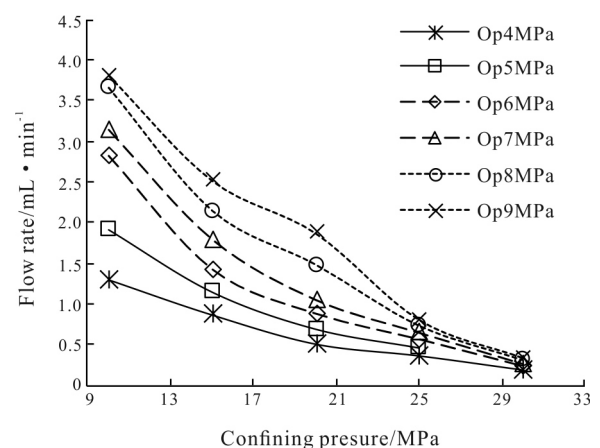


Fig. 4 Relationship between confining pressure and flow rate of sandstone fracture

3.2 Relationship between stress history and fracture seepage flow

There exists a nonlinear relationship between the

confining pressure and fracture flow rate in the first cycle of the loading and unloading processes (Fig. 5). In the unloading process , the fracture flow rate cannot be fully recovered in comparison with the value in the loading process. Hence , the recovery of fracture permeability shows obvious hysteresis effects in the unloading process of the confining pressure. Such effects can be explained by the fact that the deformation of the fracture surface cannot recover in time. Thus , the permeability of the same rock fracture can vary in significant ranges even under the same stress conditions.

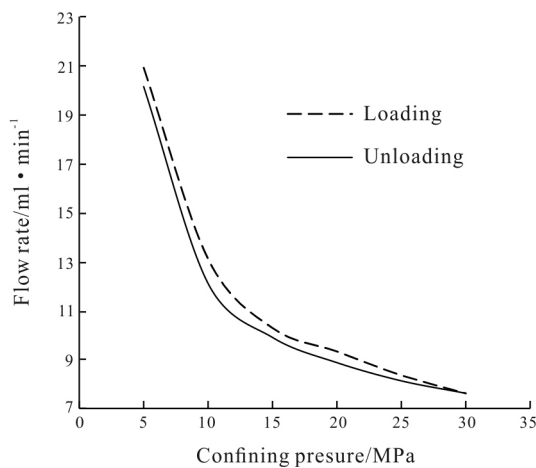


Fig. 5 Relationship between confining pressure and seepage flow rate of sandstone fracture in process of single loading and unloading

Fig. 6 illustrates that the flow rate of the fracture remains unchanged during the five cycles of loading and unloading processes of the confining pressure. In each cycle , the evolution character of the flow rate with the confining pressure remains unchanged , thus indicating that the deformation is elastic and recoverable.

3.3 Relationship between lithology and fracture seepage flow

Fig. 7 shows the seepage characteristics of granite. Compared with the experiment results for sandstone (Figs. 3 , 7) , the following conclusions can be drawn from the results for granite. There exists a linear relationship between the flow rate and seepage pres-

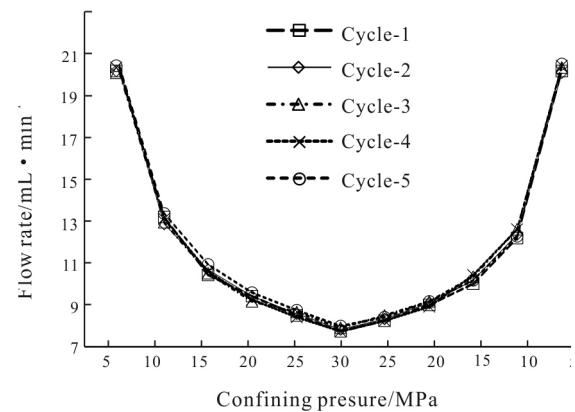


Fig. 6 Relationship between confining pressure and flow rate of sandstone fracture during five cycles of loading and unloading processes

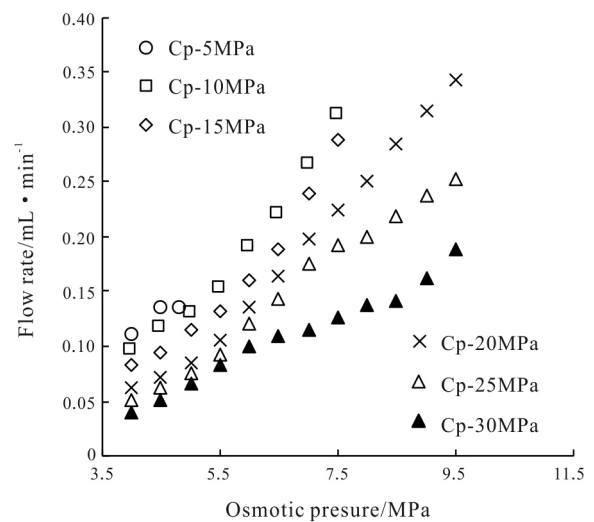


Fig. 7 Relationship between osmotic pressure and flow rate of granite fracture

sure of the granite fracture at each level of the confining pressure. The magnitude of the seepage flow rate of the single sandstone fracture is 10 times that of the granite fracture under the same confining pressure. This result can be explained by the rougher surface of the sandstone fracture and the inadequate closure of the fracture surface. With the increase of confining pressure , the permeability variation of the granite fracture is smaller than that of the sandstone fracture. Therefore , the seepage characteristics of rock fracture obviously vary with different lithologies.

4 Conclusions

(1) The flow rates and osmotic pressures of sandstone and granite fractures indicate a linear relationship. Moreover, confining pressure can significantly reduce fracture permeability.

(2) In the unloading process of confining pressure, the recovery of fracture permeability exhibits obvious hysteresis effects, which indicate that the effects of stress history cannot be ignored.

(3) These experiments show that the seepage characteristics of sandstone and granite fractures are not the same under the same stress state. Therefore, future studies need to conduct extensive experiments to further explore the seepage characteristics of rock fractures.

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