Research Article

Experiment and Model Investigation on the Permeability Evolution of Granite under Triaxial Compressive Damage

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1. Introduction

Granite has been recognized as an ideal material for the host rock of high-level radioactive waste (HLW) geological repository. For the long-term safety of HLW repository, the effectiveness of isolating radioactive mass away from the earth biosphere (long-term mass transportation) is one of the main concerns for researchers around the world. In the view of mass transportation in a porous medium within the duration of nuclide decay, the fluid performance of the host rock is one of the key factors controlling mass transportation. Evidence from laboratory experiments suggests that the permeability of granite was changed seriously due to underground excavation. Therefore, knowledge on the permeability evolution of granite is of significant importance to accessing the safety of mass isolation in HLW repository.

Despite the low permeability in granite, amounts of experiments indicate that stress-induced damage enlarged the permeability of granite seriously. Souley et al. [1] implemented in situ measurements of permeability change induced by microcrack growth in the underground research laboratory of Canada, approximately $1 \times 10^3$ m$^2$ of increment in permeability was measured in the excavation damage zone related to that in the intact granite. Oda et al. [2] also observed an increment of about two to three orders of magnitude in permeability induced by stress damage. Obviously, if such amount of enlargement in permeability was not considered, this would lead to big errors in assessing the fluid processes in the near-field confining rock.
The permeability evolution in granite is illustrated to be a complex process by a large number of literature, and damage was commonly considered the major reason for such evolution. As denoted by Chen [3], the permeability of granite was decreased by compaction initially but increased at the stage of volumetric dilation. In the experiment of Wang et al. [4], the permeability of Beishan granite was observed, showing a slight deduction versus compressing load but a dramatic rise after the peak stress. Hu et al. [5] and Zhang et al. [6] explained the initial decrease of permeability was due to the elastic compression-induced shrinkage of porous space, whereas the continuous crack propagation and interaction caused gradual increment of permeability, and once fractures were linked mutually, a fast rise of permeability occurred. Nguyen et al. [7] also declared that the evolution of permeability was dependent on the density of stress-induced cracks. Obviously, above researchers have successfully clarified the mechanism of permeability evolution in granite under mechanical loading, exhibiting pore space change and successive crack growth induced fluid channels’ evolution.

However, current permeability models are various and arguable [8–10], generally, they can be categorized into stress-based one, strain-related one, damage-dependent one, general porous model-associated one, etc. For instance, Jia et al. [11] and Yang et al. [12] defined a power law and an exponential relationship between permeability and effective stress, respectively. Chen et al. [13] gave an exponential formulation of permeability evolution versus variable damage. Liu et al. [14] pointed out that the permeability of granite is related to the volumetric strain under triaxial compression. Shen et al. [15] proposed a permeability model according to the evolution of probability density of fractal porous model. Alternatively, a large number of the permeability models were proposed based on the evolution of flow path, such as the tortuosity, fracture network, and neural networks [16–21]. Despite big progress in the aspect of permeability model have been made by these researchers, reliable permeability models for granite are still needed further study [22, 23], because of the successive evolution of fluid channels, which should be combined into a unified model.

Therefore, in order to characterize the permeability evolution of granite during compression and establish a permeability model that covers the full stages of permeability evolution associated with the compressive damage. This paper implemented hydraulic-mechanical triaxial compression tests on the granite and associated them with acoustic emission techniques to detect the damage process. The permeability of the granite specimen was measured at different states of damage during the loading processes. The analysis on the characters of permeability evolution was conducted, considering the permeability evolution of granite during triaxial compression exhibited a character of dual-continuum (pore percolation and fissure flow) fluid performance, which covers the change of pore space and successive crack growth, a permeability evolution model was proposed, which is characterized by only 2 parameters that consider both the pore percolation and fissure flow in the following process.

2. Hydromechanical Coupled Triaxial Compression Experiments

2.1. Sample Preparation. The tested granite samples were drilled from Gansu Beishan, where is the site of the Chinese Underground Laboratory of HLW repository. According to the Chinese testing standard of GB8540-84, the drilled cores were prepared into a cylinder-shaped specimen with a diameter of about 50 mm and a height of approximately 100 mm. As the content analysis made by Chen et al. [13], the Beishan granite contained the minerals of plagioclase, quartz, alkali feldspar, biotite, albite, etc. All the specimens were polished and saturated by water in a vacuum device for 8 hours. In order to load the confining pressure by hydraulic oil, the specimen was covered by a plastic sleeve.

2.2. Experiment System. The employed experiment system is the MTS-815 rock mechanics testing system associated with acoustic emission equipment of PCI-2 and a hydraulic loading device. As introduced by Liu et al. [24] and Yi et al. [25], this MTS-815 testing system has an axial loading capacity of 4600 kN and 140 MPa in confining pressure, its axial displacement meter is ranged from -2.5 mm to 5 mm, and that of the circumferential displacement meter is ranged from -2.5 mm to 8 mm. As a whole, both the accuracy of the stress and displacement sensors reached to ±0.5%. The permeability test device has a maximum osmotic pressure up to 10 MPa, which is capable to detect the permeability of a low-permeable material below $1 \times 10^{-20}$ m². The utilized acoustic emission test equipment adopted 8 sensors and its accuracy of such sensors and extensometers is about 0.5% RO. All the test data can be recorded by the controlling system automatically.

2.3. Experiment Procedure. Permeability measurement was implemented during the axial compression steps by the transient approach. The tested specimen was installed on the loading platform of the triaxial cell as illustrated by Figure 1(a), and the permeability of the tested granite was determined according to the differential pressure of the pressure at the upstream and downstream ends, and the permeability was calculated by formula (1).

$$k = \mu \beta V \frac{\ln(\Delta P/\Delta P_0)}{2\Delta A/L_v},$$

where $\Delta P/\Delta P_0$ means the ratio of initial pressure differential to final pressure differential over the measuring time of $\Delta t(s)$. Acoustic sensors were pasted at the outer surface of the triaxial cell. The confining pressure was loaded by hydraulic oil to the surrounding surface of the specimen.

In the hydromechanical triaxial compression experiment, the hydraulic pressure was set as 4 MPa and the confining pressure was set at 15 MPa, 20 MPa, and 25 MPa according to the field measurement data by Chen et al. at a depth of 500 m in the Gansu Beishan area. The hydromechanical loading was carried out by the sequence as illustrated by Figure 1(b). In the first step, both the axial and confining pressure were increased alternately to the targeted confining
pressure; then, the hydraulic pressure was loaded, after that, the axial and confining pressure were recovered to the initial confining pressure automatically with a stable hydraulic. The axial pressure and confining pressure were increased gradually by a stress-control method of 3 MPa/min and 2.8 MPa/min, respectively. When axial pressure reached to about 80% of the strength of the tested specimen, the controlling method of axial pressure loading was changed to be circumferential displacement control of 0.02 mm/min. Axial compression was stopped until obvious residual strength occurred.

The specimen was named by the code of ‘CNo.’, of which the alphabet ‘C’ means the confining pressure, ‘No.’ denotes the value of confining pressure. For instance, ‘C20’ indicates that the tested specimen was loaded with a confining pressure of 20 MPa.

3. Characters of Permeability Evolution

Measured data available in the above hydromechanical triaxial experiments are stress, strain, acoustic hits, and permeability. In order to characterize the permeability evolution, macroscopic relationships between permeability and alternative data were analyzed in the following subsections.

3.1. Evolution Processes of the Permeability during Triaxial Compression. The evolution of the stress-strain curves and permeability of the tested specimen have a similar tendency, take the specimen loaded with a confining pressure of 20 MPa and hydraulic pressure of 4 MPa as an example. As displayed in Figure 2, the stress-strain curves exhibited four stages, exhibiting a very slightly nonlinear increment in the beginning, then a nearly linear growth, plastic nonlinear arise and dramatic drop. As explained by Chen et al. [13], Zhang et al. [26], and Jiang et al. [27], the permeability of rock under compressive load changed owned to the structural evolution, as illustrated as the schematic diagrams in Figure 2, in the first stage, initial cracks were compacted, as a result, the permeability showed a slight decrease, in the elastic stage, despite limited damage occurred, the permeability had very small changes, whereas in the third stage, a large number of cracks propagated and interacted with each other, consequently, the permeability was increased quickly and reached a maximum value after the specimen was fractured.

As a whole, the permeability of granite during triaxial compression experienced a slight decrease firstly, a stable level later, and a dramatic rise to a large level. In order to take a direct insight into the characters of permeability evolution versus stress or deformation, the permeability data versus stress and strain were analyzed in the following subsections.

3.2. Permeability Evolution versus Stress and Strain. The permeability data of the specimen C15 versus derivative stress, axial strain, circumferential strain, and volumetric strain are plotted in Figures 3(a)–3(d), respectively. Obviously, the permeability has a strong nonlinear relationship with derivative and axial strain. Interestingly, from the stage of crack interaction as mentioned in Figure 2, the permeability increased almost linearly with circumferential and volumetric strain (see Figure 3(c) and Figure 3(d), respectively).

As clarified by Yi et al. [25], Chen et al. [28], Sueyoshi et al. [29], and Niya et al. [30], the dominated factor of permeability evolution under stress damage owed to be the
changes of the flow path. In the view of micro-meso structural damage in the rock mass, as denoted by Tang et al. [31], continuous compressive stress loaded on the rock will lead to structural changes as porosity-fissure evolution, once fissure occurred, shear dilation of the specimen happened which provides large fluid paths rather than pore percolation. In our case, as displayed in Figure 2, dilation occurred at the stress of about 200 MPa and the strain of around 0.25%, exhibiting the reverse volumetric strain (means from compaction changed into expansion) due to the raised

**Figure 2:** Experiment data of stress-strain and permeability in the specimen of C20.

**Figure 3:** Measured permeability versus (a) derivative stress, (b) axial strain, (c) circumferential strain, and (d) volumetric strain.
circumferential strain. Obviously, as shown in Figure 3(a) and Figure 3(b), the permeability evolution exhibited a strong nonlinear principle versus derivative stress and axial after the stress and axial strain surpassed 200 MPa and 0.25%. In addition, as displayed in Figure 3(c), although the permeability has a good linear relationship with circumferential strain, permeability is difficult to be distinguished before dilation. For the volumetric strain, as illustrated in Figure 3(d), the permeability exhibited a slight decrease before the volumetric strain arrived at about 0.25%, and continued growth thereafter. Obviously, volumetric strain is feasible to describe the permeability evolution in the stage of pore percolation and fissure flow.

3.3. Permeability Evolution versus Damage. AE counts are commonly used to analyze the damage processes indirectly, and which have been clarified to be linked with the strain of rock by researchers [32, 33]. In our case, to analyze the permeability evolution of granite under triaxial compression from pore percolation to fissure flow. The AE hits were utilized to indicate the evolution of the flow path. As plotted in Figure 4, in the compaction stage and elastic region, obviously, the AE hits occurred randomly and separately in the specimen, whereas when the axial strain overpass about 0.4%, cracks aggregated gradually and formed to macrofracture, exhibiting the high density of AE hits occurred in the area within the specimen at the end of the crack interaction stage and the fractured stage. Consequently, permeability increased slightly in the early stage of the crack interaction but dramatically at the end of the crack interaction, once the macrocrack was formed, the permeability grew slowly with the change of fracture.

4. A Permeability Evolution Model

Both the characters of the evolution in stress-strain curves, permeability and AE hits analyzed in the above subsections suggest that there is a shift of structural evolution mechanism that controls the permeability changes during the failure of granite. Namely, the dilatancy criterion shifts the fluid in the granite from pore percolation into fissure flow. This phenomenon has also been observed by Alkan [34] in the experiment of scanned electron microscope (SEM) on the salt rock as global connectivity of microfracture network into a fissure. Furthermore, by using the micro-CT techniques, Xue et al. [35], Lv et al. [36], and Jing et al. [37] also observed the processes of fissure formulation from pore-crack connectivity. Therefore, the permeability evolution of granite during triaxial compression exhibited a character of dual-continuum (pore percolation and fissure flow) fluid performance. Motivated by this mechanism, a permeability evolution model that considers both the pore percolation and fissure flow was proposed in the following process.

For the pore percolation, the compressibility of pore volume is the majority of concern for the evolution of permeability. The void ratio $e$ of a porous medium can be expressed as

$$e = \frac{v}{\nu_s} - 1,$$  \hspace{1cm} (2)

where $v$ is the volume of a representative volume element (RVE), $\nu_s$ is the volume of the solid mass. For a deformable porous medium, the formulation of void ratio can be rewritten as

$$e = \frac{v}{\nu_0 - \nu_{d0}} - 1,$$  \hspace{1cm} (3)

in which $\nu_0$ and $\nu_{d0}$ are the initial volume of the RVE and solid mass. It is notable that the initial volume of a RVE has a relationship with the deformed volume of the RVE as

$$v = (1 - e_v)v_0,$$  \hspace{1cm} (4)

and in the initial state, the volume of a RVE can also be expressed as

$$v_0 = (1 + e_0)v_{d0}.$$  \hspace{1cm} (5)

Normally, the deformation of solid mass in the RVE is regarded as nondeformable material, whereas from the view of flow path in the porous medium, not all of the pore space is effective to let fluid path through. According to the conception of effective porosity [38–42], the solid parts that contained ineffective pore space should not be calculated as the
change of effective void ratio, but these parts are deformable due to pore space compaction. As suggested by Liu et al. [43], the pore space compaction has an influence on the connectivity of pore channels by compressive closure, thereby remaining as the effective pore space, such influence can be expressed as

\[ n_s = n_{s0} \exp (e_s). \]  

(6)

Submitting Equation (4) to Equation (6) into Equation (3) we obtain

\[ e = \frac{(1 - e_v)(1 + e_0)}{\exp (e_v) - 1}. \]  

(7)

For the porosity, it is defined as

\[ \phi = \frac{e}{1 + e} = 1 - \frac{\exp (e_v)}{(1 - e_v)(1 + e_0)}. \]  

(8)

Obviously, according to the definition of porosity as the volumetric ratio of pore space to the total RVE, the second item of Equation (8) means the deformation-induced porosity changes of the effective pore space. Replacing the item of \( 1 + e_0 \) by \( 1/(1 - \phi_0) \), where \( \phi_0 \) is the initial porosity, and submitting Equation (8) into the Kozeny-Carman equation, then the permeability can be expressed as

\[ k = k_0 \frac{\phi^3}{(1 - \phi)^2} \frac{(1 - \phi_0)^2}{\phi_0^3} = k_0 \frac{(1 - e_v - \exp (e_v)(1 - \phi_0)^3}{(1 - e_v) \exp (2e_v)\phi_0^3}. \]  

(9)

For the fissure flow, according to the permeability model proposed by Louis and Maini [44],

\[ k' = \frac{\beta gd^2}{12\eta}. \]  

(10)

In which, \( k' \) is the permeability of fissure flow, \( \beta \) is a coefficient of connectivity (the area ratio of connected region to the total fracture region), \( c \) is a correlation for the roughness, \( d \) is the fracture aperture, and \( \eta \) is the dynamic viscosity. For a deformable fracture, Liu and Rutqvist [10] gave out a formulation of aperture linked to stress as

\[ b = b_i + b_j \exp (-C_i \sigma_n), \]  

(11)

where \( b_i \) is the residual fracture aperture that does not associate with deformation, \( b_j \) is the stress-sensitive portion of fracture aperture, and \( C_i \) is the fracture compressibility. It is notable that the equation of aperture is utilized to describe the evolution of fracture under fracture closure. While in our case, the fracture propagation was continuously occurred due to dilation during the loading processes. Therefore, a new aperture can be defined as

\[ b = b_j (1 - \exp (-ce^{\varphi})), \]  

(12)

where \( c \) is the coefficient describing the opening of fracture aperture under the variable plastic strain \( e^{\varphi} \).

Take Equation (12) into Equation (9), we get

\[ k' = k_1 + \frac{\beta gd^2(1 - \exp (-ce^{\varphi}))^2}{12\eta c}, \]  

(13)

where \( k_1 \) is the reference permeability before fissure flow. Let \( A = \beta gd^2/12c \) which is a constant, then the final permeability can be simplified as

\[ k' = k_1 + \frac{A(1 - \exp (-ce^{\varphi}))^2}{\eta}. \]  

(14)

Considering the pore percolation has limited influence in the fractured specimen due to large increment of permeability by macrocracks. Combining Equation (9) and Equation (14), finally, the permeability model for the granite under triaxial compression can be expressed as

\[ K = \begin{cases} (k_0 - k_1) \frac{[1 - e_v - \exp (e_v)(1 - \phi_0)]^3}{(1 - e_v) \exp (2e_v)\phi_0^3} & (e^{\varphi} \leq 0) \\ k_1 + \frac{A(1 - \exp (-ce^{\varphi}))^2}{\eta} & (e^{\varphi} > 0) \end{cases}. \]  

(15)

For the feasibility of numerical implementation, the variable plastic strain \( e^{\varphi} \) can be replaced by the plastic yield criterion \( F \), like the Drucker-Prager model. It is notable that when \( F \leq 0 \), the permeability is linked with the volumetric strain which is still consistent with Hooke’s law, when \( F > 0 \), the permeability is related to the plastic strain, which in real condition is a nonlinear curve versus the dropped stress, whereas in a normal ideal plastic model for numerical modeling, the plastic strain is of significant difference from the real condition. Therefore, an elastoplastic model is desired to describe the real condition of plastic strain evolution. Fortunately, such elastoplastic models are available, which will be discussed in the section of discussion.

It is notable that Equation (15) has only 2 parameters are needed to be determined, namely, the \( A \) and \( c \). In addition, this permeability model has the ability to describe the full-stage evolution of permeability. In order to verify Equation (15), the permeability data were fitted and analyzed in the following section.

5. Verification of the Permeability Model

According to the formulation of Equation (15), the permeability evolution model has two items, it is notable that the parameters of the first item contain the initial permeability and porosity which can be determined easily by experiment. Taking the experiment data of the specimen of \( C_{15}, C_{20}, \) and \( C_{25} \) as examples, the first permeability data was used as the initial permeability \( k_0 \) and the last data before peak strength was applied as the parameter of \( k_1 \), as suggested by Chen
et al. [13], the porosity of Beishan granite ranged from 0.29% to 0.32%, in our case, an average value of 0.305% was used as the porosity in the verification. Both the experiment data and fitted results of the permeability are plotted in Figure 5. The permeability data in Figure 5 suggest that the higher confining pressure, the larger the final permeability. Specifically, the final permeability of the specimen with a confining pressure of 15 MPa reached to about $8 \times 10^{-17}$ m$^2$ (please see Figure 5(a)), that value of the specimen loaded by a confining pressure of 20 MPa was around $12 \times 10^{-17}$ m$^2$ (please see Figure 5(b)), and when the confining pressure was 25 MPa, as displayed in Figure 5(c) which was approximately $17 \times 10^{-17}$ m$^2$. This phenomenon was also observed by Alam et al. [45] and clarified as the width of rupture planes which were increased by the enlarged confining pressure. In addition, the tendency of permeability evolution under different confining pressures is similar, and this tendency was also observed by Oda et al. [2], Baud et al. [46], and Chen et al. [47], which convince us that the measured permeability in our case is credible for verifying the permeability.

For the calculated results by Equation (15), the parameters are listed in Figure 5. Both the initial permeability $k_0$ and the reference permeability of $k_1$ were deduced by the increased confining pressure, which is caused by the enlarged degree of compaction by confining pressure that decreased the pore space. Obviously, the proposed model fits well the permeability during the first stage (pore percolation). During the fracture flow, the calculated results fitted well the data of $C_{15}$ (see Figure 5(a)), and a majority of the experiment data of $C_{20}$ and $C_{25}$ were well calculated by the proposed model. Despite the permeability of $C_{20}$ which experienced a slight increase after about $11 \times 10^{-17}$ m$^2$, as shown in Figure 5(b), exhibiting a tendency of growing to stable around $12 \times 10^{-17}$ m$^2$, both the permeability of $C_{15}$ and $C_{25}$ was increased continuously after the dilation (see Figure 5(a) and Figure 5(c), respectively). Anyway, the
The proposed model can still fit well the experiment data of $C_{20}$. The parameter $A$ was decreased by the confining pressure and $c$ was enlarged, exhibiting the parameter $A$ is 7.466 for $C_{15}$ and 1.2357 for $C_{20}$, and that of $c$ is 195.75 for $C_{15}$ and 1010.43 for $C_{20}$, whereas the parameters $A$ and $c$ were enlarged and decreased at $C_{25}$, such difference may be caused by the nonhomogeneity of the specimen of $C_{25}$.

As a whole, the calculated results of permeability according to Equation (15) match well the experiment data, including the first stage and the second stage at various confining pressures, which convince us that the proposed model is feasible and effective to reproduce the permeability evolution of granite under triaxial compression.

6. Discussion

As above analysis, the evolution tendency and mechanism of permeability in granite under triaxial compression are significantly different before and after the occurrence of macrofissures. It is notable that, the model of permeability evolution is linked with the volumetric strain and plastic strain, and there is a judgment of the occurrence of plastic deformation. Therefore, the proposed model associated with the elastoplastic model is feasible to describe the hydromechanical (HM) coupling processes.

Fortunately, the elastoplastic models proposed in recent years are numerous, such as the models proposed by Chen et al. [48], Hu et al. [49], and Zhang et al. [50], which had been verified to be well for reproducing the real evolution of plastic strain after peak strength. Therefore, it is possible to establish the controlling equations of the HM model that are able to promote the accuracy of the numerical model. Anyway, this is needed to be further studied.

7. Conclusions

This paper deals with the characterization of the permeability evolution of granite under compressive damage, triaxial compression experiments with various confining pressures were implemented associated acoustic emission techniques, permeability data of the tested specimen at different stages of the compression process were measured. According to the analysis on the characters of the permeability evolution, a model of permeability evolution was proposed which was verified by the experiment data. Experiment results suggest that the permeability of granite was decreased firstly due to pore space compaction, then which was increased slightly due to crack interaction and raised dramatically once fissures formed. The permeability evolution tendency during the compressive damage was characterized into two stages, namely, the pore percolation and fracture flow. According to this mechanism, permeability was proposed which was linked to the volumetric strain and plastic strain. Comparison between the experiment data and model calculation denotes that the proposed model of permeability is feasible and effective to describe the full-stage evolution of permeability under various confining pressures.

Data Availability

The data supporting this study are included in the paper.

Conflicts of Interest

On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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