Experimental study on gas permeability of granite close to natural joint

Long YU\textsuperscript{1,2}, Jian LIU\textsuperscript{1,2,*}, Ju WANG\textsuperscript{1,2}, Liang CHEN\textsuperscript{1,2} and Chunping WANG\textsuperscript{1,2}

\textsuperscript{1}CNNC Beijing Research Institute of Uranium Geology, Beijing 100029, China
\textsuperscript{2}CAEA Innovation Center on Geological Disposal of High-level Radioactive Waste, Beijing Research Institute of Uranium Geology, Beijing 100029, China

liujian@briug.cn

Abstract: The metal corrosion, organic degradation and waste radiolysis in the geological disposal repository of high-level radioactive waste (HLW) will lead to gas generation and form additional pressure, which will drive the nuclide migration and thereby influence the long-term safety of geological disposal. It is crucial to study the gas permeability of the host rock for the geological disposal of HLW. Therefore, the gas permeability of some granite samples close to a natural joint in the Beishan pre-selected area for China’s geological disposal project was studied in this paper. Firstly, the effective gas permeability under different confining pressures, different gas pressures and different directions was measured by the quasi-steady method. Secondly, the absolute gas permeability and slip factor were obtained according to Klinkenberg’s law. Finally, the effect of confining pressure, direction and distance to the joint surface on gas permeability were analyzed. The gas seepage in granite is found to conform to Klinkenberg’s law. The absolute gas permeability is gradually decreased with the increase of the confining pressure. The gas permeability of granite is isotropic and homogeneous because the intrinsic permeability measured in different directions and at different distances from the joint is found to be similar. The above results can provide references for the performance assessment of the surrounding rock of the HLW disposal repository.

1. Introduction
Due to the metal corrosion, organic degradation and waste radiolysis, additional gas pressure will be generated in the near field of the repository for high-level radioactive waste (HLW) and it will drive the nuclide migration from the engineering barriers to the host rock \cite{1}. Therefore, it is crucial to study the gas permeability of the host rock. The Beishan pre-selected area is the most potential area for China’s geological disposal project of HLW and the main rock type in this area is granite \cite{2}. Zhao et al. (2017) \cite{3} and Zhang et al. (2020) \cite{4} tested the gas permeability of granite from the Beishan area under different saturation levels, confining pressures and loading-unloading conditions. The above study shows the gas permeability of granite from the Beishan pre-selected area ranges from $10^{-17}$m$^2$ to $10^{-21}$m$^2$. Tanikawa et al. (2009) \cite{5} found that Klinkenberg’s effect \cite{6} becomes important when the gas permeability of the rock is less than $10^{-14}$m$^2$, and it makes the gas permeability higher than the liquid permeability. However, it is currently a lack of relevant research on Klinkenberg’s effect on the granite in the Beishan pre-selected area.
The discontinuities, such as the fault and joint, are the main pathways for the water and gas flow in the granite and so the key disposal elements are required to be disconnected with the conductive discontinuities [7]. In other words, the intact granite between the key disposal element and discontinuities plays a key role in ensuring the safety of geological disposal. The permeability of the intact granite close to the discontinuity should be tested and evaluated. Therefore, the gas permeability of some granite samples close to a natural joint in the Beishan pre-selected area was experimentally studied in this paper. Firstly, the effective gas permeability under different confining pressures, different gas pressures and different directions was measured by the quasi-steady method. Secondly, the absolute gas permeability and slip factor were identified according to Klinkenberg’s law. Finally, the effect of confining pressure, direction and distance to the joint surface on the gas permeability were discussed.

2. Test Equipement and Basic Principle

2.1. Equipement
The equipment used in this paper is a test panel mainly composed of the feed reservoir, overpressure protection valve, inlet and outlet gas buffer reservoirs, differential pressure meter and pressure chamber. The maximum design gas pressure is up to 2.5MPa and the maximum design confining pressure is up to 20MPa. Nitrogen is chosen as the test gas. Both the quasi-steady state method and transient method [8,9] can be carried out with this test panel. The quasi-steady state method was used in this paper.

![Test panel of gas permeability](image)

**Figure 1.** Test panel of gas permeability.

2.2. Quasi-steady method
To keep a constant pressure at the gas outlet, the atmospheric pressure $P_0$ is generally applied to one end of the sample by connecting to the air. At $t=0$, the gas pressure $P_{i0}(0)$ is applied to the other end of the sample. Then the gas seepage is activated by the pressure difference between the 2 ends of the sample. After a time interval $\Delta t$, the inlet gas pressure is decreased to $P_{i0}(\Delta t)$ because an amount of gas in the inlet buffer reservoir has moved to the outlet. Assuming that the pressure decrease $\Delta P=P_{i0}(0)-P_{i0}(\Delta t)$ is much smaller than $P_{i0}(0)$, the average inlet gas pressure $P_{in, mean}$ can be calculated as follows:

$$P_{in, mean} \approx \frac{P_{i0}(0) + P_{i0}(\Delta t)}{2} + P_0$$  \hspace{1cm} (1)

where $P_{in, mean}$ is the average inlet gas pressure (Pa); $P_0$ is the atmospheric pressure (Pa); $P_{i0}(0)$ and $P_{i0}(\Delta t)$ are the display values of the gas pressure meter connected to the inlet gas buffer reservoir at
\[ t=0 \text{ and } t=\Delta t \text{ respectively (Pa). Thus, the average flow rate } Q_{\text{mean}} \text{ can be estimated as follows:} \]
\[ Q_{\text{mean}} \approx \frac{V \Delta P}{P_{\text{mean}} A} \]
\[ where \ Q_{\text{mean}} \text{ is the average flow rate (m}^3/\text{s}); \ (\Delta P=P_{\text{in}}(0)-P_{\text{in}}(\Delta t)); \ V \text{ is the volume of the inlet gas buffer reservoir (m}^3). \text{According to Darcy’s law, the effective gas permeability } k_g \text{ of the sample can be expressed as follows}^{[10]}: \]
\[ k_g = \frac{\mu Q_{\text{mean}}}{A} \left( \frac{2HP_{\text{mean}}}{P_{\text{mean}}^2 - P_0^2} \right) \]
\[ where \ k_g \text{ is the effective gas permeability of the sample (m}^2); \ \mu \text{ is the Dynamic viscosity coefficient of the gas (Pa·s); } A \text{ is the sample section area (m}^2); \ H \text{ is the sample height (m).} \]

2.3. **Klinkenberg’s equation**

Klinkenberg (1941) \(^6\) found that the effective gas permeability is proportional to the reciprocal of gas pressure:
\[ k_g = k_{g,\infty} \left( 1 + \frac{b}{P_g} \right) \]
\[ where \ k_g \text{ is the effective gas permeability measured under a certain gas pressure (m}^2); \ P_g \text{ is the gas pressure in the sample (Pa), which can be practically defined as the average value of gas pressures at the 2 ends of sample}; \ k_{g,\infty} \text{ is the absolute gas permeability (m}^2), \text{which is just related to the pore structure of the sample}; \ b \text{ is the slip factor (-), which is related to the pore structure, temperature and gas properties.} \]

3. **Sample Preparation and Test Scheme**

3.1. **Sample preparation**

The granite samples tested in this paper were taken from the Xinchang block in the Beishan pre-selected area in Gansu Province, China. The sampling point is located at 40°50'50.9748" N/ 97°32'0.9708" E. The rock sample was initially sandwiched between 2 natural parallel joints with a dip direction of 304° and a dip angle of 75° (figure 2). 9 samples with 50mm in diameter and 25mm in height were then obtained from 3 orthogonal directions: X, Y and Z as shown in figure 2. The sample X1 was missed during the processing and so just 8 samples were tested.

![Figure 2. Sketch of sampling.](image-url)
3.2. Test scheme
The diameter and height of the sample were firstly measured and the volume $V$ was calculated. The sample was then water-saturated by the vacuum method for 48h and the saturated mass $m_s$ was obtained. After that, the sample was dried at 105°C for 48h and the dry mass $m_d$ was obtained. The dry density $\rho_d$ and porosity $\phi$ were calculated as follows:

$$\rho_d = \frac{m_d}{V}$$

$$\phi = \frac{m_s - m_d}{\rho_w V}$$

where $\rho_w$ is the density of water (kg/m³).

The effective gas permeability of the dry sample was then measured by the method mentioned in section 2. For each sample, the variation of initial inlet pressure with time was monitored and recorded as shown in figure 3a. The effective gas permeability was calculated by using a pressure difference $\Delta P$ equal to 0.05MPa (figure 3b). 4 confining pressures, 4, 6, 8 and 10MPa, were applied to study the influence of confining pressure on gas permeability. Besides, the P-wave velocity $v_p$ of the sample was also measured after the gas permeability test.

![Figure 3](image)

**Figure 3.** (a) Inlet gas pressure v.s. time and (b) effective gas pressure v.s. inlet gas pressure curves of sample Y1.

4. Test Results and Discussion

4.1. Density, porosity and P-wave velocity
The test results of dry density, porosity and P-wave velocity are shown in table 1. The dry density ranges from 2.607g/cm³ to 2.625g/cm³ and there is no significant difference between the samples processed in different directions. The porosity ranges from 0.830% to 0.993% and the porosity of the samples processed in the Z direction is higher than that in the other directions. It indicates that the occurrence of the micro-crack in a sample doesn’t comply with the random uniform distribution. In other words, there should exist one or several dominant extension directions for the micro-cracks. Meanwhile, P-wave velocity in the Y direction is the smallest, and that in the Z direction is slightly higher than that in the X direction. The above results show that the dominant extension direction of the micro-crack is closer to the Z direction (i.e., the direction perpendicular to the joint surface) and farther to the Y direction. Besides, no monotonic corresponding relationship between the distance to the nearest joint and the dry density, porosity or P-wave velocity.
Table 1. Physical parameters of rock samples.

| Sampling direction | Sample No. | $\rho_d$ (g·cm$^{-3}$) | $\varphi$ | $v_p$ (km·s$^{-1}$) | Distance to the nearest joint * (mm) |
|--------------------|------------|------------------------|----------|-------------------|-----------------------------------|
| X                  | X2         | 2.621                  | 0.871%   | 4.001             | 79                                |
|                    | X3         | 2.623                  | 0.830%   | 4.157             | 29                                |
| Y                  | Y1         | 2.607                  | 0.908%   | 3.189             | 27                                |
|                    | Y2         | 2.621                  | 0.870%   | 3.287             | 79                                |
|                    | Y3         | 2.625                  | 0.867%   | 3.334             | 29                                |
| Z                  | Z1         | 2.621                  | 0.910%   | 4.350             | 15                                |
|                    | Z2         | 2.625                  | 0.993%   | 4.356             | 42                                |
|                    | Z3         | 2.612                  | 0.929%   | 4.254             | 69                                |

* the minimum distance between the center of the sample and the 2 parallel joints shown in figure 2.

4.2. Effective gas permeability

Figure 4 shows that the effective gas permeability of sample Y1 is gradually increased with the increase of the reciprocal of gas pressure. The other samples show a similar pattern to sample Y1. It means that the tested granite in this paper complies with Klinkenberg’s law.

![Figure 4](image-url)  
**Figure 4.** Effective gas permeability v.s. reciprocal of gas pressure for sample Y1.

4.3. Absolute gas permeability and slip factor

The absolute gas permeability $k_{g,\infty}$ and slip factor $b$ of samples under different confining pressures are obtained (figure 5). With the increase of confining pressure, the absolute gas permeability $k_{g,\infty}$ is gradually decreased. When the confining pressure is increased from 4MPa to 10MPa, the decrease of absolute gas permeability is up to 35.5%–42.6% (figure 5a).

The slip factor $b$ is increased when the confining pressure is increased from 4MPa to 6MPa (figure 5b). But the monotonic corresponding relationship disappears when the confining pressure is greater than 6MPa. According to Klinkenberg’s law [6], the slip factor $b$ reflects the similarity of the mean free-path of gaseous molecules to the equivalent pore radius in the sample. The gas pressures applied in the tests under different confining pressures are the same and so the mean free-path can also be considered to be the same. Therefore, the above results indicate that some complex changes of pore structure take place when the confining pressure is up to 6MPa. More study is needed to reveal the mechanism under high confining pressure.
Figure 5. Influence of confining pressure on (a) absolute gas permeability and (b) slip factor.

4.4. Discussion

(1) Influence of confining pressure on absolute gas permeability

An equation for describing the relationship shown in figure 5a is proposed as follows:

\[ k_{g\infty} = k_{int} \cdot \exp \left( - \frac{\sigma_c}{\sigma_{c,r}} \right) \]  

(7)

where \( k_{g\infty} \) is the absolute gas permeability (m\(^2\)); \( \sigma_c \) is the confining pressure (MPa); \( \sigma_{c,r} \) is the reference confining pressure (MPa), which reflects the influence of compression pressure; \( k_{int} \) is defined as the “intrinsic” permeability (m\(^2\)), which represent the theoretical permeability without compression pressure and with infinite gas pressure. \( \sigma_{c,r} \) and \( k_{int} \) are identified by fitting the test data in figure 5a (table2). It is found that the reference confining pressure \( \sigma_{c,r} \) of different samples are all around 12.5MPa. It shows that the effect of confining pressure increase on the absolute gas permeability of different samples is consistent. The “intrinsic” gas permeability of different samples ranges from 1.29\( \times 10^{-17} \) to 2.60\( \times 10^{-17} \)m\(^2\).

| Sample number | \( k_{int} \) (\( \times 10^{-17} \)m\(^2\)) | Reference confining pressure (MPa) | Correlation coefficient \( R^2 \) |
|---------------|---------------------------------|---------------------------------|--------------------------|
| X2            | 2.01                            | 12.5                            | 0.994                    |
| X3            | 1.85                            | 12.5                            | 0.982                    |
| Y1            | 2.03                            | 12.5                            | 0.989                    |
| Y2            | 1.29                            | 12.5                            | 0.971                    |
| Y3            | 1.53                            | 12.5                            | 0.990                    |
| Z1            | 1.85                            | 12.5                            | 0.988                    |
| Z2            | 1.77                            | 12.5                            | 0.982                    |
| Z3            | 2.60                            | 12.5                            | 0.996                    |

(2) Heterogeneity and anisotropy of the “intrinsic” gas permeability of rocks

The influence of the distance from the sample center to the nearest joint on the “intrinsic” gas permeability is shown in figure 6. There is no monotonic relationship between the distance to joint and the “intrinsic” gas permeability. It shows that the natural joint doesn’t increase the heterogeneity in the gas permeability of the nearby granite.
The difference between the 3 directions is relatively small when the distance to the joint is less than 42 mm. When the distance to the joint ranges from 69mm to 79mm, the maximum difference between the 3 directions is up to \((2.60-1.29)\times10^{-17}\text{m}^2=1.31\times10^{-17}\text{m}^2\). However, the “intrinsic” gas permeability generally varies in a relatively narrow range from \(1.29\times10^{-17}\text{m}^2\) to \(2.60\times10^{-17}\text{m}^2\). In general, the anisotropy in gas permeability of the granite close to natural joints is insignificant.

Figure 6. The corresponding relationship between natural gas permeability and the minimum distance from the center of the sample to the fracture surface.

(3) Relationship between porosity, P-wave velocity and “intrinsic” gas permeability
The correlation coefficient \(R^2\) between porosity and “intrinsic” gas permeability is found to be less than 0.1, while for P-wave velocity and “intrinsic” gas permeability it is less than 0.3. The fitting results mean that there is no monotonic relationship between porosity, P-wave velocity and “intrinsic” gas permeability.

5. Conclusion
The following conclusions can be summarized based on the experimental study on the gas permeability of the granite sandwiched between 2 natural joints.

1. The gas seepage in granite near-natural joints still conforms to Klinkenberg’s law.
2. The absolute gas permeability is gradually decreased with the increase of the confining pressure and an equation has been successfully proposed by defining the “intrinsic” gas permeability.
3. The inclined angle between the dominant extension direction of the micro-crack and the joint surface is probably great. But the anisotropy in gas permeability isn’t significant. Besides, the natural joint doesn’t increase the heterogeneity in gas permeability of the nearby granite.

The above results can provide references for the performance assessment of the surrounding rock of the HLW disposal repository in China.

Acknowledgments
The authors wish to thank the support from the China Atomic Energy Authority (CAEA) for China’s URL Development Program and the Geological Disposal Program. The work presented in this paper was supported by the National Natural Science Foundation of China (Grant No. 11402079 and U2067203), the research projects during the construction of China’s URL (No. [2020] 194 and JCKY2020201C03).

References
[1] Ortiz L, Volckaert G, Mallants D 2002, Eng. Geol. 64 287
[2] Wang J, Chen L, Su R and Zhao X 2018, J. Rock Mech. Geotech. Eng. 10 411–35
[3] Zhao P, Liu J, Chen L, Wang C and Ma L 2017, Chin. J. Undergr. Space Eng. 13 57–62+70
[4] Zhang H, Chen L, Liu J, Wang C, Ma L and Wang W 2020, Eur. J. Environ. Civ. En. 2020 1–14
[5] Tanikawa W, Shimamoto T 2009, Int. J. Rock Mech. Min. 46 1394–5
[6] Klinkenberg L J 1941, Drilling and Production Practice (New York)
[7] Mcewen T, Aro S, Kosunen P, Mattila J, Pere T, Käpyaho A and Hellä P 2012, Rock Suitability Classification - RSC 2012 (Eurajoki: Posiva Py) p 222
[8] Liu J, Chen L, Wang C, Ma L and Wang J 2019, Rock & Soil Mech. 40 1721–30 (in Chinese)
[9] Liu J, Ni H, Pu H, Huang B, Yao Q and Mao X 2021, Chin. J. Rock Mech. Eng. 40 137–46 (in Chinese)
[10] Davy C, Skoczylas F, Barnichon B and Lebon P 2007, Phys. Chem. Earth 32 667–80