Experimental Study on Ultrasonic Velocity, Suction Curve, and Gas Permeability of Damaged Granite

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Abstract. The excavation damaged zone (EDZ) of a high-level radioactive waste (HLW) disposal repository is a key factor related to long-term safety. The essence of the damage evolution of rocks is the development of microcracks, which change the ultrasonic velocity, suction curve, and gas permeability of rocks. In this work, some granite samples with different damage degrees were generated by uniaxial compression, which is similar to the stress condition of the surrounding rocks of HLW disposal tunnels. The ultrasonic velocity was simultaneously tested during the compression process. The suction curve was then obtained by drying the damaged samples under different levels of relative humidity. The gas permeability was finally measured at different levels of water saturation. Test results indicated that the unstable development of microcracks led to a decrease in Young’s modulus and enlarged the horizontal deformability of granite. The development of microcracks did not change the longitudinal wave velocity, which tended to remain constant when the ratio of the axial stress to the crack damage stress was greater than one. However, the shear wave velocity of damaged granite was significantly decreased. Such effect indicated that the microcracks generated at the stable and unstable development stages mainly extended along the axial direction rather than the radial direction. The suction curve of damaged granite was obtained and was found to comply with van Genuchten’s model and the dual-porosity model. The results of the permeability tests revealed that almost no new gas pathways were generated at the stable development stage of the microcracks. Meanwhile, the unstable development of microcracks led to a great increase in gas permeability. Moreover, the gas permeability of the intact and damaged granite tended to be constant when the water saturation level was less than 0.5. These results will benefit the performance assessment of the EDZs in the surrounding rocks of HLW disposal repositories.

1. Introduction

The safe disposal of high-level radioactive waste (HLW) is an important issue related to the sustainable development of the nuclear industry. Deep geological disposal is considered to be the most feasible method for the final disposal of HLW [1]. It refers to the disposal of HLW in an underground repository in a stable geological formation (usually several hundred meters below the surface) and to isolate the radionuclides from the biosphere by generating a multibarrier system with the waste form, container, buffer and backfill materials, and host rock [2]. The host rock is the last barrier for retarding the radionuclide migration from the repository to the biosphere; thus, its permeability is a key factor for long-term safety. An intact rock is almost impermeable, but the excavation damaged zone (EDZ) of the surrounding rock has relatively high permeability. Cho et al. (2013) [3] measured the permeability of the
EDZ of the KURT underground research laboratory for geological disposal in Korea and found that the permeabilities seem to increase by up to two orders of magnitude relative to those of intact rocks. Existing research has generally focused on the water permeability of the host rocks of HLW disposal repositories. Hence, gas permeability is rarely studied. However, metal corrosion, organic degradation, and waste radiolysis in the nearby fields of repositories produce gases, such as oxygen and hydrogen, as well as additional gas pressure. The additional gas pressure may become a driving force for nuclide migration and thus influence the safety of HLW disposal repositories.

Therefore, the gas seepage characteristics of EDZs should be studied. In the current work, some damaged granite samples were generated by uniaxial compression, which is similar to the stress condition of the surrounding rocks of HLW disposal tunnels. The development of microcracks was then analyzed by testing the ultrasonic velocity and suction curve of the damaged samples. The gas permeability of the damaged granite was experimentally studied under different water saturation levels. The results of this study can deepen the understanding of microcrack development in EDZs and provide basic parameters, such as suction curve and gas permeability, for the performance assessment of the host rocks of HLW disposal repositories.

2. Sample preparation
The granite tested in this work was obtained from a quarry with a depth of 7 m in the Beishan preselected area for China’s geological disposal project. The main minerals of the granite included plagioclase (29.8%), alkali feldspar (30.6%), quartz (32.9%), and biotite (6.7%) (Figure 1). Standard cylindrical samples measuring 50 mm in diameter and 100 mm in height were prepared (Figure 2).

3. Test procedure
The steps of the test process are as follows:
(1) The crack initiation stress $\sigma_{ci}$, crack damage stress $\sigma_{cd}$, and uniaxial compressive strength $\sigma_{UCS}$ were measured with three intact samples (I1, I2, and I3) by conducting a uniaxial compression test.

(2) Three granite samples (D1, D2, and D3) with different damage degrees were generated by conducting loading–unloading tests, the maximum stresses of which were set at $\sigma_{cd} - 10$ MPa, $\sigma_{cd}$, and $\sigma_{cd} + 10$ MPa, respectively. Hence, the three samples were at the stable microcrack development stage, the turning point between the stable and unstable development stages, and the unstable microcrack development stage (7). Meanwhile, the variations in the longitudinal and shear wave velocities were monitored. The multifield coupling test system in Hehai University in China was used. A constant axial displacement rate of 0.02 mm/min was adopted for the loading, and a constant axial force rate of 1 MPa/min was adopted for the unloading.

(3) Three small damaged samples (SD1, SD2, and SD3) were cut from the large samples (Figure 3) and were used in the following tests on suction curve and gas permeability. The aim of cutting out small samples was to eliminate the end effect of the compression test and to improve the efficiency of the suction curve and permeability tests, which are usually time-consuming.
The three small samples were dried at 105 °C for 48 h, and the dry mass \( m_d \) was obtained.

The three small samples were saturated using the vacuum method for 45 days to ensure that they were completely water-saturated. The water-saturated mass \( m_s \) was then obtained.

The three saturated samples were put into a desiccator with a relative humidity of 98%, and the mass variation was monitored. When the mass decrease in 24 h was less than 0.01 g, the desaturation process was considered to be finished, and the final mass was marked as \( m_{RH98} \).

The gas permeability \( k_{RH98} \) of the nonsaturated sample generated in the previous step was measured using the pulse test \([9]\). The initial inlet and outlet gas pressures were set at 2.3 and 2 MPa, respectively.

The three samples were successively dried under different levels of relative humidity of 92%, 75%, 59%, 43%, and 11%; the balanced masses \( m_{RH92} \), \( m_{RH75} \), \( m_{RH59} \), \( m_{RH43} \), and \( m_{RH11} \) were then respectively obtained. Meanwhile, the gas permeabilities \( k_{RH92} \), \( k_{RH75} \), \( k_{RH59} \), \( k_{RH43} \), and \( k_{RH11} \) were measured using the same method mentioned in step (7).

The three samples were dried again at 105 °C, and the gas permeability of the completely dry sample \( k_d \) was finally measured.

The porosity \( \phi \) was calculated as follows:

\[
\phi = \frac{m_i - m_d}{V \rho_w}
\]  

where \( \phi \) is the sample porosity (−), \( m_d \) is the dry mass obtained in step (4) (kg), \( m_i \) is the water-saturated mass obtained in step (5) (kg), \( V \) is the sample volume (m\(^3\)), and \( \rho_w \) is the water density (kg/ m\(^3\)).

The water saturation level \( S_{w,RHxx} \) in the relative humidity of \( xx\% \) was obtained as follows:

\[
S_{w,RHxx} = \frac{m_{RHxx} - m_d}{m_i - m_d}
\]  

where \( S_{w,RHxx} \) is the water saturation level in the relative humidity of \( xx\% \) (−) and \( m_{RHxx} \) is the balanced mass in the relative humidity of \( xx\% \) (kg) obtained in step (6) or (8).

The suction curve was obtained according to Kelvin’s equation and Young–Laplace’s equation \([8]\) on the basis of the balance masses obtained in steps (6) and (8).

4. Test results and discussion

4.1. Strength and Deformation Parameters of Intact Granite

The strength and deformation parameters of the intact samples are shown in Table 1. The variation coefficients (the ratio of mean value to standard deviation) of crack initiation stress \( \sigma_{ci} \), crack damage stress \( \sigma_{cd} \), uniaxial compressive strength \( \sigma_{UCS} \), and Young’s modulus \( E \) are all less than 5%. This outcome shows the homogeneity of the samples. Therefore, the parameter \( \sigma_{cd} \) needed in step (2) of Section 3 is set to 93.1MPa, which is the average value of the test results in Table 1.
Table 1. Strength and deformation parameters of intact samples

| No. of sample | *σc (MPa) | σcd (MPa) | σUCS (MPa) | E (GPa) | μ  |
|---------------|-----------|-----------|------------|---------|----|
| I1            | 55.1      | 90.8      | 120.1      | 31.1    | 0.21 |
| I2            | 58.9      | 96.5      | 112.3      | 29.5    | 0.12 |
| I3            | 54.7      | 92.0      | 111.2      | 29.9    | 0.15 |
| Mean          | 56.2      | 93.1      | 114.5      | 30.2    | 0.16 |

Note: *σc is determined using the method proposed by Nicksiar and Martion (2012) [10].

4.2. Strength and Deformation Parameters of Damaged Granite

The stress–strain curves of loading–unloading tests are shown in Figure 4. For all the three samples, the unrecoverable deformation increases from the first to the second loop of loading–unloading. The unrecoverable deformation of sample D3 is greater than that of the other samples.

![Figure 4. Stress strain curves of loading–unloading test](image-url)

Table 2. Deformation parameters from loading–unloading tests

| No. | σmax (MPa) | 1st loading | 1st unloading | 2nd loading | 2nd unloading |
|-----|------------|-------------|---------------|-------------|---------------|
|     |            | E (GPa)     | μ             | E (GPa)     | μ             | E (GPa)     | μ             |
| D1  | 85.4 (<σcd)| 30.1        | 0.25          | 39.4        | 0.17          | 34.2        | 0.21          | 39.3        | 0.18          |
| D2  | 95.5 (≈σcd)| 29.9        | 0.17          | 38.1        | 0.13          | 34.5        | 0.16          | 38.5        | 0.14          |
| D3  | 105.3 (>σcd)| 29.9       | 0.11          | 36.5        | 0.07          | 33.4        | 0.27          | 37.5        | 0.26          |

The deformation parameters calculated from Figure 4 are presented in Table 2. The results can be summarized as follows:

1. The Young’s modulus E and Poisson’s ratio μ in the first loading are similar to those of the intact granite (Table 1). This result shows the homogeneity of the tested granite.

2. The calculated values of Young’s modulus of sample D3 in the first unloading, second loading, and second unloading are all lower than those of the other two samples. Hence, the unstable development of microcracks leads to a decrease in Young’s modulus.

3. The Poisson’s ratio of sample D3 in the first loading is much smaller than that in the second loading. Therefore, the unstable development of microcracks enlarges the horizontal deformability of granite.
(4) The Poisson’s ratio of sample D3 in the second unloading is much bigger than that in the first unloading. This result indicates that the loading–unloading loop with maximum compression stress greater than $\sigma_{cd}$ continuously enlarges the horizontal deformability of granite.

4.3. Ultrasonic Velocities of Damaged Granite

The variation of the longitudinal wave velocity $v_p$ monitored during the loading–unloading tests is shown in Figure 5a. No notable difference can be observed in the three samples. This result proves again the homogeneity of the tested granite. More important, no significant difference is found between the first loading and second loading. This outcome indicates that the stable and unstable development of microcracks does not change the longitudinal wave velocity $v_p$. Moreover, the velocity $v_p$ tends to remain constant when the ratio of axial stress to crack damage stress ($\frac{\sigma_1}{\sigma_{cd}}$) is greater than one. The relationship between $v_p$ and $\frac{\sigma_1}{\sigma_{cd}}$ can be fitted by the following equation:

$$v_p = \left\{ \begin{array}{ll}
(v_{p_{max}} - v_{p,0}) \sin \left( \frac{\pi}{2} \sqrt{\frac{\sigma_1}{\sigma_{cd}}} \right) + v_{p,0}, & \text{if } \frac{\sigma_1}{\sigma_{cd}} \leq 1 \\
v_{p_{max}}, & \text{if } \frac{\sigma_1}{\sigma_{cd}} > 1
\end{array} \right.$$

(3)

where $v_{p_{max}} = 5,117.9$ m/s is the maximum longitudinal wave velocity and $v_{p,0} = 3,339.6$ m/s is the longitudinal wave velocity when the axial stress $\sigma_1$ is equal to zero. $v_{p_{max}}$ and $v_{p,0}$ are determined by fitting the test results in Figure 5a.

The monitoring results of shear wave velocity $v_s$ are presented in Figure 5b. In the first loading, the shear wave velocity starts to fall when the ratio $\frac{\sigma_1}{\sigma_{cd}}$ increases to 0.9. In addition, the velocity is found to gradually decrease from the first loading to the second loading, and the decrease of sample D3 is the greatest.

Figure 5. Variations of (a) longitudinal and (b) shear wave velocities with the increase of axial stress

The test results of the ultrasonic velocities indicate that the microcracks generated at the stable stage (from $\sigma_{cd}$ to $\sigma_{cd}$) and the unstable stage (greater than $\sigma_{cd}$) mainly extend along the axial direction rather than the radial direction. Therefore, the longitudinal wave velocity does not decrease after two loading–unloading loops while the shear wave velocity shows a significant decrease.

4.4. Suction Curve of Damaged Granite

The suction curves are shown in Figure 6. The suction curves of samples SD1 and SD2 are found to be similar to the results obtained by Zhao et al. (2017) [10], who tested an intact granite taken from the same sampling point as that used in the current study. Sample SD3 gives a relatively low level of water saturation under the same suction stress. According to Young–Laplace’s equation, sample SD3 has more microcracks with larger equivalent radii than the other samples.
Figure 6. Suction curve of damaged granite

The van Genuchten’s model\(^{[11]}\) is widely used to fit suction curves:

\[
S_w = \frac{1}{\left[1 + \left(\frac{P}{P_r}\right)^n\right]^{\frac{1-1/n}{1-1/n}}}
\]  

(4)

where \(S_w\) is the water saturation level (−); \(P_r\) is the suction stress (Pa); \(n\) and \(P_r\) are model parameters, which are related to the shape of the suction curve and the equivalent radius of microcracks, respectively. Liu (2012)\(^{[12]}\) proposed the following dual-porosity model:

\[
S_w = \omega \left[1 - e^{-\frac{P}{P_1}}\right] + (1-\omega) \left[1 - e^{-\frac{P}{P_2}}\right]
\]  

(5)

where \(\omega\), \(P_1\), and \(P_2\) are model parameters. \(\omega\) represents the volume ratio of the first crack group with an equivalent radius equal to \(2\gamma\cos\theta/P_1\), and \(1-\omega\) represents the volume ratio of the second crack group with an equivalent radius equal to \(2\gamma\cos\theta/P_2\). The values of the model parameters were obtained by fitting the test results in Figure 7 (Table 3). The van Genuchten’s model and dual-porosity model are found to be suitable for fitting the suction curves of damaged samples. Meanwhile, the dual-porosity model performs relatively well because of the high values of the correlation coefficient \(R^2\). \(P_1\) and \(P_2\) gradually decrease from SD1 to SD3, thereby indicating that the equivalent radii of microcracks gradually increase from the stable development stage to the unstable development stage.

Table 3. Parameters of van Genuchten’s model and dual-porosity model

| No. | \(\sigma_{\text{max}}\) (MPa) | van Genuchten’s model | Dual-porosity model |
|-----|----------------------------|-----------------------|---------------------|
|     |                            | \(n\) | \(P_r\) (MPa) | \(R^2\) | \(\omega\) | \(P_1\) (MPa) | \(P_2\) (MPa) | \(R^2\) |
| SD1 | 85.4 (<\(\sigma_{\text{cd}}\)) | 1.45 | 3.76 | 0.93 | 0.23 | 245.22 | 5.62 | 0.97 |
| SD2 | 95.5 (≈\(\sigma_{\text{cd}}\)) | 1.41 | 3.15 | 0.96 | 0.28 | 175.30 | 4.72 | 0.99 |
| SD3 | 105.3 (>\(\sigma_{\text{cd}}\)) | 1.44 | 2.04 | 0.96 | 0.22 | 167.17 | 3.43 | 0.99 |

4.5. Gas Permeability of Damaged Granite

The gas permeability of the damaged granite dried at 105 °C, \(k_d\), and the porosity, \(\varphi\), are shown in Table 4. The results of samples SD1 and SD2 are similar to the test results of the intact granite. Therefore, the microcracks generated at the stable development stage are not interconnected, hence the absence of new pathways for gas or water. Moreover, the porosity \(\varphi\) of sample SD3 is only 1.04–1.15 times greater than that of the other samples, but its gas permeability \(k_d\) is about 4–5 times that of the other samples. This result indicates that the unstable development of microcracks contributes greatly to gas permeability.
Table 4. Porosity and gas permeability of dry damaged granite

| No.   | $\sigma_{\text{max}}$ (MPa) | $\phi$ | $k_d$ ($m^2$) |
|-------|-----------------------------|--------|---------------|
| SD1   | 85.4 ($<\sigma_{\text{cd}}$) | 0.0133 | $4.154 \times 10^{-18}$ |
| SD2   | 95.5 ($\approx\sigma_{\text{cd}}$) | 0.0137 | $4.697 \times 10^{-18}$ |
| SD3   | 105.3 ($>\sigma_{\text{cd}}$) | 0.0147 | $2.239 \times 10^{-17}$ |
| Intact (Zhao et al. 2017) | $<\sigma_{\text{ci}}$ | 0.0128–0.0142 | $3.09–4.32 \times 10^{-18}$ |

The gas permeabilities at different levels of water saturation are presented in Figure 7. The gas permeabilities of samples SD1 and SD2 are similar to those of the intact granite. Such outcome shows that the stable development of microcracks does not contribute to gas permeability. Moreover, gas permeability tends to be constant when the water saturation level is less than 0.5, which corresponds to a relative humidity of 75%. Hence, the gas pathways are almost totally dried in relative humidity less than 75%. In other words, the damaged and intact surrounding rocks of the HLW disposal repository in this work show maximum gas permeability in a relative humidity of less than 75%.

Figure 7. Variation of gas permeability with water saturation

Jiang et al. (2012) [13] found that permeability sharply increases when the compression stress reaches the crack damage stress $\sigma_{\text{cd}}$. Wang et al. (2013) [14] also found a sharp increase in the permeability of granitic gneiss before the appearance of macrocracks. These findings are consistent with the test results herein.

5. Conclusions

The following conclusions are derived from the results of this work:

1. The unstable development of microcracks in granite leads to a decrease in Young’s modulus and an increase in horizontal deformability.

2. The stable and unstable development of microcracks does not change the longitudinal wave velocity of granite, and the longitudinal wave velocity tends to remain constant when the ratio of axial stress to crack damage stress is greater than one. However, the shear wave velocity of the damaged granite is significantly decreased. This result indicates that the microcracks generated at the stable and unstable development stages mainly extend along the axial direction rather than the radial direction.

3. The suction curve of the damaged granite is successfully obtained, and it complies with van Genuchten’s model and the dual-porosity model.

4. Almost no new gas pathways are generated at the stable development stage of microcracks, and porosity is not significantly increased. On the contrary, the unstable development of microcracks greatly increases gas permeability.
The gas permeability of the damaged granite tends to be constant when the water saturation level is less than 0.5.

The above findings will benefit the performance assessment of EDZs in the surrounding rocks of HLW disposal repositories.

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