Evolution of Permeability during Fracturing Processes in Rocks under Conditions of Geological Storage of CO₂

Takashi Fujii¹⁺, Takahiro Funatsu², Yasuki Oikawa¹, Masao Sorai¹ and Xinglin Lei¹

¹Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8567, Japan
²Western Australian School of Mines, Curtin University, Kent St, Bentley WA 6102, Australia

We investigated experimentally the change in permeability in three different types of soft rocks including mudstone, sandstone, and tuff from the Fureoi and Takinoue formations, which are representative of the CCS demonstration site at Tomakomai in Japan, and another type of mudstone from the Besho Fm. (B-M). Permeability during deformation, shear fracturing, and post-failure slipping is estimated from measured flow rate and differential pore pressure. In addition, the morphologies of the shear fracture zones were examined using the X-ray CT scanning technique. All the samples exhibit typical brittle-fracturing behaviors, except for the B-M sample which does not show a major shear fracture. During the fracturing process, the permeability increased by one to three orders of magnitude. Further changes in the post-failure slipping and stress relaxation regimes show strong dependence on the type of rocks. Observed changes in permeability can be interpreted as results of fracturing creation, shear zone smoothing, closure and reactivation of fractures under different stress regimes.


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1. Introduction

An understanding of fluid transport within geological reservoirs is fundamental for the use of deep underground repositories for a number of applications such as carbon dioxide (CO₂) capture and storage (CCS). As for the CCS technology, CO₂ emitted by large point sources (e.g. power generation, steel and cement manufacturing, and oil refiner facilities) is separated and captured. It is then transported using pipelines and/or tankers and stored in geological reservoirs (e.g., aquifers) overlaying the low-permeability caprocks at least 800 m depth. Within this environment, CO₂ will be in the supercritical state, because its critical point lies at approximately 31°C, 7.4 MPa.1) During CO₂ injection into such geological storage reservoirs, changes in stress related to the increase in pore pressure could lead to deformation of caprocks and storage reservoirs. Consequently, this might have a significant effect on changes in the hydraulic properties (i.e., permeability and porosity) of the rock and might also potentially induce seismic or aseismic slip along pre-existing fractures or fault zones due to reducing rock and fault strengths.2,3)

Regarding injection-induced failure, a coupled reservoir-geomechanical simulation under conditions of CO₂ geological storage have indicated that potential for mechanical failure, and the type and orientation of fracture depends to a large extent on the initial stress field.4) In general, analyses of hydromechanical behaviors on faults and fractures and quantitative evaluation of changes in material properties are rarely if at all conducted, leading to an estimation of the maximum sustainable injection pressure and a risk assessment for CO₂ leakage from targeted reservoirs. Nevertheless, it is most difficult to predict how the extent to which the potential for such faults reactivation and shear fractures evolution could affect the hydraulic properties of a rock.

With respect to this challenge, laboratory measurements of the hydraulic properties of rocks, failing with deformation under well-controlled conditions (i.e., temperature, effective confining stress, and pore pressure), can provide significant insight into the relationship between rock deformation and hydraulic properties. Many previous laboratory studies on the investigation of change in the hydraulic properties during brittle or ductile deformation have been reported under various triaxial stress conditions for a wide variety of rock types, including argillaceous sediments and rocks (e.g., clay, mudstone, and shale), sandstone, crystalline rocks (e.g., granite, marble) and halite.5-13) But most results did not take into account change in the hydraulic properties in response with fracturing in the post-failure regime. Whereas, for permeability behavior of natural and artificial fracture surfaces in granite, the coupled effects of shear deformation and dilatancy have been reported within the constraints of normal stress levels.14,15) Therefore, a relation between fluid flow and geomechanical responses has mainly been investigated at each of deformation and fracturing stages so far. However, to model precisely the process of fluid flow transport within such reservoirs, relationship between fluid flow and geomechanical responses in the whole regime of deformation including fracturing and post slipping should be well addressed. To date, there are only a few reports on this concern for mudstone, tuff, sandstone, and granite.16,17) Based on these literature data, for argillaceous rocks and sedimentary rocks, changes in permeability by up to approximately two orders of magnitude have been identified due to formation of a main shear plane within a rock mass.

The purpose of this study is to investigate the change in permeability of rocks during deformation, fracturing, and post slipping at geological temperatures and pressures corresponding to a depth of approximately 800 m, i.e., conditions under which supercritical CO₂ could be stored within aquifers. Particularly, for implementation of fracturing processes perfectly in a given stress field, the specific

*Corresponding author, E-mail: takashi.fujii@aist.go.jp
methodology of the sample assembly is used for this study. This methodology is capable of being more easily formed a main shear plane perfectly across the sample with controlled fracturing angle (see Section 2.2.), compared to the case study based on a typical triaxial compression test. Furthermore, in order to explore the physics behind the observed facts, we also analyzed fractures and damage zones created during the experiment using X-ray computed tomography (CT) techniques.

2. Experimental Method

2.1 Specimens

The samples used in this study are Fureoi Fm. mudstone (F-M), Takinoue Fm. sandstone (T-S), and Takinoue Fm. tuff (T-T), which are the principal reservoir rocks and the caprock overlaying them for a demonstration site of the CCS at Takinoue Fm. sandstone (T-S), and Takinoue Fm. tuff 2.24

2.2 Experimental apparatus

The experimental apparatus used in this study comprised a high-pressure vessel (confining pressure: ~30 MPa), a loading frame (axial force: ~1000 kN), and three syringe pumps, as shown in Fig. 2. Axial stress was applied via a servo-controlled hydraulic system, while the confining pressure was applied via a syringe pump using pressure oil. The axial load was measured by an external load cell to an accuracy of 2 kN. The displacement was measured outside the pressure vessel by a Linear Variable Differential Transformer mounted between the moving piston and the fixed upper platen. The uncertainty in the measurement of axial displacement was 100 µm. The inlet and outlet pore pressures and the confining pressure within the vessel were monitored using three pressure transducers (accuracy: ±0.06 MPa). The pressure vessel was maintained at a constant temperature (accuracy: ±0.5°C).

The samples were ground to cylindrical shapes with 50-mm diameter and 20-mm length. They were saturated with distilled water, jacketed with a 3-mm-thick heat-shrinkage tube of silicone rubber, and silicone sealant was placed onto the rim of the silicone rubber to separate it from the confining pressure oil. Then, we coated the circumferential surface of the sample with silicone sealant to prevent from creating bypass flow between the silicone rubber and the sample during the experiment. The specimens were positioned between a pair of end loading plugs containing the fluid inlet and outlet, porous steel metal, and specific spacers which are pre-cut at 30° to the longitudinal axis to force a shear fracture to be formed along a given position, as designed by Takahashi et al. (2003).

The conceptual model of the sample assembly is shown schematically in Fig. 3. It has been known theoretically and experimentally (e.g., McLamore and Gray (1967)) that the angle of 30° is a favorable direction of shear fracturing in most brittle rocks. The end plug and the specific spacers were provided with a circumferential groove to permit maximum contact by the flowing fluid with the ends of the test specimen.

To better understand the mechanical properties of the induced shear zone, axial and circumferential pairs of electrical resistance strain gauges were mounted on the middle of the specimen, as shown in Fig. 3. Additionally, to examine the total deformation of the sample assembly during the experiment, a longitudinal-axis gauge (σ gauge) and extensometer were attached axially and circumferentially to the jacketed sample, respectively.

This apparatus was capable of performing a fluid flow test during shear deformation and fracturing under conditions corresponding to depths within a few kilometers. During the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bulk density (Mg/m³)</th>
<th>Porosity (%)</th>
<th>Specific Surface Area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Besho Fm. mudstone</td>
<td>2.70</td>
<td>0.5</td>
<td>—</td>
</tr>
<tr>
<td>Fureoi Fm. mudstone</td>
<td>2.05</td>
<td>18</td>
<td>21.0</td>
</tr>
<tr>
<td>Takinoue Fm. sandstone</td>
<td>2.29</td>
<td>9</td>
<td>7.47</td>
</tr>
<tr>
<td>Takinoue Fm. tuff</td>
<td>2.24</td>
<td>14</td>
<td>12.2</td>
</tr>
</tbody>
</table>
experiment, the sample was first loaded hydrostatically to a desired confining pressure $P_c$ ($\sigma_2 = \sigma_3$). Then axially loaded ($\sigma_1$) at a constant displacement velocity while maintaining $P_c$ constant. The permeability was estimated from pressure and flow rate at both inlet and outlet measured continuously throughout the experiment. In this study, the shear–fracture compression test was performed at 40°C, confining pressure ranging from approximately 12–25 MPa, and constant pore pressure of approximately 10 MPa (corresponding to an effective pressure ranging from about 2–15 MPa). During the axial load, the ram speed was kept constant at 0.4 mm/h.

2.3 Observation of morphologies of created fracture zones using X-ray CT technique

Nondestructive observations of the fracturing zones were conducted using the medical X-ray CT scanner21) (W2000, Hitachi Medical Inc., Tokyo, Japan) after the experiment. The imaging parameters used in this study were listed in Table 2. Two-dimensional slice images were consecutively obtained along the $x$-$y$ plane with an in-plane resolution of 0.31 mm $\times$ 0.31 mm. Then, the two-dimensional slices were stacked in the $z$-direction to construct a three-dimensional digital image, which is used to observe the morphology of created fracture zones along any cross section, as illustrated in Fig. 4. During the reconstruction of the CT image, the raw intensity data in the sample were converted to CT numbers that had a range determined by the computer system. Medical systems generally used the Hounsfield Unit (HU), in which air was given a CT number of -1000 and water was given a value of 0, causing most sedimentary rocks to have values ranging from -2000 to 4000.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>160 mm</td>
<td>Tube Voltage</td>
<td>100 kV</td>
</tr>
<tr>
<td>Image matrix</td>
<td>512 $\times$ 512</td>
<td>Tube Current</td>
<td>50 mA</td>
</tr>
<tr>
<td>Number of slices</td>
<td>20</td>
<td>Scan time</td>
<td>4 s</td>
</tr>
<tr>
<td>Reconstruction filter</td>
<td>Shepp</td>
<td>Slice thickness</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Fig. 2 Schematic diagram of the triaxial compression apparatus.

Fig. 3 Schematic of the sample assembly and flow paths under triaxial stress conditions for shear-fracture compression tests.

Table 2 List of X-ray CT scanner parameters.
2.4 Calculation of permeability

For this study, during shear deformation to fracturing, the permeability was estimated from Darcy’s Law:

\[ Q = \frac{K \cdot A_0 \cdot \Delta P}{\mu \cdot L} \]  

(1)

where \( Q \) [m³/s] is the flow rate obtained at the inlet or the outlet or the mean of them, \( A_0 \) [m²] is the area of the end face of the sample tested, \( K \) (millidarcy; \( mD \cong 10^{-15} \text{m}^2 \)) is absolute permeability (hereafter called “permeability”), \( \mu \) [Pa·s] is fluid viscosity, \( \Delta P \) [MPa] is the pressure difference between the inlet and outlet ends of the sample, and \( L \) [m] is the sample length. The flow rate and pressure were sampled at interval rate of 2 s. In terms of permeability data analysis, we adopted selected permeability data via a 10 s smoothing window.

3. Experimental Results

The pore pressure for inlet and outlet of the sample are denoted by \( P_{p\text{-in}} \) and \( P_{p\text{-out}} \), respectively, and the difference between the confining pressure and a mean pore pressure \((=P_{p\text{-in}}+P_{p\text{-out}})/2\) is referred to as the “effective pressure”, \( P_e \). The calculated permeability, \( K \), values, based on the method mentioned in Section 2.4, for both inlet and outlet ends of the sample are represented as \( K_{p\text{-in}} \) and \( K_{p\text{-out}} \), respectively. The complete sets of mechanical stress and strain data of the tested samples, could be basically classified into seven typical regions (a)-(g) (Figs. 5a–5g). The upper graph shows the axial (\( \varepsilon_a \)), and circumferential (\( \varepsilon_c \)) strains, axial stress, and \( K_{p\text{-in}} \), \( K_{p\text{-out}} \), and \( K_{ave} \) \((K_{p\text{-in}}+K_{p\text{-out}})/2\), against time. Particularly, \( \varepsilon_c \) value is determined from axial shortage by subtracting predicted values of strains of spacers based on theoretical young’s modulus of stainless steel and porous metal. In this experiment, the criteria that the test sample fails by fracturing are identified by the breakdown of the attached axial (\( \varepsilon_a' \)) and circumferential (\( \varepsilon_c' \)) strain gauges onto the sample surface, which show an abruptly change of strain to an unmeasurable level, as shown in Figs. 5a–5g. Particularly, the first breakdown, corresponding to the broken of the circumferential strain gauge, is represented here as the “break point” (\( B_a \)). The lower graph shows the displacement (\( D \)), \( P_e \), \( P_{p\text{-in}} \), and \( P_{p\text{-out}} \) against time for all experiments at a pore pressure of 10 MPa, i.e., at a constant pressure difference of about 1 MPa (\( P_{p\text{-in}} \): 11 MPa, \( P_{p\text{-out}} \): 10 MPa), and a confining pressure of approximately 20 MPa. Furthermore, to investigate the change in permeability following post-failure slipping of the created fracture, we adopted further steps of a loading-unloading \( P_e \) cycle in regions (d) to (g). Initially, \( P_e \) was increased from 10 to 15 MPa and then it was maintained at the maximum level for several hours (e), \( P_e \) was reduced from 15 to 2 MPa (f) (under hydrostatic stress conditions only for the F-M sample or while maintaining the final level of differential axial stress states for all other samples) and then \( P_e \) was kept for several hours (g).

3.1 Results of Fureoi Fm. mudstone (F-M)

As illustrated in Fig. 5, the sample deformation in region (a) shows two peak stresses. Permeability does not change following the first peak. The axial stress attains the maximum value at the second peak at \( B_a \) which exhibits a drop of \( \varepsilon_c' \) abruptly, beyond which strain softening occurs and the stress drops steeply to a residual level. Subsequently, the permeability values of the F-M sample change drastically by up to approximately one order of magnitude, relative to its initial permeability (approximately \( 2.0 \times 10^{-18} \text{m}^2 \)).

In region (b), the permeability value jumps sharply (from about \( 4.0 \times 10^{-18} \) to about \( 2.0 \times 10^{-17} \text{m}^2 \)), after which the permeability value decreases gradually with decreasing stress.
but also showing some fluctuations. Furthermore, in addition to $\varepsilon_p$, $\varepsilon_a$ also shows the behavior of strain damage induced by a deep tensioning. In region (c), the axial stress and strains are quite stable indicating stress relaxation is not significant while the axial displacement kept constant. The permeability shows a short peak and then decreases gradually with time.

In regions (d) and (e), the permeability decreases slightly with increasing $P_e$. During the unloading process in regions (f) and (g), increasing in permeability is observed, when $P_e$ was below the SL, however, the amount of increase was much smaller than the F-M sample.

### 3.2 Results of Takinoue Fm. sandstone (T-S)

As illustrated in Fig. 6, permeability in region (a) increases abruptly from about $1.0 \times 10^{-18}$ m$^2$ to about $2.0 \times 10^{-17}$ m$^2$ in relation to several minor stress-drop events before the peak stress at $B_p$ corresponding to a deep drop of $\varepsilon_p$. Note that the axial strain gauge ($\varepsilon_a$) has broken down mechanically prior to this experiment. After attaining the peak stress (region (b)), the permeability of the T-S sample shows an increasing trend with some fluctuations as the axial stress gradually decreases to a residual level. In region (c)–(e), the permeability decreases gradually when axial displacement keeps constant, showing a similar manner as the F-M sample. During the unloading process, the permeability increases clearly when $P_e$ was below the SL, however, the amount of increase was much smaller than the F-M sample.

### 3.3 Results of Takinoue Fm. tuff (T-T)

The permeability shows fluctuations of large amplitude before the peak stress (a) (Fig. 7). This might indicate that some minor fractures were created but yet connected with each other. In region (b), in the post-peak regime, similar with the F-M sample, the permeability increases sharply up to a maximum value of approximately $2.0 \times 10^{-17}$ m$^2$ during the rapid stress drop period. Then the permeability turns to decrease gradually with further deformation. As for the definition of $B_p$, the T-T sample has a significantly more complex behavior on the $\varepsilon_p$ and $\varepsilon_a$ than the F-M and T-S samples, and thus cannot be used for determining the $B_p$. This sample exhibited similar behavior to that of T-S sample during the regions (c)–(g).

### 3.4 Results of Besho Fm. mudstone (B-M)

B-M sample behaved in a significantly different manner from other samples (Fig. 8). Before the $B_p$ which shows a
significant drop of $\varepsilon_a$ such that do the F-M and the T-S samples, axial stress increases gradually and permeability values jump substantially from about $2.0 \times 10^{-19}$ to about $3.0 \times 10^{-16} \text{m}^2$. The change in permeability is the largest of all the samples. In contrast to the other samples, although there are several minor stress-drop and $\varepsilon_a$-breakdown events, the axial stress of the B-M sample keeps continuous increase after the $B_p$, which means that the sample fails imperfectly by fracturing. However, the observed change in permeability, similar to the other materials, suggests that the created fractures induced by these stress drops could be interconnected. After region (b), during this experiment, the pore pressure line and the sample assembly are invaded by confining oil due to a damage of the silicone rubber with fracturing of the sample, and after the pore pressure exhibits almost the same value of confining pressure. Consequently, we could not continue to do this experiment after this region.

3.5 Morphologies of fracture structures observed by X-ray CT analysis

Figure 9 presents X-ray CT images along a cross-section perpendicular to the fracture zone created during the experiment. These images demonstrate that, all the samples except for the B-M sample shows a single major compression-induced shear fracture zone along the extrapolated shear slippage line; while, a number of branch fractures can be seen in the T-S and the T-T samples (Fig. 9(c) and 9(d)). In the B-M sample, govern by the strong pre-existing bedding structures, a number of deeply dipped fractures occurred (Fig. 9(a)). These fractures do not linked with each other. Such kind of fracturing pattern has been identified in shale and strongly foliated rocks. Thus, for the B-M sample, the X-ray CT imaging reveals the reason why the sample did not fail by shear fracturing, even though the attached strain gauges were broken.

4. Discussion

As mentioned above, all the tested samples exhibit brittle-fracturing behavior, except for the B-M sample which do not show a major shear fracture. When a sample fails under compressional stress, the failure process including the pre- and post-failure damages is strongly dependent on lithology type, pre-existing cracks, and foliation and bedding structures. Through detailed AE monitoring, it is observed that a shear fracture in crystallized rocks is normally guided by a tensile cracking-dominated process zone, by which the fracture geometry is complicated. In sandstones, microcracking occurs along grain boundaries by one of two mechanisms: (i) widening of pre-existing intra-granular...
microcracks, which leads to the formation of wing cracks, such as in a crystalline rock like granite; or (ii) shear rupturing of the cement at the grain contacts, caused by the rotation and slip of the grains.\(^{24}\) In shale and strongly foliated rocks, the finally created fracture zone depends on the orientation of the bedding planes or foliations.\(^{22}\) All these results indicate that the stress-strain relationship and post-failure damages, which govern the rock permeability, depend on rock type and pre-existing structure within the sample. Once a macro shear fracture zone was formed, the rock deformation and permeability are controlled by the frictional rupture behavior of the shear zone. In all sample except for the B-M sample, a short-term increase followed by a long-term gradual decrease in stress is observed in the range from (a) to (b) (e.g., Fig. 6), after the sudden stress drop. This fact indicates a gradually decrease in frictional strength, which is clearly resulted from slip smoothing effect.

For all tested samples, degree of the increase amount in permeability is approximately 1-3 orders of magnitude, in agreement with literature data.\(^{16,17}\) A decrease in permeability after the peak stress was also observed in both the F-M and the T-T samples. One possible explanation for this might be attributed to the closure of microcracks during the above-mentioned slip smoothing effect, as described in Batzle et al. (1980).\(^{25}\) In fact, for mudstones, Kwon et al. (2004)\(^{26}\) identified that the closure of microcracks with deformation have a significant impact on permeability reduction within the sample. Whereas, in contrast to these rocks, the T-S sample exhibits an increasing trend in permeability in the post-failure field. This might be due to the fact that during the slip stage, some new fractures are created within the shear zone or its vicinities, as demonstrated by the X-ray CT images shown in Figs. 9(c) and 9(d).

Subsequently, for the region (c), despite the observed stress relaxation shows dependence on rock types, all samples except for the B-M sample exhibited decrease in permeability. This fact indicates crack closure and fault healing behaviors.

Increasing of effective confining pressure results in crack closure and decreasing permeability. Whereas, during the unloading process, the permeability shows a continuous decrease until the effective stress higher than SL. After that the permeability turns to increasing, indicating opening of pre-existing fractures and/or forming of new fractures, as expected from the Kaiser effects,\(^{27}\) widely observed in laboratory AE studies.

In numerical simulations, rock permeability is often modeled as a linear function of volumetric strain \(\varepsilon_v\) (coupling of the elastic and plastic components of strains).\(^{28}\) \(K = K_0 \cdot (1 + \alpha \cdot \varepsilon_v)\), where \(\alpha\) [m\(^2\)] is a constant, \(K\) and \(K_0\) are the permeability in a given stress state and initial permeability. Our results, as schematically illustrated in Fig. 10, shows that such simple model does not work for soft rocks such as that investigated in this study. Further works are required to construct better models for soft rocks, especially for including the hydraulic behavior during the post-failure regime.

It can, therefore, be concluded that a precise advanced model based on the experimental data is required in order to predict fluid transport during deformation to fracturing.

5. Conclusions

We investigated experimentally the change in permeability in three different types of rocks including mudstone, sandstone, and tuff from the Fureoi and Takinoue formations (T-R), which are representative of the CCS demonstration site at Tomakomai in Hokkaido, Japan, and another type of mudstone from the Besho Fm. (B-M). Permeability during deformation, shear fracturing, and post-failure slipping are estimated from measured flow rate and differential pore pressure. In addition, the morphologies of the shear fracture zones were examined using the X-ray CT scanning technique. All the samples exhibit typical brittle-fracturing behaviors, except for the B-M sample. During the fracturing process, the permeability increased by one to three orders of magnitude. Further changes in the post-failure regime and during stress relaxation are also observed, which depend on the type of rocks. Observed changes in permeability can be interpreted as results of fracturing creation, shear zone smoothing, closure and reactivation of fractures under different stress regimes. Based on the X-ray CT analyses, the T-R sample also exhibits branch fractures within the shear zone or its vicinities, in addition to major shear fractures. Whereas, the B-M sample does not show such fractures, like that inferred by the obtained mechanical data.

Our results, as schematically illustrated in Fig. 10, shows that existing models, which are used for hard rocks, does not work for soft rocks such as that investigated in this study. Further works are required to construct better models for soft rocks, especially for including the hydraulic behavior during the post-failure regime. Such models for soft rocks would provide a widely contribution to utilization of deep underground repositories where nature rocks of the reservoir system are “soft”, such as that in Japan. Particularly, for deployment of the CCS, this could play a critical role in establishment of the maximum sustainable injection pressure and a risk assessment for CO\(_2\) leakage from targeted reservoirs.
Acknowledgments

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