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CHARACTERISTICS OF STRENGTH FOR HYDRAULIC FRACTURING OF BUFFER MATERIAL

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ABSTRACT

The fundamental characteristics of strength for the hydraulic fracturing of highly compacted bentonite were studied. Firstly, the constant pressurize rate tests were carried out for the material having various specifications. Secondly, the cyclic pressurize test was carried out to examine the self-sealing function as a buffer material. Thirdly, the constant pressure test was carried out to observe the change in strength during seepage. The observed phenomena were analytically examined. As a result, it was found that the strength for hydraulic fracturing of the buffer material increased with the increase of initial dry density, decrease of sand-mixture ratio and decrease of water content. The swelling pressure of the buffer material worked as a constraint stress for the strength for hydraulic fracturing. The fracture made by hydraulic fracturing was fixed through the supply of water. However a long period of low-pressure supply was needed to recover the strength at the failed parts. While the tensile failure was dominant, the specimen having a low dry density might be failed initially by the shear failure. When the water content became large during seepage, the strength for hydraulic fracturing reduced.

Key words: bentonite, dry density, hydraulic fracturing, laboratory test, nuclear waste disposal, swelling, water content (**IGC**: D4/D5/D6)

INTRODUCTION

To safely dispose high level radioactive waste, the repository is composed by multi-barrier system. According to the Japanese plan, the vitrified waste packed in the canister is furthermore surrounded by the highly compacted bentonite as a buffer material (Japan Nuclear Cycle Development Institute, 1999). The repository is planned to be set at the deep geology under more than 300 m from ground level. Therefore, the high water pressure will be imposed on the buffer material after closing off the repository. The hydraulic fracturing of the buffer material is worried under such a high pressure condition. In this study, the fundamental characteristics of strength for the hydraulic fracturing of highly compacted bentonite are studied.

The bentonite has a large swelling capacity during the seepage process (Fujii and Nakano, 1984). The characteristics are expected to fix the openings and damages in the buffer material. The required swelling capacity is estimated to correspond to the minimum swelling pressure of about 1 MPa in the Swedish project (SKB, 1998). This kind of fixing phenomena is called self-sealing function of buffer material. It takes, however, a long time for water to seep into the buffer material because of very low permeability of the material, which is also one of the important properties as a barrier. The buffer material, therefore, has to have two main properties of large swelling capacity and low permeability. The main function of the buffer material is considered to prevent the transport of the leaked radioactive waste into the surrounding rocks. The properties related to the permeability and the solute transport have been intensively studied by many researchers, e.g., Börgesson et al. (1995), Suzuki and Fujita (1999), Shibutani et al. (1992). The study about swelling pressure has been also carried out by some researchers like Komine and Ogata (2003).

The strength of the buffer material has been also studied and was found as a function of the degree of saturation, dry density and the mixture ratio of sand (Takaji and Suzuki, 1999). As a general tendency, the strength of buffer material becomes low with the increase of water contents and sand contents. However, the shear failure by loading is not expected to occur, because the load acting to the buffer material is not so high under the plan of the project. On the other hand, the failure by hydraulic fracturing may occur under the condition of high water pressure after closing the repository as mentioned earlier. If the hydraulic fracturing occurs, the buffer material loses the function of prevention of the solute transport. However, the examination related to the hydraulic fracturing of the buffer material has not been carried out well

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regardless of the importance. The fundamental properties of buffer material for hydraulic fracturing are examined for the first time in this paper. In particular, the effect of swelling and seepage phenomena on the strength for hydraulic fracturing is focused on.

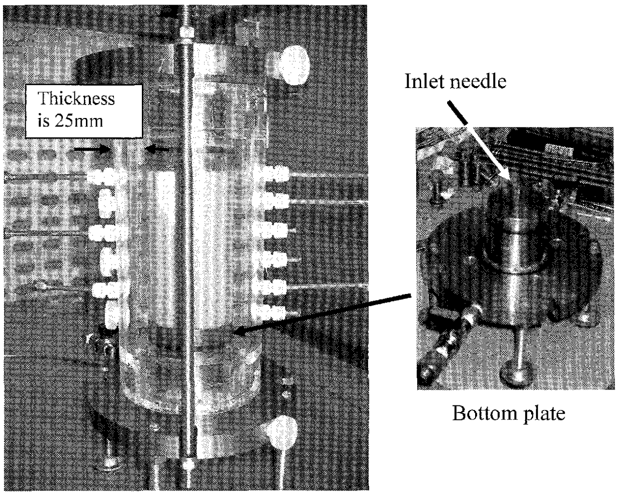
The hydraulic fracturing technique has been used to investigate the earth pressure of rock mass. Moreover, the technique was used to make the artificial fracture in the hot dry rock for the geothermal energy production (Hayashi and Abe, 1983). Thus, the experiments and theoretical development have been carried out for rocks extensively. For soils, the failure related to water flow is called a seepage failure and three types of failure are roughly identified, i.e., heaving, piping and internal erosion (Zyl and Harr, 1981). Many studies have focused on the applicability of the critical hydraulic gradient defined by Terzaghi's or Justin's theory. The typical experiment is one-dimensional and water is flowed from the bottom to the top boundary. The hydraulic gradient is gradually increased and the change in the flow rate is monitored. The failure is defined as an abrupt increase of flow rate (Sugii et al., 1989). For the safety of the dam, various types of tests have been carried out to give the criteria for the hydraulic fracturing. The slot or slit is set in the specimen and the water pressure is applied in the space of the slot. The abrupt increase of flow rate or the decrease of pressure is defined as a failure. In many studies, the confinement stress is changed to see the effect of the confinement on the failure pressure (e.g., Joworski et al., 1981) As a failure criteria, the tension failure dependent on the constraint stress has been examined by many researchers (e.g., Mori, 1987). However, Yanagisawa and Panah (1994) indicated that the hydraulic fracturing could be explained by the shear failure based on the Mohr-Coulomb criteria. For the usage to investigate the earth pressure, the theory based on the tensile failure has been also mainly applied (Heimson and Fairhurst, 1967). The theory using the tensile failure is based on the assumption of elastic impermeable media. For the poorly consolidated rocks such as oil sand and weak shale which are permeable and plastically deformed media, Wang and Dusseault (1991) indicated that the shear rupture was suitable for the failure criteria. Tsukada et al. (2005) demonstrated that the tensile failure gave the very similar rapture tendency to the shear failure for the various rocks and proposed the failure criteria for both raptures by considering the overburden pressure and the increase ratio of water pressure. For the buffer material, investigation of the failure mechanism is also a very important subject, which we will try to understand in this paper.

In this paper, as a first step, the breakdown pressure by hydraulic fracturing is investigated for various conditions of buffer material. The effect of dry density, pressurize rate, initial water content and sand-mixture ratio on the breakdown pressure is investigated by the laboratory tests. Moreover, the cyclic pressurize test is carried out to examine the self-sealing function as a buffer material. The constant pressure test is also carried out to investigate the effect of decrease of strength for hydraulic fracturing during seepage. Since these tests for a buffer material have never been carried out, the results will give the valuable information to examine the mechanical stability of the buffer material. Then, the hydraulic fracturing phenomena are examined with theory used in the ordinary hydraulic fracturing test for earth pressure measurement.

TEST DESCRIPTION

Test Apparatus

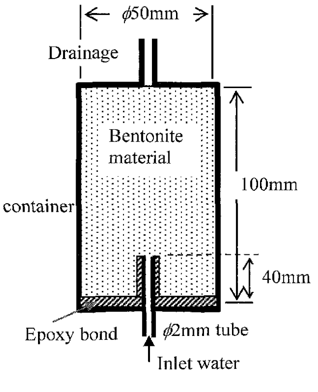
The specimen used for the test is 5 cm in diameter and 10 cm in height. Figure 1 shows the test apparatus and the schematic view of specimen. Most tests are carried out by using the canister used to examine the water movement under thermal gradient condition by JAEA (Fujita et al., 1997). The canister is made of bakelite. The thickness of the cylinder is 25 mm. The deformation during the test is expected to be completely constrained, while the confining pressure is not imposed on the specimen. The surface of the specimen can be observed as shown in the figure. The canister for CT scanning was made of aluminum. At that time, the observation of the surface cannot be car-



Bottom plate

Experimental apparatus

(a) Experimental apparatus for pressure control test and bottom plate



(b) Schematic view of specimen

Fig. 1. Experimental apparatus and specimen

Table 1. Conditions and breakdown pressure of a given pressurize rate test

Case	Parameter	Dry density Mg/m^3	Initial water content %	Mixture ratio of sand %	Pressurize rate KPa/min	Breakdown pressure MPa
1	(Reference)	1.6	12.5	30	49	1.4
2	Density	1.8	12.5	30	49	2.0
3	Density	2.0	12.5	30	49	5.0
4	Pressurize rate	1.6	12.5	30	9.8	2.2
5	Pressurize rate	1.6	12.5	30	2.0	1.9
6	Water content	1.6	18.8	30	49	1.0
7	Water content	1.6	25.0	30	49	0.9
8	Sand mixture ratio	1.6	12.5	50	49	0.6
9	Sand mixture ratio	1.6	12.5	0	49	4.7

ried out. The water is injected from the tip of the tube. Since the space around tube except for the tip is filled with epoxy bond as shown in Fig. 1, the water pressure is applied into the specimen by point wise inlet, which is the similar type of hydraulic fracturing test by Hori et al. (2002). The part to swell is very limited to the surrounding of the tip before fracturing. Therefore, the strength for hydraulic fracturing will be caused from only the fracture toughness and swelling pressure around the tip of inlet tube.

Test Cases

Table 1 shows the test cases for the investigation of strength for hydraulic fracturing for various conditions. All cases were carried out by a constant pressurize rate. In this study, the examined parameters are the dry density, pressure rate, initial water content and sand-mixture ratio. Case 1 is the reference case, of which the dry density is 1.6 Mg/m^3, the mixture ratio of sand is 30% and the initial water content is 12.5%, which corresponds to the degree of saturation of 50%. The specimens for various conditions shown in Table 1 are made by static compaction method, which is the same as that used to examine the various properties of the buffer material by JAEA (Japan Atomic Energy Agency) (Suzuki et al., 1992). Since the specimen is compacted with some strata, the joint plane is made in the specimen. While the joint plane is disturbed well before sequent compaction, the joint plane might become a weak part of the specimen. The length of the inlet tube is decided to avoid the weak joint. The bentonite used in the tests is Kunigel V1 of Kunimine Co. Ltd., which is a natural sodium bentonite, and the sand is silica sand.

Cases 2 and 3 have different dry densities from Case 1. Cases 4 and 5 have the same specimen condition as Case 1, but the different pressurize rates are applied. Cases 6 and 7 have different initial water content from Case 1. Case 7 uses a fully saturated material. Cases 8 and 9 have different sand-mixture ratios from Case 1. Case 9 uses the material composed of only bentonite.

By considering the results from above cases, the cyclic pressurize test is carried out to investigate the self-sealing function. Moreover, the constant pressure test is performed to study the effect of the decrease of strength during seepage.

Table 2. Fundamental Properties of the specimen: The dry density is 1.6 Mg/m^3 for both cases Parenthetic reference of tensile strength is the water content

Mixture ratio of sand	0%	30%
Poisson's ratio	0.3	0.3
Permeability (m^2)	4.2×10^{-21}	1.4×10^{-20}
Ultimate swelling pressure (MPa)	1.0–1.8	0.5
Tensile strength (MPa)	0.18 (6.8%)	0.05 (4.7%)

Fundamental Properties

The fundamental properties of the reference case were investigated by JAEA. While the montmorillonite content of Kunigel V1 is dependent on the time frame, the dependency of each property on the mixture ratio of sand and water content is similar regardless of the montmorillonite content. Table 2 shows the Poisson's ratio, permeability of saturated condition, the ultimate swelling pressure and tensile strength. The property about seepage in the unsaturated condition was investigated for water diffusivity. Figure 2 shows the water diffusivity as a function of volumetric water content for the sand-mixture ratio of 0% and 30% (Suzuki and Fujita, 1999a). It is found from the figure and table that the material has a very low permeability. Figure 3 indicates the water retention curves. The material has a very high potential at low water content. The potential of the material of the sand-mixture ratio of 30% is about 4 MPa at the water content of 12.5% and that of only the bentonite is about 19 MPa at the same water content. The potential was measured by a thermocouple psychrometer (Suzuki et al., 1996). Therefore, the measured potential is the chemical one including both osmotic and matric potentials. Figure 4 shows the unconfined compressive strength (UCS) as a function of water content. The UCS decreases with water content. The tendency is emphasized for the material of

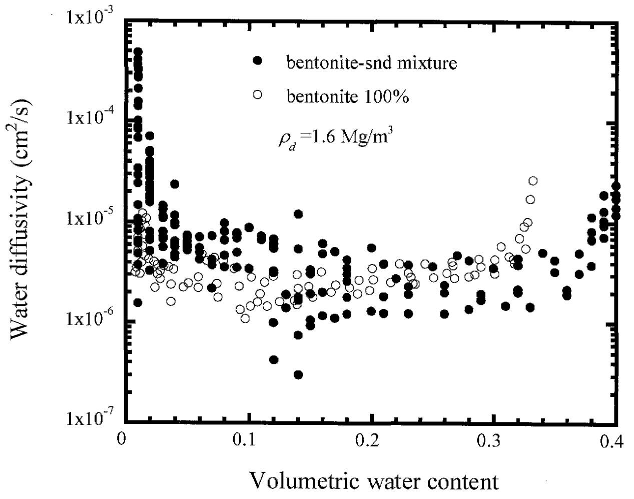


Fig. 2. Water diffusivity as a function of volumetric water content: The dry density of both materials is 1.6 Mg/m³

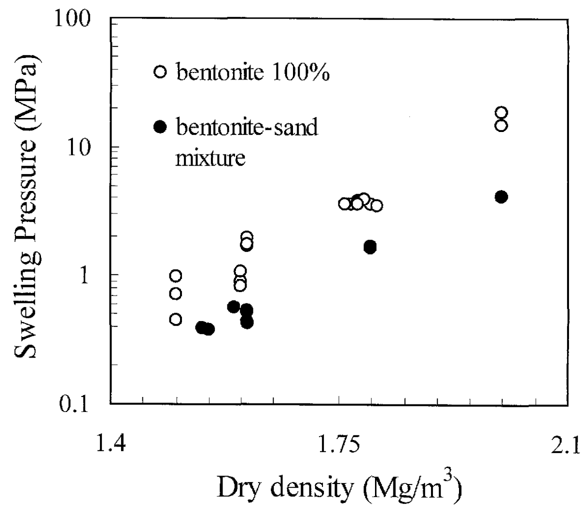


Fig. 5. Swelling pressure as a function of dry density

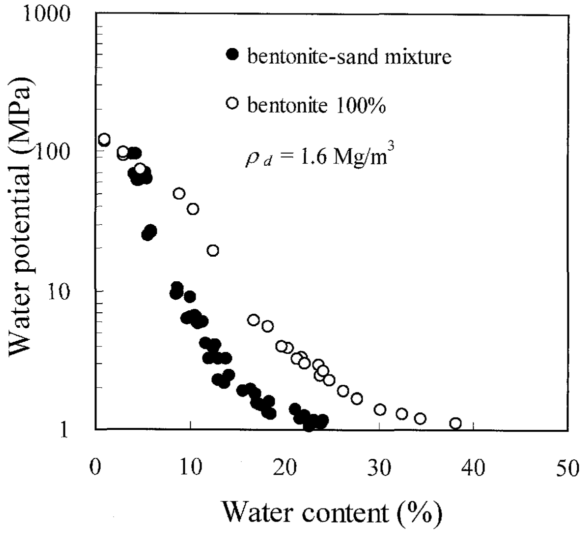


Fig. 3. Water retention curve: The dry density of both materials is 1.6 Mg/m³

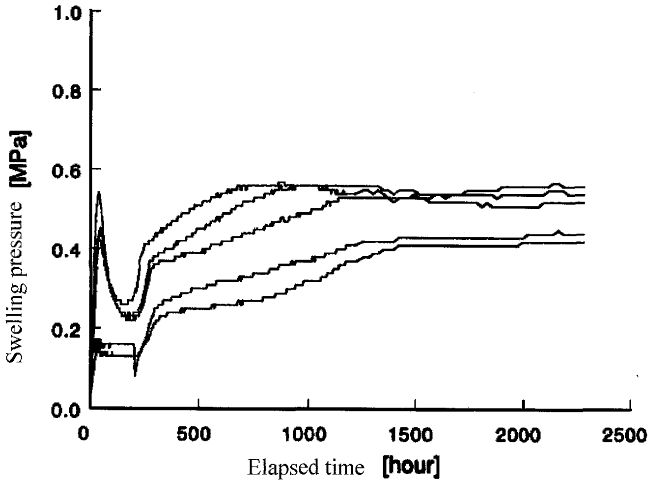


Fig. 6. Results of swelling pressure test for the material of Case 1 (Suzuki and Fujita, 1999b)

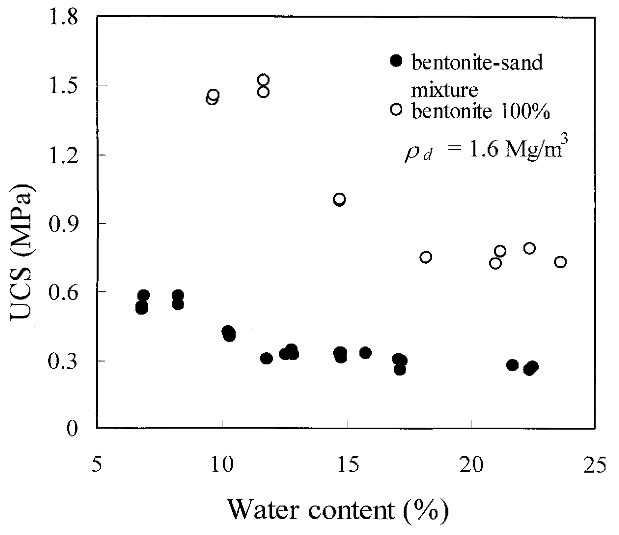


Fig. 4. Unconfined compressive strength (UCS) as a function of water content: The dry density of both materials is 1.6 Mg/m³

only the bentonite. Moreover, the material having the sand-mixture ratio of 30% has a lower strength than the one composed of only bentonite. Figure 5 indicates the swelling pressure as a function of initial dry density (Suzuki and Fujita, 1999b). It is found that the swelling pressure is strongly dependent on the dry density. The swelling pressure of the material of reference case is about 0.5 MPa and that of bentonite 100% with dry density of 1.6 Mg/m³ is about 1.0–1.8 MPa as shown in Table 2. Figure 6 indicates the swelling pressure rising history for the material of Case 1 at the test. The swelling pressure test was carried out by using the specimen having 20 mm diameter and 20 mm height. Water was supplied from the bottom with mostly zero pressure and the swelling pressure was measured at the top by load cell. The swelling pressure went up immediately after the start of test and then reduced before rising again and then reaching steady state after about 1500 hours.

RESULTS OF CONSTANT PRESSURIZE RATE TEST

Situation of Breakdown

Water was supplied with the constant pressurize rate specified in Table 1. When the pressure decreased drastically, it was judged that the failure occurred and the maximum pressure was considered as a breakdown pressure as shown in Fig. 7. Table 1 also indicates the breakdown pressure of each case. The number of the tests for each case was three except for Case 7 which was one. The averaged value is shown in the table. The error of each case was up to 15%. Figure 8 indicates the fracture observed as a typical failure pattern, which is perpendicular to the construction joint plane. The fracture emerged when the water pressure showed the peak value, and then the water flowed out from the fracture. The pressure went down rapidly after peak by withdrawal of water as shown in Fig. 7. Figure 9 shows the inner situation after failure of Case 1. While the fracture plane was wet, the inner parts remained dry. This means that there is little seepage into the material during pressurization and thus inlet pressure acts directly to make a fracture. It can be found from the fracture geometry that the tensile failure is dominant although the effect of shear failure can be partially seen.

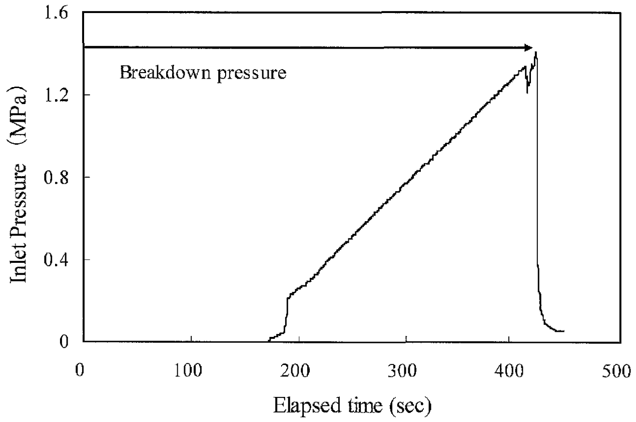


Fig. 7. Typical relation between inlet pressure and elapsed time (Case 1)

Result of Test

It is observed from the results of Cases 1 to 3 that the breakdown pressure increases with dry density. The highest breakdown pressure is observed for Case 3 of which dry density is 2.0 Mg/m^3.

It is found from Cases 1, 6 and 7 that the breakdown pressure decreases with increase of the initial water content. Case 7 corresponds to the test of fully saturated material as mentioned earlier. The fully saturated material shows the 64% strength of the reference case, of which the initial degree of saturation is 50%. This is because the strength of the bentonite material decreases with increase of the degree of saturation. Figure 4 shows similar ten-

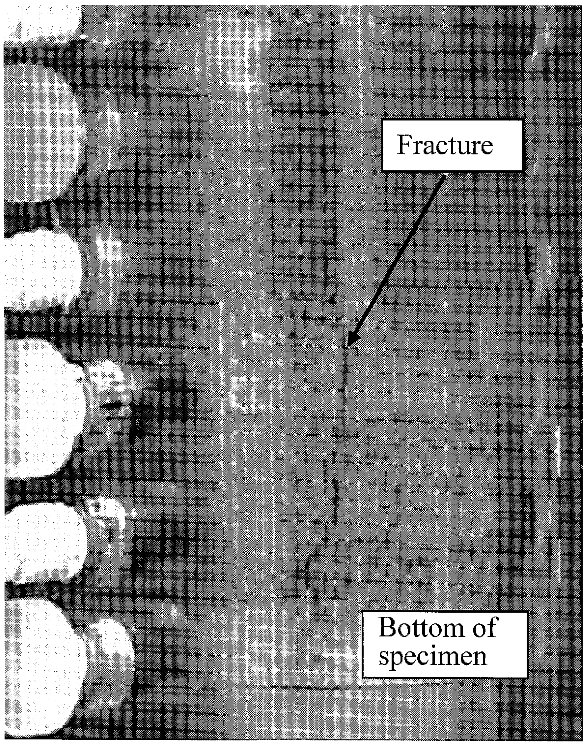


Fig. 8. Typical fracture pattern observed on the surface of the specimen

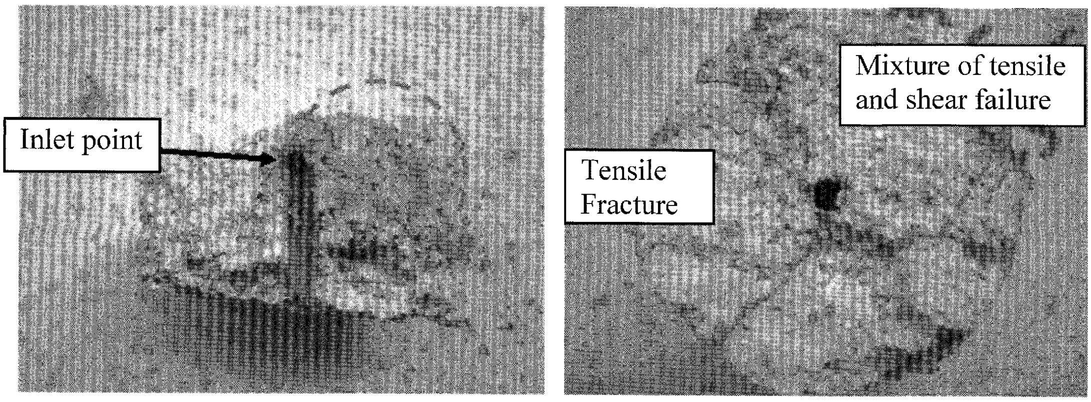


Fig. 9. Example of condition of fracture plane after failure

dency of unconfined compressive strength while the dependency of tensile strength on the water content has not been studied so well. The unconfined compressive strength at the degree of saturation of 90% was about 84% of that at the degree of saturation of 50%.

From Cases 1, 8 and 9, the breakdown pressure increases with decrease of the sand-mixture ratio. The breakdown pressure of the specimen of the sand-mixture ratio of 30% is about 30% of that of only the bentonite. Similar tendency can be seen for unconfined compressive strength as shown in Fig. 4. The unconfined compressive strength of the material of the sand-mixture ratio of 30% is about 24% of that of only the bentonite.

On the other hand, it is found from Cases 1, 4 and 5 that the pressurize rate does not affect to the strength for hydraulic fracturing with clear tendency. In general consideration, the slow pressurize rate gives a time for dissipation of water pressure by seepage into material and swelling pressure increases. As a result, the strength for hydraulic fracturing is expected to become high. However, Case 5 which has the slowest pressurize rate shows a smaller breakdown pressure than Case 4. This may indicate the probable effect of the change in the strength due to the change in the water content as shown in Cases 6 and 7.

Summary of Constant Pressurize Rate Test

For the strength for hydraulic fracturing of the buffer material, it is found that the strength increases with increase of the initial dry density, decrease of the sand-mixture ratio and decrease of the water content. This tendency is the same as that of unconfined compressive strength. In particular, the initial dry density and sand-mixture ratio have a large effect on the strength for hydraulic fracturing. The characteristics may be related to the swelling capacity because the swelling pressure is also very sensitive to both dry density and sand-mixture ratio as shown in Fig. 5. Moreover, while the reduction of the breakdown pressure with water content can be shown, the breakdown pressure of Cases 6 and 7 is mostly the same. As seen in Fig. 4, the unconfined compressive strength is also not so different for the water content over 12%. The dependency of the strength for hydraulic fracturing on water content is expected to be small at high water content.

On the other hand, the effect of the pressurize rate was not clear. The breakdown pressure did not change so much with the pressurize rate. This is probably because the gradual rising of swelling pressure during seepage did not appear in the tests as expected. The swelling pressure rose at a very early stage of the swelling test as shown in Fig. 6. It is, therefore, expected that swelling pressure works in the same way for Cases 1, 4 and 5. The reason why the variation of breakdown pressure was small can be inferred from the small difference of the strength due to the water content and the early development of swelling pressure.

Although the characteristics of strength for hydraulic fracturing of the different materials are known from the above results, the self-sealing function cannot be examined. For this objective, the cyclic pressurize test is carried out. Moreover, it is important to know the reduction of the strength from the initial stage. This may be caused from the characteristics related to the water content. To consider the process of the reduction of the strength, the constant pressure test is also conducted.

CYCLIC PRESSURIZE TEST

Test Results

To investigate the self-sealing function for the hydraulic fracturing, the cyclic pressurize test was carried out. Figure 10 shows the pressurization history. The specimen used for this test has the sand-mixture ratio of 0% and dry density of 1.6 Mg/m^3. Firstly, the specimen failed at 3.2 MPa by imposing the constant flow rate of 4 mL/min, and then the valve of water supply was shut and then the pressure was converged to the shut-in pressure, Ps1, of about 0.2 MPa. Then, the second pressurization was carried out with the same flow rate and the second breakdown pressure, Psb, of 0.8 MPa was observed. Since the confining pressure to the specimen was not applied in the test, the closing of the fracture is caused from the swelling of the bentonite. Therefore, the difference between Psb and Ps1 indicates the recovery of strength by the swelling during this period. After observation of the second shut-in pressure, Ps2, water was supplied at a small flow rate of 2 mL/min and the stable pressure, Ps3, was observed. Then, a little high flow rate of 3 mL/min was applied and then the stable pressure, Ps4, was monitored. The pressure value of Ps4, was about 1 MPa, which is less or mostly equal to the ultimate swelling pressure shown in Table 2. Finally, water was supplied at 4 mL/min after observation of Ps4 and the third breakdown pressure, Ptb, was obtained. The pressure of Ptb was mostly the same as Pb.

It can be considered that the fractured material recovered after cyclic pressurization, and thus the same breakdown pressure as the first breakdown was observed at the last pressurization. However, the early failure was observed at the second pressurization when the same inlet flow rate as the first pressurization was used. The recov-

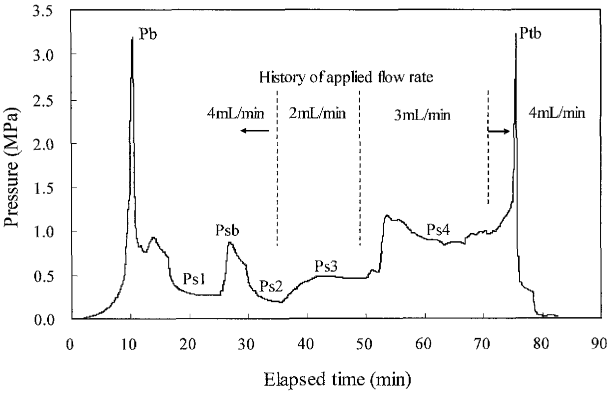


Fig. 10. Pressure history of cyclic pressurize test

ery of strength for hydraulic fracturing is probably caused from the swelling phenomena of the bentonite material. It is found that a long period of low pressurization is needed to fix the fracture by swelling phenomena.

Observation by CT Scanning

After the cyclic pressurize test, the specimen was studied by CT scanning with X ray. To emphasize the fractured parts, water was supplied with the same pressure as the breakdown one and the scanning was carried out with the pressurization. Figure 11 shows the scanning results. The sections at the different heights of the specimen are indicated. For all figures, the white color indicates the part with high density and the black color indicates low density. Since the density of water is smaller than that of the bentonite particle, the parts occupied with water are observed by black. The clear white circle in (e) indicates the stainless tube, and the black hole continuously shown in entire region is considered as water, which was supplied to emphasize the fractured parts. (f) indicates the entire profile of the CT value with 3-D view. The black hole is connected from the lower to the upper part of the specimen as shown in (f). This hole was probably made by piping by the last pressurization. While the image is not so clear, it is found that the white line is also continuously developed from top to bottom. The density at this line is larger than the surrounding parts. This line is inferred to be the fractures made by the first and second breakdown pressurizations, which are developed linearly from the inlet point and so can be expected to be produced by tensile failure. The fractures were closed through the swelling phenomena and became denser than the surrounding material. The reason why the last breakdown pressure was the same as the first one is probably because the piping newly occurred by the last breakdown pressurization. Since the piping hole exists on the white line, the piping was supposed to occur by partial failure of previous fracture plane.

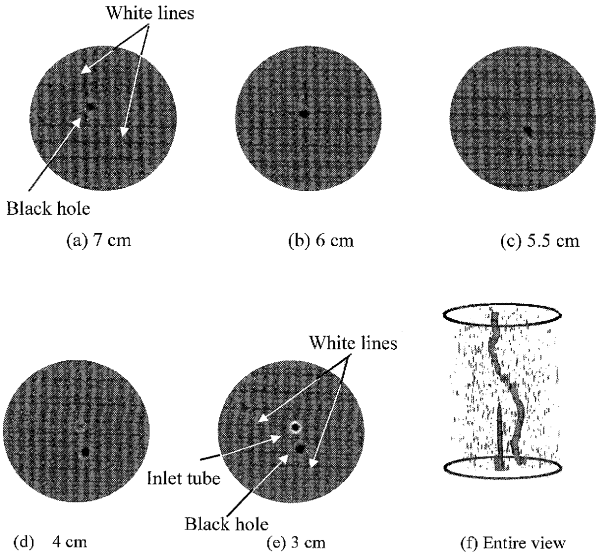


Fig. 11. Results of CT scanning: (a)-(e) show the sections at the different height from bottom of specimen

The fracture made by hydraulic fracturing will be fixed through the supply of water. However, a long period of low-pressure supply is needed to recover the strength at failed parts. If the high-pressure water is continuously supplied at the failed parts, it would be difficult to close the fracture.

CONSTANT PRESSURE TEST

From the results of Cases 1, 4 and 5 of the constant pressurize rate test, it is expected that the decrease in the strength for the hydraulic fracturing occurs by the increase of the water content. To investigate the effect of the decrease in strength for hydraulic fracturing during seepage, the constant pressure test was carried out. Acoustic emission (AE) was measured during the test to examine the process of fracturing. The specimen had a dry density of 1.8 Mg/m^3 and a sand-mixture ratio of 30%. Although the breakdown pressure of the same type of the material was 2 MPa as shown in Table 1, the specimen used for this test has the strength of about 8 MPa for hydraulic fracturing. It is found that the variation of the strength of the buffer material is quite large.

Figure 12 indicates the pressure history. The test is carried out to keep the pressure at 6.4 MPa which was 80% of the breakdown pressure and relatively high pressure than the swelling pressure of 1.7 MPa which was meas-

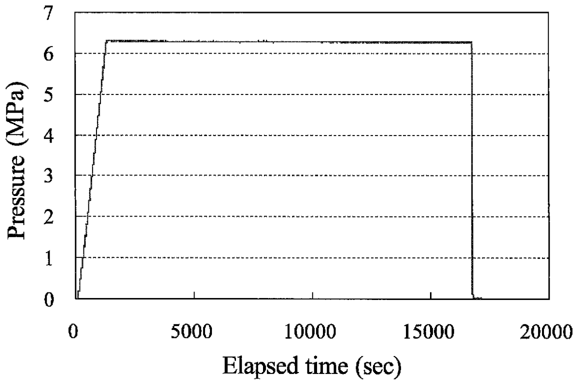


Fig. 12. Pressure history of constant pressure test

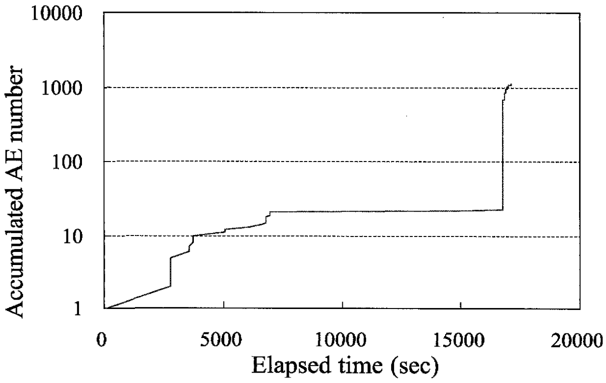


Fig. 13. History of accumulated AE number

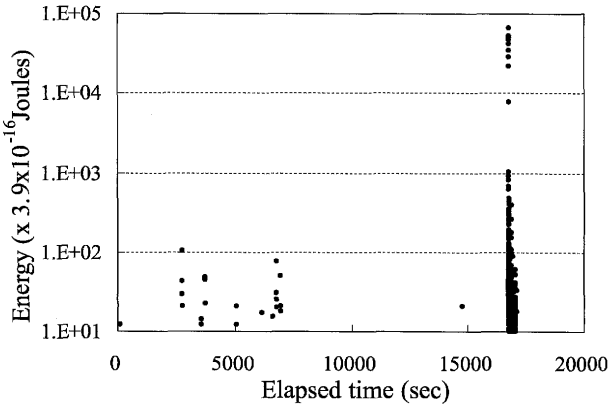


Fig. 14. History of event energy

ured from the other laboratory test (Suzuki and Fujita, 1999b). Therefore, it can be assumed that the water pressure higher than the swelling pressure acts on the buffer material, while the swelling pressure at the tip of the inlet tube is not observed. After about 6 hours, the specimen was suddenly broken down. It is found from Fig. 13 that the AE count increased rapidly when the breakdown pressure was observed. Figure 14 shows the history of event energy. Event energy also rose at the breakdown. It can be inferred from both figures that the fracturing abruptly occurred when the breakdown pressure was observed, and so the progressive failure did not occur during pressurization. This abrupt failure may be caused from the effect of the water content on the strength for hydraulic fracturing. While the change in water content was not observed in the test, the strength might decrease with increase of the water content during seepage. When the decreasing strength for hydraulic fracturing corresponded with the imposed water pressure, the hydraulic fracturing would occur.

EXAMINATION OF BREAKDOWN PRESSURE

Theory

To examine the adequacy of the breakdown pressure observed at the above-mentioned tests, the analytical consideration is carried out by using the theory used for the measurement of earth pressure. For the ordinary earth pressure measurement, the breakdown pressure by tensile failure, P_{bt}, and that by shear failure, P_{bs}, are obtained by (Amadei and Stephansson, 1997)

$$P_{\mathrm{bt}}=\frac{3S_{\mathrm{h}}-S_{\mathrm{H}}-2\eta P_0+T}{2(1-\eta)},$$
$$P_{\mathrm{bs}}=\frac{3S_{\mathrm{h}}-S_{\mathrm{H}}-2\eta P_0+M}{2(1-\eta)} \tag{1}$$

Where $\eta=\alpha(1-2\nu)/2(1-\nu)$, $M=2C\cos\phi/(1-\sin\phi)$, T is the tensile strength, S_{h} is the total minimum horizontal stress, S_{H} is the total maximum one, P_0 is the pore water pressure in the material, ν is the Poisson's ratio, C is the cohesion, ϕ is the friction angle, and α is the Biot's coefficient. α is assumed to be 1, and ν is measured as 0.33. Thus, η is 0.25. P_0 has to be considered for the saturated case and its value is positive, which works to decrease the effective stress. P_0 is negative at the initial condition. As explained in Fig. 9, since the water did not actually seep into the specimen, P_0 did not work to reduce the effective stress during the test. The potential shown in Fig. 3 may work to increase the effective stress. However, since the measured potential is the chemical one as mentioned earlier, the matric potential which works to increase the effective stress is not known well. On the other hand, the mechanical strength under the unsaturated conditions shown in Fig. 4 includes the effect of the suction corresponding to the water content. Since the strength used in this section is the one for the unsaturated condition, the effect of suction on the breakdown pressure can be taken into consideration by using the tensile and shear strength under unsaturated condition and ignoring the effect of P_0. S_{h} and S_{H} is corresponding to the confining pressure under the experimental condition. While the confining pressure was not applied in the above tests, the swelling pressure of the material, S_{w}, would work as a confining stress. Since the swelling pressure S_{w} is expected to work isotropically, we can assume that S_{h} and S_{H} is equal to S_{w}. From above consideration, the breakdown pressure can be estimated by

$$P_{\mathrm{bt}}=\frac{2S_{\mathrm{w}}+T}{2(1-\eta)},$$
$$P_{\mathrm{bs}}=\frac{2S_{\mathrm{w}}+M}{2(1-\eta)} \tag{2}$$

While the tensile strength T for Cases 1 and 9 is shown in Table 2, that of Cases 2 and 3 was also investigated by Takaji and Suzuki (1999). However, the tensile strength was examined for the material having low water content such as 4–7%. By considering the dependency of the strength on the water content, it is inferred that the tensile strength as the strength for hydraulic fracturing at the tests is less than those values.

It is apparent through the geometric consideration of Mohr-Coulomb's failure criterion that the shear strength M is the strength under the unconfined condition and thus is the same as the unconfined compressive strength. The unconfined compressive strength of Cases 1 and 9 is shown in Fig. 4 as a function of water content. That of Cases 2 and 3 was investigated by Fujita et al. (1992). The unconfined compressive strength was examined for the materials having relatively high water content such as over 13%. These values are, therefore, suitable as strength under the test condition.

The swelling pressure of Cases 1, 2, 3 and 9 shown in Fig. 5 is assumed to work as a confining pressure from the start of the test because the initial rising of swelling pressure is very rapid as shown in Fig. 6. Even if water does not seep into the material, the swelling pressure may work at very small portion around the tip of inlet tube. Moreover, it is noticeable that the swelling pressure has strong nonlinearity on the dry density and sand-mixture ratio.

Although the theory used in the examination is simple, the information about the buffer material that we have at present is not enough to apply the theory to evaluate realistically the breakdown pressure for the various conditions. If the more complicated theory is used, much more assumptions will be needed. While some assumptions mentioned above are used to evaluate the breakdown pressure, the examination is expected to provide the valuable information.

Effect of Dry Density and Sand-mixture Ratio

By using the data for Cases 1, 2, 3 and 9, the breakdown pressures are estimated by Eq. (2). Cases 1, 2 and 3 show the effect of the dry density and Cases 1 and 9 indicate that of sand-mixture ratio. Table 3 shows the estimated breakdown pressures and measured ones. While there are differences between measured and estimated breakdown pressures, the tendency of both P_{bt} and P_{bs} is quite similar to the measured one. As mentioned above, since the tensile strength of the material used at the test is estimated to be less than the one indicated in Table 3, P_{bt} could be smaller than the ones in Table 3. Although some assumptions used in this section are included into the theory, the entire tendency of the dependency of the breakdown pressure on the sand-mixture ratio and dry density is similar to the observed one. It can be, therefore, considered from Table 3 that the measured breakdown pressures are almost appropriate for the material used in the test.

While it is expected from the fracture pattern that the tensile failure is dominant, the specimen having the low dry density such as Cases 1 and 9 may be failed initially by the shear failure since the examined results for shear failure are close to the measured breakdown pressures. The mixture failure pattern shown in Fig. 9 may be the results of initial shear failure.

Table 3. Estimated breakdown pressures

Cases	Tensile strength (MPa)	UCS (MPa)	Swelling pressure (MPa)	P_{bt}	P_{bs}	Measured breakdown pressure (MPa)
Case1	0.06	0.33	0.5	0.7	0.9	1.4
Case2	0.16	0.90	1.7	2.4	2.9	2
Case3	0.65	2.50	4.2	6.0	7.3	5
Case9	0.18	1.00	1.8	2.5	3.1	4.7

Effect of Strength, Swelling Pressure and Suction

The specimen used in the constant pressure test had a large breakdown pressure in comparison with the one used in the constant pressurize rate test. To investigate the parameter having a much effect on the breakdown pressure, the parametric study is carried out for the specimen of Case 2, which is the same as the one used in the constant pressure test. The tensile strength, unconfined compressive strength and swelling pressure are set at double the value shown in Table 3. While the effect of suction was not considered in the above examination, the effect of suction is also examined. Table 4 indicates the examination results. The tensile strength and unconfined compressive strength do not have an effect on the breakdown pressure so much. In particular, the effect of the tensile strength is very small. On the other hand, the swelling pressure has a large effect on the breakdown pressure, while the effect of suction is not so much. The suction used in the examination is 1.5 MPa, which is the possible maximum value at the wilting point (Yawata, 1983). While the potential measured by a thermocouple psychrometer is very high as shown in Fig. 3, the matric potential is a small part of the total potential.

It can be considered from above results that the specimen used in the constant pressure test has a larger swelling pressure than the one used in the constant pressurize rate test. The swelling pressure is very sensitive to the dry density and the sand-mixture ratio as shown in Fig. 5. It may be inferred that the specimen used in the constant pressure test has a larger dry density and smaller sand-mixture ratio than nominal value.

Effect of Water Content

At the constant pressure test, the breakdown pressure was observed to be a function of water content. While the water content becomes large during seepage, the breakdown pressure reduces. When the breakdown pressure is larger than the imposed pressure, the fracturing does not occur. If the breakdown pressure reduces to the same as the imposed water pressure, the failure will occur. To examine the effect of the water content on the breakdown pressure, the unconfined compressive strength as a function of water content is used for Eq. (2). Takaji and Suzuki (1999) investigated the function of unconfined compressive strength q_u as water content w as followings;

$$q_u = 0.0018w^2 - 0.073w + 0.99 \quad \text{for Case 1}$$
$$q_u = 0.0053w^2 - 0.234w + 3.31 \quad \text{for Case 9}$$

Table 4. Parametric study of breakdown pressure for Case 2

Tensile strength (MPa)	UCS (MPa)	Swelling pressure (MPa)	Suction (MPa)	P_{bt}	P_{bs}	Increasing ratio of P_{bt} (%)	Increasing ratio of P_{bs} (%)
0.32	—	—	—	2.5	—	4.5	—
—	1.8	—	—	—	3.5	—	20.9
—	—	3.4	—	4.6	5.1	95.5	79.1
—	—	—	1.5	2.9	3.4	21.1	17.4

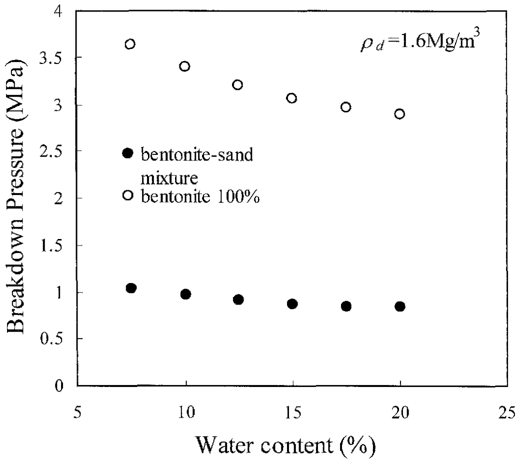


Fig. 15. Estimated breakdown pressure as a function of water content

By assuming that other parameters are the same as the ones shown in Table 3, the breakdown pressure is calculated as function of water content as shown in Fig. 15. While the direct comparison of Fig. 15 with the result of constant pressure test cannot be carried out, the following tendency is understood from Fig. 15. If the sand-mixture ratio is small, the dependency on the water content is large. With the increase of water content, the decreasing rate of the strength for hydraulic fracturing becomes low.

Since the strength for hydraulic fracturing is expected to reduce with increase of water content as shown in Fig. 15, the monitoring of the buffer material will be important until the saturation degree becomes high to some extent.

CONCLUSIONS

The fundamental behavior for hydraulic fracturing was observed for the buffer materials which are planned to be used in the high-level radioactive waste disposal projects. While the buffer material has been examined for various properties, the results of this study will be helpful for the strength for hydraulic fracturing. The conclusions can be summarized as follows;

1) The strength for hydraulic fracturing of the buffer material increases with increase of initial dry density, decrease of sand-mixture ratio and decrease of water content. In particular, the initial dry density and sand-mixture ratio has a large effect on the strength. The dependency of the strength for hydraulic fracturing on water content is expected to be small at high water content. Such characteristics for strength are related to the swelling property.
2) The effect of swelling pressure appears from the start of the pressurization, even if water does not seep into the material enough. This effect works as a constraining stress for the strength for hydraulic fracturing.
3) The fracture made by hydraulic fracturing will be fixed through the supply of water. However, a long period of low-pressure supply is needed to recover the strength at failed parts. If the high-pressure water is continuously supplied at the failed parts, it would be difficult to close the fracture.
4) While the tensile failure is dominant, the specimen having the low dry density may be failed initially by the shear failure. The mixture of failure pattern observed in the tests is the results of initial shear failure.
5) While the water content becomes large during seepage, the strength for hydraulic fracturing reduces. When the strength is larger than the imposed pressure, the fracturing does not occur. If the strength reduces to the same as the imposed water pressure, the failure will occur.

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