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Complete Slaking Collapse of Dike Sandstones by Fresh Water and Prevention of the Collapse by Salt Water

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ABSTRACT

Slaking is a well-known process, in which the surface of rock masses consisting of rocks such as mudstone, shale, etc. show rapid and complete disintegration when they are subjected to drying and then wetting with fresh water. On the other hand, dried sandstones even if they contain clay minerals such as smectite, etc., usually do not exhibit complete disintegration when they are soaked in fresh water. Instead, they usually show a strength decrease. Their slaking durability is tested by rotating them in a drum which is partially immersed in fresh water and eventually measuring the decrease in weight. On the other hand, it was found that some of the Paleogene sandstones from Kushiro Coal Mine in Japan, were completely disintegrated when they were immersed in fresh water followed by drying, but they were not collapsed when saline water was used instead of the fresh water. It was also shown that sandstones containing calcite did not show the complete breakdown even in fresh water. To understand the complete collapse of sandstones in fresh water and prevention of the collapse by salt water, sandstones sampled from Neogene dikes and Cretaceous at the mine were immersed in pure and salt water with Shikotsu welded tuff for comparison. Only dike sandstones showed a complete collapse in pure water and 3% salt water. Dike sandstone further showed severe time-dependent damage in salt water whose salinity was less than 7%. The results were explained by the dissolution of halite, swelling pressure of montmorillonite, osmotic pressure, etc.

Keywords: Dike sandstone, Slaking, Smectite, Salt water, Needle penetrating resistance

1. INTRODUCTION

Slaking (Gautam & Shakoor, 2013) is a well-known process, in which the surface of rock masses, consisting of rocks such as mudstone, shale, etc. show rapid and complete disintegration when they are subjected to drying and then wetting with fresh water. On the other hand, dried sandstones even if they contain such clay minerals as smectite, etc. usually do not exhibit complete disintegration when they are soaked in fresh water. Instead, they usually show a strength decrease (Yasidu et al., 2019). Their slaking durability is tested by rotating them in a drum which is partially immersed in fresh water and eventually measuring the decrease in weight (Dhakal et al., 2002).

There are several studies on the strength of fresh or salt water-saturated sandstones. Rathnaweera et al. (2014) suggested a slight increase of ca. 13% in uniaxial compressive strength from fresh water to 23.1% salt water. Huang et al. (2018) also suggested a slight increase of less than 20% in triaxial compressive strength from fresh water to 23.1% salt water. Nasvi et al. (2014) suggested the negligible effect of saline concentration from 0% to 15% on sandstone strength. It is also known that various chemical ions reduce the weakening of rocks which are dried and then immersed in aqueous solutions (Summersby et al., 2013). Indeed, various chemical ions are used to improve the stability of boreholes, rock slopes, etc. in or consisting mainly of clay containing rocks such as mudstone, shale, etc.

On the other hand, Nakata et al. (2004) found, some of the Paleogene sandstones from Kushiro Coal Mine in Japan exhibited complete disintegration when they were immersed in fresh water followed by drying. The sandstones did not show complete disintegration if saline water was used instead of the fresh water. It was also shown that sandstones containing calcite did not exhibit a complete breakdown in fresh water.

It is rather astonishing that the sandstones completely collapsed in fresh water and just sodium chloride instead of special chemicals prevented the complete breakdown of the sandstones. The objective of this research is to understand the collapse of sandstones in fresh water and the prevention of the collapse by salt water. To accomplish the objectives, sandstones were sampled from different seams and dikes at Kushiro Coal Mine. They were dried and then immersed in pure and salt water, and their slaking behavior was observed. Needle penetration tests were also conducted for immersed sandstones to clarify their strength variation with time and effects of salinity level on the variation.

2. SPECIMENS

Cretaceous sandstone and Neogene dike sandstones from Kushiro Coal Mine, Kushiro, Japan were used for the experiments. Shikotsu welded tuff from Sapporo, Japan was also used for comparison purposes. The Kushiro Coal Mine is the only one underground coal mine in Japan and located below the Pacific Ocean (Fujii et al., 2011). Semi-bituminous coal and methane gas are being extracted from Paleogene coal-bearing formation and the underlying Cretaceous, respectively.

The Cretaceous sandstone mainly consists of a matrix of quartz, plagioclases and a medium amount of silt-sized smectite (Fig. 1, Table 1). The grain sizes of the quartz are between 0.2–0.4 mm and the plagioclase grains are less than 0.2 mm and have an angular to subangular form. The rock is petrographically classified into a wacke fine-grained sandstone or a hard rock (Table 2) according to the engineering classification. The porosity is 11% (Table 2).

The Neogene dike sandstones were sampled from the dikes outcropped at a longwall mining face, on Jan. 25, 2017 (Fig. 2). The face was approximately 200 m deep from the sea level and the depth of the sea was approximately 10 m at that location. The dike E was stronger and blocks E1 and E2 were taken using the drum shearer. The rock block W was sampled using a handpick from the dike W which looked like a tuffaceous sandstone and softer than the dike E. The sample E2 is petrographically classified into microbreccia coarse-grained sandstone (Fig. 3) and consists of andesite fragments, plagioclase, quartz, claystone fragments, etc. XRD (X-Ray Diffraction) analysis reveals that the rock contains much halite and a little amount of smectite (Table 1) although halite is unable to be seen in the thin sectional image (Fig. 3) because it should have been lost by dissolution during the preparation process of the thin section using water. Deeper areas of the mine were mined out in the past and it was confirmed by drilling that the groundwater level was 265 m deep in 1966 and 415 m deep in 1976 (Sato & Sato, 1980). The halite would have been originated from pore seawater and formed during the drying process after the groundwater level was lowered below 200 m. The porosity is 8% (Table 2). The samples E1 and W were not inspected in detail.

Shikotsu welded tuff having a porosity of 32% (Table 2) was taken from Sapporo, Japan. The glassy rock sample, which originated from pyroclastic deposits from the eruption of the Shikotsu volcano 40,000 years ago, is predominantly composed of plagioclase, hypersthene, augite, hornblende and transparent volcanic glass having a felt-like structure in the matrix (Fig. 4). The rock also contains a little amount of illite as a secondary mineral originated from mudstone fragments and formed by thermal metamorphism. The mineral grain sizes are between 0.3–1.5 mm for the plagioclase, approximately 0.5 mm for the hypersthene, 0.3–0.7 mm for the augite, and 0.5–1.0 mm for the hornblende (Doi, 1963).

The rock samples were dried at room temperature and humidity for about one year for the Cretaceous sandstone and the dike sandstones, and years for the tuff after the sampling.

3. EXPERIMENTAL PROCEDURE

Cylindrical specimens having a diameter of 30 mm were drilled and the ends were grounded using tap water for the rocks except for the dike sandstone W. Irregular shaped specimens were prepared for the dike sandstone W by just cutting using tap water because it was subjected to disintegration during drilling and grinding using tap water. Hence, it was impossible to prepare cylindrical specimens. All tests were carried out at 295K after they were dried in an oven at 353K for several weeks and then kept at room temperature and humidity for several more weeks.

Jar slaking tests 1 and 2 were carried out. The samples were kept vacuum saturated in water and their slaking behavior was observed. The saline concentration of 0% to 26.4% (saturated at 295K) was used for 20 mm long disc specimens of Cretaceous sandstone, dike sandstone E2 and tuff in test 1. The saline concentration of 0% and 3% was used for the dike sandstones W and E1 in test 2.

Needle penetrating tests (Ngan-Tillard et al., 2011) were carried out at an arbitrary time during jar slaking test 3 for 20 mm long cylindrical specimens of Cretaceous sandstone, dike sandstone E2 and tuff in the water with the salinity of 0% to 26.4%. Needle penetration resistance (N/mm) was calculated as force (N) divided by penetration (mm). The stabbing was carried out five times for each measurement and the average value was calculated. Care was taken not to stab the same places. Studies showed that needle penetration resistance has positive correlations with the tensile and compressive strengths of rocks (Erguler & Ulusay, 2009). The variation of the penetration resistance with time and the effect of salinity on the variation were observed.

4. RESULTS

In the jar slaking test 1, the dike sandstone E2 began to collapse, after 12-hour immersion in pure water and after 24-hour immersion in 3% salt water (Fig. 5). The Cretaceous sandstone and the tuff did not collapse in three days.

In the jar slaking test 2 (Fig. 6), the dike sandstone W began to collapse after one-hour immersion in pure water and it completely collapsed after 70-hour immersion. The dike sandstone E1 began to collapse after a 20-hour immersion in pure water. They did not collapse in 3% salt water in 70 hours.

The needle penetration resistance decreased with time, in the jar slaking test 3 (Fig. 7). The decreasing behavior can be approximated by the straight lines taking a logarithm of time. The rate of decrease in the needle penetration resistance, which indicated the degree of time-dependent damage by immersion, for the dike sandstone E2 was much larger than those for the Cretaceous sandstone and the tuff for the pure water (Fig. 8). The decrease rate for E2 became smaller with salinity and almost converged for the salinity more than or equal to 7% at an almost similar level to other rocks (Fig. 8).

5. DISCUSSIONS

The experimental results can be summarized as follows. The Cretaceous sandstone and the tuff exhibited negligible damage by immersion even in the pure water. On the other hand, the dike rocks showed the complete collapse or the severe damage with time in water whose salinity was less than 3% (E1 and W) or 7% (E2). They showed neither collapse nor severe damage in the solution with higher salinity levels.

5.1 Complete collapse of the dike sandstone

It is well known that montmorillonite, which is the main mineral component of the smectite clay mineral group, largely expands with water saturation and shrinks by drying because water molecules move into and out from the space between the tetrahedral sheets of montmorillonite molecules. This strain causes microcracks in the surrounding rock matrix, leading to slaking. The matrix of the tuff mainly consists of volcanic glass which is insensitive to water and the rock does not contain smectite. Hence, tuff did not collapse in the jar test.

The Cretaceous sandstone containing more smectite and having higher porosity than the Neogene dike sandstones did not collapse in the pure water although the dike sandstones collapsed. Several reasons can be proposed to explain the above scenario. The first reason is simply the latter is weaker as shown in the dry needle penetration resistance (Fig. 7) because they are younger and less consolidated. The second reason is the dissolution of the abundant halite in the dike sandstone. A part of halite would have acted as cement and dissolution of cement means weakening of the dike sandstone. The third reason would be the difference in salinity of in-situ pore water. The salinity level of the Cretaceous ocean is estimated to be higher than the present (Friedrich et al., 2017). However, the salinity level of the fossil Cretaceous water at the mine is much lower than the present seawater (Table 3) because of various mineral-seawater reactions. On the other hand, the Neogene dike rock exhibits the presence of halite resulting from the high salinity of the pore water. These suggest that the smectite in the Neogene dike sandstones and the Cretaceous sandstone would contain mostly Na^+-type montmorillonite and a mixed type of Na^+ and Ca^{2+}, respectively. Na^+-type montmorillonite can shrink more when dried because a Na^+ holds a water molecule but a Ca^{2+} holds two. The larger contraction by Na^+-type montmorillonite would have induced denser microcracks when drying and the microcracks led the complete breakdown of the dike sandstone specimen when immersed in the pure water. One more reason would be the osmotic pressure. It is known that the rock surface can act as a non-ideal semi-permeable membrane when pores allow the migration of water molecules more than the ion migration (Sarout & Detournay, 2011). According to the list of the experimental results summarized by Neuzil & Provost (2009), the osmotic pressure of such rocks as shale, siltstone, etc. with smectite contents as much as 8–93% was 3.5–481 kPa for the aqueous solution with 0.005–218.2 g/L of NaCl except for the two extreme data. The Cretaceous sandstone in this study contains smectite less than a few percent from the thin section image (Fig. 1) and the dike sandstone E2 contains even less smectite (Table 1). The osmotic pressure of the saline pore water for the two rocks would be less than the above 3.5 kPa or in the order of 1 kPa. The pressure may act as pore pressure and disintegrate the specimens. On the other hand, the swelling pressure of tight compacted commercial Wyoming bentonite (MX-80, 2001-01-19 from American Colloid Co.) by de-ionized water, for example, is ca. 4.3 MPa under confined displacement (Karnland et al., 2007). The bentonite rock contains 89.1% montmorillonite of a mixed Na^+/Ca^{2+}-type with a predominant presence of Na^+-type (Vieillard et al., 2016). The swelling pressure for the dike rocks and the Cretaceous sandstone is therefore roughly estimated to be between 11–108 kPa assuming that the rocks contain 0.25–2.5% smectite, and the swelling pressure is proportional to the smectite content and is 4.3 MPa for 100% smectite content. The estimated swelling pressure value may contain a nonnegligible error. However, the value is much higher than the estimated osmotic pressure. Therefore the osmotic pressure, which could be one of the causes of the complete collapse of the dike sandstones, may not be the most dominating cause.

5.2 Prevention of the complete collapse of the dike rock by NaCl

Several reasons can be proposed to explain why the salinity prevented the collapse of the dike sandstones. One is that the salinity of the solution should have made the dissolution of halite slower and strengthened the dike sandstones. The other reason is the inhibition of swelling expansion by NaCl. The experiment by Karnland et al. (2006) on the bentonite MX-80 showed the reduction of the swelling pressure from 4.3 MPa to 3 MPa by 1 mol/L NaCl solution. This corresponds to 8.5–85 kPa reduction by 7% (2.6 mol/L) solution for the studied rocks under the above assumptions and also assuming that the reduction is proportional to the molar concentration of the saline water. The mechanism of the reduction of swelling by the cations would be as follows. The zeta potential of smectite is negative in water. Cations can move into the space between the tetrahedral sheets of montmorillonite and inhibit the expansion by water molecules thereby strengthening sandstones. The zeta potential of smectite became almost half at the salinity of 7% (2.6 mol/L) compared to pure water (Fig. 9). This indicates that cations moved into space and inhibited the expansion of montmorillonite by water molecules, reducing the time-dependent damage of the dike sandstone E2 to almost the same level as the other rocks. The reduced osmotic pressure by the salinity of the solutions may be in the order of 1 kPa and could have also assisted to prevent the complete collapse of the dike sandstone.

The dike sandstone E2 showed a complete collapse although it contained a medium amount of aragonite. This contradicts the finding by Nakata et al. (2004) in which Paleogene sandstones at the mine containing calcite did not show complete collapse probably because each Ca^{2+} from calcite prevents large shrinkage holding 2 water molecules while a Na^{+} can hold only one water molecule. The contribution of the carbonate minerals to the prevention of slaking should be further investigated in the future.

5.3 Potential applications

The findings in this study were obtained for the room temperature and the atmospheric pressure. They could not be directly applied to underground rock masses usually at a higher temperature and under rock stress with some pore pressure. For example, triaxial compression tests for even pure water-saturated dike rocks can be done avoiding complete collapse if the saturation process is carried out after the application of the confining pressure. The findings here, however, suggest that the surface of rock structures in those marine sediment rocks which were formed in high salinity seawater and the salinity has been kept could unexpectedly collapse by fresh water even if the rock masses do not consist of shale, mudstone, etc. And the collapse could be prevented by not only avoiding drying of rock surface or contact to fresh water but also just adding sodium chloride to the water with which the rock surface will contact. In other words, the strength of the surfaces of such rock masses could be controlled by the salinity of water with which they contact. For example, such rock masses could be intentionally softened or even completely collapsed from the free surface to accelerate closure of rock openings to improve their sealing ability or for other various purposes by decreasing the salinity level of the water with which the rock masses contact. For example, most of the abandoned workings in Kushiro Coal Mine up to fifty years old were completely closed (Fujii et al., 2011). The fresh water in the backfilling slurry should have played a great roll in the complete closure process.

6. Concluding remarks

To understand the collapse of sandstones in fresh water and prevention of the collapse by salt water, sandstones, sampled from Neogene dikes and Cretaceous at Kushiro Coal Mine were immersed in pure and salt water with Shikotsu welded tuff for comparison. Only the dike sandstones showed a complete collapse in the pure water (E1 and W) and 3% salt water (E2). The dike sandstone E2 showed severe time-dependent damage in salt water whose salinity was less than 7%. The results were explained mainly by the dissolution of halite, swelling pressure of montmorillonite and osmotic pressure. Strength control of the surfaces of rock masses by the salinity of the water with which the surface contacts was proposed as a potential application.

Further investigation should be made on various rock types because the tested rock types are limited at this stage. Effects of not only the ions which are commonly contained in seawater other than sodium chloride but also various other ions should also be investigated in the future.

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Data Availability

The data obtained by this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Table 1 Mineral composition of the Cretaceous sandstone from XRD analysis. Qz: Quartz, Pl: Plagioclases, Kf: Potash feldspar, Am: Amphibole, Hm: Hematite, Mc: Micas, Chl: Chlorite, Sm: Smectite, Ha: Halite, Ara: Aragonite and Kao: Kaolinite. +++++: Very abundant, ++++: Abundant, +++: Medium, ++: Little, +: Very little, –: None.

Rock type	Qz	Pl	Kf	Am	Hm	Mc	Chl	Sm	Ha	Ara	Kao
Cretaceous sandstone	+++++	+++++	++++	+	++	++	++	+++	–	–	–
Dike sandstone (E2)	++++	+++	+++	–	–	–	–	++	++++	+++	+++

Table 2 Physical and mechanical properties of rock samples shown as the average value(number of specimens)±standard deviation. V_P: P-wave velocity, *UCS*: uniaxial compressive strength and T_0: indirect tensile strength.

Properties	Kushiro Cretaceous sandstone		Dike sandstone (E1)		Shikotsu welded tuff	
	Dry	Saturated	Dry	Saturated	Dry	Saturated
Porosity (%)	10.53		7.81(2)±0.37		31.7	
Bulk density (g/cm^3)	2.37 (9)±0.02	2.48(9)±0.02	2.51（4）±0.004	2.54(2)±0.004	1.30(18)±0.01	1.62(18)±0.02
V_P (km/s)	3.35 (9)±0.14	3.04(9)±0.16	2.51(4)±0.08	2.32(2)±0.01	2.14 (18)±0.07	1.92(18)±0.14
V_S (km/s)			1.730(4)±0.040	1.607(2)±0.004		
Dynamic Young's modulus (GPa)			15.80(4)±0.91	13.66(2)±0.05		
Dynamic Poisson's ratio			0.0500(4)±0.0272	0.042(2)±0.001		
Thermal conductivity (W/mK)	1.980(5)±0.010					
UCS (MPa)	146.4(5)±4.7					13.53(2)±2.74
50% tangent modulus (GPa)	22.3(4)±1.8					
50% tangent Poisson's ratio	0.1350±0.0777					

Table 3 Concentration (mg/L) of typical ions in water (Mahara et al., 2006)

Water	Ca^{2+}	Na^{+}	Mg^{2+}	Cl^{-}
Present standard seawater	400	10600	1270	19000
Cretaceous fossil seawater	4100	3900	4	13300

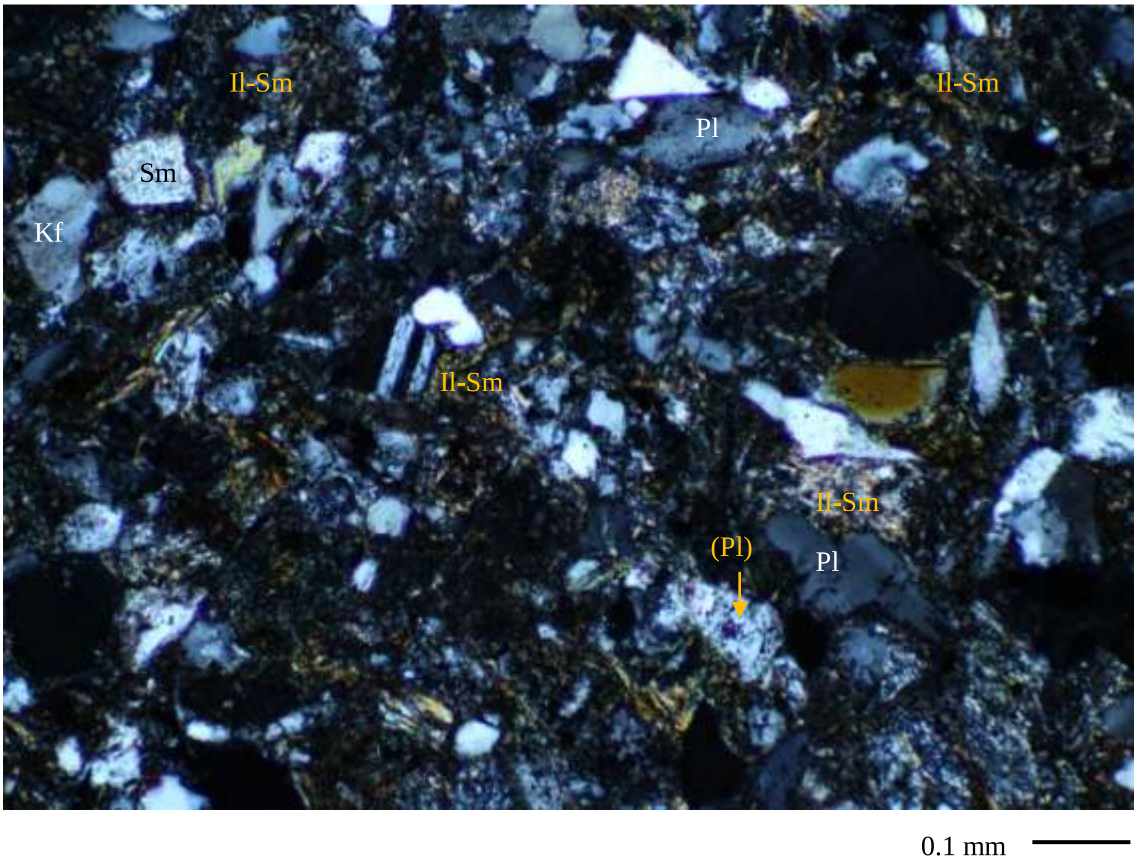


Fig. 1 A thin sectional image of the Cretaceous wacke fine-grained sandstone under crossed Nicols. Kf: potassium feldspar, PL: plagioclase, Sm: smectite, Il: illite and (): pseudomorph.

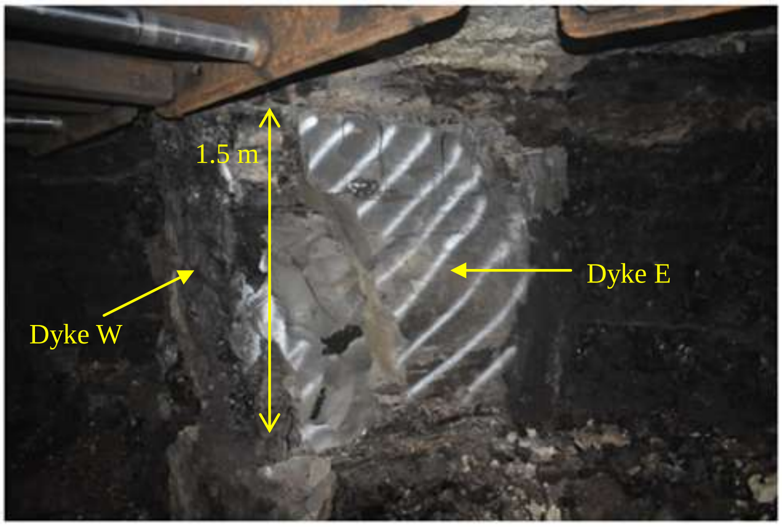
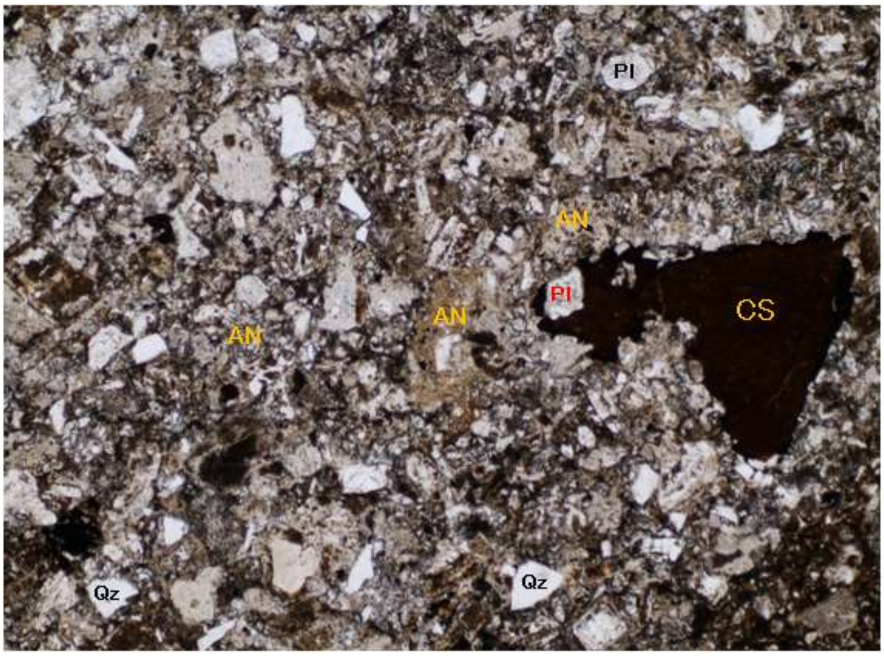


Fig. 2 Dikes E and W at the longwall coal mining face.



1.0 mm

Fig. 3 A thin sectional image of the dike sandstone E2 under open Nicol. Qz: quartz, AN: andesite fragments, CS: claystone fragments.

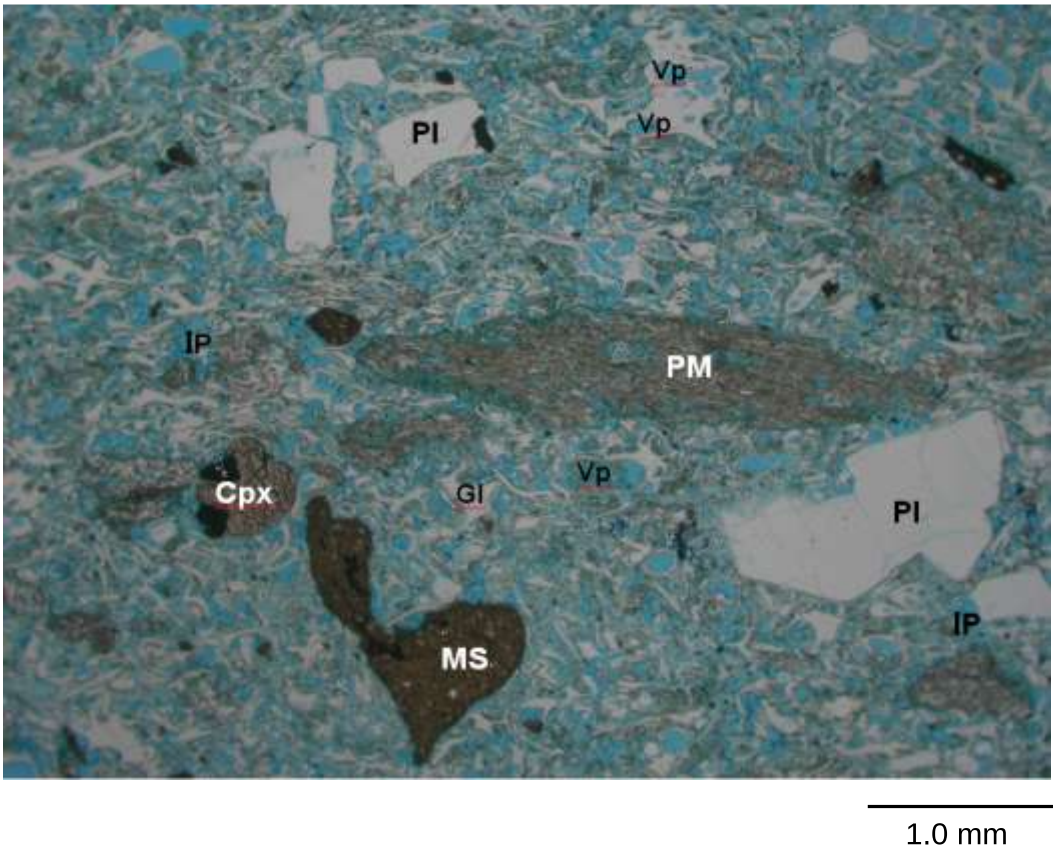


Fig. 4 A thin sectional image of Shikotsu welded tuff impregnated in blue resin under Open Nicol. Voids which are mainly pores and filled by the blue resin. PM: pumice, IP: intergranular pore, Vp: vesiculated pore, Gl: glass, Cpx: clinopyroxene, MS: mudstone.

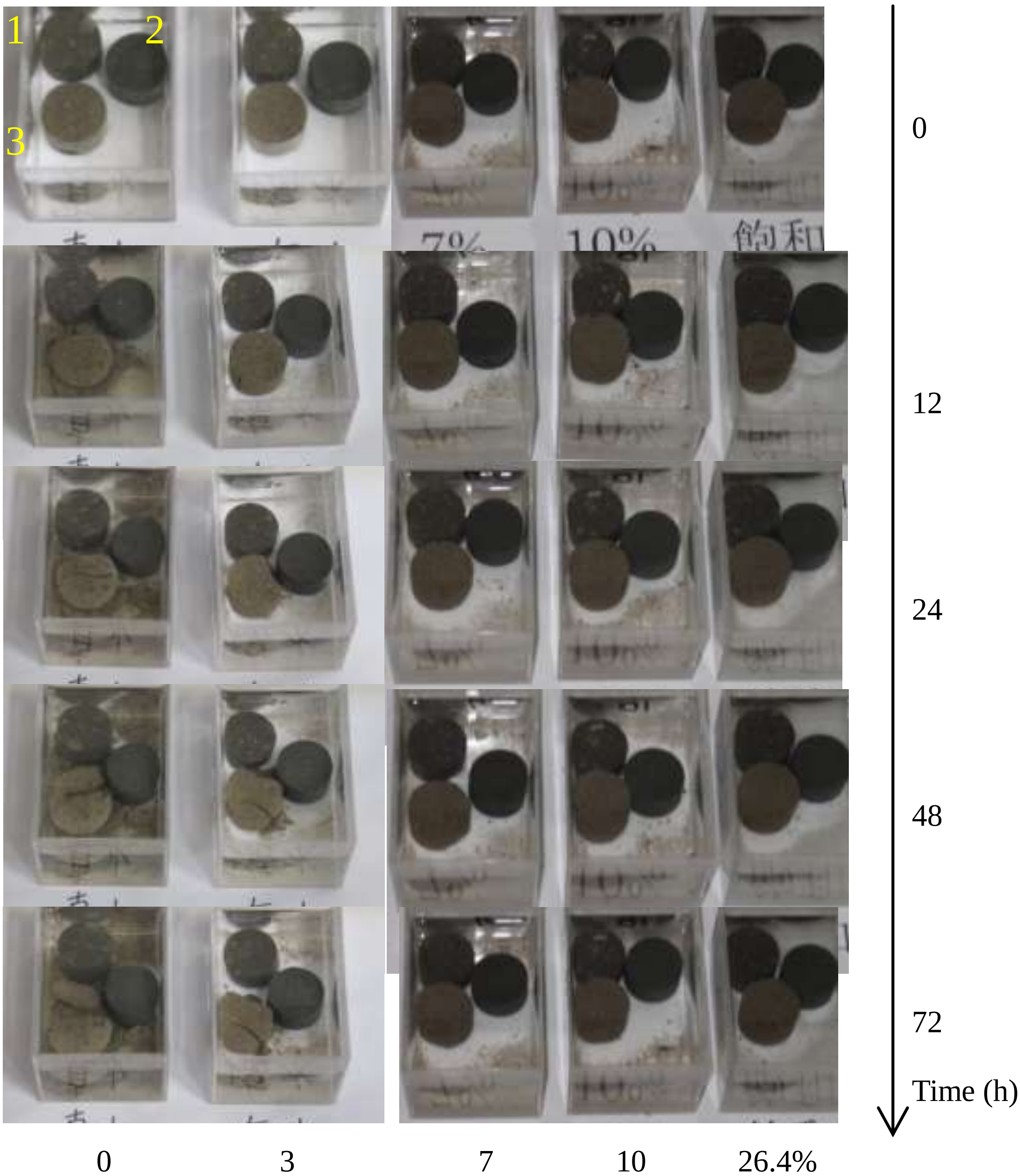


Fig. 5 Results of the jar test 1. 1: tuff, 2: Cretaceous sandstone and 3: dike sandstone E2.

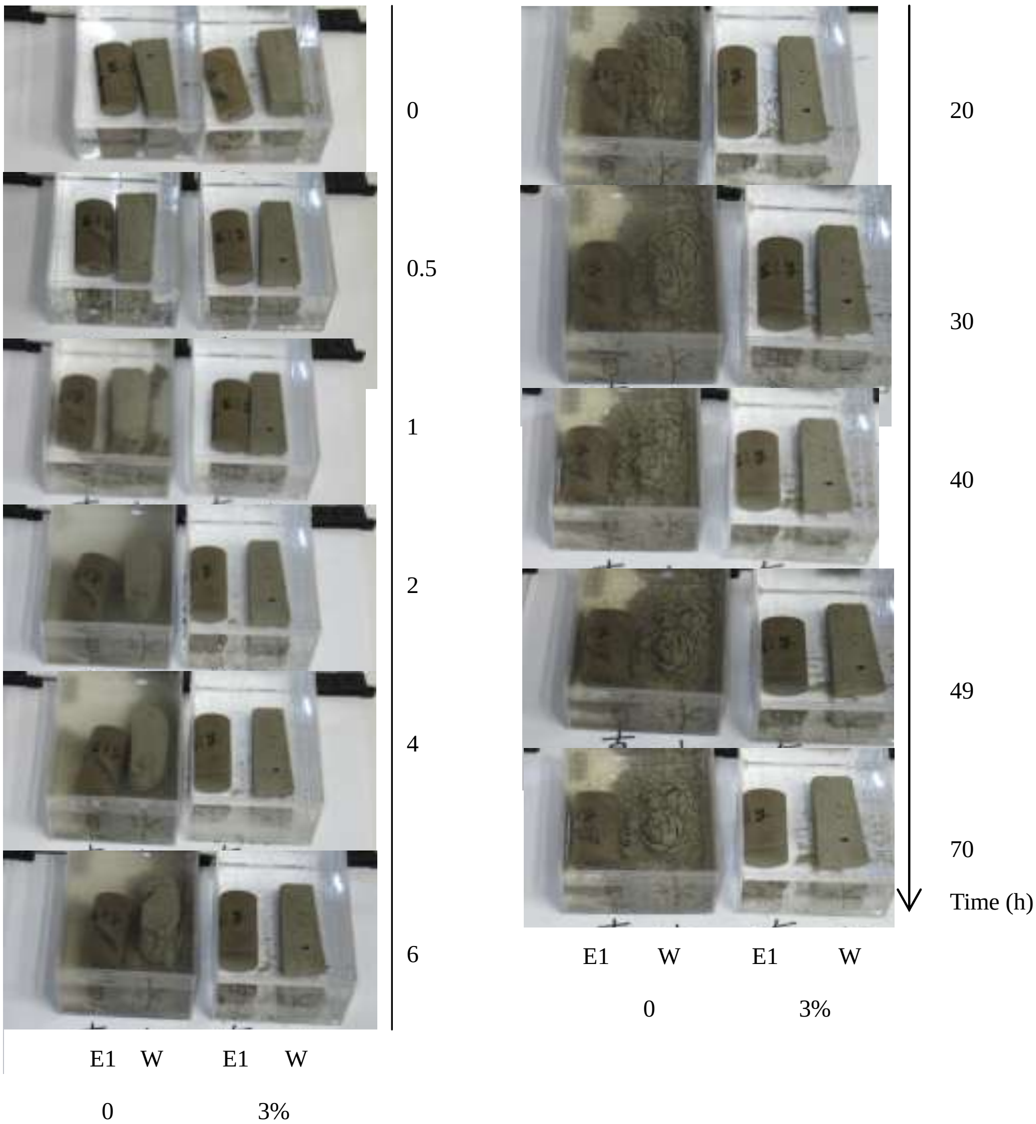
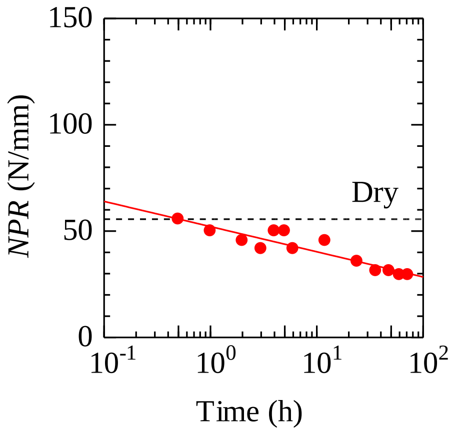
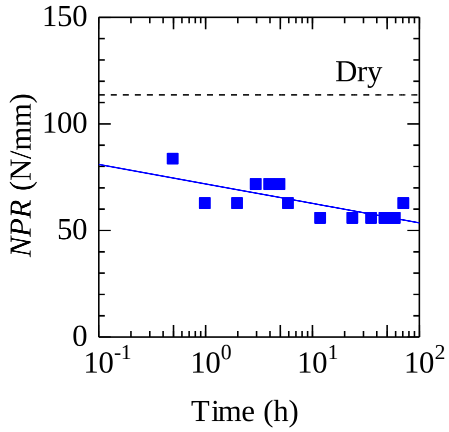


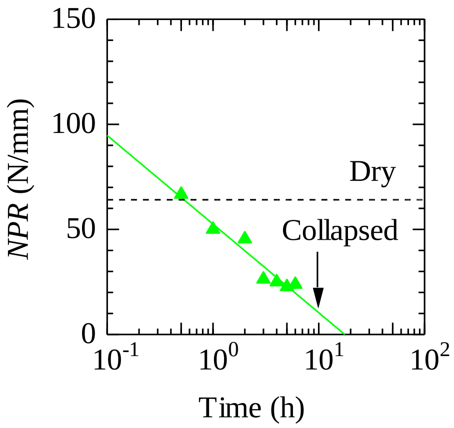
Fig. 6 Results of the jar test 2.



(a) Tuff



(b) Cretaceous sandstone



(c) Dike sandstone E2

Fig. 7 Time variation of needle penetration resistance during jar slaking test 3 in pure water. Needle penetration resistance for dry specimens is also shown for reference.

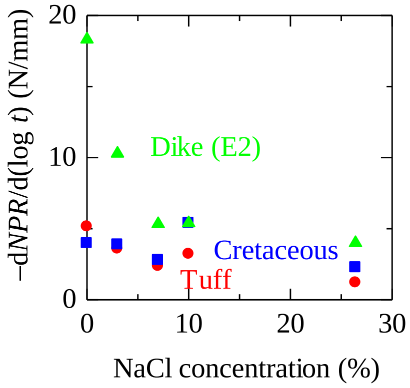


Fig. 8 Effect of salinity on the decrease rate of the needle penetration resistance.

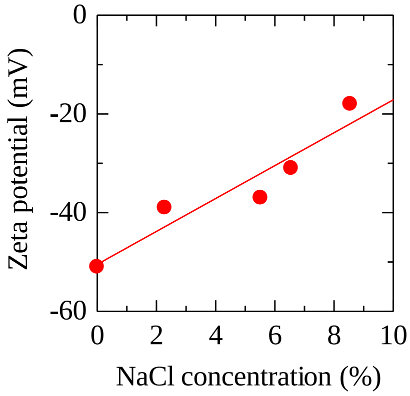


Fig. 9 Zeta potential of smectite (after Nara et al., 2014)