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SALINITY EFFECT ON SWELLING CHARACTERISTICS OF COMPACTED BENTONITE

Swelling characteristics of compacted bentonite is the most important factor for nuclear waste disposal facilities. Salinity effect on swelling behaviour of compacted bentonite was investigated experimentally. A series of one dimensional swelling deformation tests have been performed. The tests were conducted for various initial dry densities from 1.33 g/cm^3 to 1.90 g/cm^3 for compacted bentonite saturated with NaCl of various concentrations in solution from 0 to 4.0 M. It was found that initial dry density and concentration of NaCl strongly influence the swelling rate of bentonite. The swelling rate of bentonite decreases with increasing the concentration of NaCl. Swelling rate depends on the concentration of NaCl more than on initial dry density and loading effect. Bentonite may change from highly swelled material to coagulate in saline water. Liquid limit of bentonite is also remarkably decreased with the change of liquid from distilled water to saline one, while the plastic limit is slightly increased.

1. INTRODUCTION

Bentonite has attracted attention as buffer and backfill materials for high level radioactive waste (HLW) disposal. High level radioactive and hazardous wastes are required to be buried in deep underground facilities. The buffer material is filled in a partially saturated form as compacted block. After waste emplacement, buffer material hydrate and swell, being submitted to heat from radioactive waste decay. Combined effects of heat generated by radioactive decay and solutes supplied from the surrounding rock will take place several hydromechanical processes in the field. These processes may change mechanical, hydraulic, and geochemical properties of buffer materials. Bentonite is often a key component of the engineered barrier system because it has good sorption properties, microporous structure, low hydraulic conductivity, and high cation exchange capacity [1].

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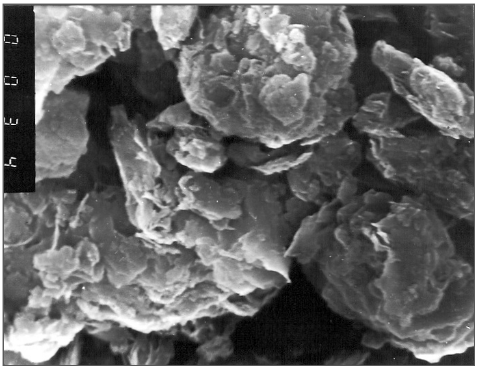

Fig. 1. Microstructure of compacted Kunigel VI bentonite

Microstructural view of compacted bentonite is presented in Fig. 1. It restricts the movement of nuclides from the waste packages after canister failure. Mechanical properties of compacted bentonite under combined effect of water from surrounding rock and heat from canister have been reported by many researchers [2–6]. The experimental information on the properties of compacted bentonite was mainly saturated with distilled water as a test fluid. However, some HLW disposal sites are constructed at the coastal area, e.g. HLW site at Horonobe in Hokkaido prefecture of Japan. At the coastal area, groundwater is blended with sea water and affects the mechanical properties of compacted bentonite. For this problem, a series of laboratory tests were performed to investigate the effect of salinity on swelling behaviour of compacted bentonite.

2. MATERIALS AND METHODS

Kunigel VI bentonite is used in this experiment which is considered to be applied as buffer material for HLW disposal in Japan. Specific gravity and montmorillonite content in Kunigel was 2.79 and 64%, respectively. Kunigel VI was compacted by a special compaction device. The specimen height and required density were maintained by the variation of mass and compaction pressure. Initial dry densities of the samples were 1.30, 1.50, 1.70 and 1.90 g/cm^3. The height of the sample was ca. 1 cm with the diameter of 6 cm. NaCl solutions were prepared by dissolving powdered NaCl in distilled water to a desired concentration. The concentrations of the solutions were 0.5, 1.0, 2.0 and 4.0 M.

Swelling deformation tests. Free swelling deformation tests of compacted bentonite were carried out with a special swelling box apparatus by absorbing saline solution under approximately zero vertical pressure except the cap plate. Swelling deformation tests were also conducted with an oedometer test apparatus under loading condition. The vertical swelling deformation of compacted specimens was measured under static load of 0.16 MPa. Saline solution was supplied at the bottom and simultaneously prescribed vertical pressure was applied to the specimen. Both tests were carried out at room temperature. Degree of saturation was about 100% for all specimens at the end of experiment. Swelling rate of the compacted specimens was calculated by the following equation.

$$S_R = \frac{\Delta h}{h_0} \times 100, \tag{1}$$

where S_R is the swelling rate, Δh is the vertical deformation and h_0 is the initial height.

Maximum swelling rate ratio was calculated by the following equation:

$$\text{Maximum swelling rate ratio} = \frac{\text{Maximum swelling rate with NaCl}}{\text{Maximum swelling rate with with distilled water}}. \tag{2}$$

3. RESULTS AND DISCUSSION

3.1. LIQUID LIMIT AND PLASTIC LIMIT

The liquid limit and plastic limits of bentonite with various concentrations of NaCl solution are presented in Fig. 2.

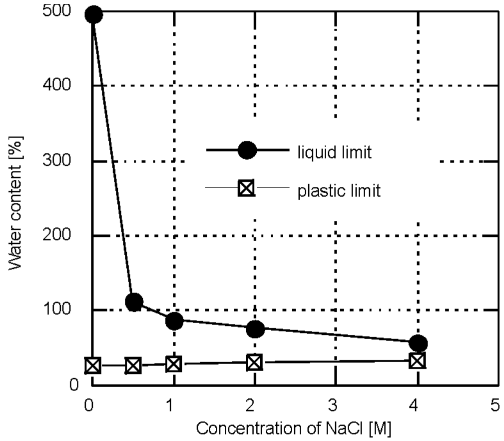

Fig. 2. Dependence of water content on concentration of NaCl for liquid and plastic limits

The liquid limit of bentonite strongly decreases after changing solution from distilled water to 0.5 M NaCl and then gradually decreases with the increasing of concentration of NaCl. The plastic limit slightly increases when the concentration of the NaCl solution is increased. This shows that salinity strongly affects the adsorption capacity of bentonite and bentonite becomes more sensitive when the concentration of NaCl increases. One may expect that squeezing out of the liquid by applied forces during rolling has more effect than interparticle repulsion within the particle. Mishra et al. [7] reported the effect of salinity of low concentration (0 ~ 1 mol/dm^3) on liquid limit of various types of bentonite. They found that the liquid limit of all type of soil decreased with increasing salt concentration. This trend can be explained in terms of the interparticle forces that play a prominent role in determining the liquid limit. In clay paste with water content equivalent to the liquid limit, the forces of interaction between clay particles become sufficiently weak to allow easy movement of particles relative to each other. In high swelling clays like montmorillonite, the dominant interparticle force is repulsion, which determines the distance between particles. Upon the increasing salt concentration, interparticle repulsion in montmorillonite decreases and the particle becomes free to move at lower interparticle distance [8–10].

3.2. FREE SWELLING

A schematic diagram of free swelling deformation of compacted bentonite is presented in Fig. 3. Swelling materials like montmorillonite gradually receive water and can be swelled against the overburden pressure (p_c).

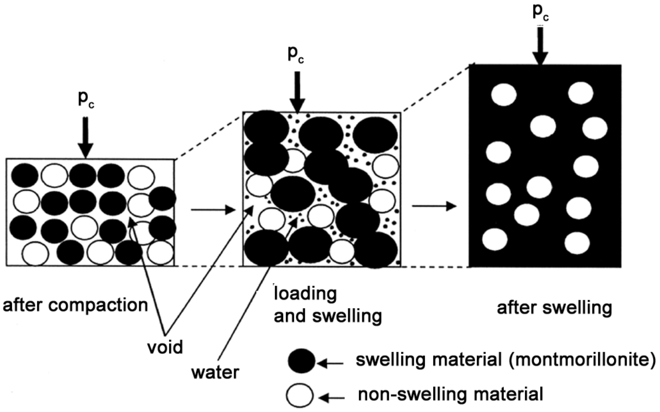

Fig. 3. Model of swelling deformation at high density

Detailed swelling mechanism was also explained by Shirazi and Kazama [4] in a previous study. Time dependences of free swelling rate of compacted bentonite of the initial dry density of 1.90 g/cm^3 at various NaCl concentrations is shown in Fig. 4. Free swelling rate of compacted bentonite markedly decreases with increasing concentration of NaCl. Figure 5 shows that the maximum swelling rate noticeably decreased upon increasing concentration of NaCl (from 0 to 1 M) for various dry densities. However, with a further increase in the concentration from 1.0 to 4 M, the swelling rate gradually decreases. Time dependences of free swelling rates of bentonite in 1 M NaCl with various initial dry densities are presented in Fig. 6.

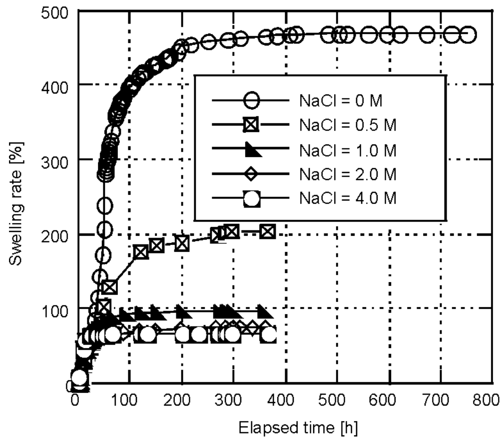

Fig. 4. Time dependences of free swelling rate for initial dry density of 1.9 g/cm^3 and various NaCl concentrations

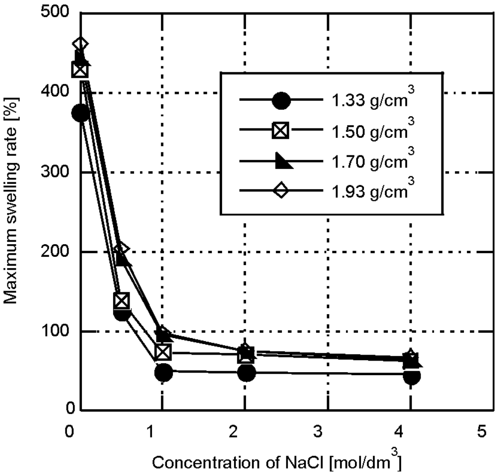

Fig. 5. Dependences of maximum swelling rate of bentonite on NaCl concentration for various dry densities

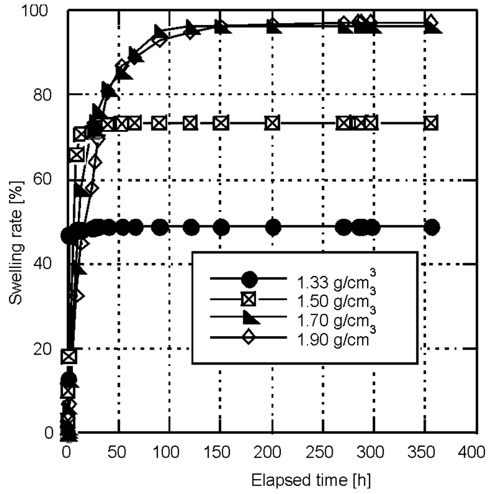

Fig. 6. Time dependences of free swelling rate of bentonite of various dry densities in 1 M solution of NaCl

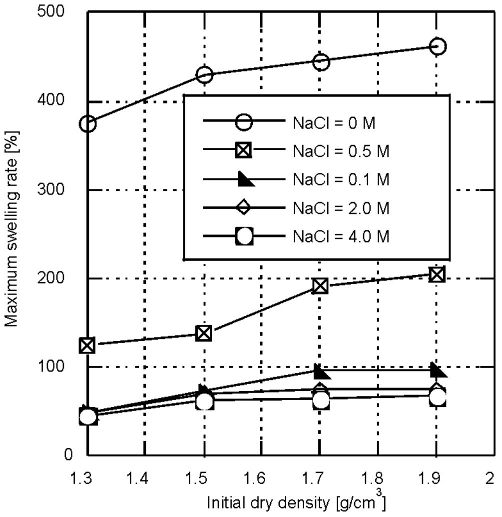

Fig. 7. Dependences of maximum swelling rate of bentonite on initial dry density for various NaCl concentrations

The swelling rate markedly increases upon increasing initial dry density of bentonite. Figure 7 shows that the maximum swelling rate of bentonite increases upon increasing initial dry density for various concentrations of NaCl. It might be due to the montmorillonite content in the specimen. Thickness of the diffuse double layer is dependent on the concentration of electrolyte and the valence of the exchanged cations. Van Olphen [11] also indicated that *increasing NaCl concentration is interpreted as being due to a decrease in double-layer swelling between quasicrystals. As the electrical double layer adjacent to the quasicrystal surface is compressed with increasing NaCl concentration, the aggregate swell may decrease.*

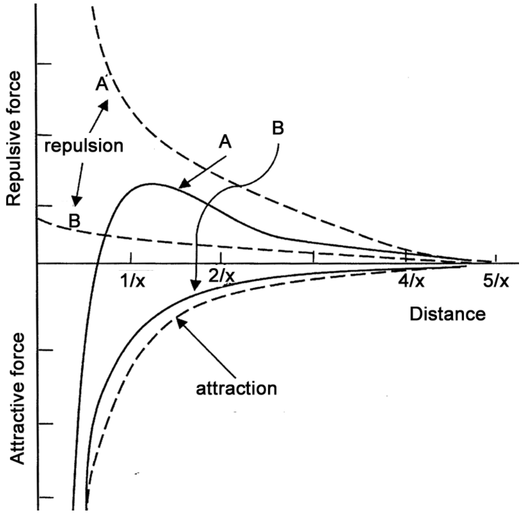

Fig. 8. Interaction forces in DLVO theory [12];
1/*x* – thickness of the diffuse double layer,
A – low concentration, *B* – high concentration

Figure 8 shows the interactions forces according to the Derjaguin Landau, Verwey and Overbeekn (DLVO) theory [12]. DLVO theory suggests that the stability of a particle in solution depends upon balance of attractive and repulsive interactions. The figure shows the difference between the resultant forces in low and high concentration of electrolytes in solution. The attractive forces at the surfaces of clay particles stay constant but repulsive forces are dependent on the concentration of electrolytes. Lower concentration induced greater repulsive forces and finally held sufficiently repulsive force. Whereas, the higher concentration induced lower repulsive force and finally resulted in attractive force at the particle surfaces. Therefore, due to low concentration of salt, the particles have sufficiently high repulsion, the dispersion will resist flocculation and the colloidal system will be stable. However, repulsion mechanism does not exist in solutions of high concentrations of electrolyte and then flocculation or coagulation eventually takes place. The results of the present study are in agreement with the findings of the DLVO theory.

3.3. SWELLING UNDER LOADING CONDITIONS

The swelling rates of compacted bentonite under static load of 0.16 MPa for various initial dry densities and NaCl concentrations (0–4 M) are shown in Figs. 9–12.

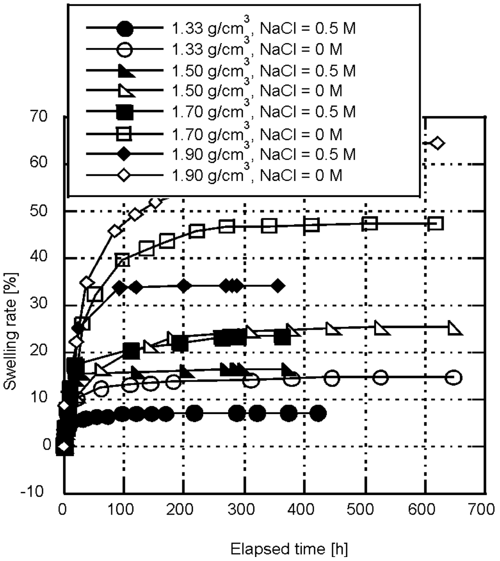

Fig. 9. Time dependences of the swelling rate of bentonite in distilled water and 0.5 M NaCl

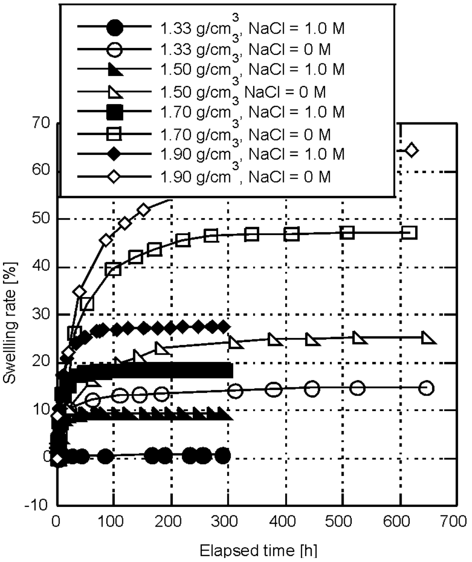

Fig. 10. Time dependences of the swelling rate of bentonite in distilled water and 1 M NaCl

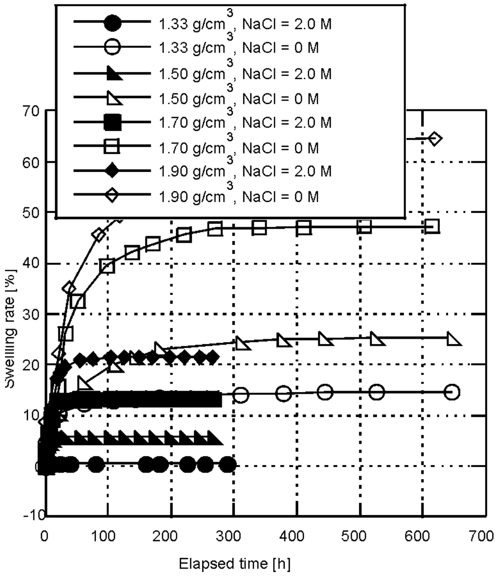

Fig. 11. Time dependences of the swelling rate of bentonite in distilled water and 2.0 M NaCl

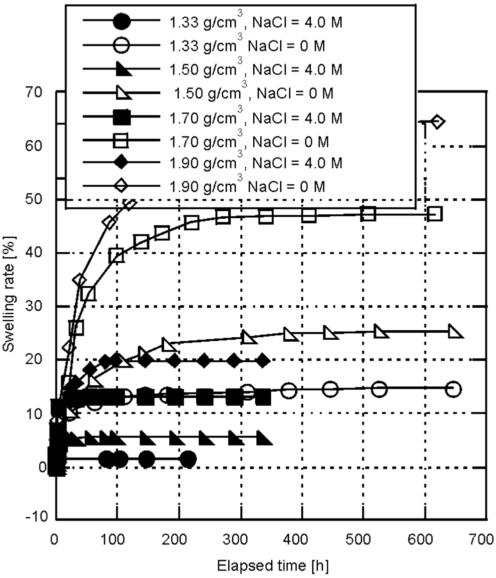

Fig. 12. Time dependences of the swelling rate of bentonite in distilled water and 4.0 M NaCl

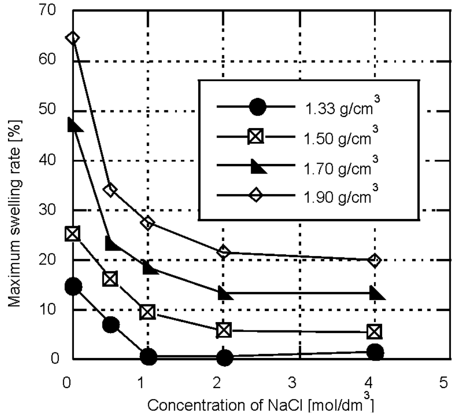

Fig. 13. Dependences of maximum swelling rate on NaCl concentration for various dry densities

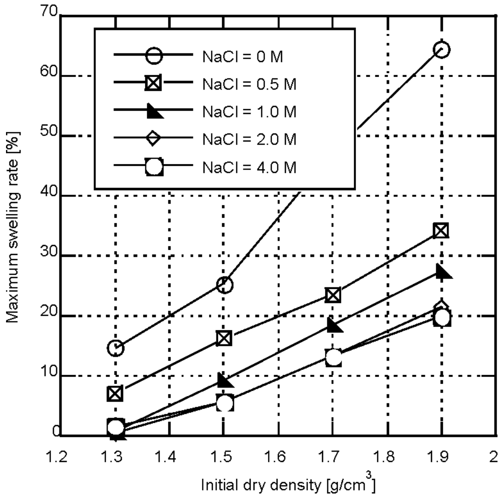

Fig. 14. Dependences of maximum swelling rate on initial dry density for various NaCl concentrations

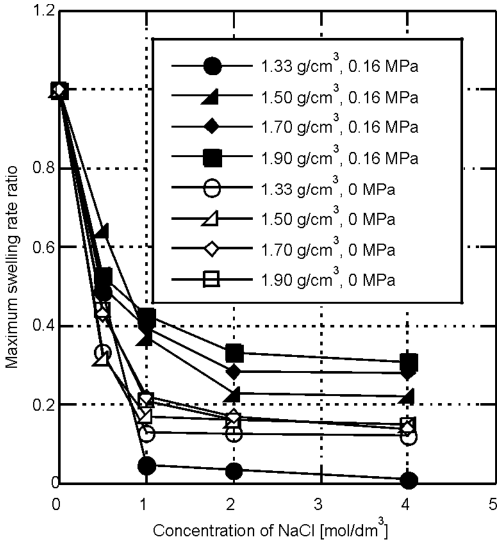

Fig. 15. Dependences of maximum swelling rate ratio on NaCl concentration for various dry densities and static loads 0 or 0.16 MPa

It is clearly seen that salinity has enormous effect on the swelling rate of compacted bentonite. Suzuki et al. [13] indicated that *it might be due to a decrease in double layer swelling between quasicrystals by NaCl. As the electronic double layer adjacent to the quasicrystal surface is compressed with increasing NaCl concentration, the aggregate swelling may decrease. Thus, aggregate swelling for NaCl solution is possibly controlled by both crystalline swelling and double layer swelling between quasicrystals*. The maximum swelling rate of the same initial dry density specimen at various NaCl concentrations decreased noticeably compared to distilled water. For the initial dry density of 1.33 g/cm^3, the specimen showed negative swelling rate at the beginning due to the applied static loads and become positive nearly zero after a few hours. However the maximum swelling rate of these specimens was markedly low. The maximum swelling rates of high initial dry density specimens is higher compared to lower initial dry density.

Figure 13 shows the dependence of the maximum swelling rate on the NaCl concentration at various densities of bentonite under static load of 0.16 MPa. The maximum swelling rate of bentonite sharply decreases for an increase in the NaCl concentration of 0 to 1.0 M. However, with a further increase in the concentration from 1.0 to 4 M, the maximum swelling rate gradually decreases. The specimen of lower initial dry density (1.33 g/cm^3) hardly shows the swelling behaviour as the final maximum swelling rate was lower than 1% at higher concentration of NaCl. Swelling rate markedly increases with the increasing initial dry density of bentonite and decreasing NaCl concentration as shown in Fig.14. It is due to the content of montmorillonite in specimens of higher initial dry density compared to those of lower initial dry densities.

The maximum swelling rates are normalized with respect to the swelling rates in distilled water and re-plotted against concentration of NaCl as shown in Fig. 15. The swelling rate ratio of bentonite markedly decreased for an increase in the concentration of NaCl from 0 to 1.0 M. The maximum swelling rate ratio decreases from 1.0 to almost 0.2. It is clearly observed that when the test fluid is blended with NaCl, the maximum swelling rate noticeably decreases. However, with a further increase in the concentration from 1.0 to 4 M, the swelling rate ratio was gradually decreased. The trend line of these curves is similar to the result of liquid limit test.

4. CONCLUSIONS

Liquid limit of bentonite remarkably decreased from 497% to 112% when the test liquid changed from distilled water to 0.5 M of NaCl solution. Then it gradually decreases upon the NaCl concentration increasing from 0.5 to 4 M while plastic limit slightly increased upon the increasing salt concentration. The controlling parameters of the swelling deformation of compacted bentonite are not only initial dry density and content of bentonite but also the salinity. The maximum swelling rate is less than 1% for lower dry density specimens with high concentration of NaCl. Maximum swelling rate of the specimens in various NaCl solutions is about 50–80% lower than in distilled water. Therefore, if the groundwater surrounding the bentonite barrier is blended with salt, the bentonite might change its characteristics from highly swelled material to coagulate in saline water. Special attention should be paid on using bentonite in nuclear waste disposal, when salt of high concentration is present in groundwater.

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