This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 3rd International Symposium on Coupled Phenomena in Environmental Geotechnics and was edited by Takeshi Katsumi, Giancarlo Flores and Atsushi Takai. The conference was originally scheduled to be held in Kyoto University in October 2020, but due to the COVID-19 pandemic, it was held online from October 20th to October 21st 2021.
Reversibility of micro and macrostructure in compacted bentonite under chemo-mechanical couplings

Kunlin Ruan, De’an Sun, Xianlei Fu, Hailong Wang, Hideo Komine and Daichi Ito

i) Ph.D student, Department of Civil and Environmental Engineering, Waseda University, 3-4-1, Okubo, Tokyo 169-8555, Japan.
ii) Professor, Department of Civil and Engineering, Shanghai University, 99, Shangda road, Shanghai 200444, China.
iii) Ph.D student, Institute of Geotechnical Engineering, Southeast University, 2, Southeast university road, Nanjing 211189, China.
iv) Assist professor, Institute for Sustainable Future Society, Waseda University, 3-4-1, Okubo, Tokyo 169-8555, Japan.
v) Professor, Faculty of Science and Engineering, Waseda University, 3-4-1, Okubo, Tokyo 169-8555, Japan.

ABSTRACT

Compacted bentonite was selected as buffer material in deep geological repository to deal with high level nuclear waste (HLW). During the long-term operations of repositories, volume change characteristics of compacted bentonite are affected by several factors, for example: (1) Change of the concentration in infiltration liquid caused by the variation of groundwater level; (2) Vary of additional stress owing to the unpredictable geological tectonic activity and the stress generated by the swelling of buffer material in confined condition. Hence, it is very crucial to study the effects of chemo-mechanical couplings on volume change characteristics of compacted bentonite. To simulate different chemo-mechanical coupled conditions, serial swell-compression-rebound tests were performed infiltrated by distilled water (DIW) and NaCl solutions with different concentrations. Multi-step salinization-desalination tests were carried out as well. Volume change behaviors of compacted bentonite were studied from microstructure to macrostructure. Experimental results showed that: (1) Final swelling strain and compression index of compacted bentonite decreased with increasing NaCl solution concentration; (2) Comparing the volume change behaviors of compacted bentonite underwent desalination-salinization cycles to those did not undergo these cycles, it was found that the plastic property at the macro level exhibits irreversible property to a certain extent. While, microstructural characteristics are somewhat reversible and elastic.

Key words: bentonite, chemo-mechanical coupling, reversibility, microstructure, macrostructure

1 INTRODUCTION

With the shortage of global energy, more and more attentions are paying to nuclear power. Many countries in the world are working to improve the proportion of nuclear power in total power generation. However, the disposal of high level radioactive waste (HLW) produced by the nuclear industry has been a major problem related to the global environment. The deep geological disposal method has been discussed by many countries to seal nuclear waste in 500–1000 m underground. The artificial barrier made up of waste tanks, buffer materials and the natural barrier formed by the appropriate surrounding rock will prevent the migration and leakage of nuclear waste (Komine, 2004; Komine and Ogata, 2004; Komine et al., 2009). Bentonite is considered as the first choice for buffer material due to its low hydraulic conductivity and good swelling capacity. Various effects on mechanical properties of bentonites were studied, such as, temperature (Tang et al., 2008; Ye et al., 2013, 2014), water chemistry (Sun et al., 2015; Zhu et al., 2013; Chen et al., 2017) and gas (Xu et al., 2017).

Firstly, during the long-term operation of repository, some minerals in surrounding rocks, bentonite materials
and concrete structures may dissolve in the groundwater (Thyagaraj and Rao, 2013). Meanwhile, the dissipation of the decay heat from the nuclear waste and the rise and fall of the groundwater all lead to the repeated change of concentrations and compositions in the groundwater, which inevitably results in the chemical swelling and shrinkage of compacted bentonite. Secondly, additional stress from the unpredictable geological tectonic activity and the stress generated by the swelling of buffer material in confined condition would affect the volume change behaviors of compacted bentonite greatly (Tripathy and Schanz, 2007). Therefore, it is important to study the volume change behavior of compacted bentonite under different chemo-mechanical couplings.

In this paper, in order to take the influence of concentration and additional stress into consideration, a series of given chemo-mechanical stress paths tests were conducted. The reversibility of microstructure and macrostructure in compacted bentonite caused by the chemo-mechanical couplings are studied.

2 MATERIALS AND PREPARATION

2.1 Materials

The sodium-bentonite was taken from Xinjiang, China. Main mineral compositions of this bentonite are montmorillonite (75.9%), Quartz (14.2%), Feldspar (5.9%), and Gypsum (4.0%).

2.2 Specimen preparation

Firstly, bentonite powders were dried in the constant temperature oven at 105°C. After 24 hours, bentonite was taken out and sprayed by distilled water to prepare powders with the initial water content of 15%. In order to achieve the uniform distribution of water, wetted powders were packed in polyethylene, and placed in a constant temperature and humidity box for 2 days. Finally, specimens with the target dry density of 1.6g/cm³, the height of 10mm and the diameter of 61.8mm were made by compressed the wetted powders in static load device.

3 TESTING METHOD

Schematic diagram of the tests is shown in Fig. 1. As can be seen from Fig.1 that tests were divided into 4 phrases in chronological order: Loaded swelling tests, compression tests accompanied with the desalination cycle under a certain load, rebound tests with salinization cycle tests.

![Fig. 1 Schematic diagram of tests](image)

3.1 Loaded swelling tests (S.T.)

The prepared specimens were placed on oedometers, and then the target vertical stress of 50kPa was applied by the step loading method. Consolidation was regarded as stable until the change of the dial reading was less than 0.01mm/h. After that, the prepared NaCl solutions (0.1 M/ 0.3 M/ 0.5 M/ 1 M NaCl solution and distilled water (DIW)) were slowly injected into the oedometer cells. While the change of the dial reading was less than 0.01 mm/24h, the loaded swelling test was considered to be completed.

3.2 Compression tests (C.T.) accompanied with the desalination cycle under a certain load

After loaded swelling tests, compression tests were carried out with the given loading path (50kPa-100kPa-200kPa-400kPa-800kPa-1600kPa). This study only considered the main consolidation stage, so that 48h was regarded as the duration of compression for each level of load. When the samples were stable under a certain vertical stress of 200 kPa (Table 1), the original infiltration solution was replaced by distilled water, which is called desalination cycle. The change of the dial reading was less than 0.01mm/24h after repeatedly cycle of distilled water, which was considered as the standard for the original void liquid was fully replaced. After desalination cycles, compression tests continued to be loaded to 1600kPa.
Table 1 Stress paths of tests

| Sample | Solution | Stress path (kPa) |
|--------|----------|------------------|
| BW     | DIW      | S.T.→C.T.→R.T.   |
| BC-1   | 0.1M NaCl| S.T.→C.T.→R.T.   |
| BC-2   | 0.3M NaCl| S.T.→C.T.→R.T.   |
| BC-3   | 0.5M NaCl| S.T.→C.T.→R.T.   |
| BC-4   | 1.0M NaCl| S.T.→C.T.→R.T.   |
| BCC-1  | 0.1M NaCl| S.T.→100→200→desalination→400→800→1600→R.T.→salinization |
| BCC-2  | 0.3M NaCl| S.T.→100→200→desalination→400→800→1600→R.T.→salinization |
| BCC-3  | 0.5M NaCl| S.T.→100→200→desalination→400→800→1600→R.T.→salinization |
| BCC-4  | 1.0M NaCl| S.T.→100→200→desalination→400→800→1600→R.T.→salinization |

Note: 1. Stress path of S.T. /kPa: 1→12.5→25→50→soaking swelling
2. Stress path of C.T. /kPa: 50→100→200→400→800→1600
3. Stress path of R.T. /kPa: 1600→800→400→200→100→50

3.3 Rebound tests (R.T.) with Salinization cycle tests

Rebound tests with a given loading path (1600kPa-800kPa-400kPa-200kPa-100kPa-50kPa) were followed after compression tests. While the specimens were stable after the finish of rebound tests (when the vertical stress was 50kPa), salinization cycle tests were conducted. Distilled water was replaced by the original solution (NaCl solutions with different concentrations), which is called salinization cycle. Similarly, in order to ensure that the void liquid was fully replaced in the specimen, the operation which was the same as the desalination cycle was carried out.

4 RESULTS

4.1 The loaded swelling strain

4.2 The compression characteristic

Figure 2 describes the relation between final swelling strain and NaCl solution concentration. Fig. 2 shows final swelling strain decreases with increasing NaCl solution concentration. Swelling strain results from the thickness of DDL, which depends on the repulsive force between DDL. According to Tripathy et al. (2013), the repulsive force is inversely proportional to the square root of infiltration solution concentration. The repulsive force of DDL decreases with increasing NaCl concentration1.

Figure 3 shows the compression indices infiltrated by different solutions. The compression index decreases as the increase of NaCl solution concentration. This investigation may because of the
greater void ratios for lower concentration saturated specimens.

4.3 The reversibility of micro and macrostructure

Figure 4 indicates the compression-rebound curves of specimens infiltrated by DIW (BW), compression-rebound curves of specimens infiltrated by NaCl solutions with different concentrations.

![Diagram](image)

(a) Infiltration concentration: 0.1M

(b) Infiltration concentration: 0.3M

(c) Infiltration concentration: 0.5M

(d) Infiltration concentration: 1.0M

Fig. 4 Compression-rebound curves of the compacted bentonite under different chemo-mechanical stress paths (BC-1, BC-2, BC-3 and BC-4) which did not experience desalination-salinization cycles, compression-rebound curves of specimens originally infiltrated by NaCl solutions and experienced desalination-salinization cycles (BCC-1, BCC-2, BCC-3 and BCC-4).

4.3.1 The reversibility of microstructure

![Diagram](image)

(a) Infiltration concentration: 0.1M

(b) Infiltration concentration: 0.3M
Infiltration concentration: 0.5M

Infiltration concentration: 1.0M

Figure 5 shows the compression-rebound curves of BCC-1, BCC-2, BCC-3 and BCC-4 (after desalination) and BW. It is easily found from Fig. 5 that, compression curves and rebound curves of BCC-1, BCC-2, BCC-3 and BCC-4 after desalination are almost the same as those infiltrated by distilled water (BW). Meanwhile, Figure 6 indicates the compression indices and rebound indices of BCC-1, BCC-2, BCC-3 and BCC-4 (after desalination, before salinization), and those of distilled water infiltrated specimens. As can be seen from Fig. 6, compression indices and rebound indices of BCC-1, BCC-2, BCC-3 and BCC-4 are almost the same as those of BW. As Mitchell and Soga (2005) pointed out that, the compression and rebound characteristics can be attributed to the microstructure of soils. The similar compression and rebound curves, compression and rebound indices indicates that, the microstructure of BCC-1, BCC-2, BCC-3 and BCC-4 (originally infiltrated by NaCl solutions) after desalination is similar with the microstructure of BW (continuously infiltrated by Distilled water). This phenomenon reveals that: no matter what liquid is infiltrated in the beginning, when using another liquid replace the original liquid, the microstructure will be the same as the subsequent liquid. On the other word, the microstructure characteristics are somewhat reversible and elastic.

4.3.2 The reversibility of macrostructure

It also can be seen from Fig. 4, for specimens (BCC-1, BCC-2, BCC-3 and BCC-4) experienced desalination and salinization cycles, the initial void ratios (e₁) are higher than the final void ratios (e₃, after desalination-salinization tests), and have a great difference with the void ratios after rebound tests (e₂).
Which means that the macrostructural irreversible characteristics are obvious under these chemo-mechanical couplings.

5 CONCLUSIONS

Based on the results of above laboratory tests infiltrated by NaCl solutions of different concentrations (0.1, 0.3, 0.5 and 1.0M) and distilled water under a series of given chemo-mechanical stress paths, the following conclusions can be drawn.

(1) Final swelling strain decreases with the increase of the concentration of NaCl solution. This phenomenon could be explained by the higher concentration in central axial line, attributing to the thicker thickness of DDL.

(2) Increasing concentration of NaCl solution would induce the decreasing compression index. This investigation may because of the greater void ratios and the bigger DDL thicknesses for lower concentration saturated specimens.

(3) The final void ratios of specimens experienced desalination-salinization are smaller than the initial ones, indicating that the plastic property at the macro level exhibits irreversible property to a certain extent.

(4) The compression curves and rebound curves of specimens experienced desalination-salinization cycles (after desalination, before salinization) are almost the same with the distilled water infiltrated specimens. This phenomenon shows that microstructural characteristics are somewhat reversible and elastic.

REFERENCE

1) Chen, Y G. Jia, L Y. Li, Q. Ye, W M. and Chen, B. (2017): Swelling deformation of compacted GMZ bentonite experiencing chemical cycles of sodium-calcium exchange and salinization-desalination effect, Applied Clay Science, 141, 55-63.

2) Komine, H. and Ogata, N. (2004): Predicting Swelling Characteristics of Bentonites, Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 818-829.

3) Komine, H. (2004): Simplified evaluation for swelling characteristics of bentonites, Engineering Geology, 71, 265-279.

4) Komine, H. Yasuhara, K. and Murakami, S. (2009): Swelling characteristics of bentonites in artificial seawater, Canadian Geotechnical Journal, 46(2), 177-189.

5) Mitchell, J. and Soga, K. (2005): Fundamentals of soil behavior 3rd Ed, John Wiley & Sons, New Jersey. pp, 154-158.

6) Sun, D. Zhang, L. Li, J. and Zhang, B. (2015): Evaluation and prediction of the swelling pressures of GMZ bentonites saturated with saline solution, Applied Clay Science, 105-106, 207-216.

7) Tang A. Cui, Y. and Le, T. (2008a): A study on the thermal conductivity of compacted bentonites, Applied Clay Science, 41, 181-189.

8) Thyagaraj, T. and Rao, S M. (2013): Osmotic Swelling and Osmotic Consolidation Behaviour of Compacted Expansive Clay, Geotechnical & Geological Engineering, 31(2), 435-445.

9) Tripathy, S. Sridharan, A. and Schanz, T. (2004): Swelling pressures of compacted bentonites from diffuse double layer theory, Canadian Geotechnical Journal, 41(3), 437-450.

10) Tripathy, S. and Schanz, T. (2007): Compressibility behaviour of clays at large pressures, Canadian Geotechnical Journal, 44(3), 355-362.

11) Xu, L. Ye, M. and Ye, B. (2017): Gas breakthrough in saturated compacted GMZ bentonite under rigid boundary conditions, Canadian Geotechnical Journal, 2017, 54(8), 1139-1149.

12) Ye, W M. Wan, M. Chen, B. Chen, Y G. Cui, Y J. and Wang, J. (2013): Temperature effects on the swelling pressure and saturated hydraulic conductivity of the compacted GMZ01 bentonite, Environmental earth sciences, 68(1), 281-288.

13) Ye, W. Zheng, J. Chen, B. Chen, G. Cui, J. and Wang, J. (2014): Effects of pH and temperature on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite, Applied Clay Science, 101, 192-198.

14) Zhu, C. Ye, W. and Chen, Y. (2013): Influence of salt solutions on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite, Engineering Geology, 166, 74-80.