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Influence of salt solutions on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite

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ABSTRACT

During the long-term operation of a deep geological repository, infiltration of groundwater with different chemical compositions can affect the buffer/backfill properties of compacted bentonite. Using a newly developed apparatus, swelling pressure and permeability tests were carried out on densely compacted GMZ01 bentonite samples, which has an initial dry density of 1.70 Mg/m^3, with de-ionized water as well as NaCl and $CaCl_2$ solutions at different concentrations. Salinity effects of infiltrating solutions on swelling pressure and hydraulic conductivity of tested samples were investigated. Results obtained show that the swelling pressure of GMZ01 bentonite decreases with increasing concentration of infiltrating solutions, while the degree of the impact decreases with the increase of concentrations. Moreover, swelling pressure reaches stability more rapidly in case of high concentrations. The hydraulic conductivity of GMZ01 bentonite increases with the increase of solution concentrations. Comparison shows that the impact of NaCl solutions on the swelling pressure and hydraulic conductivity is higher than that of $CaCl_2$ solutions at same concentrations. This may be explained by the impact of cation types on the microstructure of bentonite.

1. Introduction

Due to its low hydraulic conductivity, good swelling capacity and sorption properties etc., compacted bentonite has been considered as buffer/backfill material for construction of engineering barrier in deep geological repository for disposal of high-level radioactive nuclear waste (HLW). During the construction and long-term operation of a geological repository, compacted bentonite can work as an effective barrier, protecting the canister and restricting the transfer of radionuclide released from the waste packages after possible failure of canister (Wersin et al., 2007). Meanwhile, interaction can take place between compacted bentonite and groundwater of certain chemical compositions (Herbert et al., 2008). This can affect the physical and chemical properties of bentonite, such as the mineralogical composition and swelling capacity etc.

Previous studies show that salt content of pore fluid can significantly influence the swelling pressure of bentonite. Karnland et al. (2006) found that the swelling pressure of MX-80 bentonite decreases as the salinity of pore water increases. Confirmation was made by Castellanos et al. (2008) on the FEBEX bentonite: an increase in salt concentration decreases the swelling pressure, but this decrease is less significant in case of high density. Herbert et al. (2008) investigated the influence of ion content on the behavior of MX-80 bentonite. Observations showed that the swelling pressure of MX-80 bentonite reaches the highest value (>4 MPa) when it was hydrated with de-ionized water, a significantly lower swelling pressure (~2 MPa) was obtained with low ionic concentration solutions and the lowest one (<1 MPa) was recorded with high saline brines. Based on investigation of the influence of synthetic seawater on the swelling pressure of five common bentonites: Kunigel-VI, Volclay, Kunibond, Neokunibond and MX-80, Komime et al. (2009) also confirmed that synthetic seawater gave lower swelling pressure than de-ionized water did. Moreover, the effect of synthetic seawater was found depending on bentonite, evidencing the important role of soil mineralogy in this process.

Literature reports also show that the chemical composition of pore fluid has significant influence on the hydraulic conductivity of compacted bentonite. The hydraulic conductivity of Wyoming Na–bentonite increases with increase of concentration of the infiltrating solution (Studds et al., 1998). This observation was confirmed by Villar (2005), who found that the hydraulic conductivity of MX-80 bentonite infiltrated with pore water with a salinity of 0.5% was 135% higher than that with de-ionized water. The hydraulic conductivity of a bentonite–sand mixture increased 6 times, when infiltration fluid changed from de-ionized water to 16 g/L salt solution (Mata, 2003). A possible explanation to

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these observations is that the salinity of infiltrating solutions influences the swelling of aggregates, and in turn, changes the microstructure of bentonite, resulting in changing of the hydraulic conductivity (Pusch et al., 1990; Suzuki et al., 2005).

The program for deep geological disposal of high-level radioactive waste in China was launched in the middle of 1980s. Based on a nationwide survey, Beishan, in Gansu province, China, has been selected as one of the potential disposal sites. Related field work including geological and hydrogeological investigations has been carried out. Results show that the total dissolved solids (TDS), which is rich in Na^+ and Ca^{2+}, in the groundwater in Yemaquan, Beishan area, changes from 2 g/L to 80 g/L. The main chemical compound is $Cl \cdot SO_4$–Na, followed by $Cl \cdot SO_4$–Na·Ca (Guo et al., 2001). This large variability in terms of chemical compositions of groundwater justifies the study on the influence of infiltrating liquid on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite.

In this study, the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite (1.7 Mg/m^3 dry density) were investigated with different infiltrating solutions: de-ionized water and solutions of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) at different concentrations. The results obtained were analyzed in terms of microstructure changes.

2. Experimental investigations

2.1. Materials

The GMZ01 bentonite studied was taken from GaoMiaoZi (GMZ) in the Inner Mongolia Autonomous Region, 300 km northwest from Beijing, China (Ye et al., 2009). It is a light gray powder, dominated by montmorillonite (75.4% in mass). As a Na–bentonite, its basic physical and chemical properties are presented in Table 1 (Wen, 2006). A high cation exchange capacity and adsorption ability can be identified (Ye et al., 2010, 2012).

The salts NaCl and $CaCl_2$ used in this test were of analytical grade, corresponding to a purity of 99%.

2.2. Test apparatus

The experimental setup for the swelling pressure and hydraulic conductivity test with salt solutions is shown in Fig. 1. It is composed of four parts: a testing cell, a pressure–volume controller, a fresh/saline water conversion device and a data logger (Fig. 1(b)).

The testing cell contains a basement, a metallic sample ring, two porous stones, a stainless steel piston, a top cover, a pressure sensor and four screws for fixing all parts together (Fig. 1(a)). Two outlets are designed in the basement, one is connected to the pressure–volume controller and the second is used for air expulsion. A load sensor is placed between the top cover and the stainless steel piston for monitoring the swelling pressure. The pressure–volume controller (0–32 MPa to an accuracy of ± 1 kPa; 0–200 cm^3 to an accuracy of ± 1 mm^3) is employed for application of a stable injection water pressure and measurement of the volume of water injected.

Table 1
Basic physical and chemical properties of GMZ01 bentonite (Wen, 2006).

Property	Description
Specific gravity of soil grain	2.66
pH	8.68–9.86
Liquid limit (%)	276
Plastic limit (%)	37
Total specific surface area (m^2/g)	597
Cation exchange capacity (mmol/100 g)	77.3
Main exchanged cation (mmol/100 g)	Na^+ (43.36), Ca^{2+} (29.14), Mg^{2+} (12.33), K^+ (2.51)
Main minerals	Montmorillonite (75.4%), Quartz (11.7%), Feldspar (4.3%), Cristobalite (7.3%)

As salt solutions cannot be directly used in the pressure/volume controller, a fresh/saline water conversion device (② in Fig. 1(b)) is designed. It is made of Plexiglas, one end is connected to the pressure–volume controller and the other end is connected to the basement. De-ionized water and salt solution can be filled in the two parts respectively, which are separated by the silicone oil kept between them.

2.3. Test procedures

2.3.1. Sample preparation

According to the target cylindrical sample with a height of 10 mm, a diameter of 50 mm and a dry density of 1.70 Mg/m^3 to be compacted, GMZ01 bentonite powder at an initial water content of 10.76% was weighted (37 g) and put into a cylindrical column. Compaction load was applied through a piston at a rate of 0.4 kN/min to a maximum value of 48 kN. Then, the maximum load was kept for 1 h. After that, the sample was immediately put into the testing cell (① in Fig. 1(a)) with the metallic sample ring for the swelling pressure and hydraulic conductivity test.

De-ionized water and 8 solutions at desired saline concentrations (Table 2) were employed for the infiltration tests.

2.3.2. Swelling pressure tests

After the compacted GMZ01 bentonite sample was introduced into the testing apparatus as shown in Fig. 1, solutions at different concentrations were infiltrated into the sample through the water/salt converter under a pressure of 100 kPa. Air-bubbles in the test system were exhausted. The temperature was maintained at 20 $\pm$ 1 °C. The volume of injected solution and the evolution of swelling pressure were recorded. When the sample was saturated (which was characterized by the stabilization of swelling pressure, Villar and Lloret, 2004), the swelling pressure test was considered as completed. The constant-volume method was employed for determination of the swelling pressure of compacted samples tested.

2.3.3. Hydraulic conductivity tests

The constant hydraulic head method was employed for the determination of saturated hydraulic conductivity. After completion of the swelling pressure test mentioned above, the hydraulic conductivity test was conducted on the same sample. For this purpose, the injection pressure was increased to 1 MPa and was maintained during the whole test. The volume of solution injected was recorded by the volume/pressure controller. When the volume of infiltration solution injected reached a stable state, the test was stopped. Based on the results obtained, the hydraulic conductivity was determined using Darcy's Law.

3. Test results and discussions

3.1. Swelling pressure

3.1.1. Impact of concentration

Influences of concentration of infiltration solutions on the swelling pressure of compacted GMZ01 bentonite are presented in Figs. 2 and 3. It can be observed that the swelling pressure decreases from 5.11 MPa (de-ionized water) to 3.06 MPa (2.0 M NaCl solution) and 3.6 MPa (2.0 M $CaCl_2$ solution). Namely, the swelling pressure of the compacted GMZ01 bentonite decreases as the concentration of the infiltration solutions increases. This conclusion is consistent with the results reported by different researchers (Karnland et al., 2006; Castellanos et al., 2008; Herbert et al., 2008; Komime et al., 2009; Siddiqua et al., 2011; Lee et al., 2012).

Figs. 2 and 3 also present that the evolution curves of swelling pressure of samples infiltrated with low concentration solutions are "double-peak" shaped. Namely, the swelling pressure increases at the