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Research paper

Influence of pore fluid concentration on water retention properties of compacted GMZ01 bentonite

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ABSTRACT

Due to its low hydraulic conductivity, high swelling capacity and good adsorption properties, the Gaomiaozi (GMZ) bentonite has been proposed as a suitable buffer/backfill material for the construction of artificial barriers in a deep geological repository for the disposal of high-level nuclear waste (HLW) in China. Compacted GMZ01 bentonite with an initial dry density of 1.70 g/cm^3 was hydrated with distilled water and NaCl solutions. The swelling strain was recorded. After being saturated, suction-controlled drying tests were conducted and corresponding soil water retention curves were obtained. MIP investigations were conducted on the void ratio variation of a specimen before and after experiencing wetting and drying processes. Results show that the swelling strain of compacted GMZ01 bentonite decreases as the concentration of infiltration solution increases. The shrinkage curve of saturated compacted GMZ01 bentonite specimens evolves with controlling suctions and could be divided into three stages including a normal shrinkage stage, a residual shrinkage stage and a zero shrinkage stage. For a given suction, the measured void ratio of a specimen saturated with distilled water is slightly larger than those of specimens saturated with salt solutions after the drying equilibrium is reached. For a given suction, the degree of saturation of a compacted GMZ01 bentonite specimen increases as the salt concentration increases. According to the test results, a modified SWRC equation was proposed to account for the effect of void ratio and salt solutions on drying behaviour. The verified results revealed that the proposed equation can satisfactorily describe the SWRCs of compacted GMZ01 bentonite saturated with different solutions.

1. Introduction

Compacted bentonite has been recognized as a suitable material for the construction of artificial barriers in a deep geological repository for the disposal of high-level nuclear waste (HLW) in many countries (SKB, 1999; JNC, 1999; ENRESA, 2000; Marcial et al., 2002; Martín et al., 2006; Ye et al., 2007). During the expected long-term operation of a repository, the compacted bentonite will suffer a complex—highly coupled thermal (T), hydro (H), mechanical (M) and chemical (C) process, due to the decay heat released from nuclear waste in canisters, groundwater infiltrating from the surrounding geological formations, swelling pressure of bentonite generated on hydration and chemical components of groundwater or nuclides that possibly escaped from the canisters. To assess this coupled process in the geological repository, experimental investigations (SKB, 1999; JNC, 1999; ENRESA, 2000; Martín et al., 2006; Ye et al., 2007; Lee et al., 2008; Ye et al., 2010, 2012a, 2012b) and related modeling works (Alonso et al., 1990; Gens and Alonso, 1992; Romero, 1999; Cleall et al., 2006; Lloret and Villar, 2007; Rutqvist et al., 2008; Cho et al., 2010; Thomas et al., 2014) have been conducted. Results indicate that, after the closure of a repository, saturation and de-saturation of the initially unsaturated engineering barrier system is expected to last even thousands of years (Johnson et al., 1994; Senger et al., 2008). During this time period, the degree of saturation/water content of the compacted bentonite would increase upon groundwater absorption (wetting), or decrease from evaporation (drying) induced by increasing temperature (Garcia et al., 2006) originating from decay heat or ventilation (Guillon et al., 2012). Thus, the compacted bentonite will inevitably experience wetting or drying processes, which could be influenced by pore fluid salinity (Villar, 2006; Castellanos et al., 2008). During the operation of a radioactive waste repository, compacted bentonite may swell/shrink under (partially) confined conditions including free swelling, because of the technological voids existing between the canister and the bentonite bricks, bentonite bricks and bricks, as well as bricks and the host formations (Chen et al., 2014). However, most studies till now refer to the chemo-mechanical behaviour of compacted bentonite that is supposed to be under a

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confined condition (Mata et al., 2002; Ravi and Rao, 2013), but few works are focused on the free swelling condition.

On hydration of compacted bentonite with specific types of solutions, crystalline and diffuse double-layer swellings could happen (Madsen and Müller-Von Moos, 1989; Guimaraes, 2002; Savage, 2005; Zhu et al., 2013) and result in generating swelling pressure or swelling strain, which could be influenced by dry density, temperature, water content, ageing effects and soil structure, etc. (Basma et al., 1995; Villar and Lloret, 2004; Jacinto, 2010; Ye et al., 2013a, 2013b). In the meantime, previous works reveal that the salt content of pore fluid can also significantly influence the swelling behaviour of bentonite, which could be attributed to the effects of the diffuse double layer (DDL) or cation exchange (Villar, 2006; Schmitz, 2006; Castellanos et al., 2008; Siddiqua et al., 2011; Zhu et al., 2013; Rao et al., 2013; Ye et al., 2014). Although the hypotheses assumed by the double layer theory are very restrictive in highly compacted bentonite and their application is still limited for engineering purposes (Hueckel, 1992; Garavito, 2005), they are able to explain most of the relations between pore fluid chemistry and the macroscopic behaviour of clays (Komine and Ogata, 1996; Guimaraes, 2002; Mokni, 2011).

Experiences show that drying commonly induces volume shrinkage or even cracks (Uday and Singh, 2013), which depends on clay minerals and soil microstructures. In this aspect, contributions have been made for investigation on shrinkage induced by drying (Wilson, 1990; Tay et al., 2001; Nowamooz and Masrouri, 2010; Guillon et al., 2012). Shrinkage during progressive drying was first investigated by Tempany (1917), which was followed by many contributors using different drying methods including complete air drying (Wilson et al., 1997), atmosphere condition drying (Tang et al., 2011), relative humidity drying (Auvray et al., 2014), etc. By evaporating three different soils from a saturated to a completely air-dried state, Wilson et al. (1997) reported that the observed actual evaporation rate declined when the total suction exceeded 3.0 MPa. Basing on the monitored volume shrinkage, surface crack initiation and propagation processes of a clay specimen using an image processing technique, Tang et al. (2011) verified that shrinkage was induced by water loss (drying). Literature shows that previous works on the behaviour of bentonite on drying in a deep geological repository mainly focused on field-scale investigation by ventilation experiments (Bonda et al., 2013) or modeling study (Guillon et al., 2012). Influences of salt solutions on soil water loss and related volume shrinkage are rarely reported (Miller and Nelson, 1992; Hallett and Newson, 2005).

Soil water retention curve (SWRC), which is defined as the relationship between the degree of saturation and suction in a soil, is widely used for the description of soil–water properties. A soil water retention curve is usually obtained by drying or wetting a soil specimen under a constant stress with measurement of water released from or absorbed by the specimen (Zhou et al., 2014). Until now, many empirical equations were developed for describing SWRCs (Brooks and Corey, 1964; van Genuchten, 1980; Fredlund and Xing, 1994).

Research reveals that there are lots of factors including soil type, mineralogy, density, initial water content, temperature, soil structure, texture, stress history, method of compaction, hysteresis, ageing effects and net confining stress etc., that can influence the soil–water retention properties of geo-materials (Lu and Likos, 2004; Villar and Lloret, 2004; Delage et al., 2006; Thu et al., 2007; Thyagaraj and Rao, 2010). Lots of water retention models were developed for compacted bentonite with consideration of temperature and dry density effects (Jacinto et al., 2009; Villar et al., 2010; Wan et al., 2015). However, these models did not consider influences of soil volume change on water retention, which could produce large errors for soils with large deformation. This conclusion is confirmed by models proposed for several silts and clays that compaction under constant suction induced a significant increase of the degree of saturation (Gallipoli et al., 2003; Tarantino, 2009). Meanwhile, salt concentration of infiltration solutions can also influence the water retention properties of compacted bentonite/expansive clay for use as buffer/backfill materials in an HLW repository (Mata et al., 2002; Mata, 2003; Mokni, 2011; Ravi and Rao, 2013). However, this influence has also rarely been included in existing water retention models.

The Chinese deep geological disposal program for HLW was launched in the middle of the 1980s. Until now, Beishan in Gansu province has been chosen as the preferred construction site for the Chinese repository (Ye et al., 2009). Gao-Miao-Zi (GMZ) bentonite, originates from Gao-Miao-Zi, 300 km north-west of Beijing, and has been considered as the first choice for use as buffer/backfill material for the construction of an engineering barrier in the deep geological repository (Ye et al., 2007).

Contributions have been made for the investigation of the water retention property of GMZ bentonite with consideration of constraint conditions, dry density, temperature, hysteresis behaviour, etc. (Chen et al., 2006; Ye et al., 2009, 2010; Ye et al., 2014; Zhu, 2014; Wan et al., 2015). Based on experimental works, a revised water retention model was proposed for compacted bentonite with consideration for temperature and dry density effects (Zhu, 2014; Wan et al., 2015). A common conclusion that can be drawn is that GMZ bentonite has favorable physical, mechanical and mineralogical properties for use as a buffer/backfill material in HLW disposal (Ye et al., 2014).

Previous in-situ investigation results show that the average total dissolved solids (TDS) of the groundwater in Beishan is 3–12 g/L, and up to 80 g/L (Guo et al., 2001). Obviously, investigation on the water retention properties of GMZ bentonite with consideration of the influence of pore fluid concentration is of great importance for the Chinese HLW disposal program.

In this work, densely compacted GMZ01 bentonite has been saturated with solutions at different concentrations, followed by drying at controlled suctions using an oedometer cell under a vertical load of 0.1 MPa. Vertical deformation was monitored using a dial gauge fixed at the top of the piston (Figs. 1 and 2). Based on these, a modified equation was proposed and verified for the description of the water retention curve with consideration for the influences of shrinkage and pore fluid solutions.

2. Experimental investigation

2.1. Materials

The material tested in the present work is GMZ01 bentonite. Some basic properties of this material are listed in Table 1 (Ye et al., 2012a, 2012b). A high cation exchange capacity and adsorption ability can be identified.

2.2. Test apparatus

The experimental setups for wetting and drying tests are shown in Figs. 1 and 2. An oedometer cell with a salt solution circulation system shown in Fig. 1 was employed for the wetting test and another one with a suction controlling system presented in Fig. 2 was designed for conducting the drying test. The oedometer cell is composed of a basement, a top part, a specimen ring, two stainless steel porous plates and four screws. For the prevention of corrosion by salt solutions, all the parts of the oedometer cells were made of 316L stainless steel. The specimen ring, which has an inner space of 70 mm in height and 50 mm in diameter, was designed for holding the specimen. The four screws were used for fixing the basement, the top part, the specimen ring, etc.

For a saturation test with a circulation of salt solutions, a salt solution circulation system was designed (Fig. 1). The selected salt solution for hydration is circulated through the porous plate at the bottom of the specimen using a peristaltic pump to create constant concentration conditions. For a drying test, a given suction was applied using the vapor phase technique (Delage et al., 1998; Tang and Cui, 2005) through