Volume change behavior of highly compacted GMZ bentonite tested under chemo-hydro-mechanical conditions

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ABSTRACT

Due to its low hydraulic conductivity, high swelling capacity and good adsorption properties, Gaomiaozi (GMZ) bentonite has been selected as a potential buffer/backfill material for construction of artificial barriers in the deep geological repository for disposal of high-level nuclear waste (HLW) in China. During the long-term operation of a repository, the compacted bentonite will inevitably experience wetting or drying processes with hydration or dehydration of groundwater with different concentrations. Furthermore, these processes will take place in the repository with a limited space and certain geo-stresses generated by the upper geological formations. In this work, compacted GMZ bentonite with an initial dry density of 1.70 g/cm³ was hydrated with distilled water and NaCl solutions. For a given suction, the measured void ratio of specimen hydrated with distilled water is slightly larger than those of the specimens saturated with salt solutions after the equilibrium is reached. The degree of saturation of compacted GMZ bentonite specimen increases as the salt concentration increases under the same total suction. A modified soil water retention curve (SWRC) equation was proposed to account for the effect of void ratio and salt solutions on the drying behavior of the specimens. Verifications reveal that the proposed equation can satisfactorily describe the SWRCs of compacted GMZ bentonite saturated with different concentrations of salt solutions. In the meantime, using a modified oedometer, cyclic wetting and drying tests were conducted on compacted GMZ bentonite with infiltration of NaCl solutions under different constant vertical stresses. Results show that the swelling strain on wetting and the shrinkage strain on drying decrease with the increase of the vertical stresses or the concentration of NaCl solutions. Plastic deformations mainly occurred in the first wetting and drying cycle and decreased with the increase of the vertical stresses. However, the accumulated plastic deformation increased with increasing concentration of NaCl solutions, which could be attributed to the effects of osmotic consolidation. Based on the test results, a modified model with consideration of the influences of NaCl solutions with different concentrations was proposed in this work. The micro-/macro- coupling equations fD (suction reduction) and fI (suction increase) were improved for the specimens saturated with different concentrations of NaCl solutions. Simulations show that the modified BExM model can be used satisfactorily to describe the wetting/drying behavior of compacted GMZ bentonite specimens with consideration of the influences of NaCl solutions.

Keywords: GMZ bentonite; SWRCs; Volume change; Chemo-hydro-mechanical conditions; Wetting and drying; Modified BExM model.

1 INTRODUCTION

Deep geological repositories are planned to be built at great depths of about 500 m to 1000 m below the ground surface for the disposal of high-level radioactive waste (HLW) (Wang et al., 2006; Ye et al., 2010). Due to its high swelling capacity, low hydraulic conductivity, good sorption properties, adequate mechanical resistance, etc., compacted bentonite has been recognized as a suitable material for construction of artificial barriers in deep geological repositories for disposal of HLW in many countries (SKB, 1999; JNC, 1999; ENRESA, 2000; Marcial et al., 2002; Martin 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 the canister, groundwater infiltrated from the surrounding geological formations, swelling pressure of bentonite generated on hydration and chemical components of groundwater or nuclides possibly escaped from canister (He et al., 2016).
Researches reveal 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) originated from decay heat or ventilation (Guillon et al., 2012). Therefore, the compacted bentonite will inevitably experience wetting or drying processes. Meanwhile, pore water in the compacted bentonite barriers and the surrounding rock in the underground repository (Wang et al., 2014) generally has certain chemical components, which continually interact with the bentonite barrier or the surrounding rock during their direct contact (Ramirez et al., 2002; Fernandez et al., 2014; He et al., 2016). Moreover, 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). Therefore, it is necessary to assess the chemo-hydro-mechanical coupling effects on the volume change behavior of compacted bentonite during wetting and drying cycles.

On hydration of compacted bentonite with specific types of solutions, crystalline and diffuse double-layer swellings could happen (Madsen, 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, compaction water content, ageing effects, soil structure and salt content of pore fluid, etc. (Basma et al., 1995; Villar and Lloret, 2004; Jacinto, 2010; Ye et al., 2013a, b; He et al., 2016). Experiences show that drying commonly induces volume shrinkage or even cracks (Uday and Singh, 2013) depending on clay minerals and soil microstructures. 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), while influences of salt solutions on soil water loss and related volume shrinkage is rarely reported (Miller and Nelson, 1992; Hallett and Newson, 2005).

With suction controlled tests conducted on cyclic wetting and drying processes, the soil water retention curve on wetting or drying processes can be obtained. 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, net confining stress, salt solutions and concentrations etc., 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; He et al., 2016). 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 do not consider the influences of salt solutions.

After experiencing several cyclic wetting and drying processes, irreversible compression of compacted expansive clays could occur during the drying stages of the wetting–drying cycles. Based on this observation, Wheeler et al. (2003) proposed a constitutive model for describing the coupling of hydraulic hysteresis and mechanical behaviour of compacted expansive clays. Alonso et al. (2005) also reported that the compacted expansive bentonite and sand mixtures recorded progressive shrinkage during successive wetting-drying cycles until it reached a final reversible elastic response. Based on analyses, Alonso et al. (1999) proposed an elastoplastic model for expansive soils (Barcelona Expansive Model, BExM). This model takes into account the accumulation of swelling and shrinkage strains during the wetting and drying cycles and the equilibrium state indicating the elastic behaviour of the specimen reached at the end of several wetting and drying cycles experienced.

Previous studies also show that the swelling pressure of bentonite decreases as the salinity of pore water increases (Castellanos et al., 2008; Herbert et al., 2008; Zhu et al., 2013; Ye et al., 2014). Research on the influences of salt solution on the swelling or shrinkage accumulation and on the equilibrium state after experiencing the wetting and drying cycles is rarely reported in literature (Estabragh et al., 2013; 2015). Moreover, the influence of salt solution on volume change behaviour of soils during cyclic wetting and drying processes has rarely reported in exiting models.

The Chinese deep geological disposal program for HLW was launched in middle 1980s. Until now, Beishan in Gansu province has been chosen as the preferred construction site for Chinese repository (Ye et al., 2009). Gao-Miao-Zi (GMZ) bentonite, originates from Gao-Miao-Zi, 300km north-west Beijing, has been considered as the first choice for using as buffer/backfill material for construction of engineering barrier in the deep geological repository (Ye et al., 2007). Contributions have been made for investigation on water retention property of GMZ bentonite with consideration of constraint conditions, dry density, temperature, hysteresis behavior and salt solution, etc. (Chen et al., 2006; Ye et al., 2009; Ye et al., 2010; Wan, 2015; Ye et al., 2014; Zhu, 2014; Wan et al., 2015; He et al., 2016). Zhu et al. (2015), Ye et al. (2017) and Chen et al. (2017) found that the cyclic salinization-desalinization processes also has significant effects on volume change of compacted bentonite. However, few studies has been reported in
the literature on the chemo-hydro-mechanical effects on the volume change behavior of compacted GMZ bentonite during wetting and drying processes.

In this work, densely compacted GMZ bentonite has been saturated with solutions at different concentrations, which followed by drying at controlled suctions using an oedometer cell under different vertical loads. Based on this one cycle of wetting and drying process, a modified equation was proposed and verified for description of water retention curve with consideration of influences of pore fluid solutions on the drying process. Meanwhile, during the cyclic wetting and drying processes, the effects of NaCl solutions on the volume change of the compacted GMZ bentonite specimens under chemo-hydro-mechanical conditions was tested and analyzed. A modified model with consideration of the influences of NaCl solutions on the volume change behavior of the specimens was also proposed.

REFERENCES


