Chemical influence on water retention behaviour of compacted bentonite

Bing Qin i), Yang Lu ii) and Zheng-han Chen iii)

i) Lecturer, Department of Military Installations, Army Logistics University of PLA, North 1st Road, Chongqing College Town, Chongqing 401311, China.

ii) Teaching Assistant, Department of Military Installations, Army Logistics University of PLA, North 1st Road, Chongqing College Town, Chongqing 401311, China.

iii) Professor, Department of Military Installations, Army Logistics University of PLA, North 1st Road, Chongqing College Town, Chongqing 401311, China.

ABSTRACT

This present study investigated the chemical influence on the water retention curves of compacted GMZ bentonite. Sodium chloride solution and calcium chloride solution were mixed with the bentonite before compaction. Water retention curves were determined by measuring suctions with a high-precision humidity sensor. The chemical influences on water retention curves were predominant in the suction range less than 70 MPa. In the suction range, an increasing of solution salinity resulted in an upward movement of water retention curve, i.e. an increasing of water retention capability of the bentonite. The solution type also had notable influence on the water retention behaviour. A higher water retention capability of the bentonite added with calcium chloride solution was observed compared to that with sodium chloride solution. In the suction range larger than 70 MPa, the influences of the solution type and salinity on the water retention behaviour were insignificant, and the water retention curves with different solutions were almost identical.

Keywords: bentonite, water retention curve, suction, chemical influence

1 INTRODUCTION

Deep geological disposal of high-level radioactive waste (HLW) has been receiving an increasing attention in recent years. In the conceptual multi-barrier design of HLW repository, bentonite is usually used to construct the buffer barrier between the waste canister and the host rock (Yong et al., 2010; Pusch, 2015), due to its favourable properties including low permeability, high swelling ability, high adsorption capacity, etc. Bentonite is characterised by a high mineral content of montmorillonite, which is known to have an ability of adsorbing a great amount of water and to be sensitive to chemical condition of water (Mitchell & Soga, 2005). In several potential sites for HLW repository, high values of total dissolved solids (TDS) of groundwater have been observed at the proposed repository depths (Guo et al. 2001; Siddiqua et al. 2011). The high salinity condition may have negative impacts on the functions of the bentonite buffer (Studels et al., 1998; Pusch, 2001; Karnland et al., 2006; Lloret & Villar, 2007; Castellanos et al., 2008; Herbert et al., 2008; Komine et al., 2009; Siddiqua et al., 2011; Zhu et al., 2013; Sarkar & Siddiqua, 2016). Therefore, there is a need to investigate the chemical effects on the bentonite behaviour.

The saturation process of bentonite buffer by adsorbing groundwater from host rock is significantly affected by the water retention behaviour of the buffer. In the past two decades, much effort has been devoted to characterising water retention curves of bentonite (Delage et al., 1998; Lloret et al., 2004; Tang & Cui, 2005; Imbert et al., 2005; Villar, 2007; Schanz et al., 2010; Jacinto et al., 2012; Qin et al., 2012; Seiphoori et al., 2014; Wan et al., 2015; Gatabin et al., 2016; Dieudonne et al., 2017, among others). Dependence of water retention behaviour on suction levels has been highlighted. In the high suction range, water retention is almost unaffected by dry density and volume constraint condition, while water retention in the low suction range is sensitive to variations in dry density and volume constraint condition (Delage et al., 1998; Agus, 2005; Villar, 2007; Seiphoori et al., 2014; Gatabin et al., 2016; Dieudonne et al., 2017). The water retention capacity has been shown to decrease with increasing temperature (Lloret et al., 2004; Tang & Cui, 2005; Imbert et al., 2005; Jacinto et al., 2009; Qin et al., 2012; Wan et al., 2015). Few investigations have been carried out of the chemical effect on water retention behaviour (Zhang et al., 2012; He et al., 2016; Tabiatnejad et al., 2016; Kuusela-Lahtinen et al., 2016), and knowledge of the chemical effect is obviously incomplete.
In the present study, an experimental investigation was performed to study chemical influences on water retention curves of compacted GMZ bentonite, which were determined by measuring suction of samples with different pore fluids including distilled water, sodium chloride solutions and calcium chloride solutions.

2 MATERIAL AND METHODS

The used soil for this study was GMZ bentonite from Gaomiaozi deposit in Inner Mongolia, China, which is the Chinese candidate buffer/backfill material for the geological disposal of high level radioactive waste. Basic physical and chemical properties of the used GMZ bentonite are given in Table 1.

After oven-drying (110 °C) for 72 h, the bentonite was mixed with preselected amounts of wetting fluids according to the target water contents. Seven types of wetting fluid were used including distilled water, sodium chloride solutions (1, 2 and 5 mol/L) and calcium chloride solutions (0.5, 1 and 2.5 mol/L). The target water contents included 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20% and 22.5%. The wetted bentonite was cured for at least 14 d in waterproof bags to allow for a homogeneous distribution of pore fluid. Before compaction, the actual water content was determined with consideration of the influence of saline fluid, which can be calculated as follows:

\[
w = \frac{m_w - m_d}{m_d - m_w} \cdot \frac{c_f \cdot M_f}{\rho_f - c_f \cdot M_f} \times 100\% \tag{1}
\]

where \(w\) is the actual water content, \(m_w\) is the mass of wet sample, \(m_d\) is the mass of the sample after oven-drying, \(\rho_f\) is the density of wetting fluid, \(c_f\) is the molar concentration of wetting fluid, and \(M_f\) is the molar mass of the solvent in wetting fluid.

Total suction of compacted sample was determined by measuring relative humidity in the sample with a high-precision humidity sensor. The total suction can be calculated in terms of the relative humidity by the following thermodynamic relationship (Fredlund & Rahardjo, 1993):

\[
\Psi = -\frac{RT}{M_w} \ln \left( \frac{RH}{100} \right) \tag{2}
\]

where \(\Psi\) is the total suction, \(RH\) is the relative humidity, \(R\) is the universal gas constant, \(T\) is the absolute temperature, \(\rho_w\) is the water density, and \(M_w\) is the molecular mass of water.

A rigid cell of stainless steel as shown in Fig. 1 was designed for suction measurement, of which the internal diameter and height were 50 mm and 75 mm, respectively. The sample was directly compacted to the target dry density of 1.6 g/cm³ in the cylindrical cell body. The compaction at a rate of 0.5 mm/min was conducted in five layers to ensure the homogeneity of sample. To accommodate the humidity sensor, a hole with a diameter of 15 mm and a depth of 45 mm was drilled in the sample. The cell was equipped with the humidity sensor through the threaded hole in the middle of top plate. The temperature was maintained at 20 °C during the test.

3 RESULTS AND DISCUSSION

Water retention results of samples wetted with distilled water and sodium chloride solutions are depicted in Fig.2, in which the relationships between water content and total suction are plotted. The influence of NaCl solution on water retention behaviour was dependent on total suction levels. When the total suction was larger than 70 MPa, samples wetted with NaCl solution at different concentrations had similar total suction values for a same water content. The impact of NaCl solution on water retention capacity was insignificant in the total suction range. However, different trend was observed when the total suction lower than 70 MPa. For a given water content, the increase in concentration of NaCl solution lead to an increase in total suction. The water retention capacity was improved by the presence of NaCl solution. Moreover, the improvement seemed to be more
predominant with the decrease of total suction. The increase of water retention capacity with salinity was also reported in Zhang et al. (2012), He et al. (2016), Tabiatnejad et al. (2016), and Kuusela-Lahtinen et al. (2016). The results of He et al. (2016) and Kuusela-Lahtinen et al. (2016) also demonstrated that the salinity influence on water retention curve was more remarkable in lower suction range. Nevertheless, Zhang et al. (2012) found that the effect of salt content on water retention curve was more obvious when the suction was higher.

As shown in Fig. 2, a logarithmic relationship between water content and total suction may be established, which can be expressed as follows:

\[ w = A - B \ln \Psi \]  

(3)

where \(A\) and \(B\) are fitting parameters. The variation of parameter \(B\) with respect to solution concentration is presented in Fig. 3. The increase in concentration of NaCl solution resulted in larger values of parameter \(B\), namely, steeper water retention curves. An exponential relationship was found between parameter \(B\) and concentration of NaCl solution. With the concentration increase, parameter \(B\) would be progressively close to an asymptotic value, which meant that the salinity influence on water retention curve would gradually become stable.

Water retention results of samples wetted with calcium chloride solutions are presented in Fig. 4. Similar trends were observed to the case of sodium chloride solution. Influence of solution type on water retention behaviour is illustrated in Fig. 5. Compared to NaCl solution, a more pronounced effect on water retention curve was obtained for CaCl\(_2\) solution. The water retention capacity of sample wetted with CaCl\(_2\) solution was higher than that with NaCl solution at the same concentration. As shown in Fig. 5, at same water contents, samples wetted with 1 mol/L CaCl\(_2\) solution had larger values of total suction than that with 1 mol/L NaCl solution, especially in the suction range lower than 70 MPa. The total suctions of samples wetted with 5 mol/L NaCl solution were even smaller than that with 2.5 mol/L CaCl\(_2\) solution. Result of fitting parameter \(B\) for CaCl\(_2\) solutions is also given in Fig. 3. For same solution concentrations, higher values of parameter \(B\) were observed in the case of CaCl\(_2\) solution, indicating steeper water retention curves for samples wetted with CaCl\(_2\) solutions.

Matric suction and osmotic suction were not directly measured in the present study. If we simply assume that the osmotic suction of a sample equal to the osmotic pressure of the wetting fluid used to prepare the sample, then the matric suction can be obtained by subtracting the osmotic pressure of wetting fluid from the measured total suction. Osmotic pressure of wetting fluid can be calculated by the following equation (Sposito, 1981):

\[ \pi = \zeta RTc_j \phi \]  

(4)
where \( \pi \) is the osmotic pressure of wetting fluid, \( \varphi \) is the osmotic coefficient, and \( \zeta \) is the Van't Hoff factor, which is 2 and 3 for sodium chloride and calcium chloride solution, respectively.

Fig. 6 and 7 show the results of the calculated matric suction for sodium chloride and calcium chloride solutions, respectively. Interestingly, the water content versus matric suction curves for the three NaCl solutions appeared to merge together, but were still not coincident with the curve for distilled water. The sample wetted with distilled water had smaller matric suctions particularly in the low suction range. An impact of the concentration of CaCl₂ solution was observed on the relationship between water content and matric suction, as shown in Fig. 7. Similarly to the case of total suction, at a same water content, the matric suction increased with the increase in the concentration of CaCl₂ solution. In Fig. 7, the result for 1 mol/L NaCl solution is also plotted in order to make an comparison with that for 1 mol/L CaCl₂ solution. Still, higher matric suctions were found in the samples with the CaCl₂ solution.

Water retention behaviour can also be depicted in terms of degree of saturation. The influence of saline fluid must be taken into account when determining degree of saturation, which can be calculated as follows:

\[
S_r = \frac{w \rho_d}{\rho_f - c_f \cdot M_s} \frac{\rho_s}{\rho_s - \rho_f}
\]

(5)

where \( S_r \) is the degree of saturation, \( \rho_d \) is the dry density, and \( \rho_s \) is the density of soil particle. The variations of degree of saturation with total suction are presented in Fig. 8 and 9 for sodium chloride and calcium chloride solutions, respectively. Due to the fact that samples in the present study were compacted to a same dry density, the chemical influence on the degree of saturation versus suction curve was similar to that on the water content versus suction curve.

4 CONCLUSIONS

Influences of sodium chloride and calcium chloride solution on water retention behaviour of compacted GMZ bentonite were investigated. The saline influence on water retention capacity was dependent on the total suction levels, which was insignificant in the total suction range higher than 70 MPa. When the total suction lower than 70 MPa, the water retention capacity increased with the increase in solution concentration. Steeper water retention curves were observed for samples wetted with solutions at higher concentrations. A more pronounced effect on water retention curve was obtained for CaCl₂ solution. Compared to the case of NaCl solution, the water retention capacity of sample wetted with CaCl₂ solution was larger, and the water retention curve with CaCl₂ solution was steeper. Herein,
only preliminary results from the experimental investigation are given, further interpretation of the experimental results still needs to be done.

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