Swelling pressure characteristics of compacted Chinese Gaomiaozi bentonite GMZ01

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Abstract

Gaomiaozi bentonite (GMZ01) has been decided upon as the first option for use as buffer/backfill materials in the deep disposal of high-level radioactive waste in China. The basic functions of the materials used in the waste repositories request among others a sufficient swelling pressure and low hydraulic conductivity in order to provide long-term stability to the barrier system under environmental pressure and behavior of the waste loads. As such, it is necessary to investigate the influence of initial dry density on the swelling properties of Gaomiaozi bentonite (GMZ01) in order to achieve better design of buffer/backfill materials. In this study the swelling pressure of GMZ01 has been studied and analyzed by multi and one-step wetting constant volume tests with five different dry densities (1.15, 1.35, 1.50, 1.60 and 1.75 mg/m³). Results show that swelling pressure changes with time nonlinearly, while there is a linear relationship between time/swelling pressure and time. Curves of swelling pressure and the amount of absorbed water varying with time can be classified into typical phases. For the GMZ01 tested here, the initial dry density is an important factor influencing the swelling pressure. The results show that there is an exponential relationship between swelling pressure and dry density. Moreover, comparison was done between the experimental swelling pressure results of used GMZ bentonite in this study and other bentonites cited in literature: (i) other GMZ’s and (ii) different types of bentonites proposed as buffer/backfill materials (i.e., MX80, Kunigel, Montigel, and Calcigel). The effect on the microstructure of the density and the wetting under the constant volume condition (after the swelling pressure test) has been investigated by studying the results of pore size distribution for GMZ01 by using the mercury intrusion porosimetry (MIP) test and the environmental scanning electron microscope (ESEM) photos. Finally, two different theoretical concepts were used to estimate the swelling pressure (the modified DDL and thermodynamics approaches). The results of the two methods show that the swelling pressure results compare relatively well with the experimental data for the GMZ bentonite.

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Keywords: Soil mechanics; Gaomiaozi bentonite; Swelling pressure; Dry density; Constant volume test method

1. Introduction

The growth of the nuclear industry worldwide during last decades has resulted in a lot of nuclear waste. The safe disposal of this highly radioactive waste has become an increasingly pressing environmental problem. The safe disposal of high-level nuclear waste generated from nuclear power plants is a great concern in many countries due to the
long-term (at least 10,000 years) detrimental impact of nuclear waste on humans if released into the environment. In many countries, the chosen emplacement depth for the waste repositories has been found to vary between 500 to 1,000 m (e.g., Swedish Nuclear Fuel and Waste Management, 1983, 1992; Japan Nuclear Cycle Development Institute, 2000). According to host rock conditions, at present, the international different constructions and proposed barriers in the deep geological repository can be classified into two types: a single barrier and double barrier layout. The first one is mainly built for salt rock or clay rocks, such as in Germany, France, and the Belgian repositories (Su and Patric, 2006). The second type (double barrier) mainly built in hard rock, such as the U.S. Yucca Mountain, Japan and China sites.

The basic functions of the barrier materials used in the waste repositories require a high swelling pressure and very low hydraulic conductivity in order to provide long-term stability to the barrier system under the high overburden pressure, and the materials should possess a high radionuclide adsorption capacity and a high heat transfer capacity (Brookins, 1984). Both domestic and international research show that compacted bentonite is the ideal buffer/backfill material (Pusch and Yong, 2003; Tripathy et al., 2004). For example Calcigel is a bentonite used in Germany as a buffer martial, and Kunigel is a Japanese bentonite (Komine and Ogata, 1996; Schanz and Tripathy, 2009). Gaomiaozi bentonite (GMZ01) has been decided on as the best choice for use as buffer/backfill materials in the deep disposal of high-level radioactive waste in China. The swelling properties of the buffer/backfill material are important to the engineered barrier system. The high swelling self-healing property serves to make the buffer layer maintain its integrity and homogeneity, and also to retard the radioactive liquid waste from being transported to the underground water environment (Zhang et al., 2012). Therefore, it is necessary to investigate the influence of initial dry density on the swelling properties of Gaomiaozi bentonite (GMZ01) in order to provide useful data in the design of buffer/backfill materials. In this paper, the swelling pressure-dry density behavior of compacted Mongolia GMZ01 is studied in detail using two different techniques (one- and multi-steps wetting) and wide range of dry densities to investigate the effect of suction and initial conditions on swelling pressure behavior. For a more comprehensive analysis which is focused on the microstructure of the soil, the mercury intrusion porosimetry (MIP) test and the environmental scanning electron microscope (ESEM) images were added to the experimental program. Finally, two different theoretical concepts were used to estimate the swelling pressure (modified DDL and thermodynamics approaches) to investigate the ability of the available theoretical methods to predict the swelling pressure of Mongolia GMZ01 bentonite.

2. Measurement of swelling pressure

The pressure needed to maintain the volume of expansive soil unchanged defined as the swelling pressure (Sridharan et al., 1986; Lajudie et al., 1994; Liu et al., 2001). Swelling pressure and the swelling potential of expansive soils are affected by clay mineral composition, pore fluid, soil structure, initial dry density and other factors (Tripathy et al., 2004; Schanz and Tripathy, 2009; Estabragh et al., 2013). Many quantitative research results show that the factors that affect the swelling pressure can be attributed to two categories, namely internal and external factors. The nature of the internal factors such as specific clay surface area, cation exchange capacity, and pore water properties (type of liquid and concentration). The external factors are dry density, water content, and compaction methods.

The results of previous studies (Brackley, 1975; Sridharan et al., 1986; Xianmin and Wang, 2003) reveal three kinds of experimental protocols to determine the swelling pressure of expansive soils, namely the free swell–compression test, the loading swell–compression test and the constant volume test. The results of these three experimental methods, each carried out in the consolidation apparatus, indicate three different types of behaviors; Fig. 1. In the free swell–compression experiment, water is added and the soil sample undergoes free or full swell before it is progressively loaded, as in the consolidation test. When the same void ratio as the initial one is reached, the vertical stress measured is the vertical swelling pressure (Fig. 1, Ps1). In the loading swell–compression test, several identical samples are used. The samples are allowed to swell under different loads, resulting in different volume changes. The intersection of the straight line connecting the points of the corresponding tests with the horizontal line representing the initial void ratio in the void ratio; log vertical pressure space gives the swelling pressure (Fig. 1, Ps2). The constant volume test is conducted by making continuous adjustments after adding water to prevent the volume expansion of the sample by increasing the vertical stress until no longer vertical deformation is measured (Fig. 1, Ps3). Fig. 1 shows that the three different testing protocols tend to provide different values of the swelling pressure. No one technique results in consistently higher values. It is not unique which method results in the highest values.

Fig. 1. Three kinds of experimental protocols to measure swelling pressure (Sridharan et al., 1986).
Rather, the results of these three different test methods of the swelling pressure demonstrate that the stress path has obvious effects. In this paper, the constant volume test method (the rigid test chamber) was used to determine the swelling pressure on compacted GMZ01.

Many studies have investigated the behavior of swelling pressure for different types of bentonites (e.g. Müller-Vonmoos and Kahr, 1982; Herbert and Moog, 2002; Tripathy et al., 2004; Schanz and Tripathy, 2009; Schanz et al., 2013; Wang et al., 2013). Regarding the China GMZ01, Xie et al. (2006) carried out 12 constant volume tests to measure the swelling pressure. They reported that the vertical swelling pressure is mainly affected by the initial dry density. Xianmin and Wang (2003) studied the swelling pressure and dry density correlation. Liu et al. (2001) carried out swelling pressure tests to study the dry density in a range of 1.40–1.51 g/cm³ for GMZ01.

3. Material used

The material used in this study is the sodium bentonite GMZ01 Gaomiaozi from Inner Mongolia Gu Xing in China. The liquid limit of this bentonite is 276% and its plasticity index is 239%. The hygroscopic water content is 11.14%, which gives 96 MPa as its initial total suction (tested by chilled mirror device). The hygroscopic water content (11.14%) is used as the initial water content for the experimental program in this study. Table 1 shows the basic properties of the bentonite used.

4. Experimental programs

One and multi-step wetting swelling pressure tests under the constant volume condition were carried out in this study. Five different dry densities of compacted samples covering a wide range of initial states were tested for the one-step wetting swelling pressure test: 1.15, 1.35, 1.50, 1.60 and 1.75 mg/m³; Table 2. In addition, one more density, 1.60 mg/m³, was tested in the multi-steps wetting swelling pressure tests. Nine different suction values were used in the multi-steps wetting swelling pressure tests. Nine different suction values were used in the multi-step test, according to Table 3.

Table 2
Partial initial properties of specimen.

<table>
<thead>
<tr>
<th>No.</th>
<th>Water content (%)</th>
<th>Dry density (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.14</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>11.14</td>
<td>1.35</td>
</tr>
<tr>
<td>3</td>
<td>11.14</td>
<td>1.50</td>
</tr>
<tr>
<td>4</td>
<td>11.14</td>
<td>1.60</td>
</tr>
<tr>
<td>5</td>
<td>11.14</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Table 3
Suction path of the multi-steps wetting swelling test.

<table>
<thead>
<tr>
<th>Suction (kPa)</th>
<th>Method to apply suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>95,858</td>
<td>Initial condition of the specimen</td>
</tr>
<tr>
<td>37,721</td>
<td>Vapor equilibrium technique</td>
</tr>
<tr>
<td>21,212</td>
<td>Axis translation technique</td>
</tr>
<tr>
<td>9,827</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

As mentioned above, all the specimens were tested with the hygroscopic water content as the initial condition. That is, before the tests were commenced, the water content was checked to reveal the hygroscopic water content. Specimens with a diameter of 50 mm and 20 mm in height were prepared by the static compaction method by directly compacting bentonite (with a hygroscopic water content) in the specimen ring. The specimens in the compaction machine were compacted in 3 layers into the cell ring, and each layer was compacted under the static load.

A UPC-Isochoric cell, similar to the cell that was used by Romero (1999), Agus (2005), Ariffin (2008), and Al-Badran (2011) (Fig. 2), was used to perform the swelling tests during wetting. Distilled water was used in all swelling pressure tests. Both the axis-translation technique (ATT) and the vapor equilibrium technique (VET) were used to control the suction in this test layout. The specimen in this cell is 50 mm in

### Table 1
The basic properties of soil used.

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_s$</td>
<td>2.71</td>
</tr>
<tr>
<td>LL (%)</td>
<td>276</td>
</tr>
<tr>
<td>PL (%)</td>
<td>37</td>
</tr>
<tr>
<td>PI (%)</td>
<td>239</td>
</tr>
<tr>
<td>$w_o$ (%)</td>
<td>11.14</td>
</tr>
<tr>
<td>Initial suction, kPa</td>
<td>95,958</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>60</td>
</tr>
<tr>
<td>Fine content (%)</td>
<td>98</td>
</tr>
<tr>
<td>Total specific area (m²/g)</td>
<td>570</td>
</tr>
<tr>
<td>Cation exchange capacity (mmol/g)</td>
<td>0.783</td>
</tr>
<tr>
<td>Main exchanged cation, (mmol/g)</td>
<td>Na⁺ (0.4336), Ca²⁺ (0.2914), Mg²⁺ (0.1233), K⁺ (0.0251)</td>
</tr>
<tr>
<td>Valency</td>
<td>1.475</td>
</tr>
<tr>
<td>Mineral components</td>
<td>Monotmorillonite (75.4%), quartz (11.7%), feldspar (4.3%), cristobalite (7.3%).</td>
</tr>
</tbody>
</table>

aData from Ye et al. (2011).
diameter and 20 mm in height and is surrounded by a stainless steel ring. The device mainly consists of a pedestal, a threaded top part with a top cap and a load cell to measure the swelling force. Because the pedestal is exchangeable, it is possible to perform tests using either a ceramic disk or a porous stone. In the case of multi-step wetting, a porous stone was used in the pedestal when using VET, while a ceramic disk with an air entry value of 1500 kPa was used in the case of ATT. The top cap has a corrosion resistant metal porous disk. When the vapor equilibrium technique was used to apply suction, the cell was equipped with an Erlenmeyer flask and an air pump to circulate the vapor from above a salt solution through the specimen bottom and top boundaries (Fig. 2). The pressure-deformability of cells used was calibrated by pressurizing the cells (with the load cells installed) with air. The cells were subjected to increasing and decreasing air pressures while the deformations were recorded using linear vertical displacement transducers (LVDT). Readers are referred to Agus (2005) for more details.

5. Results and analysis

5.1. The development of swelling pressure with time

Figs. 3 and 4 show, respectively, typical curves of swelling pressure and absorbed water versus time relationships plotted in the normal scale for the five one-step wetting swelling pressure tests. The increase in both welling pressure and amount of absorbed water with time was rapid at the earlier stage of tests (i.e., up to 3000 min). The rate of both swelling pressure development and amount of absorbed water kept almost constant beyond a point which marks the end of primary swelling pressure development.

Fig. 3. Transient swelling pressure development depending on initial dry density.

Fig. 2. Schematic drawing of experimental setup of (a) UPC-Isochoric cell used to measure the swelling pressure and (b) the one-step swelling pressure measurement using water circulation method, and schematic drawing for the multi-step swelling pressure test using (c) axis-translation technique (ATT) and (d) vapor equilibrium technique (VET).
Subsequently, as the change of expansive soil structure stabilizes, the rate of swelling pressure slowly changes. At the same time, the rate of water absorption also decreases. For all specimens (except for the 1.6 mg/m³ dry density specimen) the development of swelling pressure with time had single maxima until the maximum swelling pressure was reached. Fig. 3 shows that more time is required to reach equilibrium as the dry density increases. The test results performed by Gattermann (1998) showed that swelling pressure was constant with time after the maximum value was reached. Alonso et al. (1999) showed that swelling pressure may also decrease after the maximum value was reached as a result of collapse of the clay macro-structure. Agus (2005) reported that after the maximum primary swelling pressure is reached, swelling pressure might increase, stay constant, or decrease with time depending on the initial conditions (initial water content and void ratio).

As can be seen in Fig. 3, the swelling pressure development with time for specimen of 1.6 mg/m³ dry density was found to be accompanied with two maxima (double peaks). The first maxima occurred during the saturation process at about 1500 min, followed by an increase in the swelling pressure. Finally, the specimen attained equilibrium swelling pressure after 6250 min. The reason for two maxima may be that macrostructure collapses (Pusch, 1982) due to the loss of shear strength (softening) at the clay aggregate level upon wetting (decrease in suction). A further increase in swelling pressure was attributed due to the redistribution of clay particles to a more homogenous and dispersed state. The evaluation of swelling pressure with time during the wetting process has been shown to be influenced by the initial water content and dry density of clays (Agus, 2005; Schanz and Tripathy, 2009; Baille et al., 2010).

As shown above, the swelling pressure development over time showed significant stage characteristics. As can be seen in Fig. 3, as the initial dry density increases, the swelling pressure increases. The test of dry density 1.75 mg/m³ achieves the maximum swelling pressure and it has the highest rate of swelling pressure. Therefore, the higher initial dry density provides higher swelling pressure and a faster build up of swelling pressure.

Fig. 3 also shows that compacted bentonite swelling pressure with time follows a hyperbolic trend, but the relationship of the ratio of time to swelling pressure \( \frac{t}{P_s} \) and time \( t \) is linear (see Fig. 5), approximated by

\[
\frac{t}{P_s} = a + bt
\]

where \( P_s \) is the swelling pressure (kPa); \( a \) is the intercept of the regression line; \( b \) is its slope; \( t \) is the time (min).

5.2. Swelling pressure and dry density

The experimental results of the relationship between swelling pressure and dry density of used compacted bentonite (GMZ01) are shown in Fig. 6. In Fig. 6, it is clear that higher dry density provides higher swelling pressure. The regression analysis for this experimental program gives the following exponential relationship:

\[
p_s = 0.046 \exp(6.653\rho_d)
\]
where $p_s$ is the swelling pressure in kPa; $\rho_d$ is the initial dry density in mg/m$^3$.

The results are derived from a more limited range of initial densities than those in individual studies done by other researchers (Dakshinamurthy, 1978; Kodandaramaswamy and Rao, 1981; Xianmin and Wang, 2003).

Fig. 7 shows a comparison between the experimental swelling pressure results of GMZ bentonite, and other GMZ and different types of bentonites. In this figure, two data sets of swelling pressure results for GMZ bentonite from China were investigated: GMZ-1 by Zhang et al. (2012) and GMZ-2 by Cui et al. (2012). Fig. 7 shows that the swelling pressure of tested GMZ bentonite in this study (GMZ_Exp.) is similar to the swelling pressure of GMZ in the literature. Moreover, an additional eight swelling pressure data results from different proposal bentonites as buffer/backfill material was investigated: MX80 by Buscher and Müller-Vonmoos (1989), Kunigel (K-1 by Schanz et al. (2010), K-2 by Japan Nuclear Cycle Development Institute (2000), and K-3 by Komine and Ogata (1996)), Montigel (Buscher and Müller-Vonmoos, 1989), S-1 (ENRESA, 2000), and Calcigel (Ca-1 by Baille et al. (2010) and Ca-2 by Schanz and Tripathy (2009)). The results show that the swelling pressure of the tested GMZ bentonite is lower than MX80 and higher than Kunigel, but close to the results of swelling pressure of Calcigel type of bentonite. This behavior relates to the physico-chemical properties of GMZ bentonite, such as its specific surface area (SSA), cation exchange capacity (CEC), and valence ($\nu$).

5.3. Effect of density and wetting under constant volume condition on pore size distribution (PSD)

The pore-size distribution (PSD) of the different samples was obtained by a mercury intrusion porosimetry (MIP) test. Some researchers have used the MIP data to study the PSD changes of natural clays during consolidation (Griffiths and Joshi, 1989), changes in PSDs due to the consolidation of different clay types (Al-Mukhtar, 1995), and the prediction of the coefficient of permeability for saturated soils (e.g., Garcia-Begochea et al., 1979; Romero, 1999). The PSD data was also used to estimate the soil–water characteristic curve of expansive soils (e.g., Romero, 1999; Agus, 2005; Arifin, 2008). The effect of the compaction conditions (i.e., dry of optimum and wet of optimum) on the PSD have been reported and discussed in Delage and Graham (1996) and Agus (2005).

In this research, in order to study the microstructure of GMZ bentonite, the mercury intrusion porosimetry (MIP) data was used to obtain information concerning the pore size distribution, PSD, (i.e., micro- and macro-pores) for specimens with (i) different initial densities of 1.35 mg/m$^3$ and 1.75 mg/m$^3$, under as prepared condition, as shown in Fig. 8, and (ii) heavily compacted initial density of 1.75 mg/m$^3$, at different states (before i.e., as prepared condition and after the wetting under constant volume condition for the swelling pressure test), as shown in Fig. 9.
In the MIP test, specimen preparation and the drying process are very important. Diamond (1970) found that the dry specimen was much less affected by oven drying. However, a large amount of shrinkage (i.e., 20%) was found for the wet specimen in the air-drying method (Diamond, 1970). To avoid change in the PSD of the specimens in the drying process, the freeze drying method was used in this study before the MIP test. Three types of specimens were prepared with different conditions: two different initial densities of 1.35 mg/m³ and 1.75 mg/m³, under the as-prepared condition and the third one after the wetting condition for 1.75 mg/m³ dry density under the constant volume condition after the swelling pressure test. The specimens were statically compacted to reach the desired dry densities. The specimen was hydrated under the constant volume condition in the UPC isochoric cell in order to obtain the saturated specimen under the constant volume condition. After preparing the specimens (that is, after compaction in the case of as prepared condition and after the swelling test was finished in the case of the after-wetting condition) the specimens were cut into small cubes approximately 1 cm in size. The specimen was freeze-dried prior to the MIP test. The MIP equipment used was Autopore II 9220 from micromeritics, Berlin (Germany). In order to investigate the fabric of bentonite used, an environmental scanning electron microscope (ESEM) type-XL30 from Philips was used. In this study, the fabrics of the same three conditions mentioned above were investigated.

The apparent transition between micro- and macro-pores is also shown in Figs. 8 and 9. The micro-pores represent pores in the clay clusters (or the intra-aggregate pores) while the pores between clay clusters (or the inter-aggregate pores) are considered to be the macro-pores. The non-intruded pores may therefore represent the intra-laminar pores. Unlike the lower plastic clay (e.g., kaolinite and illite) where mercury fills entire pores, non-intruded pores have been found in highly plastic clays, such as bentonite (Arifin, 2008; Delage et al., 2006). The total number of non-intruded pores increases with increasing water content in the specimen, as shown in the PSD data reported by Agus and Schanz (2005) and Delage et al. (2006). By considering the permeability and microstructure of compacted bentonite, Delage et al. (2006) stated that the immediate stress release has the effect of modifying the macro-pores (i.e., inter-aggregate pores) in particular due to the decrease in the interaggregate stresses, which then allows for global volume expansion. The authors stated that no change in the micro-pores occurs due to their very small pore size, their slow water transfer phenomena, and the strong attraction between water and minerals.

Fig. 8 shows that the percentage of larger pores with a diameter of more than 0.5 μm reduces as the density increases. On the other hand, the percentage of smaller pores with a diameter less than 0.5 μm almost remains constant or slightly increases with increasing density. The PSD results for compacted MX-80 bentonite reported by Delage et al. (2006) are in good agreement with the results for GMZ bentonite in this study. They found that, at the same water content, the change in porosity of specimen compacted with higher dry density was due to the change in the large pores. The environmental scanning electron microscope (ESEM) images of the as-prepared specimens of two different densities (1.35 mg/m³ and 1.75 mg/m³) are shown in Fig. 10, supporting qualitatively that the amount of large clay particles is reduced when the density increases from 1.35 mg/m³ to 1.75 mg/m³. Fig. 9 shows that the percentage of the larger pores in the macro-pore range reduces after the wetting under the constant volume condition, while the ratio of pore sizes remains almost unchanged for smaller pores in micro-pore range. Fig. 11 shows the environmental scanning electron microscope (ESEM) images of the heavily compacted density specimen, 1.75 mg/m³, at different states – before the as prepared condition and after the wetting under constant volume condition for the swelling pressure test. It is clear from these images that the wetting under constant volume condition for the swelling pressure test results in the formation of a wavy

![Image](324x556 to 514x709)
flake-like structure consisting of clay platelets of different orientations. It indicates the existence of an edge-to-face layer aggregation that possibly competes favorably with face-to-face layer aggregations. This behavior was also observed for compacted bentonites at higher water content (Agus, 2005). The clay clusters with a wavy flake-like structure were not observed in the as-prepared specimen (before wetting) which was allowed to absorb water until it reached a saturated equilibrium water content (Agus, 2005). As shown in (Fig. 10), for as prepared samples with the same hygroscopic water content of two different densities (1.35 mg/m³ and 1.75 mg/m³), no wavy flake-like structure is observed. Thus it would appear that the wavy flake-like structure is solely affected by water content and dry density of bentonite does not play a role (Agus, 2005).

5.4. Swelling pressure estimation

Several methods have been proposed to predict the swelling pressure of clays. Two different theoretical concepts were used in this study to estimate the swelling pressure: the modified DDL and thermodynamics.

The diffuse double layer (DDL) theory is used to predict swelling pressure and compressibility under high stresses for compacted clays (Sridharan and Jayadeva, 1982; Mitchell, 1993; Komine and Ogata, 2003; Tripathy et al., 2004; Schanz and Tripathy, 2009; Baille et al., 2010). Several assumptions used in the approach were comprehensively described, such as in Tripathy et al., (2004). The DDL theory is based on a microscopic physico-chemical concept of the clay–water interaction in which a simplified parallel two-clay platelet system is considered.

Tripathy et al. (2004) suggested three different equations for the swelling pressure of bentonites based on the diffuse double layer theory, DDL, depending on the value of the weighted average valency of the cations, $v$ ($v = 1.14–1.50$, $v = 1.66–1.73$, and $v = 1.97$). Although the bond valence model is mostly used for validating newly determined chemical structures, it is capable of predicting many of the properties of those chemical structures that can be described by localized bonds (Brown, 2009). The valence of an atom, $v$, is defined as the number of
electrons the atom uses for bonding. This is equal to the number of electrons in its valence shell if all the valence shell electrons are used for bonding. It follows from this definition that the valence of an atom is equal to the sum of the valences of all the bonds it forms. The valency of the soil is computed from the weighted average of the valencies of the cations present in the soil. The use of the equations (modified DDL) suggested by Tripathy et al. (2004) is based on weighted average valency of the cations in the bentonites, since the valency of the exchangeable cations present in clays has a significant influence on the swelling pressure. However, even though the bentonite soils in general have the same group of soil minerals (montmorillonite, illite, etc.), each bentonite has its own specific physico-chemical properties (type, shape, and varying concentrations of cations) that lead to variations in soil valency as well as soil behavior (e.g., compressibility, swelling, shear strength, and permeability), which allows us to categorize the bentonites in sub-groups. In other words, the change in soil behavior due to changes in its physico-chemical properties can be reflected by changes in the value of valency.

The GMZ01 bentonite used in this study has a valency equal to 1.475 (Table 1). Therefore, Eq. (3), which was suggested by Tripathy et al. (2004) for valencies ranging from 1.14 to 1.50, is used to predict the swelling pressure \(P_s\). Eq. (4) was used, from the original DDL, to compute the half variations between the parallel clay platelets \(d\) from the void ratio \(e\), the specific gravity of soil solids \(G\), the unit weight of water \(\gamma_{w}\), and the specific surface area of soil \(S\).

\[
p = 2nkT \cosh(-7.277\log_{10}(Kd - 2.91)) - 1
\]

\[
e = G\gamma_{w} S d \times 10^6
\]

where \(p\) is the swelling pressure; \(K\) is the double layer parameter which is equal to \((2\pi e^2 v^2 / e k T)^{0.5}\); \(e\) is the elementary electric charge \(=4.8029 \times 10^{-10}\) esu \(=1.60206 \times 10^{-19}\) C; \(k\) is the Boltzmann constant; \(n\) is the molar concentration of ions in pore fluid; \(T\) is the absolute temperature; \(v\) is the valency; \(\epsilon\) is the dielectric constant of the pore fluid; \(\Gamma\) is the surface charge density (base exchange capacity per specific surface).

Agus and Schanz (2008) presented a method for predicting the swelling pressure of bentonites based on the thermodynamic relationships between the swelling pressure and suction analyzing Gibbs free energy. Generally, the two-clay platelet system is an elastic system. When a load-free system is pressurized with a pressure of \(P_s\), water with a volume of \(V_1 – V_2\) in the system is squeezed out. \(V_1\) and \(V_2\) are the volume of water between the two-clay platelet system before and after loading with a pressure of \(P_s\), respectively. This amount of water is the water deficiency, considering the load-free system as a reference. Since the system is elastic when \(P_s\) is released, the same amount of water (or \(V_1 – V_2\)) is driven back to the system. This is the process when an external load \(P_s\), which is essentially the swelling pressure, acts on the platelets. However, water can also be drawn out of the system by suction, \(s_s\), to induce the same water volume change (\(V_1 – V_2\)). In the former case, the force acts on the solid phase of the system (i.e., the platelets) while in the latter, the force acts on the liquid phase of the system (i.e., water), and therefore they are analogous. It is hence clear that \(P_s\) should be equal to \(s_s\). Considering that the reference (or the load-free system) has zero suction, \(s_s\) is then called the undissipated suction. Since the water content of the specimen tested in the constant volume test is usually only measured at the end of the test, only the end value of the swelling pressure can be considered, not that at the transient stage (Agus and Schanz, 2008). The proposed method requires the sorption isotherm data of the bentonites (e.g. the wetting path of soil water characteristic curve, SWCC). The method required the final water content after the swelling pressure test which is equal to the saturated water content under the specific density. Then, from water content–suction relationship, the swelling pressure is equal to the suction value that corresponds to the saturated water content. The wetting water content suction relationship was obtained from Ye et al. (2011), which studied the same soil. The available water content–suction data is limited, just for a water content below the 26% that makes the predicted swelling pressure limited to the range of dry density above 1.6 mg/m^3.

Fig. 12 shows the swelling pressure–dry density results of the experimental tests, the predicted results using the modified DDL (Tripathy et al., 2004), and the predicted results using the thermodynamic relationship between the swelling pressure and suction (Agus and Schanz, 2008). As shown in Fig. 12, the swelling pressure results produced by the two methods are in quite good agreement with the experimental data for the GMZ bentonite.

The theoretical curve of the modified DDL theory shows good agreement with the experimental data even though the predicted results include slight overestimates of the values in most points. The disagreement between the theoretical (modified DDL) and experimental swelling pressure results can be attributed to several factors that arise while applying the diffuse double-layer theory to compacted bentonites systems (Schanz and Tripathy, 2009): (1) poorly developed or partially developed diffuse double layers, (2) reduced specific surface...
area because of the formation of clay particles, (3) surface and ion hydration at close platelet spacing, (4) the non-uniform size of the clay platelets, (5) the existence of electrical attractive forces, (6) the presence of various types of exchangeable cations, and (7) the presence of minerals other than montmorillonite in the clay.

In addition, Schanz and Tripathy (2009) pointed out that the intersection of the theoretical swelling pressure–dry density relationship with the experimental results indicates that different phenomena are responsible for the disagreement between the experimental and theoretical swelling pressures at lower and higher densities of the clay. The slightly overestimated values of the swelling pressures developed can be attributed to one of the following: (1) the clay contained 55% exchangeable sodium ions and that these ions dissociated from the surface of the clay platelets and took part in the double-layer repulsion and (2) the sodium ions remained in the crystal lattice and were unable to dissociate, whereas the divalent ions took part in the double-layer repulsion.

5.5. Swelling pressure–suction relationship under constant volume condition

The one-step swelling pressure test and multi-step swelling pressure test for 1.6 mg/m³ initial dry density were performed to study the two mechanisms of transporting the water molecules (i.e., in the fluid phase and in the vapor phase) and to investigate the change in swelling pressure with decreased suction (wetting) under the constant volume condition for the GMZ bentonite used. The development of swelling pressure with decreased suction results from the one-and multi-step swelling pressure tests under the constant volume condition for 1.6 mg/m³ initial dry density of GMZ bentonite is shown in Fig. 13. For the tested 1.6 mg/m³ dry density, both the one and the multi-step wetting tests shown in Fig. 13 provide almost the same swelling pressure value (about 3000 kPa).

The one-step swelling pressure test was already presented in Sections 5.1 and 5.2 and the results are shown in Figs. 3, 6, and 7. The multi-step swelling pressure test was carried out using both the axis-translation technique (ATT) and the vapor equilibrium technique (VET). The same UPC-Isorhoric cell used in the one-step swelling constant volume tests is used in the multi-steps swelling constant volume test. The sample was tested with an initial water content of about 11.4% (referred to as the hygroscopic water content) which gives suction equal to 96 MPa. Initially, the swelling pressure developed rapidly until the suction reduction unit reaches a suction of about 2000 kPa. Subsequently, a slowdown is observed in the rate of increase in the swelling pressure with decreasing suction until a maximum swelling pressure of about 3000 kPa at 100 kPa suction is reached. Swelling pressure does not increase with any reduction in suction below 100 kPa. Such behavior can be attributed to degree of saturation at 100 kPa which is near the fully saturated condition (about 98%). Agus (2005) stated that the continued reduction in suction (wetting) would be accompanied by further water absorption and that swelling pressure would increase as soon as the equilibrium between inter- and intra-aggregate pore-water was attained. In general, the sample reaches equilibrium faster when the axis-translation technique (ATT) is used to apply the suction than when the vapor equilibrium technique (VET) is used.

Fig. 13 shows that the swelling pressure curve has double peaks with regard to the reduction in suction. As observed, the swelling pressure reaches the first peak at around 20,000 kPa suction because of yielding at the constant volume condition, and then it follows the state surface at the yield state (Al-Badran, 2011) or the load collapse curve, LC, (Alonso et al., 1990; Romero, 1999). The same double-peaks were observed by Romero (1999), but the first peak has the highest value of swelling pressure. This may attributed to the shape of the LC curve and to the initial conditions, particularly density and suction. The second peak in Fig. 13 is related to the maximum swelling pressure mentioned above, which occurs near the saturated state at around 100 kPa suction.

6. Conclusions

Based on the results of the one and multi-step swelling pressure tests, MIP tests, and ESEM images of the GMZ01 bentonite of five different dry densities (1.15, 1.35, 1.50, 1.60 and 1.75 mg/m³), the following conclusions can be drawn:

(a) Swelling pressure–time relationship.

The swelling pressure of the GMZ01 bentonite over time (in the normal scale) provides a nonlinear relationship, whereas a significant linear relationship between time/swelling pressure and time is detected. The swelling pressure development over time showed significant stage characteristics. A rapid increase was noted in both the swelling pressure and amount of absorbed water at the earlier stage of tests (i.e., up to 3000 min), then the rate for both kept almost constant beyond a point. This point marks the end of primary swelling pressure development.
For all specimens (except 1.6 mg/m$^3$ dry density) the development of swelling pressure with time had single maximum until the maximum swelling pressure was reached. The swelling pressure development with time for the specimen of 1.6 mg/m$^3$ dry density was found to be accompanied with two maxima. These two maxima can be attributed to the loss of shear strength, or softening, at the clay aggregate level upon wetting which results in a decrease in suction that causes a collapse of macrostructure (Pusch, 1982). A further increase in swelling pressure was attributed due to the redistribution of clay particles to a more homogenous and dispersed state.

The evaluation of swelling pressure results with time during the wetting process has been shown to be influenced by the dry density of used GMZ01 bentonite (i.e., the results show that the higher dry density of GMZ01 grants a higher swelling pressure and faster swelling pressure build up and the time required to reach equilibrium was longer).

(b) Swelling pressure–dry density relationship.

The swelling pressure of GMZ01 increases exponentially as the dry density increases. However, the tested GMZ bentonite has a swelling pressure lower than the MX80 and higher than Kunigel, but close to the results for the swelling pressure of the Calcigel type of bentonite. This behavior relates to the physico-chemical properties of GMZ bentonite, such as its specific surface area (SSA), cation exchange capacity (CEC), and valence (v).

(c) Effect of density and wetting under constant volume condition on pore size distribution (PSD).

The results of PSD for GMZ01 bentonite show that the ratio of pores larger than 0.5 μm in diameter reduces as the density increases. On the other hand, the ratio of smaller pores, with a diameter smaller than 0.5 μm almost remains constant or slightly increases with the increasing density. The ESEM images qualitatively support these results. Moreover, the results of the PSD show that the ratio of larger pores in the macro-pore range reduces after the wetting under the constant volume condition for heavily compacted density (1.75 mg/m$^3$), while the pore size ratio remains almost unchanged for pores within the in the micro-pore range.

The ESEM photos show that the wetting under constant volume condition for the swelling pressure test results in the formation a wavy flake-like structure consisting of clay platelets of different orientations. The results show that the wavy flake-like structure is solely affected by the water content and that the dry density of bentonite does not appear to play a role.

(d) Swelling pressure estimation.

Two different theoretical concepts were used to estimate the swelling pressure: the modified DDL and thermodynamics. The swelling pressure results of the two methods are in relatively good agreement with the experimental data for the GMZ bentonite.

(e) Swelling pressure–suction relationship under constant volume condition.

For the 1.6 mg/m$^3$ dry density specimen, two different constant volume tests, the one-step and multi-step wetting tests, provided almost the same swelling pressure value (about 3000 kPa). In the multi-step wetting constant volume test characterized by controlled-suction, at first the swelling pressure developed rapidly as suction was reduced, but when the suction was below 100 kPa, the swelling pressure did not increase.

The multi-step controlled-suction wetting test shows that the swelling pressure has double peaks regarding the reduction in suction. The swelling pressure reaches to the first peak at around 2000 kPa suction when it reaches the state surface at the yield state (Al-Badran, 2011) or the load collapse curve, LC, (Alonso et al., 1990; Romero, 1999), while the second peak can be attributed to the degree of saturation at 100 kPa, which is near the fully saturated condition (about 98%).

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References


