Research Article

Experimental and Modeling Study of Soil Water Retention Curves of Compacted Bentonite considering Salt Solution Effects

Yong He ^{1,2,3}, Ke-neng Zhang,^{1,2} and Dong-yu Wu^{1,2}

¹Key Laboratory of Metallogenic Prediction of Nonferrous Metals and Geological Environment Monitoring (Central South University), Ministry of Education, China

²School of Geosciences and Info-Physics, Central South University, Changsha 410083, China

³Key Laboratory of Geotechnical & Underground Engineering of Ministry of Education and Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

Correspondence should be addressed to Yong He; heyong18@csu.edu.cn

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Due to its low hydraulic conductivity, high swelling capacity, and good adsorption properties, the Gaomiaozi (GMZ) bentonite has been selected as potential buffer/backfill materials for construction of engineered barriers in the deep geological repository for disposal of high-level nuclear waste (HLW) in China. Investigation of salt solution effects on the water retention properties of compacted bentonite is of great importance in the context of geological disposal of HLW based on the multibarrier concept. In this study, amended specimens were obtained through a spray of different concentrations of salt solutions to reach target salt contents, respectively. With employment of the vapor phase technique for suction control, water retention tests were conducted on densely compacted GMZ bentonite (1.7 Mg/m^3) with different salt contents under confined conditions. Corresponding soil water retention curves (SWRCs) were obtained. Analysis indicates that, for a given suction, the measured water content of GMZ bentonite specimen increases as the salt content (or pore fluid concentration) increases. The influencing rate depends on suction. For lower suctions (lower than 38 MPa), the water retention capacity increases as the salt content increases, while for higher suctions (higher than 38 MPa), the influence can be negligible. Based on the Fredlund and Xing (1994) equation, a soil water retention model was proposed for simulation of the SWRCs of compacted GMZ bentonite with consideration of pore fluid chemistry. Parameters were analyzed and determined with consideration of influences of the pore fluid concentration. Verification indicates that the SWRCs simulated by the proposed model are well agreed with the measured ones.

1. Introduction

Compacted bentonite has been recommended as a buffer/backfill material in many countries for engineered barriers in the deep geological repository for disposing high-level nuclear waste (HLW) [1–9]. The compacted bentonite will undergo a complex—highly coupled thermal (T), hydro (H), mechanical (M), and chemical (C)—process during the long-term operation of a repository [10–12], i.e., simultaneous heating from decay of nuclear waste in the canister, infiltration of groundwater from the surrounding geological formations, possible leakage of nuclides from the canister, and swelling pressure of bentonite on hydration. To assess these coupled processes of the engineered

barrier system, a number of investigations have been conducted [1, 3, 9, 13–15] and related modeling approaches [16–18] have been proposed.

The resaturation of the initially unsaturated repositories is predicted to last hundreds of years after the closure of a repository [19, 20]. During this period, it is inevitable for the saturation/water content of the compacted bentonite to increase by groundwater ingress or decrease by evaporation because of high temperature (50–210°C, [21]) originating from decay heat. Thus, the compacted bentonite will experience cyclic wetting/drying processes accompanied by cyclic salinization-desalination, which could be enhanced by the coupling effects of the sanitary groundwater intrusion and the possible water evaporation, or the ingress of fresh

groundwater. Therefore, the salt content or fluid concentration in the compacted bentonite will also undergo cyclic processes, which results in alterations of properties of the compacted bentonite [22].

The soil water retention curve (SWRC) has been widely used to evaluate unsaturated soil properties, including saturated and unsaturated permeability functions, shear strength parameters, and volume change [15, 23]. Meanwhile, in unsaturated soils, modeling of water distribution and flow needs knowledge of SWRC, which also plays a key role in water management and predicting transportation of solute and contaminant in the environment [24]. As an important hydraulic characteristic, water retention is closely correlated with the size and connectivity of soil pore space; therefore, it is strongly influenced by the texture and structure of the soil and other components such as soil organic matter [25]. Hence, it is important to have a reasonably accurate and more practical characterization of the SWRC.

It is generally agreed that direct measurement of SWRC in the laboratory requires hard work and is time-consuming [26]. Therefore, many empirical equations were developed for description of the SWRC in the past decades [24, 27–30]. For compacted bentonite, modified water retention models were also developed with consideration of temperature and dry density effects [31, 32]. These equations are composed of two or three fitting parameters, which are evaluated by using either laboratory results at different moisture contents or statistical relationships between the suction and other basic soil properties.

Lots of factors can influence the SWRC of geomaterials, including soil type, initial water content, mineralogy, density, temperature, texture, stress history, method of compaction, and net confining stress. In this regard, various investigations [33–36] have been conducted. Meanwhile, experimental results also indicated that the salt concentration of infiltrating groundwater can influence the water retention properties of compacted bentonite/expansive clay specimens when used as buffer/backfill materials in the HLW repository [37–39]. For wetting or drying with a given concentration pore fluid, Fredlund and Xing [28] assumed that the maximum osmotic suction in less active soils is approximately 1.5 MPa. It is worth noting that osmotic suction changes may be of importance in some cases. For instance, the effect of osmotic suction is significant when the soil salt content is in a high level [40]. Thyagaraj and Rao [35] also found that the osmotic suction, derived by salt water, should not be ignored in the suction measurement of an Indian bentonite. This observation could be confirmed by Mata et al. [38] with measurement of the water retention curve of MX-80 bentonite/sand mixture, in which different concentrations of salt solutions were used to speed up the saturation process. In Europe, the Boom Clay, which is a 100 m thick marine clay, presents favorable properties to limit and delay the migration of the leached radionuclides over extended periods of time. Based on the measurement of suction of Boom Clay containing NaNO_3 solution using the chilled-mirror psychrometer (WP4 Dewpoint Potential Meter) and investigation of the corresponding changes of the microstructure of the specimen tested with the MIP (mercury intrusion porosimetry)

technique, Mokni [41] stated that the total suction of specimens saturated with salt solution was higher compared with that of specimens saturated with distilled water, while the matric suction in the salt solution-saturated group was smaller than that in the distilled water-saturated group.

China's deep geological disposal program for HLW began in the 1980s. Beishan of Gansu has been selected as the preferred site for construction of repository in China [23, 37]. Bentonite from Gaomiaozi (GMZ), 300 km northwest of Beijing, has been reckoned as the preferred "buffer/backfill material" for building engineering barriers in deep geological repositories [37].

Efforts have been made to thoroughly understand the water retention property of GMZ bentonite in recent years [30, 42–46]. Chen et al. [42] measured the SWRCs of the densely compacted GMZ bentonite at room temperature (20°C) under confined and free swelling conditions using the vapor phase technique and the osmotic technique. Results show that influence of confining conditions on water retention depends on suction, and it becomes less significant as the suction increases from 4 .2MPa. For considering temperature effects, Ye et al. [46] measured SWRCs of GMZ bentonite at different temperatures and reported that temperature effects on the soil-water characteristics depend strongly on the constraint conditions. For unconfined compacted GMZ bentonite specimens, the effect of temperature on the hysteresis behaviour is related to the suction level: a negative correlation between hysteresis behaviour and temperature. Based on these and a comprehensive review of literatures [27, 28, 31, 47], Wan [30] extended the Fredlund and Xing [28] equation for description of water retention curves at room temperature (20°C) to a novel one that can consider temperature effects.

According to in situ investigations in Beishan, the average dissolved solid (TDS) concentration of groundwater is in the range of 3 g/L to 12 g/L, with a maximum up to 50 g/L [48, 49]. Apparently, the influence of salt solution on water retention of GMZ bentonite becomes a key issue to be reckoned with and of significance to China's HLW disposal project.

In this work, GMZ bentonite powder with different salt contents was obtained after being sprayed with different concentrations of NaCl solutions. The specimens were prepared by compacting the amended bentonite powder to target dimensions and dry density. Suction-controlled water retention tests were carried on with the compacted amended GMZ bentonite specimens under confined conditions. Based on these, a modified soil water retention model for the compacted GMZ bentonite with consideration of salt solution concentration effects was established and verified.

2. Materials and Methodology

2.1. Materials and Specimen Preparation. The material tested in this work is GMZ bentonite. The GMZ bentonite was sampled in the northern Chinese Inner Mongolia autonomous region, 300 km northwest from Beijing. There are 160 million tons with 120 million tons of Na-bentonite reserves in the deposit (Figure 1), and the mine area is about 72 km². The

FIGURE 1: Open pit of GMZ bentonite deposit.

GMZ bentonite used in this work belongs to a Na-type bentonite. The bulk chemical components of the sample were analyzed using X-ray fluorescence spectrometry as follows (in mass): SiO₂ 67.43%, Al₂O₃ 14.20%, Fe₂O₃ 2.40%, Na₂O 1.75%, CaO 1.13%, K₂O 0.73%, FeO 0.29%, TiO₂ 0.12%, MgO 0.10%, P₂O₅ 0.02%, and MnO 0.02%. In addition, GMZ bentonite contains some lanthanides, such as La, Ce, and Nd [50, 51]. Relevant properties of this bentonite are listed in Table 1 [14, 50, 51]. A high cation exchange capacity and adsorption ability can be identified. The XRD test results (Figure 2) show that the characteristic diffraction peaks of the plane at 6.03°, 20.0°, and 35.0° in 2θ values and the corresponding basal spacing are 14.70, 4.44, and 2.50 Å, respectively, indicating that the main compound in the specimens tested in the present work is montmorillonite (M). The XRD pattern also indicates the existence of quartz (Q: 26.8°), cristobalite (Cri: 22.2°), and albite (Al: 28.1°) [52].

For most investigations involving chemical effects on the hydromechanical behaviours of soils in the laboratory, various methods were developed for specimen preparation: (1) mixing the soil powder with desired solution, (2) immersing a soil specimen in a solution, and (3) percolating a soil specimen by solution [53]. Mixing the GMZ bentonite powder with desired solutions was employed for the specimen preparation in this work.

Following this aspect, a pretreating course was conducted. The GMZ bentonite powder with an initial water content of 11.7% was dried in an oven at 105°C for 24 h. After that, distilled water and 0.5mol/L, 1.0mol/L, and 1.5mol/L NaCl solutions were sprayed on the bentonite powder to achieve a target water content of 20%, respectively. The mass ratio of salt and bentonite was defined as R_s (mol/g), and corresponding salt contents of the amended bentonite powder are listed in Table 2. After being self-cured in sealed boxes for about 60 h, the amended bentonite powder was dried in an oven at 55°C [54] for another 48 h. After being cooled on a metal plate, the dried specimen was transferred to a mortar and grinded for avoiding particle clusters. Then, the grinded bentonite powder was suction-controlled to target suction (CaCl₂, 139 MPa) using the vapor phase method at a room temperature of 20°C. After the equilibrium was reached, the amended bentonite powder was compacted into

TABLE 1: Basic properties of the GMZ bentonite.

Property	Description	References
Specific gravity of soil grain	2.66	Wen [50, 51]
pH	8.68–9.86	Wen [50, 51]
Liquid limit (%)	276	Ye et al. [14]
Plastic limit (%)	37	Ye et al. [14]
Total specific surface area (m ² /g)	570	Ye et al. [14]
Cation exchange capacity (mmol/100 g)	77.06	Wen [50, 51]
Exchangeable cation (mmol/100 g)	E(Na ⁺): 37.52	Wen [50, 51]
	E(1/2Ca ²⁺): 23.18	
	E(1/2Mg ²⁺): 10.17	
	E(K ⁺): 0.55	
Main minerals	Montmorillonite (75.4%)	Wen [50, 51]
	Quartz (11.7%)	
	Feldspar (4.3%)	
	Cristobalite (7.3%)

FIGURE 2: XRD pattern for GMZ bentonite powder (M: montmorillonite; Cri: cristobalite; Q: quartz; Al: albite) [52].

cylindrical specimen with a constant speed at 0.1 mm/min to a target dimension of 6 mm in height, a diameter of 20 mm, and a dry density of 1.70 Mg/m³. The specifications of the compacted specimens used in this work are listed in Table 2.

It should be noted that, as the total salt quantity in the specimen is kept constant during the wetting/drying processes, the current salt concentration c of the pore fluid can be determined based on an assumption that there were no chemical interactions between fluid phase and solid phase [55]:

$$c = \frac{w_0 c_0}{w}, \quad (1)$$

where w_0 is the target water content (20%), c_0 is the concentration of salt solutions (0.5mol/L, 1.0mol/L,

TABLE 2: Specifications of the compacted specimens with NaCl solution.

Specimen	Salt (NaCl)/bentonite ratio R_s (mmol/g)	Dry density (Mg/m ³)	Total suction (MPa)
S_0	0	1.70	139
S_1	0.101	1.70	139
S_2	0.204	1.70	139
S_3	0.310	1.70	139

and 1.5 mol/L) used for the preparation of amended GMZ bentonite powder, and w is the current water content.

2.2. Methodology

2.2.1. Suction Control. In this work, the vapor phase technique was employed for suction control (Figure 3), in which total suction was applied. For application of the vapor phase method, the confined compacted GMZ bentonite specimens were placed in a desiccator, which was filled with a target saturated salt solution. Saturated salt solutions and their corresponding controlling suctions are listed in Table 3 [56, 57]. The specimen was regularly weighted until the equilibrium was reached. For each given suction, this process took about 2 to 4 weeks.

The wetting course from 139 MPa to 4.2 MPa, including 6 suctions listed in Table 3, was followed for each of the 4 specimens listed in Table 2.

2.2.2. Determination of Water Content. The gravimetric water content w of each specimen was measured by drying for 24 h at 105°C in an oven. Based on this, the corresponding volumetric water content θ_w can be calculated by [40]

$$\theta_w = \frac{SwG_s}{S + wG_s}, \quad (2)$$

where S is the degree of saturation and G_s is the relative density ($G_s = 2.66$ in Table 1).

For determination of the influence of pore fluid chemistry on the saturated (“zero air voids” [40]) water content, θ_s was assumed as the saturated water content corresponding to matric suction equal to 0 [31]. Following this aspect, specimens with different salt contents were inundated in distilled water. This saturation process lasted about 6–8 days [58]. After the equilibrium was reached, water content w was measured and the saturated volumetric water content θ_s was calculated using equation (2).

3. Results

3.1. Influence of Salt Content on SWRC. The measured SWRCs of confined compacted GMZ bentonite with different salt contents in wetting path are shown in Figure 4.

According to Figure 4, the measured volumetric water content decreases with the increasing suction. For a given suction, the measured water content of specimens increases as the salt content (or pore fluid concentration) increases.

Furthermore, the influencing rate depends on suction. For lower suctions (lower than 38 MPa), water retention capacity increases with the increase in salt content, while for higher suctions (higher than 38 MPa), the influence was negligible. It can be inferred that, for low suctions, the high saturation induced an increase in macropore size [38, 59], which was further enhanced due to the increase in salt content. However, this phenomenon was faded as the suction increased, which may attribute to the decrease in water content.

3.2. Influence of Pore Fluid Concentration on Saturated Water Content θ_s . For the confined compacted GMZ bentonite at a dry density of 1.7 Mg/m³ with different salt contents, measured saturated water content θ_s versus pore fluid concentration (c_s) is presented in Figure 5.

It is obvious that water content θ_s increases with the increase in pore fluid salt concentration, while the increasing rate decreases as the salt concentration increases and becomes stable for the fluid salt concentration higher than 0.735 mol/L. Possible explanations to pore fluid chemistry effects on the water content θ_s could be that the increase in the concentration of pore fluid results in the decrease in the diffuse double layer of bentonite [60]; i.e., a high water salinity of the pore fluid could induce the contraction of clay aggregates and thus increase the void volume between the aggregates (interaggregate or macropores) [59].

4. A Modified SWRC Model with Consideration of Salt Solution Effects

4.1. Equation for SWRC. As mentioned before, due to difficulties and labor costs for measuring SWRC, many empirical models for SWRC have been developed. Actually, among all the models available, the commonly used ones are those proposed by van Genuchten [29], Fredlund and Xing [28], and Houston et al. [61], while the Fredlund and Xing model appears to be the most appropriate one for fitting the experimental data [62].

The Fredlund and Xing model [28] can be expressed as follows:

$$\theta = C(\psi) \times \frac{\theta_s}{\{\ln [e + (\psi/a)^n]\}^m}, \quad (3)$$

where ψ is the suction and $C(\psi)$ is a correction function that can be defined as

$$C(\psi) = \left[1 - \frac{\ln (1 + \psi/\psi_r)}{1 + 1000/\psi_r} \right], \quad (4)$$

where ψ_r is the suction corresponding to the residual water content.

Parameter a , a suction that is closely related with the SWRC’s inflection point, can be considered as the air entry value when parameter m is small, even if the parameter a value is usually bigger than that of air entry [28]. Parameter a makes the curve towards the region of higher soil suction

FIGURE 3: Schematic setup for the vapor-phase technique (a) desiccator, (b) specimen, and (c) cell.

TABLE 3: Saturated salt solutions and corresponding suctions (20°C) [56, 57].

Saturated salt solutions	Total suction (MPa)
K ₂ SO ₄	4.2
ZnSO ₄	12.6
(NH ₄) ₂ SO ₄	24.9
NaCl	38
Mg(NO ₃) ₂	82
CaCl ₂	139

as its value increases but has no effect on the overall shape of curves [63]. Parameter m , which represents the curve asymmetry around the inflection point, is associated with the residual water content. Parameter n affects the slope of SWRC in the desaturation region. The value of n is associated with pore size distribution, which always shows a positive relationship with the uniformity of the pore sizes in the soil [63, 64].

4.2. A Modified SWRC Model with Consideration of Pore Fluid Concentration Effects

4.2.1. Determination of Parameters

(1) *Determination of θ_s with Consideration of Pore Fluid Concentration.* To consider the pore fluid concentration effects in equation (3), influence of the pore fluid concentration on the saturated water content θ_s should be included.

It can be observed from Figure 5 that the measured relationship between the water content (θ_s) and the pore fluid concentration (c_s) looks like an asymptotic line. Therefore, a second-order equation (5) was proposed for fitting the saturated water content θ_s and pore fluid concentration c_s at the saturated state.

$$\frac{d\theta_s}{dc} = k(\theta_{\max} - \theta_s)^2. \quad (5)$$

Integrating equation (5) from $c=0$, θ_0 to c and θ_c (where $\theta_0 = 0.3984$, which was calculated by equation (2) using the gravimetric water content w measured at matric suction 0 MPa, and $\theta_c = \theta_{\max}$, which was assumed as the maximum value of volumetric water content of specimens tested), yields,

$$\theta_s(c) = \theta_{\max} - \frac{\theta_{\max} - 0.3984}{kc_s(\theta_{\max} - 0.3984) + 1}, \quad (6)$$

where c_s is the pore fluid concentration of chemical components corresponding to matric suction $\psi_m = 0$ MPa, k is a coefficient related to salt concentration, and $\theta_s(c)$ is the saturated water content at the current chemical concentration. The values of c_s and saturated water content θ_s can be calculated using equations (2) and (6).

With salt concentrations 0.01, 0.384, 0.735, and 2.0 mol/L and the corresponding measured saturated water contents in

FIGURE 4: SWRCs of compacted GMZ bentonite specimens with different salt contents.

FIGURE 5: Water content θ_s versus pore fluid concentration c_s at a saturated state.

Figure 5, k and $\theta_{\max}$ can be fitted using equation (6) and substituted back into equation (6), which gives

$$\theta_s(c) = 0.4305 - \frac{0.0321}{1.894 \times c_s + 1}. \quad (7)$$

With equation (7), the relationship between θ_s and c_s can be depicted in Figure 5. Figure 5 indicates that the second-order equation (5) proposed in this work can satisfactorily describe the saturated water content with consideration of pore fluid chemistry.

(2) *Determination of a with Consideration of Pore Fluid Concentration.* To consider the pore fluid concentration effects in equation (3), the effects of the pore fluid concentration on the air entry value (parameter a) should be analyzed as well.

FIGURE 6: Relationship between the air entry value-related parameter and the pore fluid concentration.

In this respect, Karagunduz et al. [65] once proposed an approximate linear relationship (equation (8)) between the air entry value-related parameter a and the chemical concentration of the pore fluid.

$$a(c) = (1 + \beta c_s) a_0, \quad (8)$$

where c_s is the pore fluid concentration corresponding to matric suction $\psi_m = 0$ MPa, β is a concentration-related coefficient, and a_0 is the air entry value-related parameter of specimen hydrated with distilled water.

The fitted relationship between the air entry value-related parameter a and the pore fluid concentration for confined compacted GMZ bentonite is presented in Figure 6. Results show that a very good linear relationship can be observed.

With the relationship between the air entry value-related parameter and the pore fluid concentration in Figure 6, parameter β can be fitted using equation (8) with a value of 0.7734 for confined compacted GMZ bentonite.

(3) *Determination of n with Consideration of Pore Fluid Concentration.* In equation (3), n reflects the slope of the SWRC in the desaturation zone [30], which is determined by the pore size distribution of the specimen.

The concentration of infiltration pore fluid will influence pore size distribution, which results in variation of the n value and the shape of SWRC. This phenomenon has been observed and traditionally explained by means of the diffuse double-layer theory (DDL) [66]. Thickness of the diffuse double layer decreases with increasing concentration of electrolytes or their valence in the pore fluid, which results in the contraction of clay aggregates locally and the corresponding increase in connecting pores in the clay. Therefore, although the use of hypotheses assumed by the double-layer theory is still restrictive and merely for engineering purposes [60, 67], it is still

FIGURE 7: Relationship between the slope value of SWRCs and the pore fluid concentration.

helpful and reasonable to interpret most of the relations between pore fluid chemistry and macroscopic behaviour of clays [41, 68].

The influence of pore fluid concentration on water retention properties of clay has succeeded to attract sufficient attention by researchers [38, 39]. Among the literatures, the work of Ravi and Rao [39] provides a noteworthy contribution in this area. The measurement of SWRCs of bentonite/sand mixture specimens with different dry densities, respectively, in the distilled water group and NaCl solution group, was reported in the literature. Results showed that the concentration of infiltration pore fluid has a significant effect on SWRCs. On the basis of the measured data, the relationship between the slope value n/n_0 of SWRCs of bentonite/sand-mixed specimens and the corresponding concentrations of pore fluid was fitted and depicted, as shown in Figure 7.

Based on the fitted results in Figure 7, the relationship between the slope values n and the concentrations of pore fluid could be assumed as

$$n(c) = \exp(\xi c_s) n_0, \quad (9)$$

where ξ is a concentration-related coefficient to be fitted, c_s is the pore fluid concentration corresponding to matric suction $\psi_m = 0$ MPa, and n_0 is the slope value of SWRC of specimens hydrated with distilled water.

With SWRCs of confined compacted GMZ bentonite specimens with dry density of 1.7 Mg/m^3 tested using distilled water and different concentrations of NaCl solutions in this work, the relationship between the slope values of SWRCs and the corresponding pore fluid concentrations is shown in Figure 7. Parameter ξ was fitted with a value of 1.113. Therefore, the relationship between the slope

values n of SWRCs and pore fluid concentrations for confined compacted GMZ bentonite can be expressed as

$$n(c) = \exp(1.113 c_s) n_0. \quad (10)$$

It can be observed that the value of the concentration-related parameter of 1.5 Mg/m^3 ($\xi = 12.4$) bentonite/sand mixture specimens is larger than that of 1.7 Mg/m^3 GMZ bentonite specimen ($\xi = 1.113$). This observation indicates that the influence of pore fluid concentrations on the slope values n of SWRCs depends on dry density. A possible explanation to this observation could be that the specimens with lower dry density have more pore space for pore fluid intrusion, which enhanced the increase in the interaggregate or macropores induced by the contraction of clay aggregates [59]. However, for compacted bentonite with higher dry density, less pore-fluid intrusion is likely to be insufficient to form enough DDL in a small inter-layer space [37, 69].

Comparison results indicate that the proposed exponential function (equation (9)) can satisfactorily describe the relationship of the slope values n of SWRCs and the pore fluid concentrations.

4.2.2. A Modified SWRC Model with Consideration of Pore Fluid Chemistry. Substituting equations (6), (8), and (10) into equation (3), equation (11) can be obtained.

$$\theta = C(\psi) \times \frac{\theta_s(c)}{\left\{ \ln \left[e + (\psi/a(c))^{n(c)} \right] \right\}^m}, \quad (11)$$

where $C(\psi)$, $\theta_s(c)$, $a(c)$, and $n(c)$ can be calculated using equations (4), (6), (8), and (10), respectively.

It should be noted that, considering that the influence of the pore fluid concentration on the residual water content of compacted clays is insignificant (Figure 4), the influence of pore fluid chemistry on parameter m is safely neglected in this model.

Deduced from the Fredlund and Xing [28] SWRC equation, equation (11) is the modified model that can be used for predicting the SWRCs of confined compacted GMZ bentonite with consideration of pore fluid chemistry.

It should be noted that, in equation (11), for calculation of $C(\psi)$ using equation (4), the residual suction ψ_r should be determined. Commonly, ψ_r was practically determined or assumed that the maximum suction is applied, which is corresponding to a lower enough water content [30]. For instance, Phayak [70] chose the suction corresponding to 3.51% water content as the residual suction ψ_r . Wan [30] assumed the maximum suction of 309 MPa applied at 20°C to be the residual suction ψ_r corresponding to a water content of about 5% for compacted GMZ bentonite. In this study, the maximum suction of 139 MPa applied is assumed to be the residual suction ψ_r of GMZ bentonite, which is corresponding to a water content around 8%.

4.2.3. Verification. Figure 8 shows the measured SWRCs of the compacted GMZ bentonite hydrated with different salt

FIGURE 8: Relationship between water content and suction of the compacted GMZ bentonite.

concentrations (S_0 , S_1 , S_2 , and S_3) and distilled water. Based on the measured SWRCs of S_0 , S_1 , and S_2 , as well as equations (1), (2), and (11), parameters $\theta_{\max}$, k , β , and ξ in equation (11) for the compacted GMZ bentonite with 1.7 Mg/m^3 dry density can be determined: $\theta_{\max} = 0.4305$, $k = 59.01$, $\beta = 0.7734$, and $\xi = 1.113$. Substituting $\theta_{\max}$, k , β , and ξ into equation (11) gives

$$\theta = C(\psi) \times \frac{\theta_s(c)}{\left\{ \ln \left[e + (\psi/a(c))^{n(c)} \right] \right\}^m}, \quad (12)$$

where

$$\theta_s(c) = 0.4305 - \frac{0.0321}{1.894 \times c_s + 1}, \quad (12-1)$$

$$a(c) = (1 + 0.7734 \times c_s) \times 6.684, \quad (12-2)$$

$$n(c) = \exp(1.113 \times c_s) \times 0.593. \quad (12-3)$$

Equation (12) is the modified model for describing the SWRCs of the confined compacted GMZ bentonite taking account of the pore fluid concentration.

With equation (12), the SWRC of specimen S_3 was calculated. According to the contrast between the calculated results and measurement data (Figure 8), the proposed model can well describe the effects of the pore fluid chemistry process on the SWRCs of confined compacted GMZ bentonite.

5. Conclusions

In this work, the SWRCs of confined compacted GMZ bentonite with different salt contents were attained by a series of suction-controlled tests. The effects of pore fluid chemistry on the water retention properties of GMZ bentonite were

analyzed. A modified model considering the pore fluid chemistry effects for describing the SWRCs of confined compacted GMZ bentonite was proposed and verified. The main conclusions can be drawn as follows.

For the compacted GMZ bentonite, the effect of pore fluid chemistry on the water retention properties depends on suction. For a given suction, the measured water content of specimens increases with the increase in pore fluid concentration. Furthermore, the influencing rate depends on suction.

With the Fredlund and Xing equation, parameters including the air entry value-related parameter a , the saturated water content θ_s , and the slope value n of SWRCs were determined with consideration of the influence of the pore fluid concentration. Based on these, a modified model with consideration of pore fluid chemistry effects was proposed to describe the SWRCs of the compacted GMZ bentonite. The contrast of the calculated results and the experimental data demonstrates that the modified model can satisfactorily describe the water retention properties of compacted GMZ bentonite with consideration of pore fluid chemistry effects.

It should be noted that the proposed model only verified with test results of confined compacted GMZ bentonite. Further investigations should be done in the coming work for extending its applications to related geomaterials.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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