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Swelling characteristics of Gaomiaozi bentonite and its prediction

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ABSTRACT

Gaomiaozi (GMZ) bentonite has been chosen as a possible matrix material of buffers/backfills in the deep geological disposal to isolate the high-level radioactive waste (HLRW) in China. In the Gaomiaozi deposit area, calcium bentonite in the near surface zone and sodium bentonite in the deeper zone are observed. The swelling characteristics of GMZ sodium and calcium bentonites and their mixtures with sand wetted with distilled water were studied in the present work. The test results show that the relationship between the void ratio and swelling pressure of compacted GMZ bentonite-sand mixtures at full saturation is independent of the initial conditions such as the initial dry density and water content, but dependent on the ratio of bentonite to sand. An empirical method was accordingly proposed allowing the prediction of the swelling deformation and swelling pressure with different initial densities and bentonite-sand ratios when in saturated conditions. Finally, the swelling capacities of GMZ Na- and Ca-bentonites and Kunigel Na-bentonite are compared.

1. Introduction

The deep geological disposal concept has been accepted by many countries to isolate the high-level radioactive waste (HLRW) from the biological environment. In this concept, bentonite-sand mixtures are regarded appropriately as buffer/backfill materials for their low hydraulic conductivity, high swelling and good self-sealing capacities, etc. When the bentonite-sand mixture confined by the repository host rock in the disposal system is wetted by groundwater, the swelling pressure of the buffer materials of such bentonite or bentonite-sand mixture will be applied to the host rock and the nuclear waste container. In practice, the swelling pressure must be controlled over a certain value to ensure its sealing and self-healing capacity. For example, the swelling pressure is required to be greater than 2 MPa (Kim et al., 2011). Therefore, the swelling characteristics of bentonite–sand mixtures are an important technical issue for the deep geological disposal of HLRW.

The Beishan area in Gansu Province in China has been selected as the most potential area for constructing the deep geological disposal repository of HLRW. Meanwhile, the Gaomiaozi (GMZ) bentonite, produced in Gaomiaozi area, Xinghe County, Inner Mongolia Autonomous Region has been considered as a possible matrix material of buffer/backfill in the HLRW deep geological disposal project (Wang, 2010). In the Gaomiaozi deposit area, calcium bentonite in the near surface zone at the depth less than about 100 m and sodium bentonite at depth deeper than about 100 m, which are called Ca-bentonite and Na-bentonite, respectively, are observed. The GMZ Na-bentonite is an alteration devitrified of continental volcanic sedimentary tuff from interaction with groundwater and long-term weathering, and is now being selected as a buffer and backfill materials for HLRW disposal in China, but the cost to mine the GMZ Na-bentonite will be high if the buffer and backfills are all using the Na-bentonite. The Ca-bentonite is the result of transformation of the local primary sodium bentonite due to the long-term effect reaction with groundwater of HCO_3^-–Ca^{2+}–Mg^{2+} type in the region (Wen, 2006). The reserve of GMZ Ca-bentonite is about 40×10^6 tons. Therefore, the possibility to adopt GMZ Ca-bentonite as buffer/backfill materials in the disposal repository of HLRW to save project cost needs to be studied, because the Ca-bentonite exists in the near surface zone. Although the swelling characteristics of GMZ Na-bentonite has been widely studied by many researchers (Ye et al., 2007; Zhang et al., 2010; Sun et al., 2013), the swelling characteristics of GMZ Ca-bentonite are not clear. Sun et al. (2014) studied the soil-water characteristics of GMZ Ca-bentonite using the vapour equilibrium technique. The swelling characteristics of GMZ Na- and Ca-bentonites and their mixtures with sand saturated by distilled water are experimentally

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studied in the present work and a method is proposed for the prediction of the swelling deformation and swelling pressure of the bentonites or bentonite-sand mixtures. Finally, the swelling characteristics of GMZ Na- and Ca-bentonites and Kunigel Na-bentonite, produced in Japan, are compared to identify their similarities and difference in the swelling capacity.

2. Testing materials and specimen preparation

The GMZ Na- and Ca-bentonites and the Fujian standard sand were used in the tests. The GMZ Na-bentonite contains about 75.4% montmorillonite, 11.7% quartz, 4.3% feldspar, 7.3% christobalite and very small amount of kaolinite (about 0.8%) and calcite (about 0.5%) in weight, while the GMZ Ca-bentonite contains about 72%–82% montmorillonite, 14%–20% quartz, 1%–6% feldspar in weight (Liu and Wen, 2003). Some physico-chemical properties of the two GMZ bentonites are listed in Table 1. The grain density of the Fujian sand ρ_{sand} is 2.65 Mg/m^3 and its maximum and minimum grain sizes are 0.4 mm and 0.075 mm, respectively. Distilled water was used for preparing specimens in all tests and for saturating all the specimens.

The pure bentonite or bentonite-sand mixtures with different bentonite-sand ratios in weight and water contents ranging from 10% to 25% were compacted statically to different dry densities in consolidation rings. The initial degree of saturation of compacted unsaturated specimens ranges from 20% to 70%. The ring's inner diameter (i.e. diameter of the specimen) is 61.8 mm and the height is 20 mm. The specimen's height is usually smaller than the ring's height in order to prevent the specimen from exceeding the ring when swelling upon water uptake occurs at low vertical pressures.

3. Test procedure

The swelling deformation (SD) tests, constant volume (CV) tests and collapse tests on the GMZ bentonites and their mixtures were performed to measure the swelling deformation, swelling pressure or collapse deformation from unsaturated state up to full saturation. All the tests were carried out in oedometer as shown in Fig. 1. The swelling or compression deformation during wetting occurs only in the vertical direction at constant total vertical pressure. After the compression of the unsaturated specimen at a given pressure was completed, distilled water was supplied to specimens from the bottom for soaking the specimen and the expelled air went out through the air outlet from the top. Since almost no water head was applied, the specimen absorbed water merely through suction.

For the SD tests, a constant vertical pressure σ_v was first applied on the specimen and when the compression due to the applied pressure was completed, the water was then supplied from the specimen bottom. Water uptake leads to the development of swelling potential of the specimen. The deformation is considered finished when the variation in the pointer on the displacement transducer is less than 0.01 mm after an interval of 24 h.

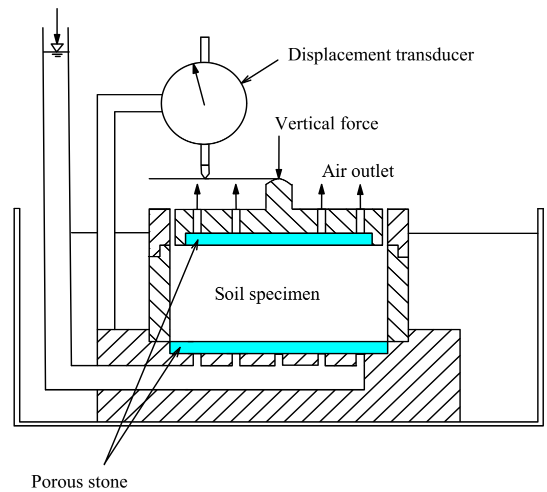


Fig. 1. Oedometer for test.

In the CV tests, the vertical pressure was adjusted constantly to keep the specimen volume unchanged during wetting. The vertical pressure must be increased to resist the swelling or decreased when the specimen trends to be contracted. The development of swelling pressure was considered completed when the pointer on the displacement transducer remains unchanged, i.e. the vertical pressure σ_v is equal to the swelling pressure p_s.

The collapse test means that the unsaturated specimen contracts during wetting. The process of collapse test consists of two stages. At the first stage, with constant water content, the vertical pressure was imposed on the specimen increasingly in steps. After the compression deformation stopped at loading steps, the pressure was increased. At the second stage, water was supplied to the specimen from the bottom, and then the specimen began to contract for loose specimens until the deformation ceased during saturating.

4. Test results and discussions

4.1. Swelling deformation test

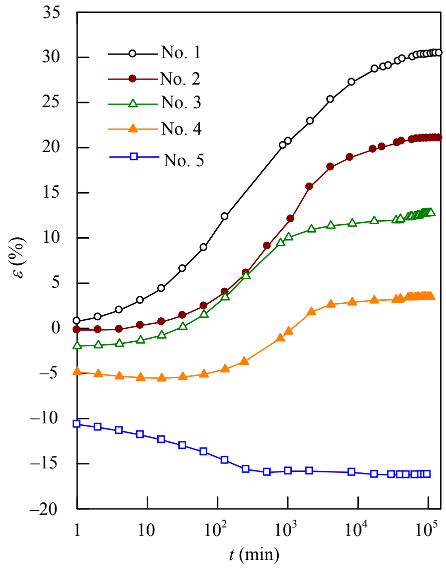
Twenty-seven specimens were used in the SD tests on the GMZ Na-bentonite and its mixtures with sand. They are in different Na-bentonite-sand ratios of 100:0, 70:30, 30:70, 20:80 and 10:90. The initial void ratio and water content of all tested specimens are different. The initial void ratios range from 0.54 to 1.71 and the initial water contents range from 10% to 23%. The swelling deformation of the bentonite-sand mixtures due to wetting depends on the bentonite content and initial density.

Fig. 2 shows the developments of the vertical swelling strain with elapsed time for the specimens No. 1 to No. 12 at respective vertical pressures. Different specimen numbers mean that the specimens have different bentonite-sand ratios, initial dry

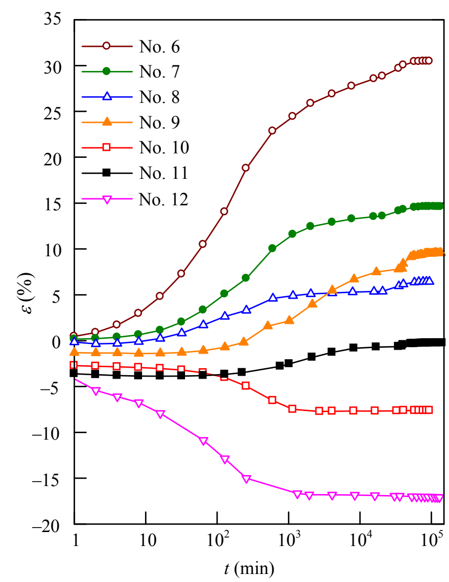
Table 1
Physico-chemical properties of GMZ bentonites.

GMZ bentonites	Grain density of bentonite (Mg/m^3)	Liquid limit (%)	Plastic limit (%)	Plastic index	Free swell ratio (%)	Montmorillonite content β (%)	Specific surface area (m^2/g)	Cation exchange capacity (meq/(100 g))	Exchange capacity (meq/(100 g))			
									Na^+	Ca^{2+}	Mg^{2+}	K^+
Na-bentonite	2.71	276	37	239	160	74	570	76	34.7	22.9	11.5	0.56
Ca-bentonite	2.72	99	41	58	115	73–82	617	83	1.6	52.9	27.8	0.34

Note: Most data are taken from Liu and Wen (2003) and Ye et al. (2007).



(a) Pure Na-bentonite.



(b) Na-bentonite-sand mixture (bentonite:sand=70:30).

Fig. 2. Swelling strain vs. time relation for Na-bentonite and Na-bentonite-sand mixture from the SD tests (after Sun et al., 2013).

densities, initial water contents and stress paths during wetting. The test time is counted from the beginning of wetting. The initial state is considered just after compaction, i.e. zero strain state. As shown in Fig. 2, some deformation at zero time has occurred before the wetting tests, because the compression was completed at unsaturated state. Negative strain means that the specimen is compressed during wetting. It can be observed that the equilibrium time is reached at approximately 10^5 min or 10 weeks. As the vertical pressure is small, the specimens Nos. 1, 2, 6 and 7 swelled immediately when wetted; while the specimens Nos. 3, 4, 8, 9 and 11 contracted first and then swelled as the specimens absorbed more water. The specimens Nos. 5, 10 and 12 contracted during the whole wetting period, as the vertical pressures were large and the dry density was relatively small.

Fig. 3 shows the void ratio e vs. vertical pressure σ_v at full saturation for the SD tests on compacted pure Na-bentonite and its mixture with Fujian sand in the weight ratios of 70:30. At the same vertical pressure, a higher bentonite content results in a larger finial

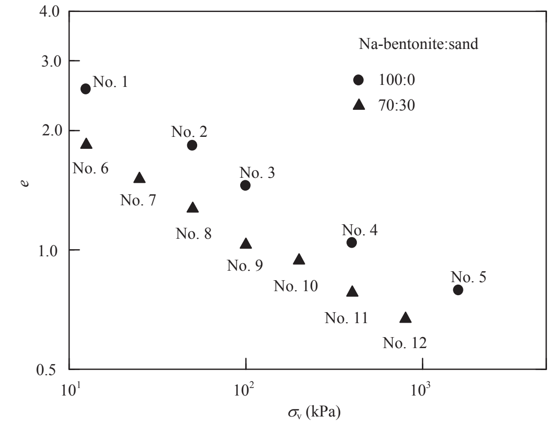


Fig. 3. Void ratio vs. vertical pressure relation at full saturation from the SD tests on Na-bentonite-sand mixture.

void ratio at full saturation. For the specimens with the same bentonite content, the final void ratio e and vertical pressure σ_v have a deceasing linear relationship in their logarithmic scales, irrespective of the initial dry density and the initial water content. Therefore, at the fully saturated state, the void ratio of the mixture at a given pressure is independent of the initial conditions such as the initial dry density and initial water content, and is merely dependent on the bentonite-sand ratio.

4.2. Constant volume test and collapse test

The GMZ Na- and Ca-bentonites and Na-bentonite-sand mixture with the weight ratio of 70:30 are used for the CV tests and collapse tests, respectively. Two types of the CV tests were conducted, by adjusting the vertical pressure in order to keep the specimens at a constant initial volume (i.e. as-compacted volume) and a constant volume after completion of the compression due to applied pressure under unsaturated state, respectively, during wetting. Fig. 4 shows the measured relationship between the dry density and the swelling pressure obtained from the two types of CV tests on GMZ Ca-bentonite. It can be seen that the relationships are almost the same for the two types of tests on the identical bentonite.

Fig. 5 shows the results from the compression tests on the Ca-bentonite at unsaturated state and subsequent wetting tests at different vertical pressures. It can be seen that even the bentonite specimen can also show volume contraction due to saturation when the specimen is compacted at a relatively loose density and relatively high pressure, and the contraction deformation ceases following a unique line *AB* at full saturation.

Fig. 6 shows the void ratio e vs. vertical pressure σ_v at full saturation from the SD, CV and collapse tests on the pure Ca-bentonite with different compacted densities and initial water contents. It can be seen that the e–σ_v relationships at full saturation are the same for the different test paths, suggesting that there is a unique e–σ_v relationship for a given bentonite and the e–σ_v relationship is independent of the initial dry density and the initial water content. The straight line in Fig. 6 is the same as the dotted line *AB* in Fig. 5.

The e–σ_v relationships at full saturation from the SD, CV and collapse tests on the Na-bentonite or the Na-bentonite-sand mixture with different compacted densities and water contents are also in good agreement, as shown in Fig. 7. The addition of sand decreases the swelling capacity, i.e. at the same vertical pressure the void ratio of the mixture with bentonite-sand ratio of 70:30 at full saturation is lower than that of pure bentonite, as shown in

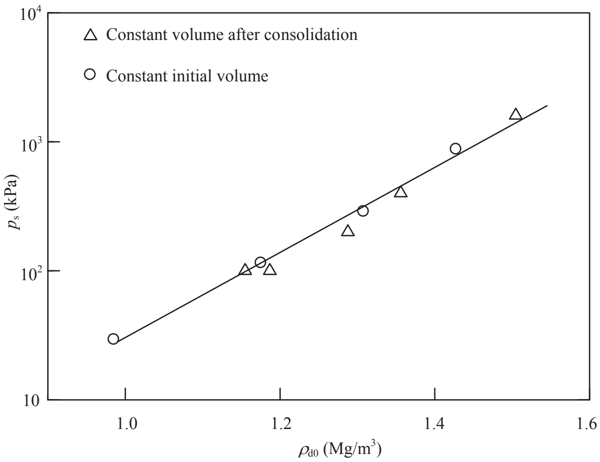


Fig. 4. Swelling pressures obtained from two types of the CV test on Ca-bentonite.

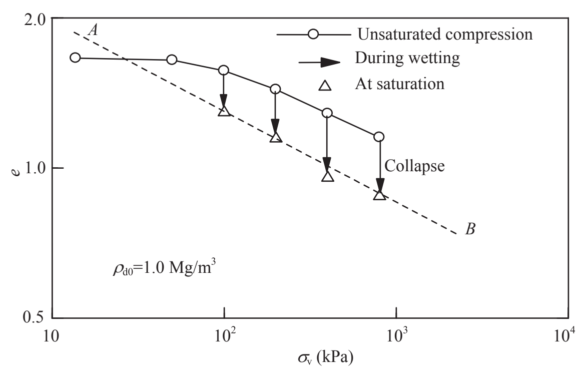


Fig. 5. Compression tests on Ca-bentonite at unsaturated state and subsequent wetting tests.

Fig. 5. Therefore, the e–σ_v relationships at full saturation depend on the ratio of bentonite to sand, regardless of the testing method, the initial dry density and/or the initial water content.

4.3. e_m–σ_v relation and prediction of swelling behaviour

Sun et al. (2009) conducted various swelling and collapse deformation tests and the swelling pressure test on the compacted Kunigel-V1 Na-bentonite, produced in Japan, and on its mixtures

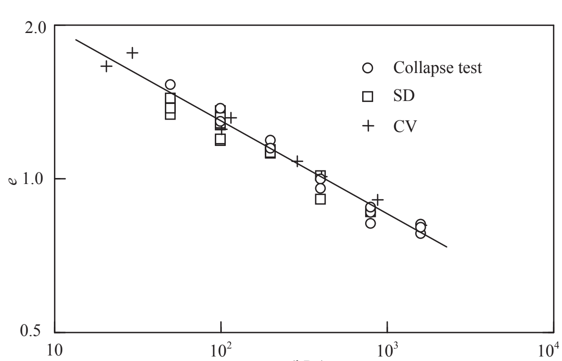


Fig. 6. Void ratio vs. vertical pressure from the three kinds of tests on compacted Ca-bentonite.

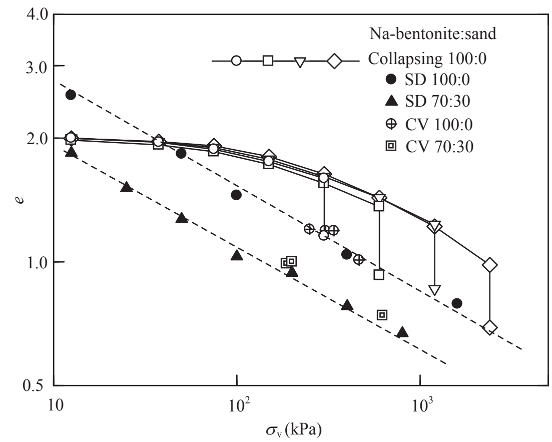


Fig. 7. Void ratio vs. vertical pressure from the three kinds of tests on the pure Na-bentonite and the Na-bentonite-sand mixture.

with sand. They proposed that the swelling deformation of bentonite-sand mixture can be characterized using a void ratio of montmorillonite, defined as a ratio of water volume at full saturation V_w to the volume of montmorillonite V_m, which is based on the concept that the maximum water volume absorbed by montmorillonite per unit volume for a given bentonite is constant at a certain stress. The montmorillonite void ratio e_m can be expressed as follows:

$$e_m = \frac{V_w}{V_m} = e\frac{\rho_m}{\rho_s \alpha \beta} \tag{1}$$

where e is the void ratio at full saturation; ρ_m and ρ_s are the grain densities of montmorillonite and the mixture, respectively; α is the bentonite content in the mixture; and β is the montmorillonite content in bentonite.

Fig. 8 shows the montmorillonite void ratio e_m vs. vertical pressure σ_v at full saturation from the SD, CV and collapse tests on the Kunigel-V1 Na-bentonite and Toyoura sand mixtures with different compacted densities and water contents (Sun et al., 2009). It can be seen that the concept of the montmorillonite void ratio is very useful for identifying the swelling behaviour of the bentonite, because there is a unique e_m–σ_v relationship at full saturation for a given bentonite with different bentonite and sand ratios, initial water contents and densities. By using this relationship, it is possible to predict the swelling deformation at a given stress and the swelling pressure at a given density for the mixtures with any bentonite and sand ratio, initial water content and density.

In order to identify the swelling behaviour of GMZ Na- and Ca-bentonites and to establish their prediction method of the swelling deformation and swelling pressure, the results from the swelling tests on the two GMZ bentonites are analyzed using the concept of the montmorillonite void ratio.

By using Eq. (1), the different swelling behaviours of GMZ Na-bentonite and sand mixtures with different bentonite and sand mixing ratios can be described subsequently, as shown in Fig. 9. The results from the three types of tests at full saturation are also given. The relationship between the montmorillonite void ratio e_m and the swelling pressure p_s (or externally imposed vertical pressure σ_v) is independent of the initial dry density, initial water content and bentonite-sand ratio of the mixtures. There is a unique straight line in the double logarithmic scales, which can be expressed by

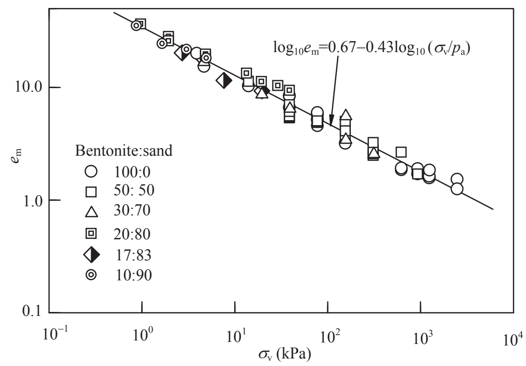


Fig. 8. e_m–σ_v relationship of Kunigel-V1-Na-bentonite-sand mixtures at full saturation (after Sun et al., 2009).

$$\log_{10} e_m = 0.321 - 0.245 \log_{10}(\sigma_v/p_a) \quad (2)$$

where p_a is the atmosphere pressure (kPa), and σ_v is the vertical pressure (kPa).

The relationship between dry density ρ_d and swelling pressure p_s of GMZ Na-bentonite and sand mixtures could be predicted by combining Eq. (1) with Eq. (2) as follows:

$$\log_{10} p_s = 3.312 - 4.088 \log_{10}\left[\frac{\rho_m(\rho_s - \rho_d)}{\rho_s \alpha \beta \rho_d}\right] \quad (3)$$

where ρ_d is the dry density of the mixture.

For example, using Eq. (3) and $\alpha = 100\%$, the ρ_d–p_s relationship of GMZ Na-bentonite specimen ($\beta = 74\%$, $\rho_s = 2.71$, see Table 1) can be expressed as

$$\log_{10} p_s = 3.312 - 4.088 \log_{10}\left(\frac{3.6621}{\rho_d} - 1.351\right) \quad (4)$$

Fig. 10 shows the predicted results by Eq. (4) with some published data of compacted GMZ Na-bentonite from Ye et al. (2007) and Zhang et al. (2010, 2012). It can be observed that the ρ_d–p_s relationship of GMZ Na-bentonite predicted using the proposed method and material parameters obtained here fits well with the test data from other researchers, which indicates that the proposed method for predicting the swelling pressure is powerful and the test data of the void ratio vs. vertical pressure at full saturation given here are consistent with those from the other researchers.

Fig. 11 summarizes the void ratio e vs. the vertical stress σ_v at full saturation from the SD tests on the compacted specimens of GMZ Na- and Ca-bentonites and Kunigel-V1 Na-bentonite. In the range of stress lower than about 500 kPa, the swelling capacity of Kunigel-V1 bentonite is greater than those of the two GMZ bentonites while the swelling capacity of GMZ Na-bentonite is greater than that of GMZ Ca-bentonite. On the other hand, the swelling capacity of the three bentonites is almost the same when subjected to a higher stress, i.e. greater than 500 kPa.

Fig. 12 summarizes the results obtained from the SD, CV and collapse tests on compacted specimens of GMZ Na- and Ca-bentonites and Kunigel-V1 Na-bentonite in the $e_m - \sigma_v$ plane. At the same stress state, the swelling capacity of Kunigel-V1-bentonite is greater than those of the two GMZ bentonites for the same montmorillonite volume. The water that the montmorillonite per unit volume in Kunigel-V1 Na-bentonite can absorb is larger than that in GMZ Ca- or Na-bentonite. In other words, the swelling pressure of Kunigel-V1 bentonite is greater than those of the two GMZ bentonites at the same montmorillonite

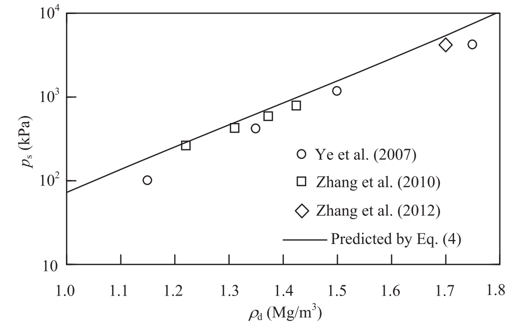


Fig. 10. Swelling pressure vs. dry density for the Na-bentonite at full saturation.

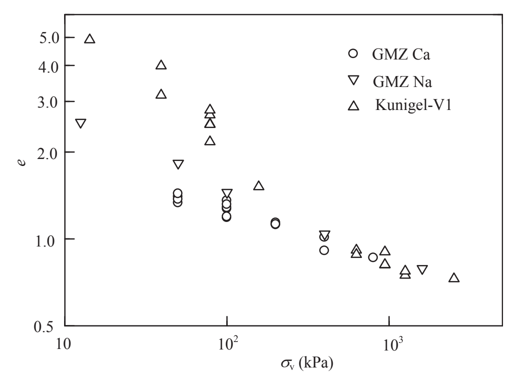


Fig. 11. $e - \sigma_v$ relationship of three bentonites at full saturation from the SD tests.

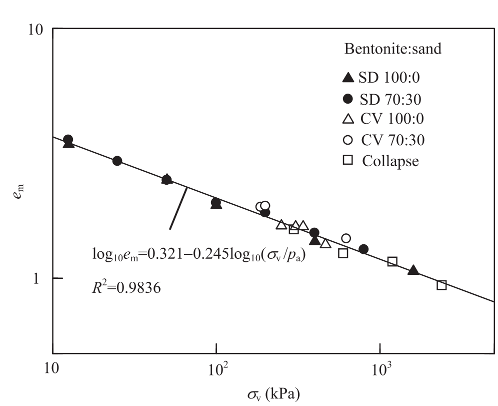


Fig. 9. e_m-σ_v relationship of GMZ Na-bentonite and sand mixtures at full saturation from the SD, CV and collapse tests.

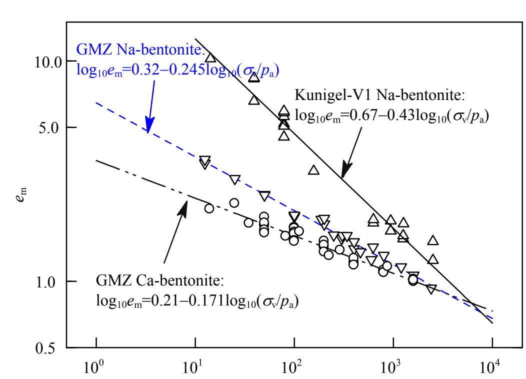


Fig. 12. e_m–σ_v relationships of three bentonites at full saturation.

content. For the two GMZ bentonites, the swelling capacity of the Na-bentonite is greater than that of the Ca-bentonite at the same stress state, or the swelling pressure of Na-bentonite is greater than that of Ca-bentonite at the same dry density. However, when the specimens are compacted at a relatively high density, the swelling capacity and swelling pressure of the two GMZ bentonites are almost the same. From Figs. 11 and 12, it can be concluded that the swelling capacity and swelling pressure of the two GMZ bentonites are almost the same when the dry density ρ_d is greater than about 1.7 Mg/m^3, which is an expected dry density of the buffer material composed of GMZ Na-bentonite in the HLRW repository in China. Therefore, in terms of the swelling characteristics at higher density, the two GMZ bentonites are the same, thus it is possible to use GMZ Ca-bentonite as a matrix material of the buffer material.

From Fig. 12, the montmorillonite void ratio vs. vertical pressure relationship of GMZ Ca-bentonite at full saturation is

$$\log_{10} e_m = 0.21 - 0.171 \log_{10}(\sigma_v/p_a) \tag{5}$$

Combining Eq. (5) with Eq. (1), we can obtain the relationship between the void ratio and corresponding swelling pressure of GMZ Ca-bentonite. The line in Fig. 6 is drawn by the above method. Here σ_v is considered as the swelling pressure. It can be seen that the prediction of the swelling pressure is in a good agreement with the observed data.

5. Conclusions

The swelling characteristics of GMZ Na- and Ca-bentonites and their mixtures with sand wetted with distilled water were studied by performing a series of SD, CV and collapse tests. The relationship between the montmorillonite void ratio e_m at full saturation and the swelling pressure p_s in their logarithmic scales has been found to be unique for a given bentonite, which is independent of the bentonite-sand ratios, initial density and initial water content. The swelling characteristics of GMZ Na- and Ca-bentonite are almost identical in the range of higher density. By using Eq. (4), the swelling or collapse deformation of GMZ Na-bentonite and sand mixtures due to wetting can be predicted if the initial state of the mixture and the stress state are given, and the swelling pressures of GMZ Na-bentonite and sand mixtures can also be predicted if the initial dry density of the mixture is given; and the swelling behaviours of Ca-bentonite and sand mixtures can also be predicted using the same method; only the montmorillonite void ratio vs. the stress relationship of Eq. (5) is different.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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