Volume change behavior of saturated compacted GMZ bentonite and slurry during cyclic loading-unloading processes

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ABSTRACT

In order to investigate the volume change behavior of saturated GMZ bentonite during cyclic loading-unloading processes, oedometer tests with cyclic loading-unloading process were conducted on saturated compacted GMZ bentonite and slurry specimens. A significant hysteretic loop was observed in compression curve of saturated compacted GMZ bentonite during cyclic loading-unloading process. Compression curve of the slurry specimen presented a bilinear shape. Under smaller stresses (< 0.5–2 MPa), the unloading-reloading loop was insignificant. However, under higher stresses (> 0.5–2 MPa), the unloading-reloading loop was significant. The unloading-reloading loop could be explained by the competition between the mechanical and physico-chemical effects on the microstructure changes. When stress was higher than 10 MPa, compression curve of the slurry gradually closed to and coincided with the compression curve of the compacted bentonite specimen. Therefore, normal consolidation line of GMZ bentonite could be determined based on the overlapped part of the compression curves.

Keywords: GMZ bentonite, compression, rebound, slurry, unloading/reloading loop, NCL

1 INTRODUCTION

Compacted bentonite has been selected as buffer/backfill materials for high-level radioactive waste (HLW) disposal in many countries (Pusch et al., 1980; Komine and Ogata, 1996; Villar, 2006; Siddiqua et al., 2011; Wen, 2006; Ye et al., 2009). According to the conceptual design, repositories were planned to be built at great depths ranging from 500 to about 1000 m below ground surface surrounded by intact host rock with a geostatic stress expected to be about 9.0–16.0 MPa (Tripathy and Schanz, 2007; Ye et al., 2012).

During the long-term operation of a geological repository, working as buffer materials, compacted bentonite could experience compression due to extra loading or rebound deformation due to stress redistribution or unloading (Chen et al., 2017). In the meantime, due to the infiltration of groundwater from the surrounding geological formations, compacted bentonite could be saturated. Therefore, investigation on the compression and rebound behavior of saturated bentonite is of great importance for safely design of HLW repositories.

In the last decades, laboratory studies have been reported in literature focusing on the compressibility of saturated bentonite (Marcial et al., 2002; Lloret et al., 2003; Di Maio et al., 2004; Baille et al., 2010). Lloret et al. (2003) and Baille et al. (2010) have studied the compressibility of compacted bentonites after swelling under confined conditions, which is near field situation. In the meantime, bentonite with water contents higher than its liquid limit was also considered as a reference state to study the compression behavior (Bag and Rabbani, 2017). Marcial et al. (2002) and Di Maio et al. (2004) have investigated the compressibility of bentonite slurries.

However, investigations on rebound behavior of bentonite were relatively scarce (Di Maio et al., 2004; Gasparre and Coop, 2008; Tanaka et al., 2014; Chen et al., 2017). Mechanisms related to volume change behavior in unloading path have not been well understood (Cui et al., 2013).
Gaomiaozi (GMZ) bentonite has been selected as a possible buffer/backfill material for construction of engineering barriers in the HLW repository in China (Liu and Wen, 2003; Wen, 2006; Ye et al., 2010). Studies on the compression behavior of GMZ compacted bentonite have been conducted (Ye et al., 2012; Zhang et al., 2013; Ye et al., 2014; Chen et al., 2017). However, works related to unloading/reloading behavior of compacted GMZ bentonite and slurry specimens are limited.

In this study, oedometer tests with cyclic loading-unloading processes were conducted on a slurry specimen and a compacted GMZ bentonite specimen with initial dry density of 1.7 Mg/m³, which experienced hydration under vertical stress of 0.12MPa. The volume change behavior of saturated compacted GMZ bentonite and slurry during cyclic loading-unloading process was analyzed. The unloading behavior and unloading-reloading loop were analyzed by competition between the mechanical and physico-chemical effects, which is also the competition between compression and swelling. Based on the compression curves of the GMZ bentonite, the normal consolidation line (NCL) of saturated GMZ bentonite was determined.

2 MATERIALS AND METHODS

2.1 Materials
The GMZ01 bentonite tested in this work is a sodium bentonite, which is originated from Inner Mongolia, China, 300 km northwest from Beijing (Ye et al., 2009). The main minerals in GMZ01 bentonite are Montmorillonite (75.4%), Quartz (11.7%), Feldspar (4.3%), Cristobalite (7.3%), etc. The liquid limit and plastic limit are 276% and 37%, respectively. The specific gravity is 2.67, and the cation exchange capacity (CEC) is 77.3 meq/100 g (43.36% Na⁺, 29.14 Ca²⁺, 12.33 Mg²⁺, 2.51 K⁺) (Ye et al., 2012).

2.2 Test apparatus
The experimental setup employed for conducting oedometer tests in this work was shown in Fig. 1. The oedometer with a water circulation system developed by Ye et al. (2012) was presented in Fig. 1(a). The oedometer cell is composed of a basement, a top part, a specimen ring, two stainless steel porous plates and four screws. The specimen ring, which has an inner space of 70 mm in height and 50 mm in diameter, is designed for holding the specimen. The basement, the top part, the specimen ring, etc. can be fixed together with the four screws. A strain gauge fixed on the loading piston with a precision of 0.001 mm and a total run of 12.5 mm is employed for recording the vertical deformation of the specimen.

For applying the vertical stress, the oedometer was placed in a special high pressure load frame (Fig. 1(b)), which has a double arm lever system with ratios equal to 12 and 6, giving a total ratio of 72. With a maximum weight being 145 kg, a force of 10 tons can be applied to the specimen, which corresponds to a maximum vertical pressure of 50 MPa within a diameter of 50 mm ring.

2.3 Test procedures

2.3.1 Specimen preparation
For preparation of the compacted specimen, first of all, GMZ01 bentonite powder was equilibrated to a suction 110 MPa, which corresponds to a water content 10.2%, using the vapor equilibrium technique. Then, the equilibrated powder was weighed and statically compacted to a specimen with designed dimensions of 50 mm in diameter and 10 mm in height, as well as a target dry density around 1.7 Mg/m³.

For preparation of slurry specimen, the GMZ01 bentonite powder was mixed thoroughly with distilled water to a targeted water content about 1.5 time of its liquid limit. The soil-water mixture was sealed in a water tight plastic bag for 7 days in order to ensure moisture equilibration.

2.3.2 Swelling and compression test of compacted bentonite

![Diagram](image-url)
Firstly, the compacted GMZ01 bentonite specimen was put into the apparatus (Fig. 1(a)). A vertical stress of 0.12 MPa was applied and the vertical deformations of specimen was measured by the strain gauge. When the variation of the vertical displacement measured during 8 h was less than 0.01%, the volume change measured under current vertical stress was stable (Ye et al., 2012).

Then, distilled water was infiltrated from the bottom of the specimen for saturation (Fig. 1(a)). The vertical displacement was measured and when the vertical swelling strain recorded was stable, the specimen was recognized as being saturated.

Finally, compression test was conducted following the stress path shown in Table 1. A volumetric strain rate of 0.01% per 8 h was adopted as a standard for judging the stabilization at each step.

Table 1. Stress path of the compression tests.

| Test       | Stress paths (MPa)                  |
|------------|-------------------------------------|
| compacted  | 0.12–0.40–0.7–1.44–2.84–1.44–0.7–0.40 |
| bentonite  | ~0.2–0.12–0.40–0.7–1.44–2.84–5.34–11. |
| slurry     | 57–5.34–2.84–1.44–0.7–0.40–0.2–0.12  |
|            | ~5.34–2.84–1.44–0.7–0.40–0.2–0.12    |
|            | 0–0.7–1.44–2.84–5.34–11.57–17.32–29. |
|            | 29–41.25                            |

2.3.3 Oedometer test on bentonite slurry specimen

After equilibration, slurry was carefully poured into the oedometer cell to avoid trapping any air bubbles. The initial height of the specimen was approximately 90 mm. The initial void ratio of the specimen was deduced from the initial volume and water content of the slurry. A piston was placed and consolidation was conducted under the piston weight (0.013 MPa). After consolidation under current vertical stress was completed, displacement of the piston was measured with the cathetometer for determination of void ratio (Marcial et al., 2002).

Then, the oedometer cell was placed in special high pressure load frame (Fig. 3(b)) for conducting oedometer tests, which was performed following the stress paths shown in Table 1. A volumetric strain rate of 0.01% per 8 h was adopted as standards for judging the stable state at each stress.

3 RESULTS AND DISCUSSION

3.1 Volume change behavior of saturated compacted bentonite during cyclic loading-unloading processes

Evolution of vertical swelling strain and void ratio with time for a compacted GMZ01 bentonite specimen hydrated under a vertical load of 0.12 MPa were respectively presented in Figs. 2 and 3. Result in Fig. 3 shows that void ratio of the compacted GMZ01 bentonite specimen after swelling is 1.1013.

Fig. 2. Evolution of swelling strains with time for compacted GMZ01 bentonite specimen.

Fig. 3. Evolution of void ratio with time for the compacted specimen.

Curves in Fig. 4 show that a significant hysteretic
loop can be identified in the cyclic loading-unloading process. This observation is similar with the results reported by Cui et al. (2013) on natural stiff clays. 

Explanations to this phenomenon could be that the unloading-reloading loops of compression curves resulted from the competitions between the mechanical and physico-chemical effects.

Due to the high content of montmorillonite, physico-chemical effect in saturated compacted bentonite is more significant. Hydration of the bentonite specimen depends on the stress applied. Volume change behavior is a result of balance between the physico-chemical and mechanical effects and is also the balance between swelling and compression. When the vertical stress is small, more water molecules absorbed in space between elementary clay sheets, inducing high degree of hydration/swelling. Especially for a Na-bentonite, clay particles could be fully broken up to be elementary layers due to hydration if no stress was applied on the specimen (Pusch, 2001).

During unloading process, physico-chemical effect becomes prevailing and hydration will continue, the rebound of the specimen is not only due to mechanical rebound of soil skeleton, but also the hydration and swelling of aggregate. However, in the reloading process, the mechanical effect becomes dominant resulting in volumetric compression through possible contraction of soil skeleton.

Consequently, competition between the mechanical and physico-chemical effects results in the hysteretic loop during cyclic loading-unloading process.

3.2 Volume change behavior of GMZ bentonite slurry during cyclic loading-unloading processes

The compression curve of the GMZ bentonite slurry was presented in Fig. 5. Result in Fig. 5 shows that a bilinear shaped curve with a transition point at around 0.5–2MPa can be observed in a semi-logarithmic plot. For a vertical load higher than 2 MPa, the compression coefficient decreases significantly.

For comparison, the compression curves of the GMZ01 bentonite slurry with that of some other bentonite (Marcial et al., 2002) were presented in Fig. 6. Curves in Fig. 6 show that the compression curve of GMZ bentonite slurry is similar with that of the other bentonite.

Explanations to the bilinear nature of the compression curves involve different mechanisms depending on the stress applied (Marcial et al., 2002).

For lower stresses (< 0.5–2MPa), gel structure develops in smectites inducing soil swelling. In the meantime, as stress increases, large pores of the gel structure will be compressed with expelling of “free water” (Tessier, 1984, 1990).

For higher stresses (>0.5–2MPa), most of the water contained in bentonite is interlayer water or double layer water, while almost no free water due to the limited space and closing structure (Bradbury and Baeyens, 2003). Expelling of water is relatively difficult and correspondingly compression coefficient of significantly decreases.

Curves in Fig. 5 also show that, for the first unloading/reloading cycle, the loop is insignificant, while for the second one, the unloading/reloading loop is significant, which is similar with that of the saturated compacted bentonite in Fig. 4.

Based on the analysis mentioned above, under lower stresses, volume change comes from the compression of larger interaggregate pores, which occurs with the
expulsion of water molecules. This process was characterized by lower clay–water physic-chemical interactions (Marcial et al., 2002). The rebound behavior during the unloading phase is mainly induced by the mechanical rebound of soil skeleton leading to an insignificant unloading/reloading loop.

However, for higher stresses, soil structure is relatively dense and physio-chemical effect is more significant. Competition between the mechanical and physic-chemical effects are serious during the unloading/reloading processes, resulting in an extremely significant hysteretic loop.

3.3 Normal consolidation curve

Compression curves of the slurry specimens (Fig. 6) show that the normal consolidation line (NCL) is not a straight line.

For comparison of the compression behaviors for the saturated compacted bentonite and slurry specimens, compression curves of the compacted bentonite and slurry specimens were presented in Fig. 7. Curves in Fig. 7 show that, when the vertical stress is higher than 10 MPa, the compression curve of the slurry specimen are gradually coincides with that of the compacted bentonite specimen. This observation may indicate that, as the slurry specimen is compressed to a high density, the compression behavior is similar with that of a saturated compacted specimen.

![Fig. 7. Comparisons of compression curves of saturated compacted GMZ bentonite with slurry.](image)

Considering the stress level (9~16MPa) at the location of the waste disposal repositories and void ratios range of saturated compacted bentonite, the overlapped part (>10 MPa) of the compression curves could be considered as the normal consolidation line (NCL) of saturated GMZ bentonite (Fig. 7).

The NCL could be fitted by the equation,

\[ e = N - \lambda \log p \]  (1)

Where, \( N \) is the void ratio corresponding to a vertical stress 1MPa and \( \lambda \) is plastic compression index. For GMZ01 bentonite tested in this work, \( N \) and \( \lambda \) equal to 0.9525 and 0.3202, respectively.

4 CONCLUSION

In this study, cyclic loading-unloading oedometer tests were conducted on the compacted GMZ01 bentonite specimens with an initial dry density 1.7 Mg/m³, which experienced hydration under vertical stress of 0.12MPa, and slurry specimens. The volume change behavior of saturated compacted GMZ01 bentonite and slurry specimens during the cyclic loading-unloading processes was analyzed.

A significant hysteretic loop was observed in the compression curve for a saturated compacted bentonite specimen tested under cyclic loading-unloading processes. The rebound behavior during unloading progress is not only due to the mechanical rebound of soil skeleton, but also the hydration and swelling of aggregate. The unloading-reloading loop could be explained by competition between the mechanical and physic-chemical effects.

The compression curve of the GMZ01 bentonite slurry specimen presents a bilinear type curve with a transition point at around 0.5~2MPa. In the first part of the compression curve, the unloading-reloading loop is insignificant, while in the second part, the unloading-reloading loop is significant.

When the vertical stress is higher than 10 MPa, the compression curve of the slurry specimen gradually closes to and coincides with the compression curve of compacted bentonite specimens. Based on the compression curves of the GMZ bentonite, the normal consolidation line (NCL) of saturated GMZ bentonite was determined.

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