Mechanical properties of sand-bentonite composite material used as a buffer material of nuclear waste repository

Les propriétés mécaniques du matériau composite Sable silico-argileux (bentonite) utilisé comme matériau tampon du dépôt de déchets nucléaires

Janaka J. Kumara, Takeshi Kodaka, Ying Cui
Department of Civil Engineering, Meijo University, Japan, jjkumara@meijo-u.ac.jp

ABSTRACT: Buffer material of deep geological repository undergoes changes in water content when subjected to local groundwater flow. Strength and volumetric behaviour are affected by the change in water content. In this study, a sand-bentonite material of a constant dry density subjected to various degree of saturation was investigated to understand its strength and volumetric behaviour by conducting triaxial compression test. Total suction of the tested specimens was also measured using the chilled-mirror hygrometer technique. The results reveal that strength and volumetric behaviour are affected by the change in water content. The results however indicate no change in total suction due to shear loading or confining pressure. Total suction of dry sand-bentonite decreases from a high as 100MPa to a low as 1-2MPa near its full saturation. The results also indicate that compressive strength decreases with decreasing total suction, and reduction is larger at higher confining pressure.

RÉSUMÉ : Le matériau tampon d'un dépôt géologique profond subit des changements dans la teneur en eau, lorsqu'il est soumis à l'écoulement local des eaux souterraines. La force et le comportement volumétrique sont affectés par la variation de la teneur en eau. Dans cette étude, un matériau composite Sable silico-argileux (bentonite) de densité sèche constante, soumis à divers degrés de saturation, a été analysé pour pouvoir comprendre sa résistance, ainsi que son comportement volumétrique, en effectuant un essai de compression triaxial. L'aspiration totale des échantillons testés a également été mesurée avec un Hygromètre à miroir refroidi. Les résultats révèlent que la force et le comportement volumétrique sont affectés par la variation de la teneur en eau. Par contre, les résultats ne montrent pas de changement au niveau de l'aspiration totale due à la charge de cisaillement ou à la pression de confinement. L'aspiration totale de Sable silico-argileux (bentonite) passe de 100MPa à 1-2MPa lors de sa pleine saturation. Les résultats indiquent aussi que la résistance à la compression diminue avec la chute de l'aspiration totale. En outre, la baisse est plus grande lors d'une pression de confinement plus élevée.

KEYWORDS: buffer material, deep geological repository, strength, suction, triaxial test, volumetric behaviour.

1 INTRODUCTION

Bentonite-based materials are widely used as buffer and backfill materials in radioactive waste repositories thanks to their excellent swelling properties and low permeability. In Japan, sand-bentonite material is mainly used as the buffer material for deep geological respositories. In Japan, it is recommended to construct deep geological repositories at least 300m below the ground surface. It is expected that under such depth, a stable rock can be found. Generally, radioactive wastes are stored in canisters in either horizontal drifts or vertical boreholes (see Fig. 1 for the latter). Given a leak of radioactive wastes could bring devastations to humans and the environment, it is vital the radioactive wastes are sealed tightly by an engineered barrier constructed by expansive clayey materials. An engineered barrier system provides various function to a radioactive waste facility including mechanical stability for the waste canisters, sealing discontinuities in the boreholes and drifts, and delaying water infiltration from the host rock (Ye et al. 2014). Bentonite-based materials are generally selected as buffer material for engineered barrier systems due to their high swelling capacity, low permeability and micro-porous structure (Pusch 1992).

Buffer material at the construction stage of a radioactive waste facility is basically under unsaturated (dry) condition due to low water content. However, after it is decommisioned, the buffer material is subjected to local groundwater flow, and eventually may become saturated. Various types of bentonite have been proposed as possible buffer material and backfill materials in many countries. In Japan, Kunigel VI has been recommended as a suitable bentonite material (Imbert and Villa 2006). There had been various works on swelling and permeability characteristics of bentonite-based materials (Nachabe 1995, Schanz et al. 2010). However, strength and volumetric behaviour of sand-bentonite material had not been studied sufficiently. Also, a small number of studies carried out on strength properties had been restricted to limited conditions such as dry-state specimen (Mitachi 2008), pure bentonite material (Kwon et al. 2013) or evaluation by direct shear tests (Kodaka and Teramoto 2009).

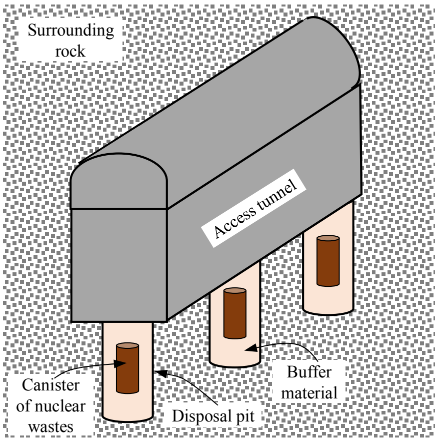


Figure 1. A schematic diagram of a deep geological repository (inspired by Komine and Ogata 2004)

In this study, strength and volumetric behaviour of sand-bentonite material subjected to various degree of saturation were investigated. In addition, suction characteristics of specimens before and after loading were also studied using a newly available chilled-mirror hygrometer technique (Agus et al. 2010).

2 MATERIALS AND TESTING METHODS

Sand-bentonite material was prepared using 70% of bentonite and 30% of sand (on mass-based) as identified as buffer material of radioactive waste facilities in Japan (Mitachi 2008). In this study, dry density of sand-bentonite material was maintained constant at 1600kg/m^3 as recommended for high-level radioactive waste facilities in Japan. A sodium-type bentonite, called Kunigel VI is used in this study. It contents around 48% of montmorillonite, which is essential mineral for sealing properties. The initial condition of bentonite and sand are included in Table 1. Mineral components of Kunigel VI bentonite can be found in Cui et al. (2008). Particle size distribution of sand is shown in Fig. 2.

Table 1. Intial condition of bentonite and sand

Property	Bentonite	Sand
Particle density, ρ_s (kg/m^3)	2767	2666
Liquid limit, w_L (%)	430.5	n/a
Plastic limit, w_P (%)	26.7	n/a
Plasticity index, I_p	403.8	n/a
Montmorillonite content (%)	48^a	n/a

Note ^{a}Komine and Ogata (1999)

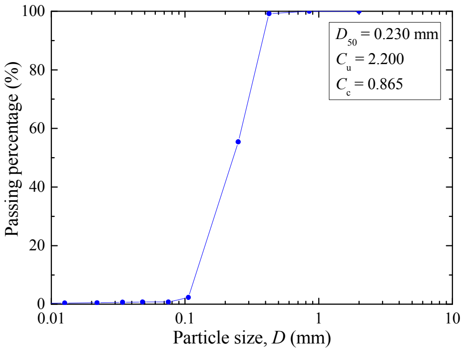


Figure 2. Particle size distribution of sand (C_u is coefficient of uniformity and C_c is coeffiecint of curvature)

Specimens were prepared under different water content such that 30, 50, 70 and 90% of degree of saturation were obtained. In addition, bentonite under its natural water content was also used to prepare a sand-bentonite specimen. Two identical specimens were used for suction measurement and triaxial compression test. Total suction of the specimens after the triaxial testing was also measured using Dewpoint PotentiaMeter (WP4C) by Decagon Devices (see Fig. 3). It has a digital display to read the measurements. Total suction is measured using the chiller-mirror hygrometer technique (Agus et al. 2010). When a sample is inserted onto its tray (see Fig. 3), it starts to equibibrate with the headspace of the sealed chamber. At the equilibrium, water potential of the air in the chamber is same as the water potential of the sample.

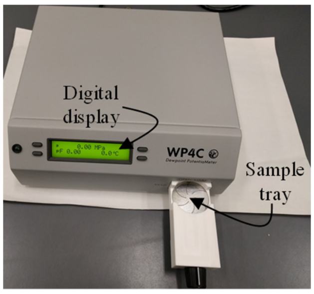


Figure 3. Dewpoint PotentiaMeter (WP4C)

In sample preparation, special care should be taken in mixing sand and bentonite as bentonite absorbs water quickly. We used a pressuried water sprayer to spread water uniformly and lightly on the sand-bentonite mixture. Then, material was poured into a mold of 35mm in diameter and 160mm in height. After it is compacted manually using a light-weight tool three times, approxiamately 100mm high specimen is prepared. Then, it is compacted by a hydraulic jack to get the required height of 80mm. After both edges are trimmed by roughly 5mm each, the final specimen of 70mm in height and 35mm in diameter is prepared for triaxial test. In case of suction measurement, a small piece from the middle is collected (e.g., roughly half size of the measuring cups, i.e., 10mm). In collecting materials and water, degree of suturation is controlled by water content.

Triaxial compression tests were conducted using a newly built double-cell type triaxial testing apparatus shown in Fig. 4. Unconsolidated undrained triaxial tests were conducted according to Japanese standard (JGS 2009). The specimen is mounted in the inner cell. Volume change of a specimen is measured using the burrette connected to the inner cell. The confining pressure applied into the outer cell also applies onto the specimen mounted in the inner cell. Shearing was applied with a loading rate of 0.1%/min by a Mega-torque motor.

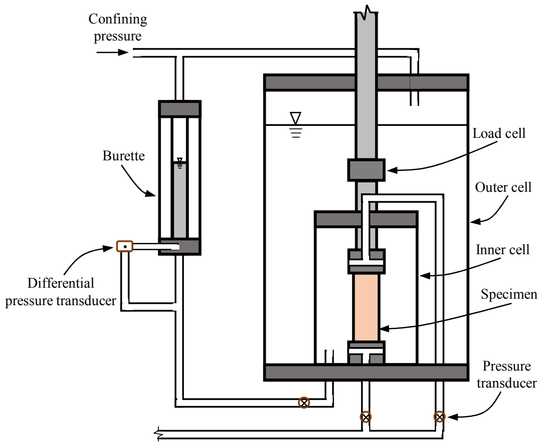
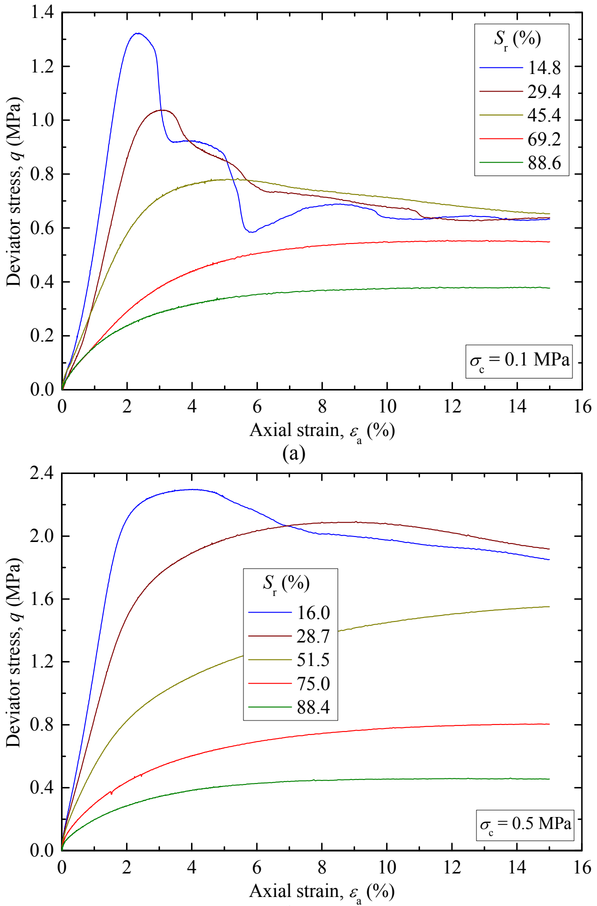


Figure 4. A schmatic diagram of the double-cell type triaxial test apparatus

3 RESULTS

Figs. 5a and 5b illustrate stress-strain behaviour of buffer material under 0.1 and 0.5MPa confining pressure respectively. The results indicate that dry bentonite-sand material exhibits the highest deviator stress, which deteriorates with the degree of saturation under both 0.1 and 0.5MPa confining pressures. It also indicates that strain-hardening behaviour becomes dominant under a higher confining pressure. Strain-softening behaviour of less-saturated specimen disappears with the degree of saturation such that a sand-bentonite buffer material subjected to local groundwater flow exhibits mainly strain-hardening behaviour regardless of confining pressure. As shown in Figs. 6a and 6b, specimens of less water content exhibit clear shear failure compared to the specimens of more water content. Therefore, specimens subjected to local groundwater flow restrains from shear failure until large deformation occurs compared to sand-bentonite buffer material of its initial water content.

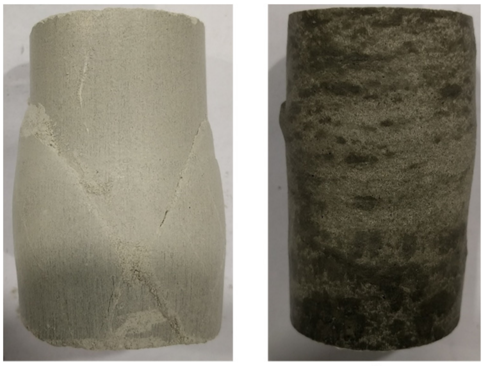
Figs. 7a and 7b show the volumetric behaviour of buffer material under 0.1 and 0.5MPa confining pressure respectively. The strain-hardening specimens yield continuous volumetric compression while strain-softening specimens yield volumetric expansion after the post-failure. The magnitude of volumetric compression reduces with the degree of saturation regardless of confining pressure. It also indicates that a higher confining pressure results in smaller volumetric compression.



(a)

(b)

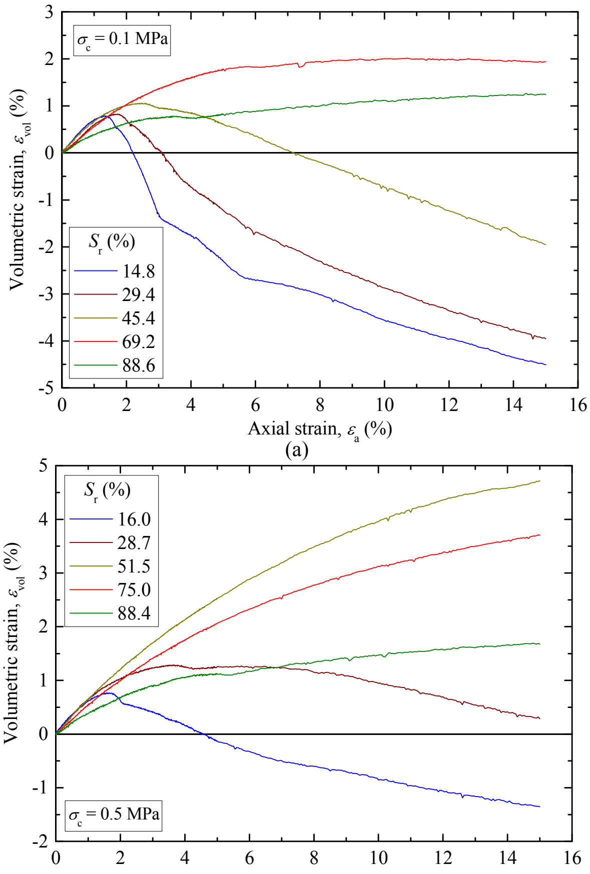
Figure 5. Stress-strain relationships under (a) 0.1 and (b) 0.5MPa confining pressure (S_r is degree of saturation)



(a) (b)

Figure 6. The failure pattern of specimens of S_r (a) 15 and (b) 70% under 0.5MPa of confining pressure (S_r is degree of saturation)

Fig. 8 shows a typical Mohr stress circle and its failure envelope. Fig. 9 illustrates the variations of undrained cohesion and friction angle with the degree of saturation. The results suggest that cohesion is less affected by water content compared to frictional behaviour. The dry sand-bentonite material yields a higher cohesion roughly around 0.30MPa, which varies in other specimen from 0.17-0.21MPa. Thus, it is clear that cohesion is hardly affected by water content after initial saturation. In contrast, friction angle decreases roughly linearly with the degree of saturation with a rapid reduction after initial saturation.



(a)

(b)

Figure 7. Volumetric strain-axial strain relationships under (a) 0.1 and (b) 0.5MPa confining pressure (S_r is degree of saturation)

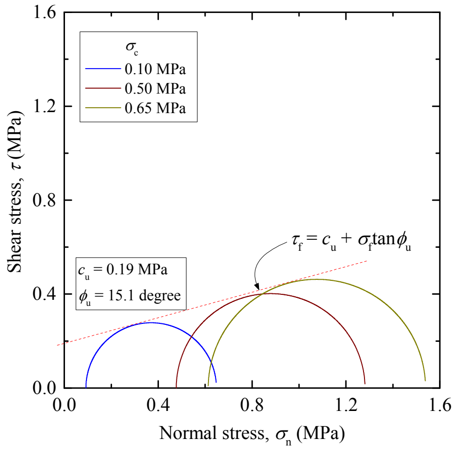


Figure 8. A typical Mohr circle and its failure envelope (S_r= 70%; S_r is degree of saturation and σ_c is confining pressure)

Fig. 10 illustrates the variation of total suction with the degree of saturation under various confining pressures. This graph indicates that total suction decreases with the degree of saturation. However, there is no clear changes in total suction affected by confining pressure. There is also no changes in total suction influenced by the shear loading.

Fig. 11 indicates the relationship of compressive strength and total suction under 0.1 and 0.5MPa confining pressures. As shown in Fig. 11, the compressive strength decreases with decreasing total suction. The decrease in compressive strength is however large under a higher confining pressure. This results clearly indicate that initial sand-bentonite specimens, which have high suction and compressive strength, reduces after subjected to local groundwater flow upon decommission of a radioactive waste facility.

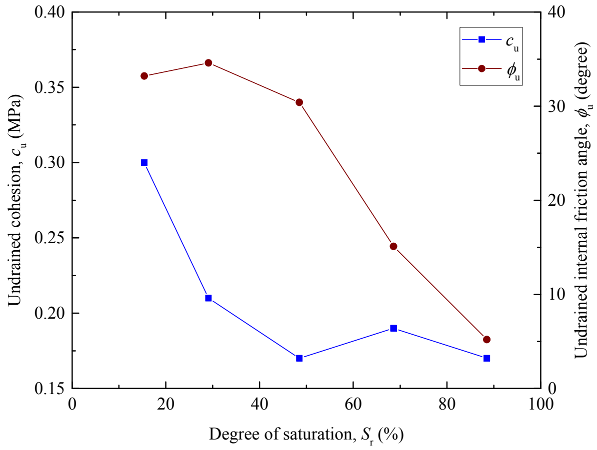


Figure 9. The variation of cohesion and internal friction angle with the degree of saturation

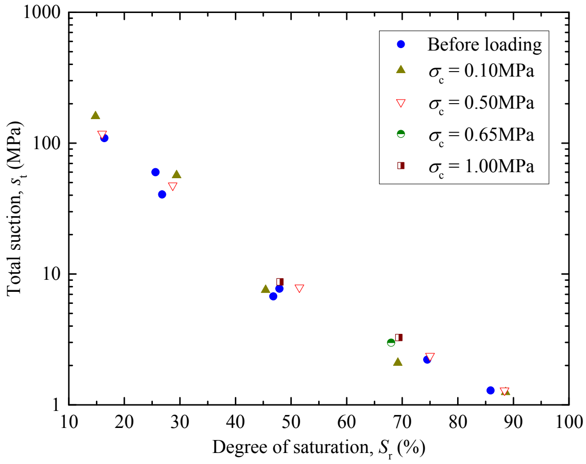


Figure 10. The variation of total suction with the degree of saturation (σ_c is confining pressure)

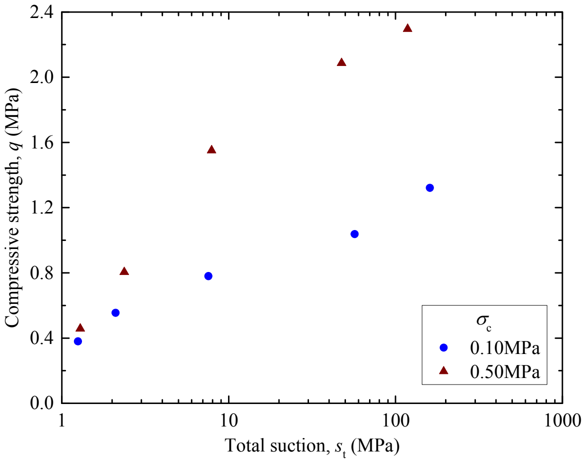


Figure 11. The variation of compressive strength and total suction (σ_c is confining pressure)

4 CONCLUSIONS

Strength, volumetric behaviour and suction characteristics of sand-bentonite buffer material of radioactive waste facilities were investigated in this study. The buffer material was subjected to various degree of saturation to simulate the effects of local groundwater flow after a radioactive waste facility is decommissioned. The following conclusions are drawn from the study.

Strain-softening behaviour of buffer material deteriorates with the degree of saturation. A higher confining pressure also leads to strain-hardening. With saturation, specimens starts to yield continuous compression whereas less-saturated specimens yield volumetric expansion after yielding volumetric compression in pre-failure. The magnitude of volumetric compression decreases with the degree of saturation.

While cohesion remains less affected by the degree of saturation beyond initial saturation, friction behaviour is largely affected by the degree of saturation, particularly after initial saturation. Total suction decreases with the degree of saturation. However, shearing load or confining pressure seem not affecting total suction. The compressive strength decreases with decreasing total suction, and the reduction is larger at higher confining pressure.

5 ACKNOWLEDGEMENTS

Mr. K. Takeuchi, a graduate student of Meijo University is appreciate for his supports in the laboratory experiments. The financial supports offered by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan is also appreciated.

6 REFERENCES

Agus, S.S., Schanz, T. and Fredlund, D.G. 2010. Measurements of suction versus water content for bentonite-sand mixtures. *Canadian Geotechnical Journal* 47 (5), 583-594.

Cui, Y.J., Tang, A.M., Loiseau, C. and Delage, P. 2008. Determining the unsaturated hydraulic conductivity of a compacted sand-bentonite mixture under constant-volume and free-swell conditions. *Physics and Chemistry of the Earth* 33 (S1), 462-471.

Imbert, C. and Villar, M.V. 2006. Hydro-mechanical response of a bentonite pellets/powder mixture upon infiltration. *Applied Clay Science* 32 (3-4), 197-209.

JGS 2009. Method for unconsolidated-undrained triaxial compression test on soils (JGS 0521), Japanese Geotechnical Society Standard, Tokyo.

Kodaka, T. and Teramoto, Y. 2009. Shear failure behavior of compacted bentonite. *Proc. of International Symposium on Prediction and Simulation Methods for Geohazard Mitigation*, Kyoto, 331-337.

Komine, H. and Ogata, N. 1999. Experimental study on swelling characteristics of sand-bentonite mixture for nuclear waste disposal. *Soils and Foundations* 39 (2), 83-97.

Komine, H. and Ogata, N. 2004. Predicting swelling characteristics of bentonite. *Journal of Geotechnical and Geoenvironmental Engineering* 130 (8), 818-829.

Kwon, S., Cho, W.J. and Lee, J.O. 2013. An analysis of the thermal and mechanical behavior of engineered barriers in a high-level radioactive waste repository. *Nuclear Engineering and Technology* 45 (1), 41-52.

Mitachi, T. 2008. Mechanical behavior of bentonite-sand mixtures as buffer materials. *Soils and Foundations* 48 (3), 363-374.

Nachabe, M.H. 1995. Estimating hydraulic conductivity for models of soils with macropores. *Journal of Irrigation Drainage Engineering* 121 (1), 95-102.

Pusch, R. 1992. Use of bentonite for isolation of radioactive waste products. *Clay Minerals* 27 (3), 353-361.

Schanz, T., Arifin, Y.F., Khan, M.I. and Agus, S.S. 2010. Time effects on total suction of bentonites. *Soils and Foundations* 50 (2), 195-202.

Ye, W.M., Borrell. N.C., Zhu, J.Y., Chen, B. and Chen, Y.B. 2014. Advances on the investigation of the hydraulic behavior of compacted GMZ bentonite. *Engineering Geology* 169, 41-49.