Effects of Dry Density and Water Content on Mechanical Properties of Sand-Bentonite Buffer Material

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Abstract. Mechanical properties of the buffer material of deep geological repository are influenced by various factors. The engineered barrier system of a deep geological repository is subjected to local groundwater flow after it is decommissioned. The changes in water content of buffer material could affect deformation and suction properties. In this study, the influence of water content and dry density on the mechanical properties of sand-bentonite buffer material were investigated. The triaxial compression tests were performed on sand-bentonite specimens of 1400, 1600 and 1800 kg/m^3 of dry density and 6, 12 and 18% of water content. The volumetric strains of specimens were evaluated using a newly built double-cell type triaxial testing apparatus. Total suction of specimens was measured using the chiller-mirror hygrometer technique. Total suction was measured on identical specimens prepared for suction measurement and triaxial compression tests. The results indicate that water content reduces deviator stress while dry density increases it. The results also suggest that water content changes strain-softening behaviour of relatively less saturated specimens into strain-hardening behaviour when water content is high. A high confining pressure (of 1.0 MPa) inclines towards strain-hardening behaviour than a small confining pressure (of 0.1 MPa). Water content also increases strain-hardening behaviour. In contrast, dry density reduces strain-hardening behaviour, particularly under a small confining pressure. The results also indicate that dry density reduces the magnitude of volumetric expansion. A high confining pressure encourages volumetric expansion. While water content decreases frictional behavior, it increases cohesive behaviour under a relatively low dry density (of 1400 and 1600 kg/m^3). In contrasts, water content reduces cohesive behaviour under a high dry density (of 1800 kg/m^3). Thus, a micro-scale analysis would produce more insights on this. While water content has huge influence on total suction, both dry density and confining pressure have no effects on it.

1 Introduction

Radioactive wastes are classified according to various standards. As illustrated in Fig. 1, the radioactive wastes can be classified into six different classes based on the half-life time of radioactive wastes (IAEA 2009). High level radioactive wastes need advanced disposal system to keep them away from people and environment as

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radioactive wastes emit heat for very long time. It has been widely accepted that deep geological repository is a safe solution for high level radioactive wastes in many countries. The concepts and designs of deep geological repositories are still being discussed in many parts of the world.

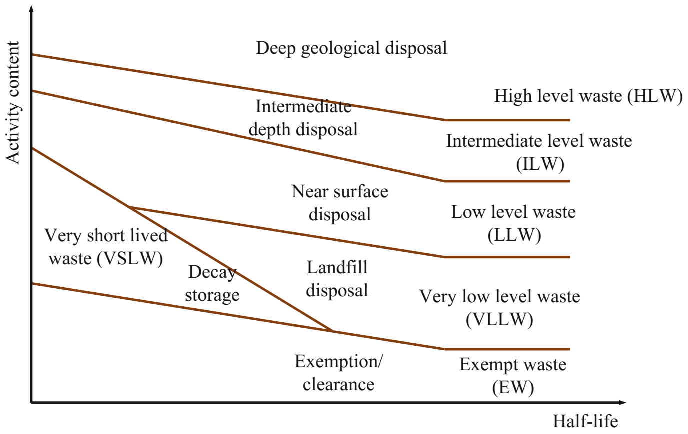

Fig. 1. A conceptual illustration of the radioactive waste classification (inspired by IAEA 2009)

The basic features of deep geological repository are shown in Fig. 2. As illustrated in Fig. 2, a deep geological repository is constructed in a deep stable hard rock. It could be several hundred meters below the ground surface. The nuclear wastes are stored in canisters either in horizontal drifts or vertical boreholes. As a part of the multi-barrier system, the buffer material is used to protect the radioactive wastes being infiltrated into the outside environment as illustrated in Fig. 2. The engineered barrier system is constructed by an expansive soil to allow swelling such that any voids can be filled by the buffer material. There have been various types of clayey soil discussed as potential buffer material in many countries. In Europe, MX-80 has widely been selected as a buffer material (Herbert and Moog 1999; Nakashima 2006; Hurel and Marmier 2010). In China, Gaomiaozi (GMZ) bentonite has recently been proposed as a potential buffer material (Ye et al. 2009). In Japan, Kunigel VI bentonite has been studied as a possible buffer material (Komine and Ogata 2004; Imbert and Villar 2006).

An engineered barrier provides various purposes including the mechanical stability for the waste canisters, serving as a buffer around it, sealing discontinuities in the boreholes and delaying water infiltration from the host rock (Ye et al. 2014). Bentonite-type materials are generally selected as a buffer material for an engineered barrier system because of its high swelling capacity, low permeability, micro-porous structure and good sorption properties (Pusch 1992; Komine and Ogata 1994). The buffer material during the construction and early stage of a deep geological repository remains unsaturated due to low water content. However, in its running time, water could infiltrate into the buffer material, and thus makes it saturated or partially-saturated. It could be several hundred or thousand years due to low permeability of the host rock. Swelling and permeability characteristics of bentonite materials have been studied in greater capacity compared to strength properties of bentonite-based buffer material (Cui et al. 2008; Schanz et al. 2010; Wang et al. 2012). In this study, we investigated the influence of water content and dry density on deformation and suction behaviour of sand-bentonite buffer material.

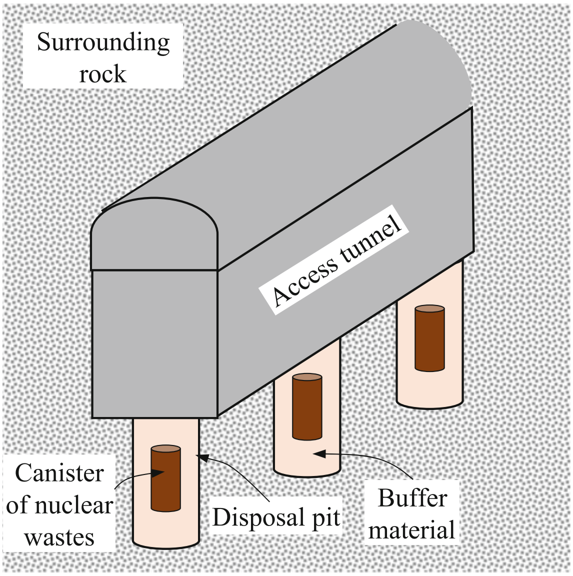

Fig. 2. A schematic diagram of a deep geological repository

2 Materials and Testing Program

The buffer material is prepared using 70% of bentonite and 30% of sand (by mass-based). This ratio has been accepted as a possible buffer material for the deep geological repositories in Japan (Mitachi 2008). The sodium-type bentonite contains around 48% of montmorillonite, which is an essential mineral for sealing properties. Kunigel VI also consists of quartz, which is an important mineral for thermal conductivity (Tang et al. 2008). The mineral compositions of Kunigel VI bentonite are given in Table 1. The index properties of bentonite and silica sand are given in Table 2. The grain size distribution of sand is shown in Fig. 3.

Table 1. Mineral compositions of Kunigel VI bentonite (Cui et al. 2008)

Mineral	Amount (%)
Montmorillonite	46–49
Pyrite	0.5–0.7
Calcite	2.1–2.6
Dolomite	2.0–2.8
Analcite	3.0–3.5
Feldspar	2.7–5.5
Quartz	29–38
Field organic	0.31–0.34

Table 2. Index properties of Kunigel VI bentonite and silica 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
Mean grain size, D_{50} (mm)	n/a	0.230
Coefficient of curvature, C_c	n/a	0.865
Coefficient of uniformity, C_u	n/a	2.200

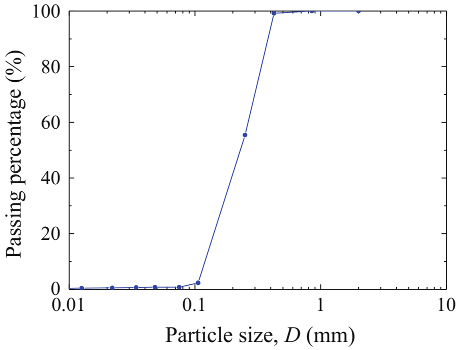

Fig. 3. Particle size distribution of sand

2.1 Triaxial Compression Test

The specimens for triaxial compression tests were prepared with 6, 12 and 18% of water content and 1400, 1600 and 1800 kg/m^3 of dry density. Two identical specimens of each condition were prepared for triaxial compression tests as the tests were performed under 0.1 and 1.0 MPa of confining pressure. First, pre-determined amount of sand and bentonite are mixed. Then, water is added to the sand-bentonite mixture using a high-pressurised sprayer, and simultaneously mixed water and the sand-bentonite mixture. As bentonite absorbs water and could make larger particles, water should be spread uniformly and mixed quickly. Then, the sand-bentonite mixture is put into the mold shown in Fig. 4a. The soil is placed in three layers, and each layer is given a hand compaction by a small tool shown in Fig. 4a. Then, it is compressed by a hydraulic jack shown in Fig. 4b. A prepared specimen is shown in Fig. 4c. Once the specimen reaches its pre-defined height (around 80 mm), it is removed from the mold by applying a hydraulic force. It is important to note that, height of the specimen again reduces slightly here. However, the reduction in height is affected by water content and dry density because the cohesion between the surfaces of the mold and the specimen is influenced by water content and dry density. Therefore, ± 2% difference in the design dry density and measured dry density is accepted for dry density. Finally, after trimmed both ends (roughly by 5 mm each), a specimen of 70 mm high and 35 mm diameter is prepared. A difference of ±5 is accepted for water content as it is measured by three disks of 20 g each (from roughly 170–220 g of the sand-bentonite mixture). Table 3 includes the details of the specimens prepared for triaxial compression tests. In Table 3, the measured values are reported.

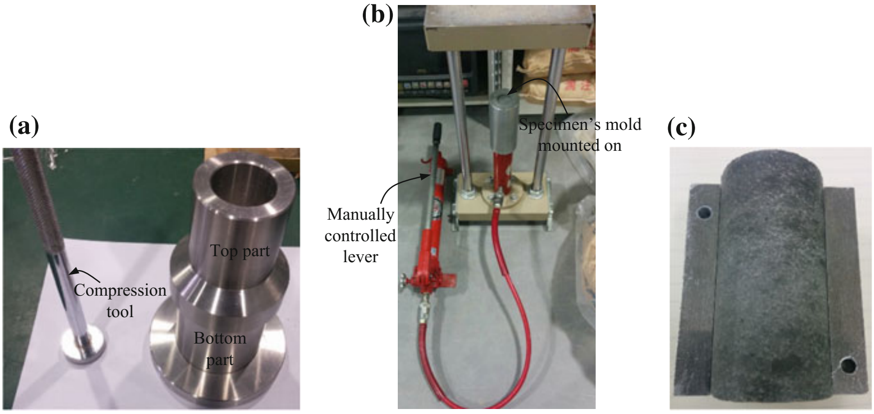

Fig. 4. The sample preparation: **a** the mold and its compaction tool, **b** hydraulic jack and **c** a prepared specimen

Triaxial compression test is performed using the newly built double-cell type triaxial testing apparatus shown in Fig. 5. The triaxial compression tests were performed under unconsolidated undrained condition. The specimens are covered with a 3 mm thick rubber membrane. The testing apparatus is designed such that the confining pressure applied to the outer cell also applies to the inner cell, in which the specimen is mounted. The volume change of specimens is measured by a burette attached to it as shown in Fig. 5. The shearing load is applied with a loading rate of 0.1%/min. The load is applied by a Mega-torque motor. The triaxial compression tests are performed based on the Japanese standards (JGS 2009).

Table 3. The details of the specimens for triaxial compression tests

Specimen notation	Water content, w (%)	Total density, ρ_t (kg/m^3)	Dry density, ρ_d (kg/m^3)	Degree of saturation, S_r (%)	Void ratio (e)
TT_6_1800_0.1	7.16	1925	1796	37.4	0.524
TT_6_1800_1.0	5.83	1900	1795	30.4	0.525
TT_12_1800_0.1	13.13	2029	1793	68.3	0.526
TT_12_1800_1.0	11.90	2021	1806	63.2	0.515
TT_18_1800_0.1	17.52	2084	1773	88.2	0.543
TT_18_1800_1.0	18.05	2101	1780	91.9	0.537
TT_6_1600_0.1	6.78	1681	1574	25.1	0.739
TT_6_1600_1.0	5.99	1688	1593	22.8	0.718
TT_12_1600_0.1	13.26	1778	1570	48.8	0.744
TT_12_1600_1.0	12.26	1791	1595	46.9	0.715
TT_18_1600_0.1	18.20	1889	1598	69.9	0.712
TT_18_1600_1.0	17.81	1894	1608	69.4	0.702
TT_6_1400_0.1	5.63	1460	1382	15.7	0.980
TT_6_1400_1.0	5.55	1473	1396	15.8	0.961
TT_12_1400_0.1	11.20	1554	1398	32.0	0.958
TT_12_1400_1.0	12.08	1562	1393	34.3	0.964
TT_18_1400_0.1	17.04	1689	1443	52.0	0.897
TT_18_1400_1.0	17.40	1603	1365	47.4	1.004

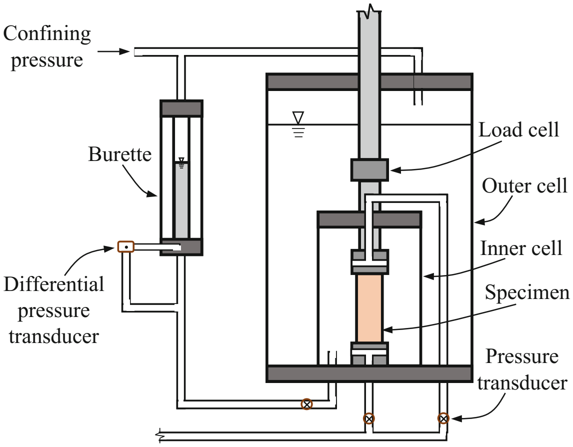

Fig. 5. A schematic diagram of the double-cell type triaxial testing apparatus

2.2 Total Suction

In addition to the specimens prepared for triaxial compression tests, identical specimens were also prepared for suction measurements. Then, a small piece around the half size of the sample cup is prepared from the specimen of 70 mm high and 35 mm diameter. When a sample is placed on the sample cup and inserts into the chamber, it starts to equilibrate with the headspace of the sealed chamber. Total suction is measured using the Dewpoint PotentiaMeter (WP4C) shown in Fig. 6. The device has a digital display to read the measurements. Total suction is measured using the chilled mirror hygrometer technique (Agus et al. 2010). The temperature of samples should be managed such that the temperature difference between a sample and the chamber should ideally be within 0 and −0.5 °C (it should always be negative). Suction measurements were also obtained on the specimens tested in triaxial compression tests.

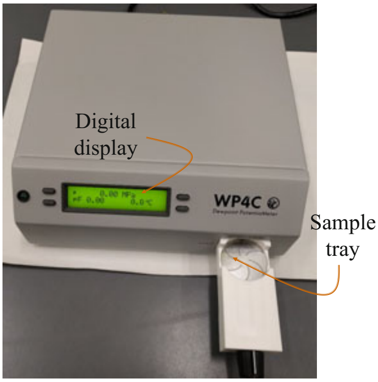

Fig. 6. The suction measurement device

3 Results and Discussion

Figures 7 and 8 show the influence of water content and dry density on stress-strain behaviour of sand-bentonite buffer material under a small (i.e., 0.1 MPa) and high confining pressure (i.e., 1.0 MPa) respectively. Figures 7 and 8 clearly indicate that water content decreases deviator stress while dry density increases it. Thus, it suggests that the buffer material of a deep geological repository reduces its strength after several years; could be several hundreds of thousands, when the local groundwater flow makes into the buffer material through the impermeable host rock. As indicated in Fig. 7a–c, water content also changes strain-softening behaviour of relatively dry specimen into strain-hardening behaviour under a small confining pressure regardless of dry density. Thus, the buffer material of a deep geological repository mainly yields strain-hardening behaviour in its long life time. Under a high confining pressure, as shown in Fig. 8a–c, many specimens yield strain-hardening behaviour compared to a small confining pressure. Therefore, the buffer material of a deep geological repository constructed in deep ground simply yields strain-hardening behaviour. We can see only the specimen of low water content (e.g., around 6%) and high dry density (i.e., 1800 kg/m^3) yields strain-softening behaviour under a high confining pressure. Thus, less likelihood of such behaviour in a deep geological repository in its long-term life cycle. The results also indicate that buffer materials of high water content under high confining pressure exhibit large deformations before shear failure as proven by strain-hardening behaviour in Figs. 7 and 8.

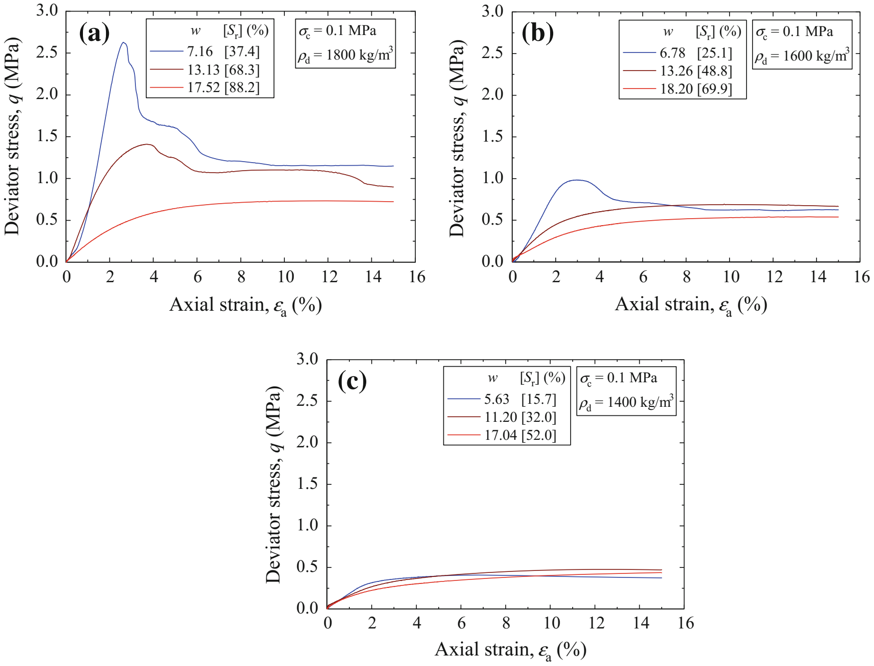

Fig. 7. The influence of water content and dry density on stress-strain behaviour under **a** 1800, **b** 1600 and **c** 1400 kg/m^3 of dry density and a small confining pressure, σ_c of 0.1 MPa (w is water content, S_r is degree of saturation and ρ_d is dry density)

Figures 9 and 10 show the influence of water content and dry density on the volumetric strain behaviour under a small and high confining pressure respectively. Under a small confining pressure (of 0.1 MPa), water content increases volumetric expansion as illustrated in Figs. 9a–c. In contrast, dry density discourages volumetric expansion. The results further indicate that a highly compacted specimen (e.g., 1800 kg/m^3 of dry density) encourages volumetric contractions, particularly until the specimens become fully saturated. When the specimens become full saturated, volumetric expansion appears as shown in Fig. 9a. Under a high confining pressure (of 1.0 MPa), the specimens yield only volumetric expansion as shown in Fig. 10a–c. It is also worth to note that unlike a small confining pressure (of 0.1 MPa), the highest water content (of 18%) does not yield the largest volumetric expansion as depicted in Fig. 10a–c. In fact, the specimens of around 12% water content yield the largest volumetric expansion under a high confining pressure. The results further indicate that dry density decreases the magnitude of volumetric expansion as indicated in Fig. 10a–c (except the sole specimen of 12% water content and 1800 kg/m^3 of dry density shown in Fig. 10a. This case needs to be further studied as it behaves differently to other specimens). Volumetric expansion is a key parameter in designing a deep geological repository as the buffer material should expand to occupy any voids made by chemical reactions of the radioactive wastes. A low dry density would increase volumetric expansion, but it would also reduce the strength as illustrated in Figs. 7 and 8. Therefore, the results suggest that dry density should be carefully designed along with the confining pressure (influenced mainly by the depth) and water content of the buffer material, which is mainly influenced by the initial water content of bentonite and permeability characteristics of the host rock.

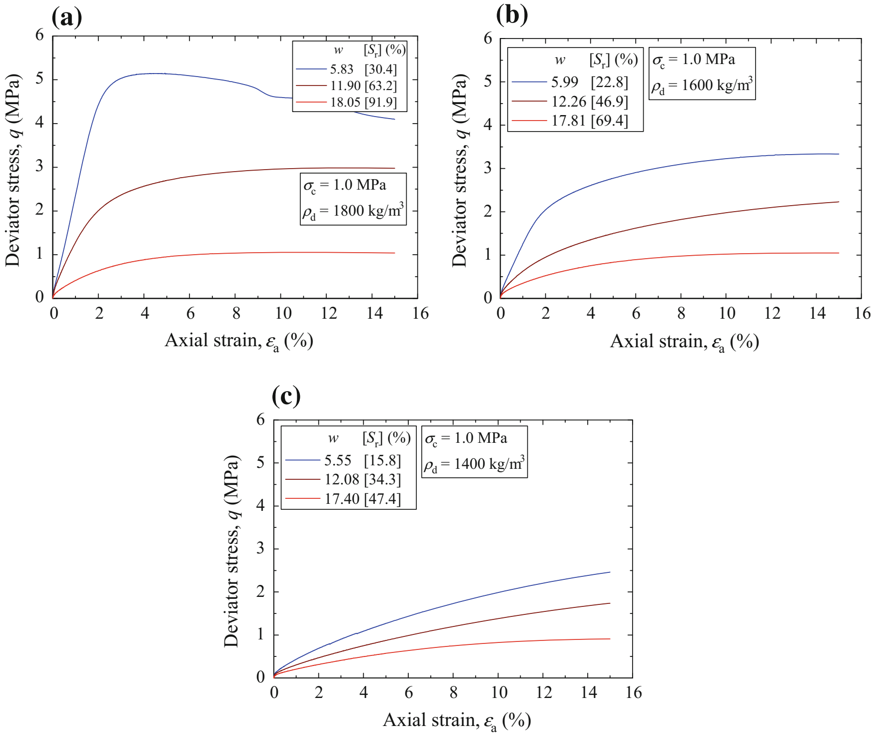

Fig. 8. The influence of water content and dry density on stress-strain behaviour under **a** 1800, **b** 1600 and **c** 1400 kg/m^3 of dry density and a high confining pressure, σ_c of 1.0 MPa (w is water content, S_r is degree of saturation and ρ_d is dry density)

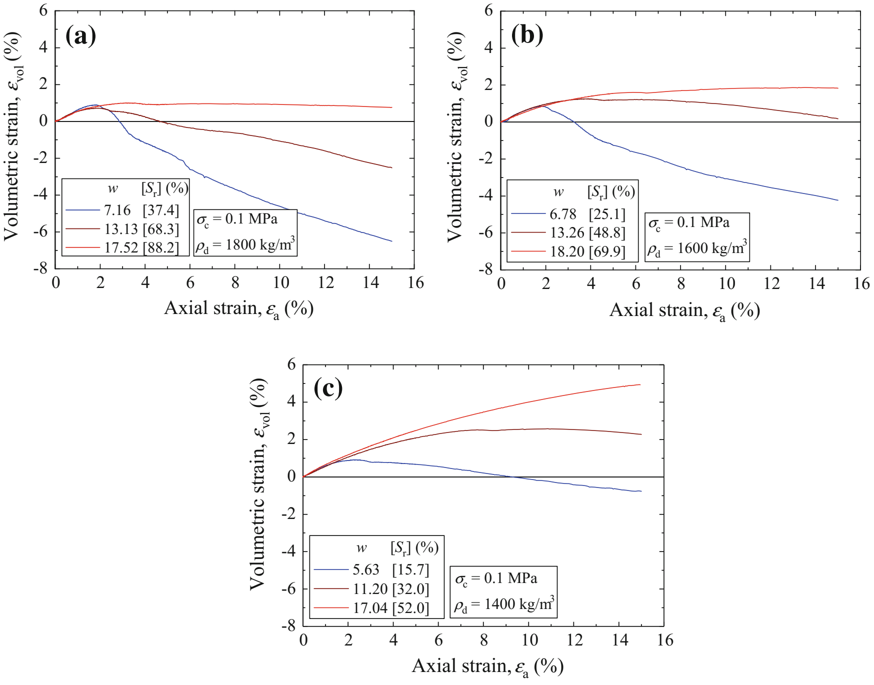

Fig. 9. The influence of water content and dry density on volumetric strain behaviour under **a** 1800, **b** 1600 and **c** 1400 kg/m^3 of dry density and a small confining pressure, σ_c of 0.1 MPa (w is water content, S_r is degree of saturation and ρ_d is dry density)

The strength parameters were evaluated using the Mohr Coulomb failure criteria. Figure 11 illustrates a typical Mohr stress circle. In Fig. 11, the data from an additional triaxial compression test under 0.5 MPa of confining pressure is also included to confirm the accuracy of the Mohr Coulomb failure criterion from two specimens. Figure 12a, b illustrate the variations of cohesion and internal friction angle with water content and dry density. Figure 12a depicts a highly compacted specimen (e.g., of 1800 kg/m^3 of dry density) reduces its cohesion with water content. In contrast, relatively less compacted specimens (e.g., of 1600 and 1400 kg/m^3 of dry density) increase cohesion with water content. A micro-level analysis would give more insights as water seems to produce bigger particles upon bentonite absorbing water. As shown in Fig. 12b, internal friction decreases with water content, and at highly wet specimens (e.g., water content of around 18%), there is no big variation due to dry density. In fact, both 1600 and 1800 kg/m^3 dry densities exhibit similar frictional angles under all water contents. Figure 13 illustrates the variation of compressive strength with water content and dry density. Except the specimens of loosely compacted (i.e., 1400 kg/m^3 of dry density) under a small confining pressure (of 0.1 MPa), all other specimens indicate both water content and dry density reduce the compressive strength. The loosely compacted specimen under a small confining pressure seems to slightly increase compressive strength with water content up to 12%, and then slightly reduces. In Fig. 13, the ultimate strength in strain-softening specimens and peak strength in strain-hardening specimens are considered as the compressive strength.

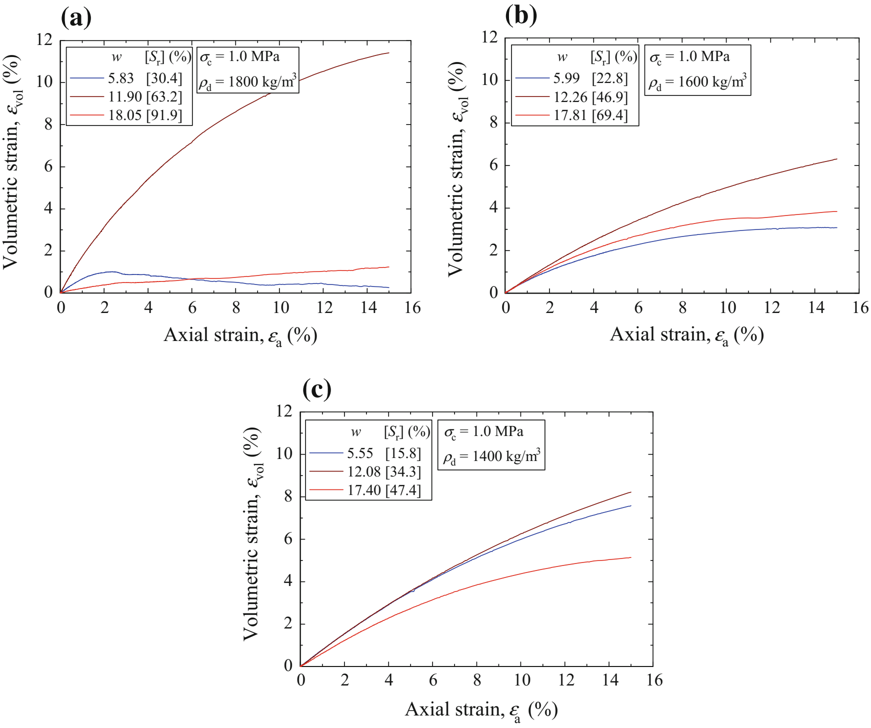

Fig. 10. The influence of water content and dry density on volumetric strain behaviour under **a** 1800, **b** 1600 and **c** 1400 kg/m^3 of dry density and a high confining pressure, σ_c of 1.0 MPa (w is water content, S_r is degree of saturation and ρ_d is dry density)

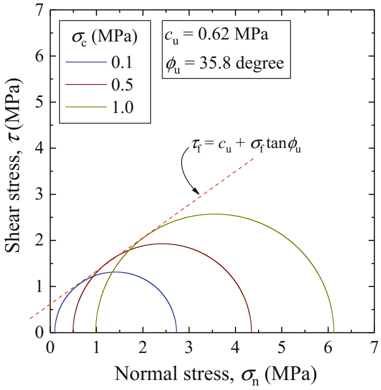

Fig. 11. A typical Mohr circle and its failure criteria (of 6% of water content and 1800 kg/m^3 of dry density)

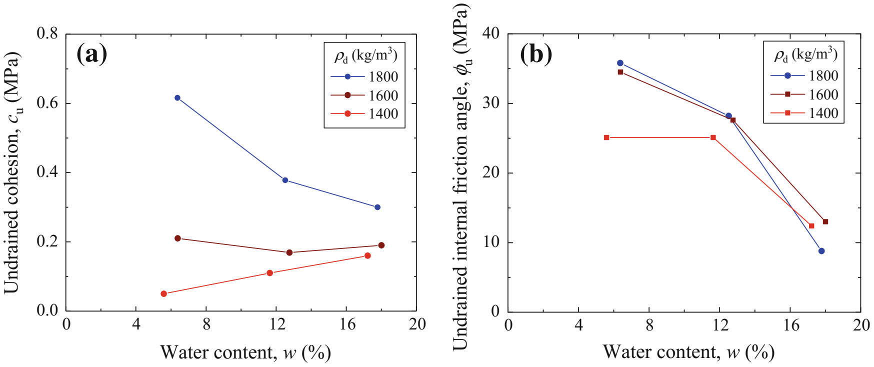

Fig. 12. The influence of water content and dry density, ρ_d on **a** cohesion and **b** internal friction angle

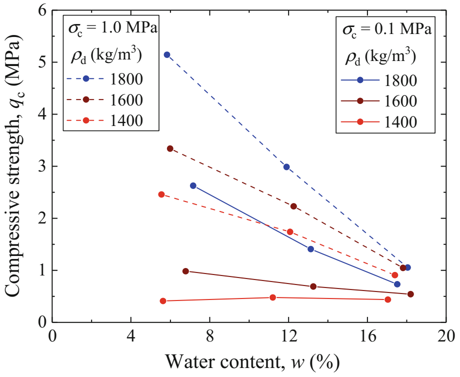

Fig. 13. The influence of water content and dry density on compressive strength

Figure 14 shows the variation of total suction with water content and dry density. The results clearly indicate that total suction drastically decreases with water content. However, dry density does not affect total suction. Also, it indicates that there is no effects of confining pressure on total suction or any effects from shear loading from triaxial compression tests. This is an important observation as it hints that suction of a buffer material is not affected by the depth (i.e., confining pressure) or loading. Thus, an earthquake might not change suction properties of the buffer material of a deep geological repository. However, more studies are needed before concrete conclusions are drawn on this.

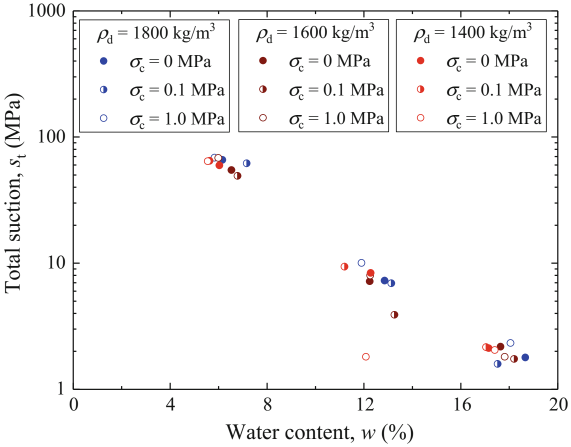

Fig. 14. The influence of water content and dry density, ρ_d on total suction (σ_c is confining pressure; 0.1 and 1.0 of it means the s_t measurements after triaxial tests)

4 Conclusions

In this study, triaxial compression tests and suction measurements were performed on sand-bentonite buffer material of deep geological repository. The buffer material was prepared with 6, 12 and 18% of water content and 1400, 1600 and 1800 kg/m^3 of dry density. The following conclusions are drawn from the study.

Water content decrease deviator stress while dry density increases it under both a small (0.1 MPa) and high confining pressure (1.0 MPa). The results also indicate that the specimens of less water content and high dry density under a small confining pressure yield strain-softening behaviour. In contrast, highly compacted specimens of high water content yield strain-hardening behaviour. Under a high confining pressure, all the specimens except very low water content and high dry density yield strain-hardening behaviour. In contrast, highly compacted specimen of less water content yields strain-softening behaviour under a high confining pressure.

Under a small confining pressure, water content encourages volumetric expansion. Thus, the specimens of high water content yield volumetric expansion whereas the specimens of low water content exhibit volumetric contraction. Under a high confining pressure, all specimens yield volumetric expansion. The results also indicate that irrespective of confining pressure, dry density reduces the magnitude of volumetric expansion.

Water content reduces the internal friction angle while dry density has less effects on internal friction angle. In fact, irrespective of dry density, the specimens of high water content (e.g., around 18%) tend to produce similar internal friction angle. Therefore, it would suggest dry density has less effects on frictional behaviour of a buffer material after several thousand years. In contrast, except high dry density (e.g., 1800 kg/m^3), water content increases cohesion. Therefore, it suggests after a long time, a buffer material might have similar cohesion irrespective of dry density. However, under a high dry density (e.g., 1800 kg/m^3) water content reduces cohesion.

The compressive strength of buffer material also indicates that the effects of dry density on it diminish when water content is high as it approaches a similar value under high water content. Therefore, it suggests that a high dry density such as 1800 kg/m^3 is not necessary to maintain a high compressive strength when a buffer material is infiltrated by local groundwater flow.

The results of total suction indicates that while water content drastically reduces total suction, dry density has no effects on total suction. The results also suggest that confining pressure has no effects on total suction, which would indicate that an earthquake might have no effects on suction behaviour. However, it needs further studies to draw concrete conclusions on this.

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