Wetting Characteristics of Compacted Bentonites at Large Applied Suctions

Claire L. Bennett, Snehasis Tripathy, and Hywel R. Thomas

Abstract. The wetting suction-water content soil-water characteristic curves of two bentonites (MX80 and Yellow) were experimentally established using vapour equilibrium technique for a suction range of 3.0 to 300.0 MPa. Compacted bentonites specimens were prepared by statically compacting bentonite powder at targeted densities of 1.2, 1.3, and 1.4 Mg/m^3. The bentonite specimens still within the specimen rings were equilibrated at several relative humidities in test desiccators at zero applied stress. The test results clearly showed that the influence of compaction dry density on the wetting characteristics of the bentonites was insignificant for the entire range of suction considered. On the other hand, the chemical properties of the bentonites influenced the equilibrium water contents.

Keywords: suction, soil-water characteristic, bentonite, swelling.

1 Introduction

Bentonites have numerous industrial uses (Alther 2004, Lagaly & Ziesmer 2004), but have attracted particular interest in specific fields of application, such as landfill cover lining systems and underground toxic waste disposal repositories. The low permeability and high swelling ability of bentonites prevent pollutants and leachate from permeating through the engineered barrier systems into the surrounding environment.

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A detailed understating of the hydration processes and the water uptake capacities of compacted bentonites are required in order to assess their behaviour in placement conditions.

The wetting suction-water content soil-water characteristic curves of two bentonites were experimentally determined for laterally confined condition and at zero applied stress. The effects of compaction dry density and the exchangeable cation type on the equilibrium water contents of the bentonites were studied.

2 Background

Bentonites are clays that are composed of mineral crystals of montmorillonite commonly arranged in stacks of several unit layers. Swelling of bentonites occurs in two stages; crystalline swelling and osmotic swelling (van Olphen 1963). Crystalline swelling is a step-wise process of the adsorption of discrete water layers between dry clay platelets (Grim 1968). Hydration of the exchangeable cations and of the exposed clay surfaces occurs at low water contents, whereas osmotic phenomenon is more effective at high water contents (Schanz & Tripathy 2009).

Water vapour transfer within compacted soils generally occurs under thermal, thermo-hydraulic, and hydraulic gradients. Under an applied thermal or thermo-hydraulic gradient, an equilibrium is attained in which the water content of soil increases with an increasing distance from the drying front, whereas it decreases with an increasing distance from the wetting front. Swelling upon adsorption of water vapour is significant in the case of bentonites. Studies on the water adsorption characteristics of homo-ionised bentonites equilibrated at various relative humidities have been well researched in the past (Grim 1968, Likos & Lu 2006). However, studies on the influence of compaction conditions on the water adsorption behaviour of bentonites containing mixture of various exchangeable cations are scarce in the literature.

Keren & Shainberg (1975) stated that at low water contents or high suctions, the adsorption energy of the water is the main driving force responsible for the crystalline swelling in bentonites. An increase in the interlayer space in bentonites occurs while overcoming two attractive forces, such as an electrostatic attraction between the negatively charged clay platelets and the exchangeable cations and van der Waals forces of attraction between the clay platelets. The net effect of the hydration energy and the attraction energies along with the changes in the water phase, lattice geometry and position of the cations influence the amount of water adsorbed by a bentonite.

The amount of water vapour adsorbed by Ca-bentonite has been shown to be greater than Na-bentonites within a relative humidity range of 0 to 85.0% (Grim 1968, Keren & Shainberg 1975, Likos & Lu 2006). Keren & Shainberg (1975) stated that in Ca-bentonites, the energy of interaction between the negatively charged surfaces of clay platelets and first mono-layer of water molecules adsorbed is greater than the energy of condensation of the subsequent layers, whereas in Na-bentonite, the difference between these two energy terms is less, indicating that the hydration forces in Na-bentonite are less than those in Ca-bentonite.

Meleshyn & Bunnenberg (2005) stated that a demixing of divalent and sodium cations occurs in the interlayer spaces of a sodium-rich/magnesium-poor montmorillonite, and such a demixing strongly changes the swelling behaviour of bentonites. Likos & Lu (2006) showed that for a range of void ratio of 0.65 and 1.35, Ca-bentonite exhibited greater axial deformations as compared to Na-bentonite at a relative humidity of 93.0%.

3 Materials and Methods

Two commercially available bentonites were selected for the current study: MX80 bentonite, from Wyoming, and Yellow bentonite, from Greece. The total and fractional cation exchange capacities of the bentonites were determined. The exchangeable cations present in MX80 bentonite were found to be sodium (51.24 meq/100g), calcium (28.24 meq/100g), and magnesium (9.43 meq/100g). A majority of exchangeable cations in Yellow bentonite were found to be calcium and magnesium (63.42 and 12.97 meq/100g) with a small fraction of sodium ions (7.66 meq/100 g). The properties of the bentonites used are presented in Table 1.

Table 1. Properties of the bentonites.

Properties	MX80 bentonite	Yellow Bentonite
Specific gravity of soil solids, G_s	2.80	2.84
Liquid limit, w_L (%)	437.0	135.0
Plastic limit, w_P (%)	63.0	58.0
Shrinkage limit, w_S (%)	12.2	13.6
Specific surface area, S (m^2/g)	676.0	797.0
Cation exchange capacity, B (meq/100g)	90.31	84.91
Weighted average valency, v	1.42	1.90

The initial water content of Yellow bentonite (17.6%) was found to be greater than that of MX80 bentonite (9.8%). The wetting suction-water content soil-water characteristic curves of the bentonites were established using vapour equilibrium technique. In total six saturated salt solutions were considered (ASTM E 104-85, 1998). The saturated salt solutions generated relative humidities between 11.0 and 98.0% (Table 2). The total suction is related to the relative humidity by Kelvin's law. The applied suction varied between 3.3 and 294.8 MPa.

Compacted bentonite specimens were prepared by statically compacting bentonites powder at hygroscopic water contents in thick-walled stainless steel specimen rings in a single lift to targeted dry densities of 1.2, 1.3, and 1.4 Mg/m^3. The diameter and height of the specimens were 45.0 mm and 8.0 mm, respectively. The bentonite specimens, still within the specimen rings, were equilibrated at several relative humidities in the test desiccators at zero applied stress. Additionally, powder specimens of the bentonites were also tested for comparison. The laboratory tests were carried out in a temperature controlled laboratory at 20 ^{0}C.

Table 2. Details of the saturated salt solutions used in this study.

Salt	Relative humidity (%), at 20^{0}C	Suction (MPa)
Potassium Sulphate (K_2SO_4)	97.6 ± 0.5	3.3
Potassium Nitrate (KNO_3)	94.6 ± 0.7	7.5
Potassium Chloride (KCl)	85.1 ± 0.3	21.8
Sodium Chloride (NaCl)	75.5 ± 0.1	38.0
Potassium Carbonate (K_2CO_3)	43.2 ± 0.3	113.3
Lithium Chloride (LiCl)	11.3 ± 0.3	294.8

The equilibration time was found to be less than two months in all tests. In general, the equilibration time reduced with a decrease in the relative humidity. Typical elapsed time versus water content test results for Yellow bentonite specimens are shown in Fig. 1. The test results are for a dry density of 1.4 Mg/m^3.

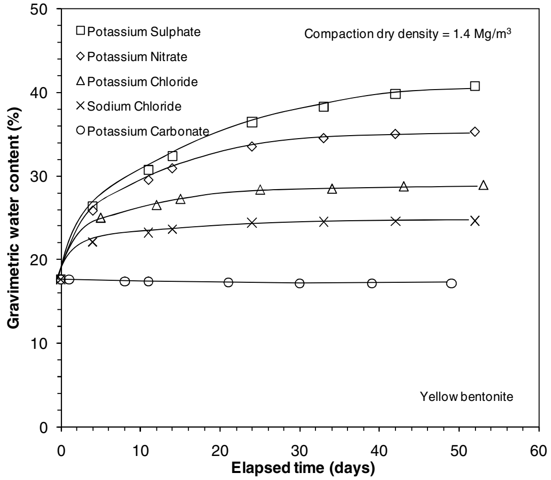

Fig. 1. Typical vapour equilibrium test results for Yellow bentonite specimens.

4 Results and Discussion

The wetting suction-water content soil-water characteristic curves for MX80 and Yellow bentonites are presented in Fig. 2. Fig. 3 presents the test results in a semi-*log* plot. The test results clearly showed that the gravimetric water contents for

Yellow bentonite were considerably greater than that of MX80 bentonite at all suctions considered in this study. This occurred primarily due to greater fractions of divalent cations present in Yellow bentonite as compared to MX80 bentonite. Additionally, the influence of compaction dry density on the equilibrium water contents of the bentonites was found to be negligible. Some minor differences were noted between the test results of the powder specimens and the compacted specimens, particularly at smaller applied suctions (< 21 MPa) and can be attributed to microstructural differences between the powder and compacted specimens.

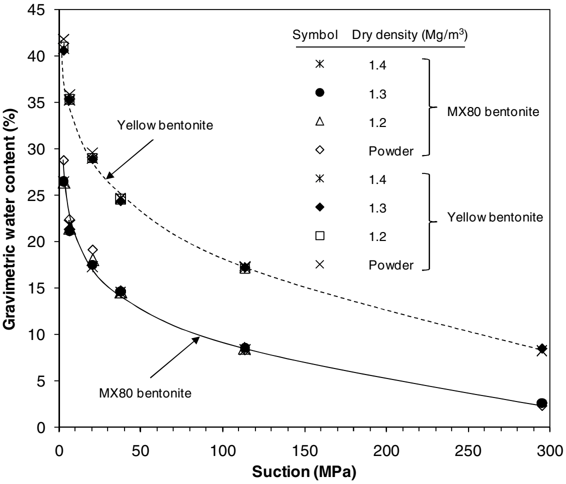

Fig. 2. Wetting suction-water content soil-water characteristic curves of the bentonites.

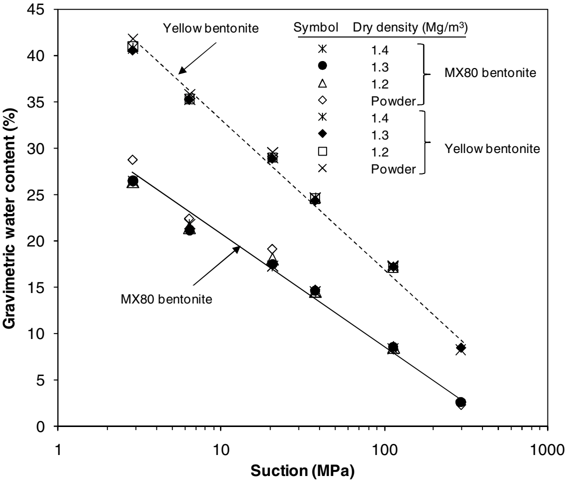

Fig. 3. Wetting soil-water characteristic curves of the bentonites (semi-*log* plot).

The suction-water content soil-water characteristic curves of the bentonites (Fig. 2) were found to be concave upward, similar to that which has been observed for Ca-bentonite (Keren & Shainberg, 1975). This indicates that the energy of interaction between the first mono-layer of water molecules adsorbed and the negatively charged surfaces in both cases were similar, with only difference being the magnitude of hydration force. In a semi-*log* plot the wetting suction-water content soil-water characteristics exhibited near-linear relationships (Fig. 3).

5 Conclusions

The water adsorption characteristics of two bentonites were investigated for a range of suction of 3.0 to 300.0 MPa. Compacted bentonites specimens with dry densities of 1.2, 1.3, and 1.4 Mg/m^3 and powder specimens of the bentonites were allowed to equilibrate at several relative humidities in vapour equilibrium tests. The test results showed that the effect of dry density had negligible impact on the water uptake behaviour of the bentonites. The divalent-rich Yellow bentonite demonstrated greater water uptake capacity than the Na-rich MX80 bentonite. The difference in the water adsorption behaviour of the bentonites is primarily due to the difference in the adsorption energy.

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