Chemico-osmotic behaviour of a modified "Multiswellable" bentonite

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Abstract — The potential for membrane behaviour of a chemically modified bentonite (MSB) is evaluated. Test results showed that MSB exhibited initial membrane behaviour. However, the membrane behaviour was gradually destroyed in the presence of a 0.005 M CaCl$_2$ solution. Conversely, the impact of the 0.005 M CaCl$_2$ solution on the hydraulic conductivity of MSB is shown to be mild.

Keywords — Chemico-osmosis, impermeable liners, "multiswellable" bentonite, permeability

I. INTRODUCTION

LOW permeability clayey soils (e.g., bentonites) have been shown to behave as semipermeable membrane, i.e., restrict the movement of solutes while allowing the flow of water in direction opposed to the chemical gradient (chemical osmosis).

In the case of charged solutes, membrane behaviour is generally attributed to electrostatic repulsion of the ions by electric fields generated by the overlapping diffuse double layers of closely spaced clay particles. The osmotic behaviour may be altered by the migration of solutes that cause double layer compression, e.g., multivalent ions and/or high electrolyte concentrations (Mazzieri et al., 2003; Shackelford and Lee, 2003). Typically, multivalent ions also increase the permeability of clayey soils.

The proposed paper deals with the behaviour of a modified "Multiswellable" bentonite (MSB, Hojun Corp., Japan), obtained by treating natural sodium bentonite with an organic polymer (propylene carbonate). It has been proven that MSB exhibits higher swelling capacity and lower hydraulic conductivity values than untreated bentonite (Katsumi et al., 2001).

II. MATERIALS AND METHODS

A. Multiswellable bentonite

Onikata et al. (2000) showed that propylene carbonate (PC) forms complexes with montmorillonite by intercalation, and that the PC-montmorillonite complexes exhibit osmotic swelling even in concentrated aqueous electrolyte solutions. MSB is composed by 80 % Na-bentonite and 20 % PC on dry weight basis.

B. Testing apparatus and procedures

The chemico-osmotic test was carried out by means of the testing apparatus described in Mazzieri et al. (2003). The complete set-up consists essentially of two main parts: the pumping system and the testing cell (Fig. 1).

The pumping system is used to circulate solutions of different concentrations of an electrolyte at either end of the soil specimen in order to induce a chemical gradient across the soil. No fluid flow occurs across the soil. In the presence of osmotic behaviour, a differential pressure arises across the soil sample, measured by means of the differential pressure transducer (Fig. 1). The steady-state osmotic efficiency coefficient can be calculated as follows:

$$\omega = \frac{\Delta P}{\Delta \Pi}$$  \hspace{1cm} (1)

Where $\Delta P$ is the measured differential pressure and $\Delta \Pi$ is the osmotic pressure difference according to the van’t Hoff’s equation, which can be calculated by measuring the steady-state concentration gradient.

A 0.005 M CaCl$_2$ solution was selected as the electrolyte solution to be infused at the top of the specimen during the chemico-osmotic stage. Free swell tests (ASTM D5890) were preliminarily conducted in DW and 0.005 M CaCl$_2$ to observe the impact of the electrolyte on the swelling behaviour of MSB. The MSB specimen was prepared by spreading a thin layer of dry MSB (0.45 g dry solids/cm$^2$) into the lower mould. The mould was then inundated with DW and the MSB specimen allowed to saturate and swell freely to a height of about 10 mm.

The electrolyte solution was circulated at the top end of the specimen until the steady state. Permeation with 0.005 M CaCl$_2$ finally carried out in order to assess the impact of the electrolyte solution on the hydraulic conductivity of MSB.
B. Chemico-osmotic efficiency

The results of the chemico-osmotic test are illustrated in Figure 2. During circulation of the 0.005 M CaCl₂ solution caused an immediate increase of the differential pressure to a peak value of 7.3kPa. Thereafter, the differential pressure gradually dropped to a steady state value close to ΔP₀.

The osmotic efficiency can be calculated using Eq.(1) at steady state (ss). MSB initially exhibited membrane behaviour, that was gradually destroyed during the test (Fig. 2). The results obtained qualitatively resemble previous findings on untreated bentonites (Shackelford and Lee, 2003).

The impact of solute diffusion in the present study can be assessed by the analysis of concentrations of Ca²⁺ and Cl⁻ in the outlet solutions over time (Fig. 2).

The results suggest that migration of Ca²⁺ into the MSB caused compression of the membrane layers as a result of increased pore water concentration and cation valence. The results obtained on MSB are qualitatively very similar to those obtained on untreated Na-bentonite.

C. Permeability

Hydraulic conductivity of the MSB was measured with DW during the flushing phase and with 0.005 M CaCl₂ after the chemico-osmotic phase. The hydraulic conductivity k of MSB in DW was 1.0 · 10⁻¹¹ m/s, whereas in 0.005 M CaCl₂, k increased to about 6.9 · 10⁻¹¹ m/s.

The increase in hydraulic conductivity tends to support the interpretation of chemico-osmotic test proposed above, since at constant porosity, compression of the double layers caused by diffusion of Ca²⁺ into the soil results in increase of the pore space available to ions and water transport.

Katsumi et al. (2001) performed permeability tests on MSB and with DI and CaCl₂ solutions ranging from 0.1M to 0.5M. The MSB was of slightly different composition from the type used in this study (25 % PC vs. 20 % PC) and the specimens contained 0.79 g/dry solid/cm². They found k = 1.5 · 10⁻¹¹ m/s with DI, that is very similar to value k = 1.0 · 10⁻¹¹ m/s obtained in this study with DW. However, they obtained k = 2 · 10⁻¹¹ m/s with 0.1 M CaCl₂ and k = 7 · 10⁻¹¹ m/s with 0.3 M CaCl₂.

IV. Conclusions

Test results showed that MSB exhibited initial membrane behaviour. The membrane behaviour was gradually destroyed as a result of salt migration into the MSB. An electrolyte solution 0.005 M CaCl₂ was sufficient to destroy the membrane behaviour. In analogy with untreated bentonite, MSB appears unable to sustain membrane behaviour in the presence of Ca²⁺ ions. Nonetheless, more research is warranted to extend this conclusion to different solutes and to different porosities of MSB. It is noteworthy to mention that the hydraulic conductivity, that represents the major concern in pollutant containment problems, increased only slightly in the presence of CaCl₂.

Therefore, the use of MSB in containment application remains very promising.

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