Technical note

The role of physical pretreatments on the hydraulic conductivity of natural sodium bentonites

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ABSTRACT

The role played by physical pretreatments applied to sodium bentonites, such as pre-hydration, pre-consolidation and pore water salt removal, has been analyzed in this technical note looking at the results of a series of hydraulic conductivity tests that have been carried out using both deionized water (DW) and a calcium chloride solution (CCS) as permeants. Moreover, the effect of the presence of needling across the bentonite layer has also been investigated.

The DW and CCS have been used in order to simulate respectively the short and long-term conditions performances of bentonite based barriers (e.g. geosynthetic clay liners) for pollutant control.

Given an initial pre-hydration for all the tested samples, the experimental results have pointed out that physical pretreatments, such as pre-consolidation and salt removal, can significantly influence the response of bentonite to the cation exchange phenomenon and, in turn, to its swelling behaviuor and hydrated fabric or microstructure of the solid skeleton.

When a geosynthetic clay liner (GCL) sample and two simple basic specimens, prepared in the laboratory with the same bentonite type, are preliminarily permeated with DW and, thereafter, with CCS in order to simulate long-term conditions in the field, the hydraulic conductivity (K) tests have shown that the presence of needling in GCL sample can strongly deteriorates its performances (i.e. from $K = 2 \cdot 10^{-11}$ m/s to $K = 7 \cdot 10^{-10}$ m/s) whereas, the other two basic bentonite specimens, without needling, present a much less degradation (i.e. from $K = 2 \cdot 10^{-11}$ m/s to $K = 1.2{-}1.6 \cdot 10^{-10}$ m/s), all the other test conditions being the same.

On the other hand, laboratory test results also show that the pre-consolidation process is able to greatly improves the long-term behaviour of the basic bentonite specimens ($K = 1.8 \cdot 10^{-11}$ m/s referring to the CCS permeation) with negligible hydraulic conductivity variations referring to the short-term permeation phase with DW.

Moreover, a specimen, further pre-treated by pore water salt removal with a cyclic squeezing process, showed in absolute the best hydraulic performances of the test series in both short and long-term conditions reaching a value of $K = 8 \cdot 10^{-12}$ m/s with DW and a $K = 6 \cdot 10^{-12}$ m/s in the long-term with CCS as permeant.

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1. Introduction

Geosynthetic clay liners (GCLs) are the most common manufactured barriers used in landfill applications. GCLs generally contain a thin layer of sodium bentonite (dry thickness of between 5 and 10 mm), needled between two geotextiles or glued to a geomembrane. GCLs are commonly used as hydraulic barriers for landfill leachate containment, cover systems and for the remediation of polluted sites. GCLs ensure excellent containment performances, in the short-term, as far as both volumetric flux and contaminant advective transport are concerned. These performances should be attributed, in the absence of a glued geomembrane, to the characteristics of sodium bentonite (Shackelford et al., 2000).

Bentonite is an industrial clay soil that usually contains at least 70% of the three-layered (2:1) clay mineral montmorillonite. Isomorphic substitution in montmorillonite usually results in the replacement of a portion of the tetravalent silicon (Si^{4+}) and the trivalent aluminum (Al^{3+}) in the crystalline structure with a divalent metal, such as magnesium (Mg^{2+}), and this causes a permanent negative layer charge.

Montmorillonite crystals consist of parallel-aligned elementary alumino-silicate lamellae, which are approximately 10 Å thick and 1000−2000 Å wide, and this crystalline structure determines a very high specific surface (≈ 760 m^2 g^{-1}). Owing to the permanent negative charge and the very high specific surface, a large quantity of water penetrates between the bentonite lamellae during imbibitions, thus determining a dispersed structure of the individual platelets or small tactoids, which are characterized by considerable swelling behaviour. The hydrated and swollen material shows very low hydraulic conductivity to permeation with water and diluted aqueous solutions. The swelling and hydraulic performances of sodium bentonite are influenced to a great extent by the electrical characteristics of the pore solution, such as the cation concentration and valence in the pore solution, and, as a consequence, by the chemical composition of the landfill leachate and of the water contained in the soil surrounding the barrier. The main problem concerning the use of sodium bentonite as a sealing material is represented by the exchange of sodium with calcium, which is dominant in the pore water of many soils. The cation exchange causes a transformation of sodium bentonite into calcium bentonite and, consequently, a reduction in the repulsion forces between the lamellae, as well as the formation of an aggregated structure characterized by a lower osmotic efficiency and, in particular, a higher value of hydraulic conductivity (Dominijanni and Manassero, 2012a,b).

A landfill bottom barrier is required to ensure hydraulic and pollutant containment during the entire active life of a landfill (i.e. during the waste storage phase) and over decades in the post-closure period. During this period, the barrier must guarantee performances according to the regulations in force, and the cation exchange phenomenon can lead to the risk of this requirement not being guaranteed in long-term conditions.

Several authors (Petrov and Rowe, 1997; Petrov et al., 1997a,b; Ruhl and Daniel, 1997; Shackelford et al., 2000; Jo et al., 2001, 2005; Rowe, 2005) have studied the behaviour of untreated sodium bentonite and GCLs in long term landfill conditions and have shown the hydraulic performance and swelling ability degradation induced by the permeation of electrolyte solutions containing divalent cations.

The factors that seem to have most effect on the hydraulic conductivity of GCLs, before and after the development of cation exchange, are: 1) the type of bentonite and its mineralogical composition; 2) the bentonite mass-per-unit area of GCL (or the bulk dry density); 3) the form of the bentonite, i.e. powder or granular; 4) the structures adopted to contain bentonite (e.g. nailing or needle-punching); 5) the physical or chemical pretreatments (Shackelford et al., 2000; Bouazza, 2002; Jefferis and Jones, 2003; Rowe et al., 2004; Likos et al., 2010).

In the case of the experimental activity described in this technical note, the use of the same bentonite type during the whole laboratory scheduling made it possible to ignore factors 1−3 and to focus on the presence/absence of needling and the physical pretreatments, such as pre-consolidation and pore water salt removal, as described hereafter.

All of the tests have been performed, as far as possible, under the same confining effective stress (σ'), initial void ratio (e_0) and hydraulic gradient (i) conditions. Nevertheless, in this regard, it could be useful to mention that Bouazza (2002) has demonstrated that confining stress plays rather a limited role in controlling hydraulic conductivity in comparison with the other factors listed above. For instance, a confining stress variation from 1 to 300 kPa (more than two order of magnitude) produces a decrease in hydraulic conductivity ranging only around one order of magnitude for pre-hydrated and then permeated specimens. Moreover, Ahn and Jo (2009), referring to hydraulic conductivity tests in flexible wall permeameters, have shown that also a significant change of the bentonite initial void ratio in the order of 32% has from a reduced to negligible effect on its hydraulic conductivity.

1.1. Pre-hydration

All the specimens tested in this study were subjected to pre-hydration with deionized water before permeation with electrolyte solutions. Pre-hydration was accomplished by permeating the specimens with DW, as described by Jo et al. (2004). This method makes it possible to also measure the initial hydraulic conductivity to water of the specimens. Several authors (Ruhl and Daniel, 1997; Shackelford et al., 2000, 2010; Jo et al., 2004) have reported that the hydraulic conductivity of water pre-hydrated specimens is generally lower than that obtained for non pre-hydrated specimens. Shackelford (1994) referred to this as a "first exposure effect", since, when permeated with sequential solutions, the GCLs are mainly affected by the first permeation liquid. Moreover, Vasko et al. (2001) showed that this phenomenon is more significant when GCLs are exposed to high-concentration electrolyte solutions, while Lee and Shackelford (2005) found evidence that it may be insignificant when the permeant liquid contains relatively low concentrations of ions, provided permeation is continued until chemical equilibrium is reached.

1.2. Needling

The presence of needling is expected to influence the hydraulic behaviour of bentonite in the presence of electrolytes. Ruhl and Daniel (1997) performed a hydraulic conductivity test on a needle-punched GCL and a geotextile-encased GCL, which was produced using adhesive and, consequently, without needling. These GCL specimens did not contain the same sodium bentonite, since they were two different brand products. However, a brief comparison was made on the results obtained for the two GCLs. Ruhl and Daniel (1997) found that GCLs presented approximately the same value of hydraulic conductivity with water, a value that ranged from $7 \cdot 10^{-12}$ m/s for a needle-punched GCL to $1 \cdot 10^{-11}$ m/s for a GCL without needling, but different behaviour was observed when they were subjected to a calcium rich MSW simulated leachate. The needle-punched GCL presented a hydraulic conductivity value (K = $2 \cdot 10^{-8}$ m/s) that was approximately two orders of magnitude higher than that found for the GCL without needling (K = $3 \cdot 10^{-10}$ m/s).

1.3. Pre-hydration and pre-consolidation

The pre-hydration and pre-consolidation process is a laboratory-scale procedure that consists of saturation with deionized water and static consolidation. The procedure was set up with the aim of simulating the same pre-hydration and densification industrial processes in the laboratory as those used to produce dense factory-prehydrated (DPH) GCLs. DPH GCLs are manufactured by mixing sodium bentonite clay with a hydrating aqueous solution in a high-speed, high shear mixer. The hydrated bentonite is then calendered under vacuum into a dense bentonite sheet with a low void ratio (e ~ 1.5) (Mazzieri et al., 2013). Vacuum extrusion