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Hydraulic conductivity and swelling ability of a polymer modified bentonite subjected to wet–dry cycles in seawater

Michela De Camillis [a], Gemmina Di Emidio [a,*], Adam Bezuijen [a], Ramiro Daniel Verástegui-Flores [b]

[a] Laboratory of Geotechnics, Ghent University, Technologiepark 905, 9052 Zwijnaarde, Belgium
[b] Institute of Mechanics, Materials and Civil Engineering (iMMC), Université catholique de Louvain, Belgium

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ABSTRACT

The performance of clay liners may be impaired when in contact with aggressive solutions due to cation exchange. The efficiency of these liners can further deteriorate if cation exchange is combined with wet and dry cycles as a result of seasonal changes in temperature, rainfall and groundwater migration. The performance of untreated sodium bentonite is compared to the performance of a treated clay, HYPER clay, under wet and dry cycles, in seawater. HYPER clay is a polymer modified bentonite with enhanced performance in presence of electrolyte solutions. In this study, the bentonite is treated with 2% and 8% polymer by dry weight of clay. The swelling ability, self-healing capacity and permeability are investigated by means of swell index tests, one-dimensional swell tests in oedometer cells and hydraulic conductivity tests. The specimens were subjected to 6 wet–dry cycles in swell tests and to 4 cycles in hydraulic conductivity tests.

The swell index tests showed that the swelling ability increased as the polymer content increased. Similar results were obtained from one-dimensional swell tests. The height of HYPER clay (8% polymer content) during the sixth wet–dry cycle was still considerably larger compared to the height of the untreated clay. The hydraulic conductivity of untreated sodium bentonite sharply increased within three cycles, while HYPER clay maintained its low permeability to seawater. During the fourth wet–dry cycle, the hydraulic conductivity of untreated bentonite was three orders of magnitude higher than HYPER clay 2%. Sodium bentonite was not able to heal cracks formed during drying, which constitute preferential flow paths for the solution.

1. Introduction

Geosynthetic clay liners (GCLs) are increasingly used for waste disposal facilities and they have been subject of numerous investigations (Shackelford et al., 2000; Egloffstein, 2001; Bouazza, 2002; Lee and Shackelford, 2005; Jo et al., 2005; Chevrier et al., 2012; Ishimori and Katsumi, 2012). GCLs are employed to isolate waste disposals from the environment, to avoid infiltration of water to the waste and to prevent the release of leachate. GCLs are factory-manufactured hydraulic barriers containing a thin uniform layer of sodium bentonite sandwiched between two geotextiles or glued to a geomembrane. Bouazza (2002) described the advantages of GCLs with respect to compacted clay bottom and cover lining and explained why GCLs are nowadays considered an efficient alternative. The main advantages include the very low hydraulic conductivity to water, excellent self-healing capacity, capability of withstanding differential settlement, limited thickness and cost effectiveness. On the other hand, the bentonite is sensitive to chemical interactions in presence of liquids other than water. Sodium ions present between the clay platelets usually confer low hydraulic conductivity to the clay. However, exposure to leachate or to electrolyte solutions can cause a loss of efficiency of the clay as hydraulic barrier, which could increase the vulnerability of the environment.

Several laboratory studies focused on the hydraulic conductivity of bentonites in contact with various permeant liquids (Ruhl and Daniel, 1997; Shackelford et al., 2000; Bouazza, 2002; Jo et al., 2005; Katsumi et al., 2008; Rosin-Paumier et al., 2011;

* Corresponding author. Tel.: +32 9 264 5720; fax: +32 9 2645849.
E-mail addresses: michela.decamillis@gmail.com (M. De Camillis), gemmina.diemidio@ugent.be (G. Di Emidio), adam.bezuijen@ugent.be (A. Bezuijen), ramiro.verastegui@uclouvain.be (R.D. Verástegui-Flores).

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Barral et al., 2012; Chun-Ming et al., 2013; Hosney and Rowe, 2014; Bradshaw et al., 2016). For instance, Jo et al. (2005) conducted long-term hydraulic conductivity tests on GCLs permeated with inorganic single-species salt solutions with $CaCl_2$ concentrations ranging from 5 mM to 500 mM and 100 mM for NaCl and KCl solutions. The hydraulic conductivity obtained with NaCl and KCl were comparable to those obtained with deionized water, even considering the different hydrated radii of Na^+ and K^+. However, the hydraulic conductivity increased of about 3 orders of magnitude with the 100 mM of the divalent solution. Strong Ca^{2+} concentrated solutions (≥50 mM) led to a rapid exchange for Na^+, resulting in high hydraulic conductivity ($\geq 10^{-8}$ cm/s). Katsumi et al. (2008) performed hydraulic conductivity tests on granular sodium bentonite with 1 M NaCl solution and the permeability increased two orders of magnitude ($>10^{-9}$ m/s). The increase of salinity in the infiltrating solution considerably affects both swelling and permeability, as was also demonstrated by Chun-Ming et al. (2013).

The service life of a GCL cover can also be affected by other factors like environmental loading. Heat waves, seasonal rainfall and groundwater migration may negatively affect the hydraulic performance of the liners subjected to wet–dry aging. Bouazza et al. (2014) quantified heat and moisture migration in a geomembrane-GCL composite liner overlying a compacted subgrade subjected to high temperatures and low vertical stresses. Continuous elevated temperature on the liner, up to 70 °C, influenced the temperature profile for around 200 mm below the GCL cover liner. Although no cracks were detected, moisture migration from the GCL to the subgrade material was observed. In general, the consequences of wet–dry cycles are a dramatic increase of permeability and loss of self-healing capacity, due to the combination of ion exchange and simultaneous desiccation (Egloffstein, 2001). In particular, desiccation may damage the barrier layer forming crack networks in the bentonite and gaps between GCLs panels. In such a scenario, size, distribution and connectivity of cracks govern the flow of solutes in the soil (Tang et al., 2011).

Several investigations have been undertaken to evaluate the effect of wet and dry cycles combined with cation exchange on hydraulic conductivity and swelling ability of clay barriers (Hewitt and Philip, 1999; Lin and Benson, 2000; Bouazza et al., 2006, 2007; Thiel et al., 2006; Komine et al., 2009; Rowe et al., 2011; Tang et al., 2011; De Camillis et al, 2014; Mukunoki et al., 2014; He et al., 2015).

Amended clays have been developed to improve their resistance in aggressive environments. Several studies have proposed new alternatives (Kondo, 1996; Katsumi et al., 2007, 2008; Mazzieri et al., 2009; Di Emidio, 2010; Di Emidio et al., 2012; Malusis and McKeehan, 2013; Scalia et al., 2013; Malusis and Di Emidio, 2014; Di Emidio et al., 2015; Mazzieri and Di Emidio, 2015; Razakamanantsoa et al., 2016). Kondo (1996) developed Multiswellable Bentonite (MSB), which is a bentonite compounded with Propylene Carbonate (PC). The PC is able to activate the osmotic swelling capacity of the clay in both fresh water and electrolyte solutions. Another manufactured patented GCL is the Dense Pre-Hydrated GCL (DPH GCL). This material is densified by vacuum extrusion after prehydration with a polymeric solution containing Na-CMC, sodium polyacrylate and methanol. Katsumi et al. (2008) reported long-term permeability tests on MSB and DPH GCL. The results have shown appreciable resistance to electrolyte solution of both GCLs. The main issue of these modified bentonites is that the polymer adsorption onto the clay might not be permanent (Mazzieri and Pasqualini, 2006; Di Emidio, 2010).

In this study the HYPER clay technology is investigated. HYPER clay is a polymer-treated bentonite created by combining natural Na-bentonite with carboxymethyl cellulose (CMC). Once the CMC intercalates the clay platelets, the diffuse double layer is maintained open even in presence of factors that generally produce the collapse of the interlayer (Di Emidio, 2010). A feature of this bentonite is the irreversible adsorption of the polymer into the clay, following the HYPER clay treatment, due to a dehydration step. Moreover, the intercalation of the polymer in the interlayer region of the clay was demonstrated.

The objective of this research is to evaluate the performance of the innovative polymer-amended HYPER clay subjected to wet–dry aging in contact with seawater. The results have implications on the barrier resistance of HYPER clay against wet and dry cycles combined with highly concentrated solution, e.g. seawater.

2. Background

2.1. Properties of sodium bentonite

Bentonite is a naturally occurring clay widely used in GCLs as the low-permeability element. It can be mainly sodium or calcium bentonite, depending on the dominant exchangeable cation. The quality of bentonite is related to the montmorillonite content, the surface area, the surface charge deficiency, and the composition of the exchange complex (Shackelford et al., 2000). Sodium montmorillonite is part of the smectite family characterized by a high specific surface area, weak interlayer bonds and high cation exchange capacity. Sodium cations are able to bond with water molecules, increasing the interlayer space and forming a barrier to water flow. The swelling resulting from the water adsorption and the fine-dispersed microstructure contributes to small and tortuous flow paths. The thick diffuse double layer (DDL) of sodium bentonite is reflected by its large swelling ability and low hydraulic conductivity (Lin and Benson, 2000; Di Emidio, 2010).

On the other hand, sodium bentonite is prone to cation exchange when permeated with electrolyte solutions. Multivalent cations can easily replace Na^+ ions leading to low swellable and high permeable bentonite. The cation exchange process is in accordance with the Gouy-Chapman diffuse double layer theory. The thickness of the DDL depends on the valence, concentration, and size of the cations on the interlayer surface. Generally, Na^+ is susceptible to cation exchange with cations of greater valence and smaller size (McBride, 1994; Kolstad et al., 2004). Consequently, swelling capacity and hydraulic efficiency are reduced when the cations are divalent or trivalent because of the small DDL thickness (McBride, 1994; Jo et al., 2001).

2.2. Wet–dry aging

Lin and Benson (2000) assessed how exposure to pore water containing divalent cations at natural concentrations in combination with wet and dry cycles affects plasticity, swelling and hydraulic conductivity of GCLs. They found that initial exposure to deionized water or tap water temporarily delayed the reduction in swell. The swelling capacity was reduced, from 21 mm during the second cycle to around 5 mm in subsequent cycles, when the bentonite was wetted directly with 0.0125 M $CaCl_2$. The GCL permeability increased by approximately two orders of magnitude after 4–6 wet–dry cycles because of crack formation and loss of self-healing capacity of the bentonite.

Bouazza et al. (2006) investigated gas permeability on needle punched GCLs after wet–dry cycles with 0.0125 M $CaCl_2$ and 0.125 M $CaCl_2$. The gas permeability after permeating with 0.0125 M $CaCl_2$ increased by one order of magnitude. The breakthrough of gas flow was reached before permeability could be measured due to the presence of cracks.

Malusis et al. (2011) evaluated the potential change in hydraulic conductivity of two model soil-bentonite backfills subjected to