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Hydraulic conductivity of a dense prehydrated GCL subjected to partial desiccation

Permeabilité d'un géosynthétique bentonitique préhydraté à haute densité partiellement séché

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ABSTRACT

A dense prehydrated GCL (DPH) was subjected to partial but increasingly severe drying cycles alternated with permeation with a calcium solution. The permeability remained low for desiccation water contents higher than the manufacturing (prehydration) water content. Increasingly long permeation was however necessary to recover low permeability. The permeability increased irreversibly for desiccation water content lower than that of prehydration. Test results indicate the permeability of DPH GCLs subjected to dry/wet cycles coupled with cation exchange strongly depends on the extent of desiccation.

RÉSUMÉ

L'article discute de la perméabilité d'un géosynthétique bentonitique densifié et préhydraté (DPH GCL) soumis à des cycles de dessiccation partielle, de caractère plus sévère à chaque tour et alternés à l'infiltration d'une solution de calcium. La perméabilité s'est maintenue de basse pour des teneurs en eau de dessiccation plus élevées que la teneur en eau initiale. Toutefois, des infiltrations progressivement plus longues ont été nécessaires pour récupérer la perméabilité. La perméabilité a augmenté irréversiblement pour des teneurs en eau de dessiccation plus basses que la teneur en eau de pré-hydratation. Ces résultats indiquent que la perméabilité du DPH GCL soumis à des cycles de dessiccation-humidification, associés à l'échange des cations dépend du niveau de dessiccation

Keywords : dense prehydrated GCL, hydraulic conductivity, ion exchange, desiccation, water content.

1 INTRODUCTION

Geosynthetic Clay Liners, (GCLs), that consist of a thin layer of bentonite sandwiched between two geotextiles or glued to a geomembrane, are increasingly used as hydraulic barriers in landfills covers and liners as well as in remediation projects for contaminated sites. The hydraulic performances of GCLs that do not contain a geomembrane depend on the low hydraulic conductivity of sodium bentonite ($\sim 10^{-9}$ cm/s) when permeated with dilute solutions (e.g. distilled water or tap water). Under typical field conditions, sodium bentonite is prone to cation exchange since multivalent cations (e.g. Ca^{2+}) are dominant in most coverd soils, and calcium will replace sodium almost completely in a few years (Fleisher & Heilbaum 2008)

Several laboratory studies and reported case histories have suggested that the hydraulic conductivity of GCLs can increase of several orders of magnitude if cation exchange is combined with desiccation and cracking of the bentonite (Lin & Benson 2000; Melchior 2002). Typical applications where such circumstances may occur are landfill covers systems, as a result of seasonal fluctuations of temperature and moisture content and inadequately thick protection layers (Meer & Benson 2007). For a given climatic condition, the extent of desiccation strongly depends on the thickness and on the properties of the soil covering layers.

The gravimetric water content of exhumed GCLs was found to be strictly correlated to the hydraulic conductivity (Meer & Benson 2007). If desiccation combined with cation exchange does occur, k values on the order of 10^{-4} cm/s to 10^{-6} cm/s should be expected and the effects are permanent once the gravimetric water content drops below about 100% (Shackelford, 2007).

Dense Prehydrated (DPH) GCL have been recently proposed as an alternative to conventional GCLs. A few studies in the literature have addressed the hydraulic performance of DPH

(Shroeder 2001; Kolstad et al. 2004; Katsumi et al. 2008). These studies have demonstrated that DPH GCLs preserve much lower permeability than conventional GCLs in the presence of various chemical solutions as long as they remain saturated. Should DPH GCLs be used in cover systems and landscaping applications, they could potentially be exposed to dry/wet cycles as well as to contact with salts leached from adjacent soils. Mazzieri & Pasqualini (2008) simulated in the laboratory dry-wet cycles on DPH GCLs using distilled water and 12.5 mM CaCl_2 as hydrating liquids. They found that the hydraulic conductivity of DPH GCLs increased slightly with dry/wet cycles using DW as hydrating liquid. Conversely, the permeability increased drastically after few dry/wet cycles with CaCl_2 . The DPH GCL was desiccated to very low water content ($w=5-10\%$) that are unlikely to occur in the field. The DPH bentonite was converted into a calcium exchanged bentonite.

In this paper, a DPH GCL was initially permeated with 12.5 mM CaCl_2 and subjected to gradually more severe drying states alternated with permeation stages. The purpose of the study was to obtain information on the occurrence of exchange of sodium for calcium and to examine the behaviour of the DPH GCL subjected to increasingly severe drying states combined with possible cation exchange. The results have implications on the resistance of DPH GCLs against dry/wet cycles combined with cation exchange.

2 MATERIALS AND METHODS

2.1 Dense prehydrated GCL

Dense PreHydrated GCL (DPH GCL) have been patented and introduced on the market in the mid 90s. The principle of the material is to combine the well known benefits of prehydration

and densification on the hydraulic conductivity of the sodium bentonite. During production of DPH GCL, sodium bentonite clay is mixed with a hydrating solution in a high speed, high shear mixer; this mass is then calendered under vacuum into a bentonite sheet with a low void ratio ($e=1.5$). Moreover, vacuum extrusion produces alignment of the clay platelets in a very tight arrangement. The bentonite sheet is then sandwiched between one high strength woven polypropylene geotextile and a perforated polyester scrim geotextile.

Besides the benefit of prehydration, the hydrating solution of DPH GCLs contain organic molecules that are intended to improve the workability of the mixture during production as well as the resistance of bentonite to chemical interaction in the presence of aggressive permeants. The solution contains the polymer sodium carboxymethyl cellulose (CMC) and methanol. It is believed that large polymer molecules such as CMC bind to the solid surfaces thus keeping the interlayer open (Kolstad et al. 2004) even in presence of factors that would collapse the interlayer (e.g. increase of ionic concentrations and/or pore space invaded by multivalent ions).

The main physical and chemical properties of the DPH GCL used in this study are reported in Mazziari & Pasqualini (2008). Possible variations to the basic "recipe" of the prehydrating polymer solution include sodium polyacrylate (PAAS) and sodium hexametaphosphate (Flynn & Carter 1998). The results described in this paper refer to the DPH GCL version used in this study and may not necessarily be relevant to different versions.

2.2 Hydrating liquids

Distilled water (DW) was used as a reference liquid. DW had $EC=0.014$ mS/cm and $pH=6.8$. Soil pore water was represented by a 0.0125 M $CaCl_2$ solution (corresponding to 500 mg/L Ca^{2+}), based on the study by Lin & Benson (2000) and in order to compare the results with previous investigations. Calcium concentration in pore waters of common soils are expected to be lower (40 - 160 mg/L Ca^{2+}) with the possible exception of gypsum-rich soils (up to 600 mg/L Ca^{2+}). The solution had Electrical Conductivity (EC)= 2.85 mS/cm and $pH=6.56$.

2.3 Testing methods

Test specimens 10.16 cm ($4''$) in diameter were obtained from the DPH roll by means of a circular template and of a sharp cutter. The putty-like nature of the clay prevented loss of clay in preparation of test specimens

Two specimens of DPH specimens was permeated with the test solutions, with the purpose to establish the baseline hydraulic conductivity. Permeability tests were performed in flexible wall permeameters. The specimens were allowed to equilibrate inside the permeameter without gradient for about two weeks. The average applied effective stress was 15 kPa during hydration and 12.5 kPa during permeation. Tests were of the variable head type with the applied head ranging from 100 to 130 cm.

Previous experience acquired in long-term permeability tests of DPH GCL with DW (Di Emidio et al. 2008) revealed that gas bubbles develop in drainage lines, probably as a result of biological activity. In the attempt to minimize gas production, DW was spiked with 500 mg/L of the biocide Dowicil[®] Qk-20. Addition of the biocide to DW changed only slightly the chemical parameters of DW ($EC=0.078$ mS/cm and $pH=6.92$); moreover, the biocide was not expected to interact chemically with the clay (Jo et al. 2005).

Gas bubbles did not develop significantly in the test with $CaCl_2$ solution at least up to about 600 days of permeation; thereafter, temporary interruptions of hydraulic flow occurred, that appeared to be connected with biological clogging. The influent solution was then spiked with biocide, which improved but did not eliminate the problem of flow interruptions.

Termination criteria stated in ASTM D6766 were generally pursued. Calcium, sodium and chloride concentrations were measured in the effluent solutions in order to evaluate the release of soluble ions in the case of permeation with distilled water and the breakthrough of ions in the influent solution in the case of permeation with calcium chloride.

After the first permeation stage, that lasted 720 days the specimen permeated with 12.5 mM $CaCl_2$ was subjected to a series of controlled dehydration stages, each followed by a new rehydration and permeation stage. Each dehydration stage was aimed at obtaining progressively decreasing target water contents (85% , 75% , 65% , 55% , 45% , 35%). The water contents were estimated gravimetrically, assuming that the solid mass (soils plus adsorbed polymers) had remained constant.

Dehydration was performed in a thermostatic chamber at constant temperature of 35 C° and relative humidity ranging between 20% and 40% . A vertical pressure of 12.5 kPa was applied during the drying phase by a dead load with the purpose of simulating the presence of overburden stress. In order to monitor the mass loss, the specimen was momentarily unloaded and weighed.

At the end of the dehydration phases, the specimen was transferred in the permeameter and rehydrated for 48 hours with the 12.5 mM $CaCl_2$ solution. Permeations was then started and continued until stabilization of k . An average effective stress of 12.5 kPa was applied during permeation.

3 RESULTS AND DISCUSSION

3.1 Hydraulic conductivity of as-received DPH GCL

The hydraulic conductivity values, k , of DPH GCL to DW and 12.5 mM $CaCl_2$ are illustrated in Figure 1. The results refer to about 400 days of permeation with DW (pore volumes= 2.98) and 720 days (pore volumes= 8.12) with the $CaCl_2$ solution respectively.

Mazziari & Pasqualini (2008) reported the k values for the test with DW and for the test with 12.5 mM $CaCl_2$ until 580 days of permeation (4.98 pore volumes). The average k to DW was 8.8×10^{-10} cm/s whereas the average k to 12.5 mM $CaCl_2$ at 4.98 pore volumes was 8.1×10^{-10} cm/s. The termination criteria stated in ASTM 6676 were generally met with the exception of the EC effluent-to-influent ratio.

The test with 12.5 mM $CaCl_2$ was continued to longer durations in order to approach more closely the requirement for the EC ratio, that reflects the achievement of chemical equilibrium. Unfortunately, for longer permeation times, the hydraulic flow repeatedly stopped, as suggested by the abrupt drops in k values. The test had to be interrupted and temporarily dismantled to inspect the specimen. In disassembling the apparatus, the effluent drainage lines and bladder accumulators were kept closed in order to minimize changes of the monitored concentrations.

No visible clogs were observed in the drainage lines or porous plates, however a strong odour was perceived upon dismantling, which may suggest some form of biological activity. Upon restoring permeation with the influent solution spiked with the biocide, a jump in hydraulic conductivity was observed, most probably as a result of unloading, followed by a gradual reduction. The addition of the biocide to the influent solution did not eliminate the problem of flow interruptions. Nonetheless, the test was continued until the monitored concentrations in the effluent suggested chemical equilibrium.

The final hydraulic conductivity value was 1.1×10^{-9} cm/s, that is only slightly higher than the average value measured before the first interruption (8.1×10^{-10} cm/s). This slight increase is to be attributed mostly to the disturbance induced by the series of loading and unloading than to chemical interaction with calcium chloride.

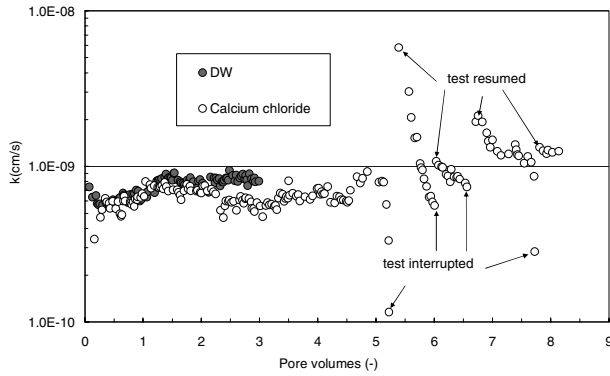


Figure 1. Hydraulic conductivity of DPH GCL to DW and 12.5 mM CaCl_2 solution

Previous studies regarding the permeability of DPH GCLs (Kolstad et al. 2004; Katsumi et al. 2008) showed in fact that DPH GCLs exhibit hydraulic conductivity values on the order of 1×10^{-10} cm/s for electrolyte concentrations up to 1M CaCl_2 and for testing duration of up to 4 years.

The trends of calcium (Ca^{2+}) and sodium (Na^+) concentrations in the effluents are plotted versus the number of pore volumes of flow in Figure 2a and 2b respectively. The concentrations measured during permeation with DW reflect the tendency of DPH bentonite to release soluble salts into the pore water. Soluble sodium has significantly higher concentration than calcium, which is consistent with the use of base sodium bentonite and of various sodium salts in the prehydration solution of DPH GCLs. Moreover, the release of calcium was essentially completed after 2.66 pore volumes, whereas the soluble sodium concentration was still on the order of 40 mM.

The trend of calcium concentrations in the effluent during permeation with CaCl_2 did not display the typical “breakthrough” shape. This is partly due to the fact that the CaCl_2 solution was initially contained also in the effluent accumulator, as confirmed by the measured calcium concentration at 0.0 pore volumes, that is very close to the theoretical concentration (12.5 mM). The hydraulic flow did not start immediately after application of the hydraulic gradient, rather the specimen initially absorbed some permeant from the effluent end. To avoid negative pore volumes, the second sample is also plotted at zero pore volumes. The lower concentration of calcium is probably due to diffusion towards the specimen. Thereafter, the hydraulic flow effectively started and a sudden increase of the calcium concentration was observed. The concentration passed through a “plateau” and then abruptly dropped to about zero. Next, a gradual increase to values close to that of the influent solution was observed.

The trend of calcium concentration was probably influenced by the presence of the solution in the effluent drainage lines from the beginning of the test and it is therefore difficult to interpret, however the effluent concentrations at 6.66 and 8.12 pore volume suggest a condition close to equilibrium with the influent solution. In order to fully understand the transient behaviour of calcium, the test is being replicated with only distilled water initially contained in the effluent drainage lines.

The trends of sodium concentration versus the pore volumes of flow show a substantially greater release of sodium during permeation with calcium chloride than with DW. Moreover, as opposed to calcium during permeation with CaCl_2 , the sodium concentration should not be influenced by the presence of the solution in the effluent lines. In particular, the difference between the two curves of effluent sodium concentrations can be assumed to represent the fraction of sodium that is released, most probably as a result of cation exchange.

After the permeability test, the specimen permeated with CaCl_2 was disassembled and the gravimetric water content, $w = 95\%$ was estimated.

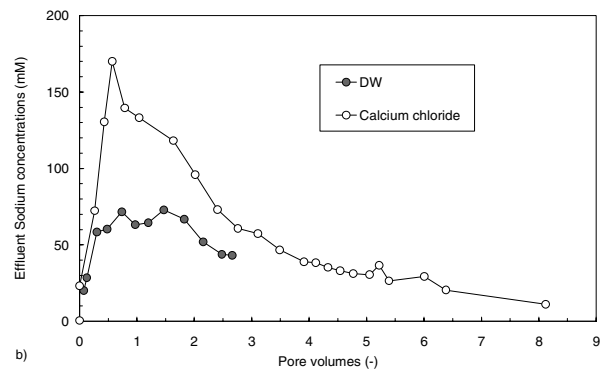
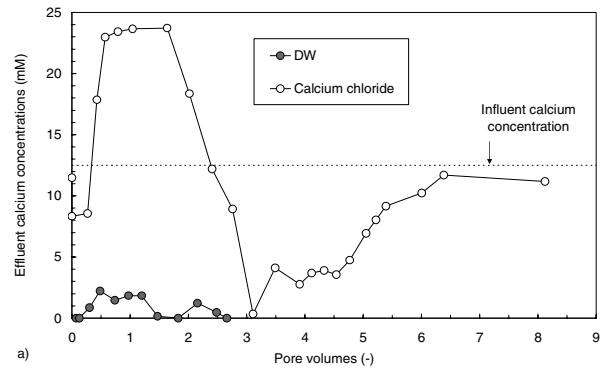


Figure 2. Trends of calcium (a) and sodium (b) concentrations in the effluent during permeation with DW and 12.5 mM CaCl_2

The specimen was then reinstalled in the permeameter for the following permeation stage. Six dehydration and permeation cycles were carried out. The results of successive permeation stages are illustrated in Figure 3.

The k values usually displayed a decreasing trend. The initial values of each permeation stage were gradually higher. For $w_{\text{dry}} = 65\%$ or lower k values on the order of $10^{-5} \div 10^{-6}$ cm/s were obtained, which indicate preferential flow through cracks. Visible cracks indeed appeared at dehydration water contents of 65%. The size of cracks also increased with decreasing w_{dry} .

For the first few cycles ($w_{\text{dry}} = 85\%$; $w_{\text{dry}} = 75\%$; $w_{\text{dry}} = 65\%$), the hydraulic conductivity decreased relatively rapidly (within 10 pore volumes of flow) to values very similar those of first permeation stage. For the following stages ($w_{\text{dry}} = 55\%$ and $w_{\text{dry}} = 45\%$) the reduction was much slower but k values similar to ($w_{\text{dry}} = 55\%$) or slightly higher ($w_{\text{dry}} = 45\%$) than in the first permeation were eventually obtained. For the lowest dehydration water content ($w_{\text{dry}} = 35\%$), no significant reduction was observed despite approximately 100 pore volumes of permeation. In essence, the cracks formed during the drying stage were closed as a result of swelling during rehydration for w_{dry} greater than or equal to 45%, whereas they remained open for $w_{\text{dry}} = 35\%$: Inspection of the specimen at the end of permeation confirmed this interpretation.

The EC was continuously monitored during the various permeation stages. The effluent-to-influent EC ratio remained constantly close to 1, suggesting a condition of chemical equilibrium. Although the concentrations were not monitored, nor was the exchange complex of the bentonite evaluated at the end of the test, it is believed that cation exchange was essentially completed.

The gravimetric water content of DPH GCLs estimated during the various permeation and drying stages are shown in Figure 4. The water content at the end of permeation stages gradually decreased. Hence, the water binding capacity of the GCL bentonite gradually decreased, which is consistent with the gradual conversion into a cation-exchanged bentonite (Jo et al. 2004).

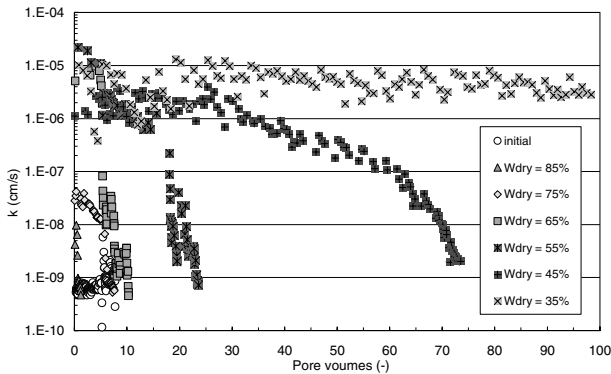


Figure 3. Hydraulic conductivity versus pore volumes of flow during successive permeation stages with 12.5 mM CaCl_2

Permeability test results indicated that as long as the w_{dry} is higher than or equal to the prehydration water content ($\sim 45\%$), the DPH appeared able to recover the hydraulic performance. However, the number of pore volumes required to recover low hydraulic conductivity increased substantially with decreasing w_{dry} . Even in case of complete recovery, long-lasting high permeability phases might be not acceptable for the overall efficiency of the barrier.

During the post-desiccation high permeability phases, permeation had to interrupted overnight and at weekends due to the limited capacity of the permeability apparatus, therefore permeation was not continuous; different results might be obtained for strictly continuous permeation or allowing the specimen to simply rehydrate in absence of hydraulic gradients.

For w_{dry} less than the prehydration water content, cracks were not closed, at least within the time scale of the test, and eventually impaired the hydraulic efficiency, with k values on the order of 10^{-5} – 10^{-6} cm/s.

Mazziери & Pasqualini (2008) studied the permeability of the same DPH GCL subjected to dry/wet cycles and using a 12.5 mM CaCl_2 solution as hydrating liquid. They induced severe desiccation with $w_{\text{dry}} = 5 \div 10\%$ and observed that the hydraulic conductivity increased to 8×10^{-9} cm/s after the 1st drying and to 5×10^{-6} cm/s after the 2nd drying. The results of this study indicate that one single desiccation phase below the prehydration water content impaired the hydraulic performance. The extent of cation exchange was probably larger in the present study because the “critical” desiccation was achieved at a later stage of testing.

It must be pointed out that the specimens were not clamped laterally during drying, which may induce a different cracking pattern than in situ. Moreover, in this study only one desiccation phase was simulated for a given water content; different results may be obtained by repeated cycles for a given water dehydration water content w_{dry} .

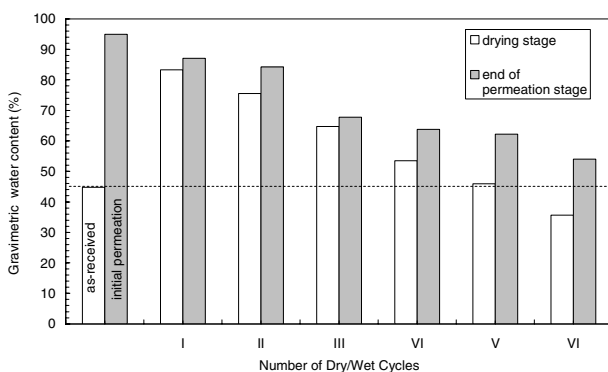


Figure 4. Estimated gravimetric water contents during the various stages of the test.

4 CONCLUSIONS

A dense prehydrated GCL (DPH) GCLs was subjected to permeation with a 12.5 mM CaCl_2 solution and to a series of dehydration stages to decreasing water contents (i.e. increasingly severe desiccation) followed by permeation. Release of sodium was observed during permeation that was ascribed to cation exchange with calcium. The hydraulic conductivity of the DPH GCL remained low ($\leq 2 \times 10^{-9}$ cm/s) for dehydration water contents $w_{\text{dry}} \geq 45\%$, that is approximately equal to the prehydration (manufacturing) water content. Increasingly long permeation phases were however necessary to recover low hydraulic conductivity, which may or may not be acceptable in the context of barrier efficiency. For $w_{\text{dry}} < 45\%$, the hydraulic conductivity increased irreversibly. Unhealed cracks were responsible for the increase in hydraulic conductivity. From a practical standpoint, test results indicate the response of cation-exchanged DPH GCLs to dry/wet cycles depends on the extent of desiccation which in turn depends on installation conditions. More experimental/theoretical studies are required to estimate the extent of desiccation that is possible for DPH GCLs in typical applications; examination of samples from actual-scale installations is also recommended.

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