Hydraulic conductivity of non-prehydrated and prehydrated attapulgite-polymer bentonite GCLs

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ABSTRACT: Three different types of geosynthetic clay liners (GCLs) were used in this study in terms of bentonite inside of the GCLs. These GCLs are polymer bentonite (PB GCL), 50% attapulgite + 50% Na-bentonite (%50A + %50NaB GCL) and 50% attapulgite + %50 polymer bentonite (50%A + 50%PB GCL). Different prehydration conditions were applied during the study. That is, GCLs were subjected to hydration with no-prehydration (non-prehydrated), 24h (or 1 day)-prehydration (prehydrated) and 30days of hydration over compacted zeolite (prehydrated over zeolite). The prehydration had little influence on the hydraulic conductivity of PB GCL and 50%A + 50%PB GCL when DIW was the permeant. The hydraulic conductivities for these GCLs did not depend on the prehydration condition and were around 5.8×10^{-11} m/s and 1.5×10^{-10} m/s, respectively. In contrast, hydraulic conductivity of %50A + %50NaB GCL hydrated over compacted zeolite was about four orders of magnitude less than non-prehydrated %50A + %50NaB GCL. In the case of permeating with 50 mM $CaCl_2$ solution, the prehydration had significant effect on the hydraulic conductivity of PB GCL and 50%A + 50%PB GCL. The hydraulic conductivity reduced by the prehydration from 4.9×10^{-7} m/s to 1.6×10^{-7} m/s for PB GCL and from 1.6×10^{-6} m/s to 1.5×10^{-8} m/s for 50%A + 50%PB GCL. At this time, however, the hydraulic conductivity of prehydrated 50%A + 50%PB GCL was an order of magnitude less than the hydraulic conductivity of PB GCL, indicating adding attapulgite into bentonite may not have an influence when the permeant is other than DIW.

Keywords: *Attapulgite, $CaCl_2$ solution, GCL, hydraulic conductivity, polymer bentonite*

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are one of the primary constituents of landfills or barrier systems which limit the liquid flow through the environment. The limitation of flow is mostly evaluated in terms of hydraulic conductivity. Bentonite is the clay part of GCLs that satisfies low hydraulic conductivity ($<10^{-11}$ m/s). Although bentonite has high affinity for water, their swelling characteristics may change and hydraulic conductivity of GCLs may increase during the post construction stage (Meer and Benson 2007, Benson and Meer 2009, Scalia and Benson 2010, 2011).

Researchers put some effort to enhance the barrier performance of GCLs (Katsumi et al. 2008, Di Emidio et al. 2015, Mazzieri and Emidio 2015, De Camillis et al. 2016). Most preferable way is to treat bentonite with different types of polymers. Although the details about the polymers are generally not shared with the manufacturers, the tendency is to mix sodium polymers with bentonite at different percentages (Scalia Iv et al. 2011, Scalia et al. 2013, De Camillis et al. 2016, Sato et al. 2017, Scalia and Benson 2017). The second way is to mix bentonite and different types of clay minerals. Based on authors' knowledge, the use of clay blends in GCLs has not been considered by neither researchers nor manufacturers so far.

The principal purpose of this study is to investigate the hydraulic conductivity of GCLs that were manufactured with polymerized bentonite (PB GCL), the mixture of polymerized bentonite and attapulgite at 50% by weight (50%PB+50%A GCL) and the mixture of sodium bentonite and attapulgite at 50% by weight (50%NaB+50%A GCL). The results are discussed considering several factors such as effects of attapulgite, test duration, polymer treatment, prehydration and pore fluid chemistry on the hydraulic conductivity.

2 MATERIALS AND METHODS

2.1 *Materials*

Three needle-punched GCLs were manufactured with bentonite and bentonite/attapulgite mixtures. Polymerized bentonite (PB) was treated with sodium polyacrylate and used in the first GCL (i.e. PB GCL). The bentonites used in the other two GCLs were blended with attapulgite at 50% by weight. The difference is that the second GCL was manufactured with the blend of PB and attapulgite (A) (i.e. 50%PB+50%A GCL) and the third one was produced with conventional sodium bentonite (NaB) and attapulgite mixture (i.e. 50%NaB+50%A GCL). The mass per unit area were 7.0, 7.3 and 5.9 m^2/kg; whereas initial thicknesses were 7.0, 7.7, and 6.5 mm for PB, 50%PB+50%A and 50%NaB+50%A GCLs, respectively. Initial water contents of GCLs were within the range of 9-10%. Some index properties of GCLs are also summarized in Table 1.

Table 1. Index properties of GCLs

GCL Type	Specific Gravity	Liquid Limit (%)	Plasticity Index (%)
PB	2.77	385	327
50%PB+50%A	2.63	253	175
50%NaB+50%A	2.73	244	*

* Not available.

The hydraulic conductivity tests were performed using Type II deionized water (DIW) and $CaCl_2$ solution. DIW was obtained using Milli-Q Gradient water purification system. Merck brand calcium chloride ($CaCl_2.2H_2O$) was used to prepare 50 mM solution concentration.

2.2 *Methods*

Mass per unit area of GCLs were determined according to ASTM:D5993-99 (2010). In addition, circular GCL samples were directly cut from the rolls in 100 mm diameter. The top of GCLs were marked at four different locations and the thicknesses were measured from these marked surfaces using a vernier caliper. The average of four measurements is reported herein. The water contents of bentonite part of GCLs were determined in a conventional way of drying in an oven at 105°C (ASTM:D2216-10 2010). Specific gravity and index properties or bentonites were determined by following ASTM:D854-14 (2014) and ASTM:D4318-05 (2005), respectively.

Hydraulic conductivity tests were performed using flexible-wall permeameters and following ASTM:D6766-12 (2014). GCLs were initially placed over the base pedestal of the permeameter and the circumferences were sealed with the bentonites taken from each GCL. The latex membranes were placed around the sealed samples and three O-rings were attached on the top and bottom pedestals. The cell pressure was arranged to 35 kPa and the resultant effective stress was an average of 29 kPa. Backpressure was not applied during the saturation phase of the hydraulic conductivity tests. Depending on the thickness of GCLs, the hydraulic gradients ranged between 85 and 140. The tests were lasted at least two months with DIW and several weeks with $CaCl_2$ solution.

Three different scenarios were examined to determine the influence of prehydration on the hydraulic conductivity of GCLs. Based on prehydration case, these GCLs are named as: i) non-prehydrated, ii) 24 hours prehydrated and iii) 30 days prehydrated. For non-prehydrated GCLs, the flows were begun immediately after installing the samples in the permeameter. In contrast, the prehydration case was applied in two different ways. In the first case, prehydration was applied by closing the outflow valves and opening the inflow valves of permeameters for 24 h. The flow was initiated by opening the outflow valves at the end of 24 h. Note that the prehydrating liquid was same as the permeant. In the second case of prehydration, GCLs were hydrated over compacted subsoils for 30 days in the flexible-wall permeameters. Zeolite was chosen as the subsoil which had higher optimum water contents (~ 40%) when compared to natural soils. Based on X-Ray diffraction pattern, the main mineral was clinoptilolite in zeolite (Ören et al. 2014).

After compacting zeolite at 2% wet of optimum water content (43%), GCL was placed in the permeameter cell in that order: Zeolite (at the bottom), GCL (non-woven part was facing downwards), geotextile and geomembrane (at the top). Then, hydration applied by closing the influent and effluent tubings throughout the hydration duration. The effective stress during hydration was 10 kPa. At the end of hydration duration of 30 days, the permeameter cell was dismantled and zeolite was removed. GCL was placed in the permeameter cell again and subjected to hydraulic conductivity test in a similar was as described above.

3 RESULTS AND DISCUSSIONS

In this research program, total of 14 hydraulic conductivity tests were conducted ten of which were permeated with water and the rest were permeated with 50 mM $CaCl_2$ solution. The final hydraulic conductivities of GCLs are summarized in Table 2. Note that final hydraulic conductivity is the average of last four consecutive readings.

Table 2. Final hydraulic conductivities of GCLs.

Test No	GCL Type	Permeant	Prehyration	Hydration Duration (days)	Concentration	HC (m/s)
1	PB	DIW	NP	-	-	5.8×10^{-11}
2	PB	DIW	P	1	-	1.9×10^{-11}
3	PB	DIW	P over zeolite	30	-	3.7×10^{-11}
4	%50NaB+%50A	DIW	NP	-	-	3.6×10^{-7}
5	%50NaB+%50A	DIW	NP	-	-	1.3×10^{-6}
6	%50NaB+%50A	DIW	P over zeolite	30		6.1×10^{-11}
7	%50PB+%50A	DIW	NP	-	-	1.2×10^{-10}
8	%50PB+%50A	DIW	NP	-	-	6.7×10^{-11}
9	%50PB+%50A	DIW	P	1	-	3.6×10^{-10}
10	%50PB+%50A	DIW	P over zeolite	30		5.6×10^{-11}
11	PB	$CaCl_2$	NP	-	50 mM	4.9×10^{-7}
12	PB	$CaCl_2$	P	1	50 mM	1.6×10^{-7}
13	%50PB+%50A	$CaCl_2$	NP	-	50 mM	1.6×10^{-6}
14	%50PB+%50A	$CaCl_2$	P	1	50 mM	1.5×10^{-8}

Under the content of this study, the influences of several factors such as attapulgite, test duration, bentonite type (or polymer treatment), prehydration and pore fluid chemistry on the hydraulic conductivity of GCLs have been investigated. The details about the findings are given henceforth.

3.1 *Effect of attapulgite*

The influence of attapulgite on the hydraulic conductivity was investigated on the non-prehydrated GCLs and is shown in Figure 1 as a function of pore volumes of flow (PVF). The hydraulic conductivity of PB GCL and 50%PB+50%A GCL had almost the same hydraulic behavior. The hydraulic conductivities of both GCLs increased from 2.0×10^{-11} to 1.0×10^{-9} m/s at 4 PVF. Since GCLs had low water contents (~10%) prior to permeation, increment of hydraulic conductivity was expected at the initial step of permeation. Then hydraulic conductivity decreased more than 50 times for both GCLs. This reduction is due to the gradual swelling of polymer bentonite within GCLs while continuing permeation. The final hydraulic conductivity of PB GCL is 5.8×10^{-11} m/s and 50%PB+50%A GCL is 9.4×10^{-11} m/s (average of 1.2×10^{-10} and 6.7×10^{-11} m/s) (Table 2). In other words, GCL with 50% attapulgite content had about 1.6 times greater hydraulic conductivity than that of PB GCL.

Attapulgite is a non-expanding (non-swollen), negatively charged and needle shaped mineral which is composed of long double chains of silica tetrahedra when compared to plate-like clay minerals (Broderick and Daniel 1990). A few studies in the literature reported that the hydraulic conductivity of compacted sand-attapulgite mixtures is between 1.0×10^{-7} and 1.0×10^{-10} m/s when water is the permeant (Broderick and Daniel 1990, Stern and Shackelford 1998, Al-Rawas et al. 2006). This indicates that hydraulic conductivity of the attapulgite is several orders of magnitude higher than that of bentonite.

The findings of this study are compatible with the literature to some extent. Studies in the literature have been conducted on attapulgite and sand mixtures. Although there are no data available in the literature for the comparison, having greater hydraulic conductivity for 50%PB+50%A GCL than for PB GCL confirmed the ability of attapulgite to increase the hydraulic conductivity. However, despite replacement of 50% polymer bentonite (PB) with attapulgite, the hydraulic conductivity of 50%PB+50%A GCL is still controlled by PB, resulting negligible difference between the final hydraulic conductivities of PB and 50%PB+50%A GCLs (1.6 times).

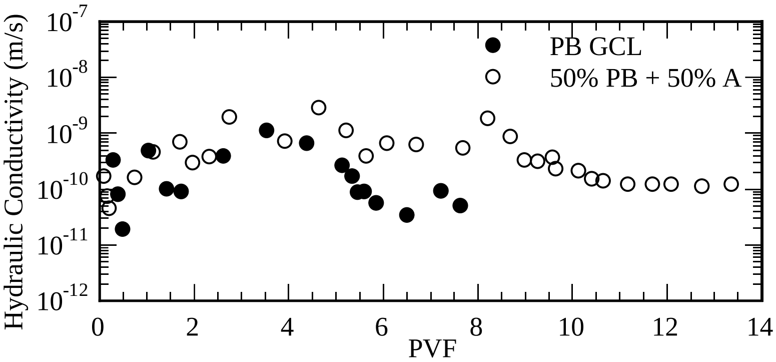


Figure 1. Hydraulic conductivity of non-prehydrated PB and 50%PB+50%A GCLs as a function of pore volumes of flow (PVF).

3.2 *Effect of test duration*

The hydraulic conductivity of 50%PB+50%A GCL was tested twice under non-prehydrated conditions. In the first test, the hydraulic conductivity was lasted two months and therefore, the name of this sample was denoted as “short term”. The other test was continued little longer and terminated after five months (long-term). The comparison of short and long-term hydraulic conductivity behaviors of non-prehydrated 50%PB+50%A GCL is shown in Figure 2. The initial hydraulic conductivity for the long-term sample was significantly greater than that of short term (more than 3 orders of magnitude). It may be due to the uneven distribution of polymer bentonite inside of the GCL and thus, the initial flow rate might have been controlled by the attapulgite particles. However, the hydraulic conductivity decreased around 15 PVF with the swelling of bentonite particles and remained unchanged beyond this level. As summarized in Table 2, the final hydraulic conductivity of long-term sample is 1.8 times less than that of short term sample (6.7×10^{-11} versus 1.2×10^{-10} m/s).

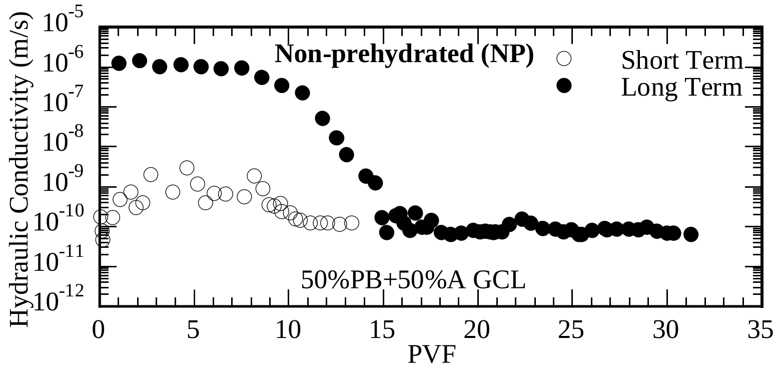


Figure 2. Comparison of the short and long-term hydraulic conductivities of non-prehydrated 50%PB+50%A GCLs as a function of pore volumes of flow.

3.3 *Effect of polymer treatment*

Two tests were applied on 50%NaB+50%A GCL under non-prehydrated condition. The hydraulic conductivity of 50%NaB+50%A GCL was high at the first attempt and around 1.0×10^{-7} m/s (Test-1 in Figure 3). Thus, another sample was prepared for the hydraulic conductivity test (i.e. Test-2 in Figure 3) to check the previous value. The hydraulic conductivity of Test-1 GCL decreased from 3.0×10^{-6} to 1.5×10^{-7} m/s at

70 PVF, whereas Test-2 GCL decreased from 5.0×10^{-6} to 5.0×10^{-7} m/s at 100 PVF. These reductions are due to gradual swelling of bentonite during permeation. However, the hydraulic conductivity started to increase (Table 2) because sodium bentonite in 50%NaB+50%A GCL had no ability to control the flow rate when compared to polymer bentonite in 50%PB+50%A GCL.

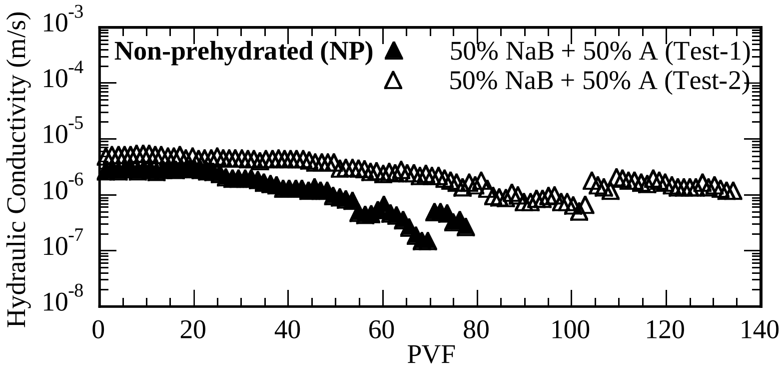


Figure 3. Hydraulic conductivity of non-prehydrated 50%NaB+50%A GCLs as a function of pore volumes of flow.

The effect of bentonite type and hence, polymer treatment can clearly be seen in Figure 4. The comparison in Figure 4 is given in terms of final hydraulic conductivities. The average hydraulic conductivity for 50%PB+50%A and 50%NaB+50%A is 9.4×10^{-11} and 8.3×10^{-7} m/s, respectively. This difference can be attributed to the polymers used in 50%PB+50%A GCL. It is known that some polymers are eluted from bentonite with the permeation which can block the pores and lowers the hydraulic conductivity (Scalia et al. 2013, Scalia and Benson 2017). The same is also valid for this study. Attapulgite particles act as sand grains in clays. This can be seen from Figure 4 where the hydraulic conductivity of 50%NaB+50%A GCL is about four orders of magnitude greater than that of 50%PB+50%A, indicating the role of attapulgite and insufficient swell of NaB within GCL. However, the flow channels between the attapulgite particles are clogged with the polymers eluted from 50%PB+50%A GCL which leads about four orders magnitude difference between the hydraulic conductivities. Thus, use of polymer bentonite instead of conventional sodium bentonite may be better in terms of hydraulic conductivity if GCL is manufactured with attapulgite and installed with non-prehydrated condition (Figure 4).

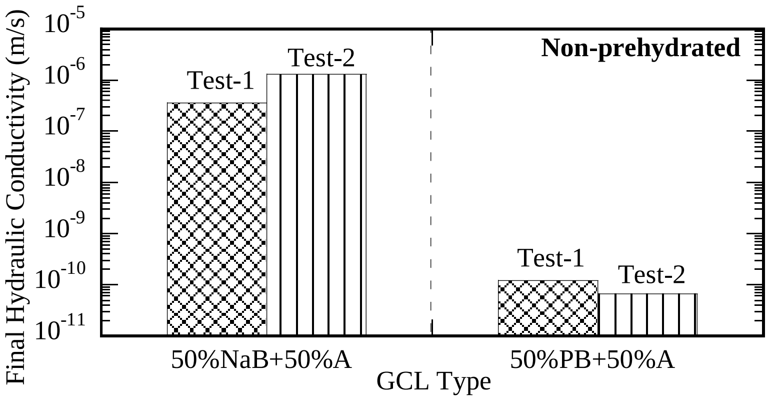


Figure 4. Comparison of the hydraulic conductivities between 50%NaB+50%A and 50%PB+50%A GCLs.

3.4 *Effect of prehydration*

The impact of prehydration on the hydraulic conductivity of GCLs is shown in Figure 5 in terms of final hydraulic conductivities. Prehydrating PB GCL for 24 h decreased the hydraulic conductivity with a factor of 3.1 when compared with the non-prehydrated GCL (from 5.8×10^{-11} to 1.9×10^{-11} m/s). Similarly, the hydraulic conductivity of PB GCL hydrated over zeolite for 30 days was between non-prehydrated and 24h prehydrated GCLs (3.7×10^{-11} m/s).

Unlike PB GCL, the hydraulic conductivity of 24h prehydrated 50%PB+50%A GCL was the greatest among others (3.6×10^{-10} m/s). This value is greater than the value obtained for non-prehydrated GCL. However, it may be come from the small differences between GCLs such as mass per unit area and bentonite distribution inside the GCL. Prehydrating the same GCL over zeolite had the lowest hydraulic conductivity when compared to non-prehydrated and 24 h prehydrated GCLs (5.6×10^{-11} m/s). However, the differences depending on the prehydration are 6.4 times at most.

The greater reduction in the hydraulic conductivity with the permeation was obtained for 50%NaB+50%A GCL. The reduction is over three orders of magnitude when this GCL was hydrated over zeolite for 30 days. Since sodium bentonite had no time for the swelling during the non-prehydrated case, the hydraulic conductivity was an average of 8.3×10^{-7} m/s. However, sodium bentonite tended to absorb water from underlying zeolite and swell during hydration which led to significantly decrease the hydraulic conductivity (6.1×10^{-11} m/s).

Although it is not the primary concern of this study, the influence of subsoil hydration on the hydraulic conductivity is also obvious. Regardless of GCL type, the hydraulic conductivities were ranged between 3.7×10^{-11} and 6.1×10^{-11} m/s when GCLs were hydrated over compacted zeolites for 30 days, indicating the importance of subsoil hydration on the hydraulic conductivity.

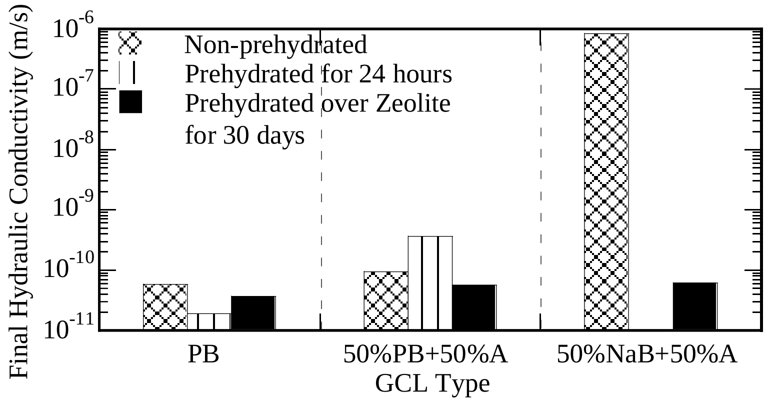


Figure 5. Comparison of the hydraulic conductivities of GCLs in terms of prehydration.

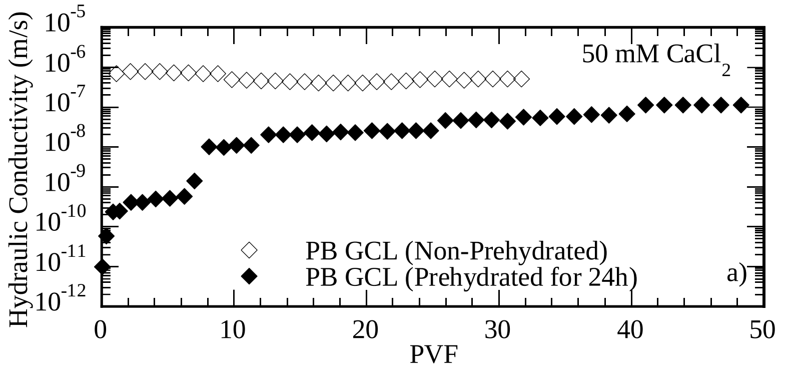
3.5 *Effect of pore fluid chemistry*

The influence of pore fluid chemistry on the hydraulic conductivity of GCLs is narrowly investigated herein. Only 50 mM $CaCl_2$ solution was considered as the permeant which is neither strong nor weak salt solution. It should also be noted that prehydration for the GCLs was applied with the permeant liquid (i.e. 50 mM $CaCl_2$) for 24 h. Since GCLs absorb water from the underlying soil, this case would not be the same as with the GCLs prehydrated with 50 mM $CaCl_2$ for 24 h. Thus, GCLs hydrated over zeolite had been left out of the test program when the effect of pore fluid chemistry was investigated.

The hydraulic conductivity of non-prehydrated and prehydrated PB GCLs permeated with 50 mM $CaCl_2$ solution is shown in Figure 6a. Non-prehydrated PB GCL had hydraulic conductivities around 5.0×10^{-7} m/s and did not change along the test duration. This was expected because water contents of GCLs were within the range of 9-10% in the non-prehydrated condition. Thus, flow was rapid.

In contrast, the prehydrated PB GCL had lower hydraulic conductivities (~5.0×10^{-10} m/s) at the beginning of the permeation. Unlike non-prehydrated GCL, bentonite tended to swell when exposed to $CaCl_2$ solution during prehydration phase. However, the swell type was crystalline and therefore, the hydraulic conductivity increased gradually because of cation replacement between GCL and pore fluid (Jo et al. 2001).

Non-prehydrated and prehydrated 50%PB+50%A GCL had similar initial hydraulic conductivities, indicating negative influence of attapulgite on the hydraulic conductivity. Unlike PB GCL, the amount of polymer bentonite in 50%PB+50%A GCL was not capable of reducing the initial hydraulic conductivity. However, although hydraulic conductivity of non-prehydrated GCL increased furthermore at 25 PVF, the prehydrated GCL decreased down to 4.0×10^{-10} m/s at 70 PVF and then increased to final value of 1.5×10^{-8} m/s (Table 2). The hydraulic behavior beyond 70 PVF for the prehydrated 50%PB+50%A GCL resembles to that of prehydrated PB GCL. That is, hydraulic conductivity gradually increased. However, it is still less than that of prehydrated PB GCL. Thus, it can be suggested that adding attapulgite delayed cation exchange induced hydraulic conductivity increase up to 70 PVF (Figure 6b).



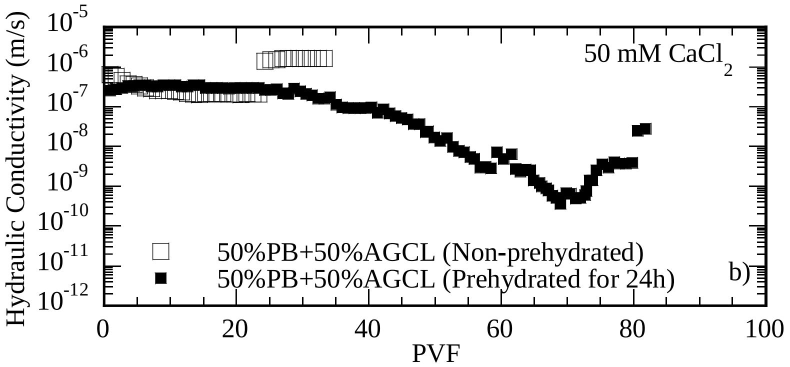


Figure 6. Comparison of the hydraulic conductivity of non-prehydrated and prehydrated GCLs when permeated with 50 mM $CaCl_2$ solutions: a) PB GCL and b) 50%PB+50%A.

4 CONCLUSIONS

Hydraulic conductivity of GCLs manufactured with polymer bentonite (PB GCL) and mixture of polymer/conventional bentonite and attapulgite (50%PB+50%A and 50%NaB+50%A GCLs) have been investigated. The discussion was made by considering the influence of several factors on the hydraulic conductivity. The findings are summarized below:

- Adding 50% attapulgite into GCL increased the hydraulic conductivity of non-prehydrated GCLs only 1.6 times (from 5.8×10^{-11} to 9.4×10^{-11} m/s) when DIW was the permeant.
- The difference between the short and long term hydraulic conductivities of non-prehydrated 50%PB+50%A GCLs is negligible (i.e. 6.7×10^{-11} versus 1.2×10^{-10} m/s).
- The hydraulic conductivity of non-prehydrated 50%PB+50%A GCL was more than three orders of magnitude lower than that of non-prehydrated 50%NaB+50%A GCL. This can be attributed to presence of polymers in 50%PB+50%A GCL which block the flow paths.
- Although prehydration slightly changed the hydraulic conductivity of prehydrated PB and 50%PB+50%A GCLs, the remarkable reduction was obtained for 50%NaB+50%A GCL (from 8.3×10^{-7} to 6.1×10^{-11} m/s).
- When permeant type was switched to 50 mM $CaCl_2$ solution, the hydraulic behavior of GCLs remarkably changed. The hydraulic conductivity of prehydrated PB GCL gradually increased to 1.6×10^{-7} m/s. In contrast, the hydraulic conductivity of prehydrated 50%PB+50%A GCL gradually decreased until 70 PVF because of homogeneous distribution of polymers between attapulgite particles. The hydraulic conductivity tended to increase beyond 70 PVF, but it was still less than PB GCL.

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