

INVESTIGATION OF HYDRAULIC PERFORMANCE FOR A GCL SPECIMEN USING A MIXED IONS SOLUTION

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Abstract: Geosynthetic clay liners (GCLs), though developed in late 80's, are currently gaining acceptance as a liquid barrier system in many geo-environmental applications. GCLs have some unique advantages (fast and easy installation, low permeability and the ability to self-repair small rips or holes) over conventional liners because of the swelling properties of the natural sodium bentonite. However, there have been many debates on their uses in various engineered applications.

Hydraulic performance of GCL has been investigated by using a single layer specimen in a flexible-wall permeameter. Bentofix® NSP 4900 and two types of permeant, tap water and a solution of mixture of salts (KCl, MgCl₂, CaCl₂ and ZnCl₂) of 0.01 M, were used, both with cell pressure of 30 kPa and a constant hydraulic head of 1200 mm. An inductively coupled plasma optical emission spectroscopy (ICP-OES) instrument was used for determination of the ion contents in both influent and effluent. pH of the ionic solution was set at 5.0 for the permeation through the GCL specimen considering the effect of acid rain on a cover liner.

The research has found that using a 0.01 M solution of K, Mg, Ca, and Zn at a point of equilibrium the value of hydraulic conductivity (i.e. 5.27×10^{-12} m/s) of the GCL specimen decreased by 77% relative to that measured using tap water (2.32×10^{-11} m/s). Using the mixed solution of 0.01 M in this research showed a lower value of hydraulic conductivity than any other 0.01 M single ion solution from previous research, which was as expected. The investigation has clarified some previous controversies related to GCLs subjected to ionic solution.

Keywords: Adsorption, geosynthetic clay liner, hydraulic conductivity, landfill, leachate, permeability.

INTRODUCTION

GCLs are being subjected to severe adverse conditions after installation, from relatively low stress situations when used as a cover, to those with higher stress levels where there are many metres of waste overburden with associated leachate when used as a base liner for a landfill site. Their hydraulic performance is under question because of the ionic content from the leachate on to the liner. Many studies dealing with permeation of single ion solutions have been reported, but little concerning alterations in hydraulic performance resulting from permeation by a solution with a mixture of ions.

The purpose here is to investigate the hydraulic performance of a GCL using a solution of mixed salts simulating more realistic leachates. The specific objective is to undertake controlled experiments to determine the effect on a particular single layer of GCL with permeant of 0.01 M mixed mono-valent and di-valent cations in tap water.

BACKGROUND AND LITERATURE REVIEW

GCLs have been used in landfills, remediation of contaminated sites and secondary containment systems (Rowe, 1998). There are growing numbers of cases where GCLs come in to contact with saline water, for example, in landfills located near coastal areas, or where acid rain (pH < 5.6) might be one of the major environmental impacts and could be the liquid that hydrates the GCL, as well as complex landfill leachates. The coefficient of permeability, k , of a GCL permeated with chemical solutions, such as actual or simulated leachates, can be significantly different from the same GCL permeated with water. Schubert (1987), Mitchell and Madsen (1987), Shan and Daniel (1991), Daniel et al (1993), Shackelford (1994), Ruhl and Daniel (1997), Shan and Lai (2002) and Lee and Shackelford (2005) have all permeated GCLs with various chemical solutions including, saline and chemical mixed water, and real or synthetic landfill leachate. The studies have shown that changes in k can be related to changes in the thickness of the diffused double layer (DDL) of cations that surrounds negatively charged clay particles (Mitchell 1993). Hydraulic conductivity decreases with an increase in the thickness of the DDL and shrinkage of the DDL tends to increase k .

Permeation with mono-valent cation solution

Petrov et al (1997a) reported that the k of one GCL, permeated with distilled water was 6.4×10^{-11} m/s, while sequential permeation with aqueous mono-valent salt solution, 0.6 M NaCl, increased it to about 8.0×10^{-10} m/s. They also showed that k values of specimens hydrated and permeated with 0.6 M NaCl solution were in a range of 5.5×10^{-9} m/s to 7.6×10^{-10} m/s. However, using 0.2 M NaCl solution the range was 2.7×10^{-8} m/s to 7.8×10^{-9} m/s.

Petrov and Rowe (1997) used three different permeants, distilled water, aqueous single salt solutions with concentrations between 0.01 and 2.0 M NaCl and a synthetic municipal solid waste leachate. At a given confining stress GCLs hydrated and permeated with the lower salt concentrations generally reached greater thickness and hence larger void ratios than those of the higher salt concentrations. The void ratios tended to be smaller for samples hydrated and permeated with the salt solutions than for samples hydrated and permeated with distilled water. Increases in the salt concentration and decreases in confining stress caused increases in k and they showed that using salt water hydration, at any confining stresses, k was linearly related to the NaCl concentration on a log – log scale with values

highly dependent on the salt concentration, varying by a factor between 280 and 570 as the concentration was increased from 0.1 to 2.0 M NaCl. They concluded that the thickness of the adsorbed layer is more influential than void ratio when the GCL is permeated directly with NaCl solution relative to initial permeation with distilled water. The bentonite swelling properties are highly degraded by concentrated salt solutions (Petrov and Rowe, 1997) leading to a double-layer that produces a more open structured, flocculated clay fabric with greater effective pore space for permeant flow (Petrov et al 1997a).

Malusis and Shackelford (2002) studied chemico-osmotic efficiency and k for a GCL with varying potassium chloride, KCl, concentrations. Using four samples from the GCL they conducted tests first with tap water and subsequently with a KCl solution (between 0.0039-0.047M) and showed that increase in concentration compressed the DDL and resulted in an increase in k .

Shackelford et al (2000) discussed factors affecting k for a GCL permeated with various liquids. They showed that both high concentrations of mono-valent cations (0.6 M NaCl) and low concentrations of divalent cations (0.0125 M CaCl_2) individually can cause significant increases in k , provided the tests continued sufficiently long to allow for exchange of adsorbed cations. They conducted their test over 540 days in a flexible-wall permeameter with an average effective stress of 18 kPa and a high hydraulic gradient of 80. They found no change in k during the first 5 pore volumes of flow after which it began to increase gradually. After 51 pore volumes of flow k increased to 3×10^{-10} m/s using 0.0125 M CaCl_2 solution from a reference k of 1×10^{-11} m/s using deionised water (Lin, 1998). They concluded that the Ca^{+2} from the solution gradually exchanged for Na^+ , produced a gradual compression of the adsorbed layer with a consequent increase in k . Specimens were also permeated with 0.025 M solutions of LiCl and MgCl_2 and k values of 4.1×10^{-11} m/s and 4.1×10^{-8} m/s were obtained. Similarly, use of 0.0125 M CaCl_2 solution through a GCL sample yielded an increase of permeability by a factor of approximately 3 – 5, from approximately 5×10^{-12} m/s using de-ionised water, to 1.9×10^{-11} m/s (Lin and Benson, 2000). Increasing the CaCl_2 concentration to 0.3 M, 24 times higher than Lin and Benson (2000), the permeability of a GCL (8000 g bentonite/m²) increased by an average factor of 3.1 and the permeability of another GCL (4700 g bentonite/m²) by an average factor of 6.4 (Egloffstein, 2001).

Permeation with di-valent cation solution

Shan and Daniel (1991) permeated a GCL with water and then with various chemicals, including 0.005 M CaSO_4 and 0.25 M CaCl_2 solutions under an effective stress of 35 kPa and the permeating pore volumes ranged from 0.2 to 24.2. They reported that k increased almost 10 fold using CaSO_4 and CaCl_2 solutions individually. Gleason et al (1997) have shown that k for a compacted sand mixture increased about 100 fold when permeant was switched from tap water to 0.25 M CaCl_2 solution. In practice, a field installation of a GCL in which the sodium in the bentonite was inadvertently replaced by calcium, leaching out from overlying limestone, showed a large increase in k (Dobras and Elzea, 1993). Imamura et al (1996) using a compacted sand bentonite specimen permeated with $\text{Ca}(\text{OH})_2$ solution reported that the k increased more than two orders of magnitude after more than 25 pore volumes of flow.

Lee and Shackelford (2005) studied two GCLs permeated with water and chemical solutions containing different amounts of CaCl_2 , using a flexible-wall permeameter, as recommended in ASTM D 5084, but with an average hydraulic gradient of 200 and mean effective stresses of 23.5 kPa. Using 0.005, 0.01, 0.02, 0.05, 0.1 and 0.5 M CaCl_2 solutions chemical equilibrium was reached after 58, 60, 22, 18, 11 and 1.6 pore volumes of flow (PVF) respectively for a high quality bentonite GCL and after 57, 31, 21, 9.3, 6.8 and 1.7 respectively for a low quality bentonite. At chemical equilibrium they found k ranged from 1.7×10^{-10} m/s to 6.2×10^{-7} m/s for the HQB and from 6.7×10^{-11} m/s to 1.8×10^{-8} m/s for the LQB.

Shackelford et al (2000) used a di-valent cation salt solution of ZnCl_2 permeated through a needle-punched GCL. With solutions ranging from 0.01 to 0.1 M, using a flexible-wall permeameter with an effective stress of 20 kPa and i of 100, they noted that as the concentration of the electrolyte increases, thickness of the adsorbed layer decreases hence the swell volume decreases and the k increases.

In summary, previous researchers have used single ion solutions, either mono-valent or a di-valent, with various concentrations and investigated the hydraulic performance of GCLs. The novelty of the present investigation lies in using a mixed ion solution as permeant.

EXPERIMENTS

Materials and methods

Bentofix® NSP 4900 is used here. A nonwoven polypropylene geotextile and a woven polypropylene geotextile, having mass per unit area of 220 g/m² and 110 g/m² respectively, are mechanically bonded (needle-punched) and encapsulate the bentonite that ensures the long-term performance of the composite. The bentonite used is natural sodium bentonite in powdered form with a mass of 4670 g/m² of GCL. The properties of Bentofix® NSP 4900 are given in Table 1. The initial unconfined and non-stressed dry thickness of the GCL was a nominal 6 mm with a specific gravity, G_s , of the clay of 2.78 and the bentonite had initial moisture content of approximately 10% and was light brown in colour in its essentially air dry, powdered form.

Tap water (pH 7.2) used as the permeant in this study was de-aired and met the criteria to comply with ASTM D 5084 for permeation prior to use for the hydraulic conductivity test.

An ionic solution was made of inorganic salts dissolved in de-ionised water. A mixture of four different salts, each of them 0.01 M, was used to prepare an ionic solution of 0.01 M. The inorganic salts were chosen according to their mono-valent and di-valent cations that are common in landfill leachate. Mono-valent cation KCl and di-valent

cations $MgCl_2 \cdot 6H_2O$, $CaCl_2$ and $ZnCl_2$ in a solution of 0.01 M were used. All chloride salts were chosen, as these were easily available, less toxic than some other salts, had no bad odour and maintained a consistent anion in the solution. The solution as prepared was clear and transparent with initial pH of 4.21. This was raised to a standard value of 5.0 using sodium hydroxide and the solution was taken as the basis for the rest of the ionic tests.

Constant head hydraulic conductivity tests were conducted using a flexible wall permeameter (triaxial cell, in accordance with ASTM D 5084 and ASTM D 6766-02). The base of the cell was connected to a pressure supply line and inlet and outflow lines for the specimen. A 100 mm diameter GCL specimen was sandwiched between two 100 mm diameter porous stone disks (5 mm thick with a pore diameter of 100 μm , porosity $n \sim 0.6$). Two filter papers with a pore diameter of 20 μm were placed between the specimen and the porous disks. A rigid cap with drainage line was fitted on top of the specimen sandwich and the assembly was enclosed in a rubber membrane sealed by four O-rings. The body of the cell consisted of an acrylic cylinder 180 mm in diameter and 280 mm high. The end cap contained O-ring sealing the contact between the cylinder and the base. The cell pressure line allowed water into the cylinder and subsequently application of a constant pressure into the cylinder.

The porous discs were strong enough to withstand the maximum vertical pressure that was imposed during the test, were checked before each use to ensure that they were not clogged by fine particles and were boiled for at least 10 minutes before use and kept immersed in de-aired water until required.

Table 1. Properties of Bentofix® NSP 4900

Properties	Value	Test method
Geotextile layers:		
Polypropylene nonwoven cover layer.		
Mass per unit area, g/m^2	220	EN 965
Polypropylene woven carrier layer		
Mass per unit area, g/m^2	110	EN 965
Powdered natural sodium bentonite layer:		
Mass per unit area, g/m^2	4670	EN 965
Swell index, ml/2g	24	ASTM D 5890
Fluid loss, ml	≤ 18	ASTM D 5891
Moisture content, %	Approximately 10	DIN 18121
Composite geosynthetic clay liner:		
Mass per unit area, g/m^2	5000	EN 965
Thickness, mm	6.0	EN 964 – 1

Specimen and cell set up

GCL specimens of 100 mm diameter were prepared by cutting from a roll, following the method described by Daniel (1994). A small amount of test liquid was applied along the inner circumference of the cutting ring to prevent bentonite loss when removing the specimen from the ring. Excess geotextile fibres were removed from the edge of the specimen with sharp scissors to eliminate potential preferential flow paths between the GCL and flexible membrane (Petrov et al 1997 a, b). Bentonite paste was prepared using some dry bentonite powder and the test permeant. The paste was then carefully placed along the perimeter of the specimen with a small spatula to minimize the potential for sidewall leakage during permeation. The specimen was sandwiched between two porous stone disks with filter papers and submerged in de-aired water for half an hour to ensure complete saturation.

The triaxial cell base was submerged in a large tank. A flexible membrane was fitted to the base platform using two rubber O-rings. The 100 mm diameter sandwich was inserted into the membrane and carefully rested on the base before the specimen cap with the outlet line was inserted and sealed with further O-rings. The cell body was then bolted into place, with the whole still submerged to ensure that all the voids of the specimen and the cell were saturated and there was no trapped air left inside either the specimen or the cell.

The triaxial cell was taken from the water tank with all connection valves closed, and placed on a laboratory bench. The valves on both the inlet and outlet lines were opened for initial drainage. The single layer specimen was left to swell over night under a cell pressure of 15 kPa with a constant hydraulic head of 1200 mm. After swelling over night the cell pressure was increased to 30 kPa for the test.

The inlet line pushed permeant upwards through the specimen under a constant head and the outlet line allowed collection of the effluent for flow assessment and chemical analysis. The effluent was collected in a 50 ml plastic beaker with care taken to eliminate evaporation losses. The permeant pressure at the inlet side of the specimen, u_i , was calculated using the constant head of the supply tank and at the outlet, u_o , was zero. Cell (vertical) stress, σ_v , was applied using a standard pressure system. The derived mean σ_v' on the GCL specimen was calculated from

$$\sigma_v' = \sigma_v - \frac{(u_i + u_o)}{2}$$

As the permeant was seeping through the GCL specimen the total head was gradually transferred to the specimen skeleton through frictional drag. Seepage induced stresses during a hydraulic conductivity test with high hydraulic gradient may produce significant vertical consolidation, which might produce an erroneous k value for a material that

compresses. The pressure difference used was such as to produce a reasonable rate of flow through the specimen. BS 1377-6:1990 recommends a gradient of 20 or more in clay soils to achieve any measurable flow.

The volume of water passed through the specimen in a known time, and under a constant gradient, was measured. Assuming the flow was steady k was calculated using Darcy's law,

$$k_{at\ T^{\circ}C} = \frac{q \times t}{\Delta h \times A}$$

where q , t and A are the equilibrium flow rate, thickness and cross-sectional area of the specimen, respectively.

Tap water and the ionic solution were used as permeants. 15 samples of approximately 20 ml of water were collected from the tap, daily over 15 working days and were then tested for ion concentrations to identify whether these would have an influence on the permeability of the GCL sample. The test results showed ion concentrations were much lower than the allowable limits for drinking water and it was concluded that there would be no ionic influence on the permeability test using the tap water.

After permeation through the GCL specimen the outflow permeant was collected in the capped beaker and for a specified time interval the outflow was measured by weighing of the beaker using a digital balance.

All tests were carried out in a laboratory in which the temperature was maintained constant to $17^{\circ}C \pm 2^{\circ}C$, in accordance with BS 1377-1:1990. Everyday when the effluent quantity was recorded, the temperature of the effluent was also noted. A temperature correction was made to the calculation to normalise k to that at $20^{\circ}C$.

$$k_{ar20^{\circ}C} = k_{at\ T^{\circ}C} \times R_T$$

where determination of the temperature correction factor R_T to a water temperature of $20^{\circ}C$ follows (BS 1377-6:1990, EN ISO 11058:1999).

On completion of the test, the specimen was removed from the permeameter and the final thickness (at 25 locations) and mass were measured to nearest 0.01 mm, using a digital Vernier calliper, and 0.01 g, using a digital balance. An average of the 25 measurements was taken as the effective thickness, t , of the specimen under the final σ_v . Moisture content of the specimen was measured and one pore volume was calculated assuming G_S , as above.

Procedure for testing using ionic solution

After a night of swelling and permeation with tap water the inlet valve of the permeameter was closed, the tap water was drained from the inlet line and replaced by the permeant liquid 0.01 M solution. The inlet valve was re-opened and the cell pressure was raised to 30 kPa, as recommended by ASTM D 6766-02. Effluent was weighed daily on a digital balance and amount of flow in specific hours was tabulated.

Every day over 16 weeks the inlet and outlet flows were measured. The inlet flow was measured using the solution level in a burette, and the outlet flow by taking the weight of the plastic beaker. Effluent was collected and sampled in a capped bottle (maximum 25 ml) on the 2nd and 5th working days of each week for measurement of electrical conductivity (EC), pH and ion concentrations. The procedure was repeated until equilibrium for ion concentrations in the effluent samples was observed. It is noted that Jones et al (1977-78) suggested a time for chemical equilibrium based on the minimum amount of time needed to establish a rate of change of the solute concentration equal to, or less than, 10% during a 6-hour period, whereas EPA (1992) suggested that the time needed for equilibrium should be defined as the minimum amount of time needed to establish a rate of change in the solute concentration equal to or less than 5% during a 24- hour period. Lee and Shackelford (2005) suggested that effluent ion concentrations within $\pm 10\%$ of those in the influent solution would be considered as equilibrium and this has been accepted here.

Calibration and method of test results analysis

Radiation energy is inversely proportional to wavelength. Based on this principle ICP-OES has been constructed and is used for quantitative measurement of ions in a solution (Fazal 2007). For each element, vapour absorbs and emits radiation at unique and characteristic wavelengths, Figure 1. Qualitative analysis of individual elements provides identification for the specific wavelengths, which have different emission intensities that vary with concentration of the elements in the solutions, Figure 2. Using an ICP-OES for measuring each ion requires at least two standard solutions, one of lower value and another of higher value than the expected result. This study used a 0.01 M solution and measurements from this solution were compared with those from two standard solutions of 0.008 M and 0.012 M. Ion concentrations of the 0.01 M solution were calculated arithmetically by each individual salt's molecular weight. Measured ion concentrations were higher than calculated values by up to 10%, due to the presence of some impurities in the solution and/or other ions that came under the plasma and increased the apparent intensity of the ions with appropriate wavelength.

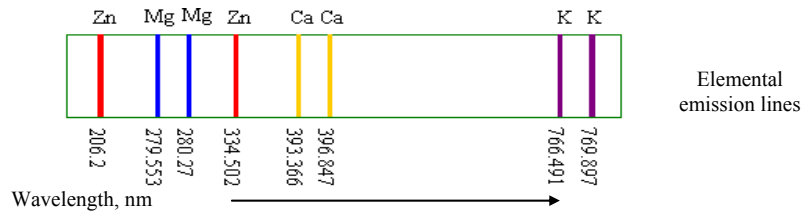


Figure 1. Unique and characteristic wavelengths of elements used

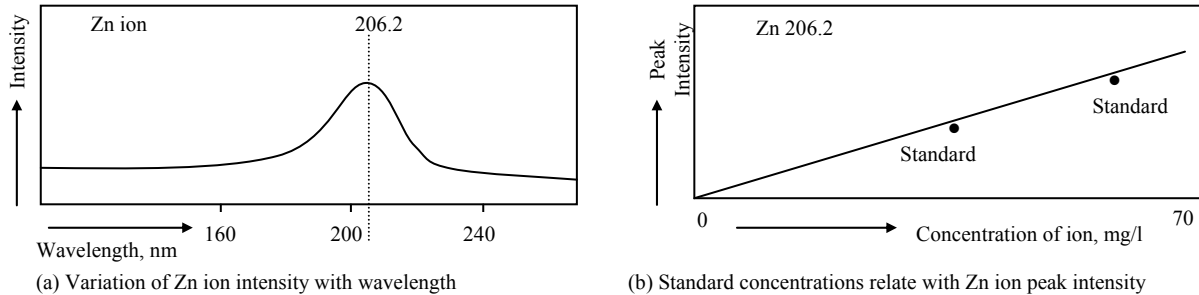


Figure 2. Measuring of Zn ion concentration at a wavelength of 206.2 nm

PRESENTATION AND INTERPRETATION OF TEST RESULTS

Permeation of GCL with tap water

The test was conducted using the cell pressure of 30 kPa and a constant hydraulic head of 1200 mm. After four weeks a steady state final flow rate was 1.07×10^{-3} ml/min. The average thickness, moisture content and one pore volume of the specimen under σ_v' of 24.1 kPa were 11.36 mm, 140 % and 59.2 ml respectively. The hydraulic conductivity of the GCL permeating the tap water was 2.32×10^{-11} m/s at 20°C (Fazal, 2007).

Permeation of GCL with ionic solution

Effluents were collected and their pH, EC and ionic contents were measured. σ_v' on the specimen was 24.1 kPa as above and the test was conducted over 16 weeks. Influent and effluent quantities and the electrical conductivity, pH and ion concentration of outlet samples were measured. The average temperature of the laboratory over successive four-week periods was 17.1°C, 17.5°C, 18.9°C and 18.6°C. Figure 3 shows total influent and effluent flows with time. Totals of 618 ml and 652 ml of the ionic solution permeated through and entered the specimen respectively. After the test, thickness, moisture content and pore volume of the specimen were 6.23 mm, 117 % and 37 ml respectively. As soon as the ionic solution started permeating the GCL the liquid exchanged its cation content with sodium and hence sodium would leach out throughout the test until the chemical equilibrium was reached.

Performance of ion adsorption for pore volumes

16.51 pore volumes flowed through the specimen. Figure 4 shows the variation of ion concentrations (out/in) with the total flow. It can be seen that Mg ions started showing in the effluent after 0.45 PV, K and Ca ions after 1.03 PV and Zn ions after 3.26 PV. After about 3.26 PV of flow, the slope of all the ion concentration lines changed. After 8.60 PV of flow, ion concentrations in the effluent became almost constant (except Zn with 334.502 nM wavelength) up to 14.42 PV of flow. However, from 14.42 PV up to 15.87 PV of flow the lines were showing equilibrium of ion concentration. It can be seen that all four ions were adsorbed and exchanged their position with Na and the adsorption rate was high initially and then equilibrium happened after around 8.60 PV of flow. Considering the eight lines in the graph it can be seen that the affinity for ion adsorption is $\text{Zn}^{+2} > \text{K}^+ > \text{Ca}^{+2} > \text{Mg}^{+2}$ before the chemical equilibrium. Considering Figure 4 with Figure 3 it can be concluded that, adsorption or exchange of ions has determined the changes of the flow rate as well as the thickness of the specimen.

Effect on specimen thickness

Final thickness of the specimen was 6.23 mm under σ_v' of 24.1 kPa, whereas when permeating tap water under otherwise similar conditions the final thickness of a specimen was 11.36 mm - higher by a factor of 1.82. Egloffstein (2001) reported that ion exchange of a Na-bentonite into a Ca-bentonite reduced volume due to the decreasing distances between the montmorillonite flakes and a loss of water of approximately 6 – 12 %. Na^+ is at the lower end of the lyotropic series, Na-bentonites are prone to cation exchange when permeated with solutions containing divalent or trivalent ions (Sposito, 1981). Swelling depends on the sodium properties and quantities in a specimen. The effect on thickness can be explained: as the four types of ions were adsorbed on the specimen, the Na^+ was reduced, hence the swelling. Chemical equilibrium was reached for the specimen well before the end of the test.

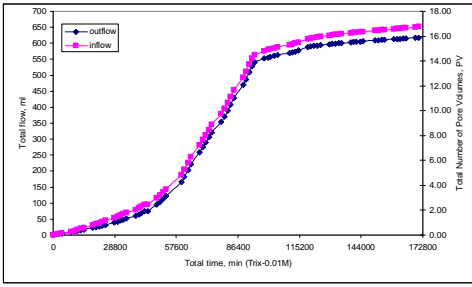


Figure 3. Total influent and effluent flows with time

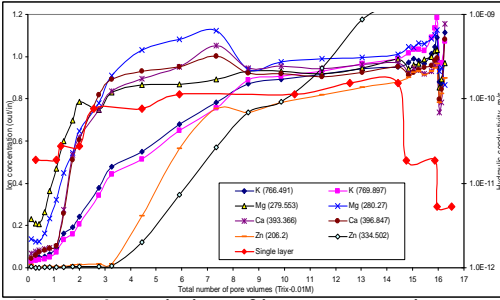


Figure 4. Variation of ion concentrations (out/in) with the total flow

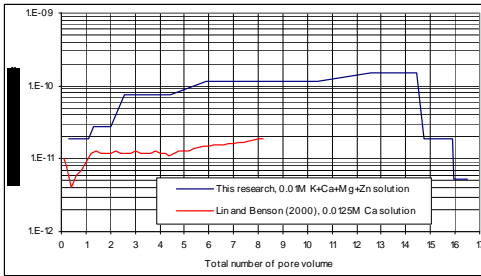


Figure 5. Hydraulic conductivity – pore volume, comparison

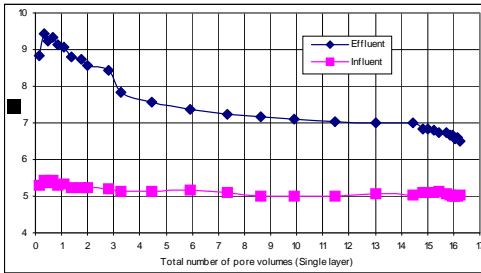


Figure 6. Pore volume - pH

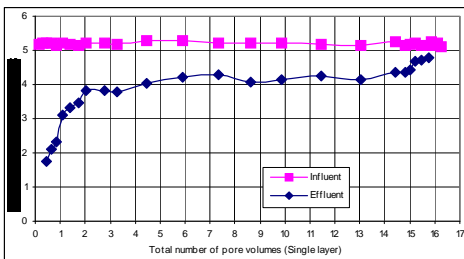


Figure 7. Pore volume - electrical conductivity

Performance in terms of k

Figure 3 shows the inflow line is above the outflow line but both follow a similar pattern indicating that the specimen adsorbs some liquid (34.2 ml) during the test, which is approximately 10% (initial moisture content) less than one pore volume of 37 ml. It has been observed that flow rate and k increased with the adsorption of the ions and cation exchange with sodium. This can be called the unsteady chemical state, and then after equilibrium the k decreased stepwise, this state can be called steady state of the chemicals, and remained constant at 5.27×10^{-12} m/s through to the end of the test, Figure 5. The changing of k with the number of pore volumes using the GCL specimen is compared with a lower line in the figure reported by Lin and Benson (2000). Both show a similar pattern of increased k with up to 8 pore volumes of flows. Shackelford et al (2000) have permeated 0.0125 M CaCl₂ solution through a single layer of GCL specimen and have shown that k increased gradually from 1.00×10^{-11} m/s up to 2.80×10^{-10} m/s after 37 pore volumes of permeation (during the unsteady state of the chemicals) and then just about to the equilibrium the trend of the k line was found downwards, but after 51 pore volumes of permeation they have stopped their test. If they had continued their test they might have seen a final k below 1.00×10^{-11} m/s because of the complete equilibrium of the chemicals. This present research has looked into the ionic content in the effluent and has determined the chemical equilibrium, but Shackelford et al (2000) have determined their chemical equilibrium by considering final pH level of the effluent therefore they have missed out the final state of the test and hence the final k of the specimen.

Performance in terms of pH and EC

The 0.01 M liquid was made up at pH 5.0 and the effluent pH was measured throughout the tests and plotted in Figure 6 as a function of the total number of pore volumes. It was found that, though the inflow pH was maintained close to 5.0 the outflow pH was initially 9.5 but dropped to 6.8 over 16.51 PV. This indicated the wet specimen was alkaline with de-aired water (pH was 7.2) and the influence of the acidic liquid (pH 5.0) had changed its behaviour with the total number of pore volumes. From Figure 6 it also can be seen that up to 3.26 PV the pH changed rapidly and then more slowly up to 8.60 PV and then became steady up to 14.42 PV then again changed rapidly. This is consistent with data reported by Ruhl and Daniel (1997) who used a permeant with pH of 1.0. Wider range of results of hydraulic conductivity tests conducted at various pH for various GCLs are summarized in Fazal (2007).

Figure 7 shows the changing EC of the effluent fluid as a function of the total flow – effluent EC changed rapidly up to 3.26 PV then more slowly, eventually approaching the inflow value.

CONCLUSIONS

The following conclusions are drawn from the research

- The affinity for ion adsorption on the GCL specimen is $Zn^{+2} > K^+ > Ca^{+2} > Mg^{+2}$ before chemical equilibrium.
- The adsorption or exchange of ions determines both the permeant flow rate and the specimen thickness.
- Using a 0.01 M solution and comparing the behaviour when using tap water, the thickness reduces by a factor of 1.82 for a GCL specimen at σ'_v of 24.1 kPa.
- Using an ionic solution the permeability, k, of a specimen increases with the adsorption of the ion and cation exchange with sodium up to chemical equilibrium.
- Using a 0.01 M mixed solution of K, Mg, Ca and Zn at a point after equilibrium the value of k decreases by 77% (i.e. 5.27×10^{-12} m/s) relative to that measured using tap water.
- The mixed ion solution of 0.01 M produces a lower value of k for a GCL specimen comparing with that of any other 0.01 M single ion solution.
- The value of k of a GCL specimen varies with pH.
- The value of k of a GCL is a function of ion concentrations, pH of the permeant and alteration of EC.

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