

FACTORS IMPACTING LIQUID AND GAS FLOW THROUGH GEOSYNTHETIC CLAY LINERS

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ABSTRACT: Over the past decade, geosynthetic clay liners have gained widespread popularity as a substitute for compacted clay liners in cover systems and composite bottom liners. They are also used as environmental protection barriers in transportation facilities or storage tanks, and as single liners for canals, ponds or surface impoundments. As a result, they are being investigated intensively, especially in regard to their hydraulic and diffusion characteristics, chemical compatibility, mechanical behaviour, durability and gas migration. In this paper, a review of the main findings is presented with the focus on the critical aspects affecting the hydraulic/gas performance of GCLs. From this work, a general insight is gained on the design implications for systems that incorporate GCLs.

1. INTRODUCTION

Geosynthetic clay liners (GCLs) are thin (typically 5 to 10 mm) manufactured hydraulic barriers comprised of a thin layer of bentonite bonded to layers of geotextiles and/or a geomembrane. Presently, the International Standards Organization (ISO) refers to them as Clay Geosynthetic Barriers (CGBs) (Zanzinger et al., 2002). Over the past decade, design engineers and environmental agencies have shown a growing interest in the use of geosynthetic clay liners as an alternative to compacted clays in cover systems or in some cases bottom lining of waste containment facilities because they often have very low hydraulic conductivity to water ($k_w < 10^{-10}$ m/s) and are also relatively inexpensive. GCLs are also used as environmental protection barriers in transportation facilities (roads and railways) to minimize pollution of subsurface strata from accidental spills and seepage of chemicals; or as secondary liners for underground storage tanks at fuel stations for groundwater protection, and single liners for canals, ponds or surface impoundments.

Geotextiles based GCLs are bonded with by either an adhesive, needle-punching or stitch-bonding, with the bentonite contained by the geotextiles on both sides. The needle-punching process causes some fibres from the top geotextile to extend through the bentonite and into the bottom geotextile, holding the entire structure together (von Maubeuge and Heerten, 1994). The fibres that are punched through the bottom geotextile either rely on natural entanglement and friction to keep the GCL together or are heated, causing them to fuse to the bottom geotextile and potentially creating a stronger bond between the two geotextiles and bentonite (in this case they maybe referred to as "thermal locked GCLs"). Alternatively, the reinforcement can be carried out by sewing the entire geotextile-bentonite composite together with parallel rows of stitch bonded yarns. For the geomembrane-supported GCL, the bentonite is bonded to the GM using a non-polluting adhesive and a thin open weave spun-bound geotextile is adhered to the bentonite for protection purposes during installation.

In addition to the possible adhesives added to the bentonite as just mentioned, very thin polymer films (≈ 0.10 mm thick) have been added to the composite material for further reduction of permeability (Koerner, 2005). Such films are placed either above or below the cap geotextile to lower its permeability from the as-manufactured condition. A different approach in achieving very low hydraulic conductivity is to polymer treat the cap geotextile to lower its permeability from the as-manufactured condition. It is also possible to polymer modify the bentonite particles themselves within their molecular structure or adhere polymers to the outside of the platlets (Koerner, 2005). However, such processes, are not widespread and presently the low hydraulic conductivity component of GCLs is entirely provided by the bentonite.

The primary differences between GCLs are the mineralogy and form of bentonite (e.g., natural sodium versus sodiam activated calcium bentonite, powder versus granular forms, etc.) used in the GCL, the type of geotextile (e.g., woven versus nonwoven geotextiles) and the addition of a geomembrane and the bonding methods. In the following sections we will discuss in general terms how the properties of the bentonite and geotextile components, in combination, impact on GCL hydraulic and gas performance.

2. BENTONITE IN GCLs

Due to the thinness of GCLs and the fact that they typically are intended to replace compacted clay liners, the bentonite used in GCLs must be of high quality. Current specifications for bentonites used in GCLs are spelled out in ASTM standards, ISO, etc. to name few, the reader can refer to them for further details. Montmorillonites, major constituents of bentonite, typically have moderately high cation exchange capacities (80 – 150 meq/100g). The CEC attracts hydrated exchange cations such as Na^+ or Ca^{2+} , which impart different limited or crystalline swelling, layer stacking and clay fabric properties due to differences in their hydration energy, size and charge. Na^+ -saturated montmorillonites are capable of imbibing several times their mass in water (Odom and Low, 1978; Laird, 2006) whilst undergoing unlimited or osmotic swelling. In most bentonites used in GCLs, the dispersed montmorillonite particle size fraction is predominantly $<0.5 \mu\text{m}$. This small particle size means that montmorillonites have large specific surface areas of 500 to 850 m^2/g . High specific surface area due to small particle size, in combination with high swelling, result in a material that presents a tortuous path for water flow, thus very low hydraulic conductivities (Mitchell and Soga, 2005). Besides montmorillonite, other mineral constituents of bentonite may include a few percentages of quartz, feldspars, carbonites, or mica, as well as additional discrete or mixed-layer clay minerals. The mineral impurities tend to reduce the bentonite quality in terms of its ability to hydrate, swell, disperse and gel. The montmorillonite component, with its extremely large specific surface area and capability for both crystalline (interlayer) and bulk (inter-particle) swelling, is responsible for the desirable physical and chemical attributes that make the use of bentonite omnipresent in many industrial and engineering applications, including geosynthetic clay liners.

Natural sodium bentonite is the material of choice in GCLs. Natural sodium bentonites only exist in extensive deposits in the states of Wyoming, South Dakota and Montana, in the United States, and in a few generally isolated deposits in Greece, Turkey, India and Iran (Harvey and Keeling, 2002). For this reason, "sodium activation of calcium bentonite (in which the exchangeable calcium cations have been replaced with sodium ions) are a common material in GCLs. Sodium activation is usually done to increase swelling, dispersion, hydration and gelling properties of the bentonite, which in its normal Ca^{2+} -form, would have sub optimal properties (Harvey and Lagaly, 2006). In general high swelling and good dispersion of bentonites are correlated with lower void ratios which in turn result in lower hydraulic conductivity (Churchman et al., 2002). It should be noted that many GCLs are marketed as "sodium bentonites", rather than sodium activated bentonites.

The typical distribution of cations in sodium bentonite used for GCLs has been given by Egloffstein (2001) to be: 50-90% Na^+ , 5-25% Ca^{2+} , 3-15% Mg^{2+} , 0.1-0.5% K^+ . Much of the Ca^{2+} and Mg^{2+} may be associated with a carbonate phase that precipitates during sodium activation (Guyonnet et al., 2005). Upon hydration, a part of these carbonates dissolve and release Ca^{2+} and/or Mg^{2+} , which can displace Na^+ . Thus swelling, dispersion and gelation of sodium activated bentonites may be sub optimal (Harvey and Lagaly, 2006). In such cases, other additives are often added to improve these properties. Harvey and Lagaly (2006) report that the flow behaviour of sodium activated bentonite suspensions is improved with addition of 5mmol/g Na_2CO_3 . It is now common practice for manufacturers of GCLs to add ~1% of an anionic polymer to the bentonites. These polymers improve the dispersion and sealing capability of sodium activated bentonites.

Calcium bentonite has also been used in GCLs, but since the hydraulic conductivity of calcium bentonite is about one order of magnitude higher than that for sodium bentonite they are not commonly used. Where they are used, GCLs with calcium bentonite typically have a much larger mass per unit area than GCLs with sodium bentonite to help overcome the sub optimal performance.

3. HYDRATION MECHANISMS AND SWELL CHARACTERISTICS OF GCLs

Bentonite's low conductivity to water results primarily from its small particle size, large surface area and correspondingly low void ratio. These result in its ability to adsorb and effectively immobilize pore water through a variety of short-range and long range hydration mechanisms (Mesri and Olson, 1970). Understanding these hydration mechanisms provides a basis to better understand the overall hydraulic performance of bentonite for GCL applications. Vangpaisal and Bouazza (2004) have shown that the form of bentonite (i.e., powdered or granular) could affect the hydration mechanisms of the GCLs. This is illustrated in Figures 1 and 2, for GCLs containing dry powdered bentonite, it was shown that the outermost bentonite started to absorb water and hydrate. Consequently, a thin film of hydrated bentonite was formed which had the effect of slowing further water flow through to the inner dry bentonite. As dry bentonite absorbed more water, the layers of hydrated bentonite gradually moved inward, until the water potential of the bentonite was equilibrated. Conversely, in the case of GCLs containing dry granular bentonite, it was observed that hydrating water passed through the large

voids between bentonite grains throughout the entire GCL thickness, and all bentonite grains started to absorb water and hydrate simultaneously. The outer surface of each bentonite grain formed a hydrated film covering its dry core. The bentonite then gradually absorbed the water deeper into the core until the water potential was equilibrated.

The most dominant reasons why GCLs provide low levels of hydraulic conductivity are the double layer (DDL) effect and osmotic swelling. The double layer effect generally occurs between clay particles, while the osmotic phase of swelling is a specific phenomenon of smectites. Smectites in general; and montmorillonites in particular, are capable of significant interactions with water. Solid-liquid (mineral-pore water) interactions occur on the external particle surface and, for swelling clay minerals, on the interlayer surfaces as well. The surface area and the surface charge properties of the clay mineral dictate the extent and range of the solid-liquid interactions (e.g., Odom and Low, 1978; Laird, 2006). The large specific surface area of smectite is clear indication of the importance of solid-liquid interaction in governing the overall system behavior. Detailed discussion of these topics is beyond the scope of the present paper. However, the readers can consult Mitchell and Soga (2005), who covered extensively these topics, for further details.

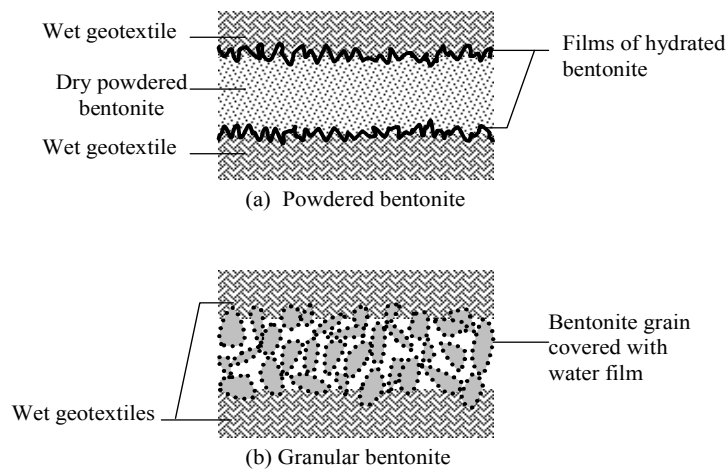


Figure 1. Hydration mechanisms of different forms of bentonite (from Vangpaisal & Bouazza, 2004)

Swell test results for fully hydrated GCLs are shown in Figure 3 (confined swell, $\sigma = 20$ kPa) and Figure 4 (free swell). It can be seen that both free and confined swelling of GCLs increases with hydration time. Each GCL swells at different rates and achieves different final moisture contents. GCL-1 swells the least for both hydration conditions. GCL-2 and GCL-3 swell the most for the confined hydration, while GCL-4 swells the most for the free swell hydration. In addition, a slightly higher swell was achieved in GCL-3, compared to GCL-2, for both the confined hydration and the free swell hydration conditions.

Confining stress clearly limited the hydration and swelling of the GCLs (Figure 3). The confined GCLs achieved final gravimetric moisture contents of 140% to 190%, whereas the free swell GCLs achieved higher final gravimetric moisture contents of 200% to 300% (Figure 4). The presence of the confining stress resulted in the reduction of GCL swelling by approximately 50% and 70% for the needle punched GCLs (GCL-1, GCL-2 and GCL-3) and the stitch bonded GCL (GCL-4), respectively. It should be noted that in the case of free swell hydration, the measured thickness of GCL-4 represented the upper value of the actual thickness, because as the stitch bonded GCL undergoes swelling it is partly confined along the stitch lines (Figure 5), but swelled freely between them. In contrast, the measured thickness of the needle punched GCL represented the average thickness of the flat surface GCL. This is because the needle punched fibres are more evenly distributed throughout the GCL. However, flat surfaces can be achieved for all types of GCLs when hydrated under confinement, as for example occurs in field applications.

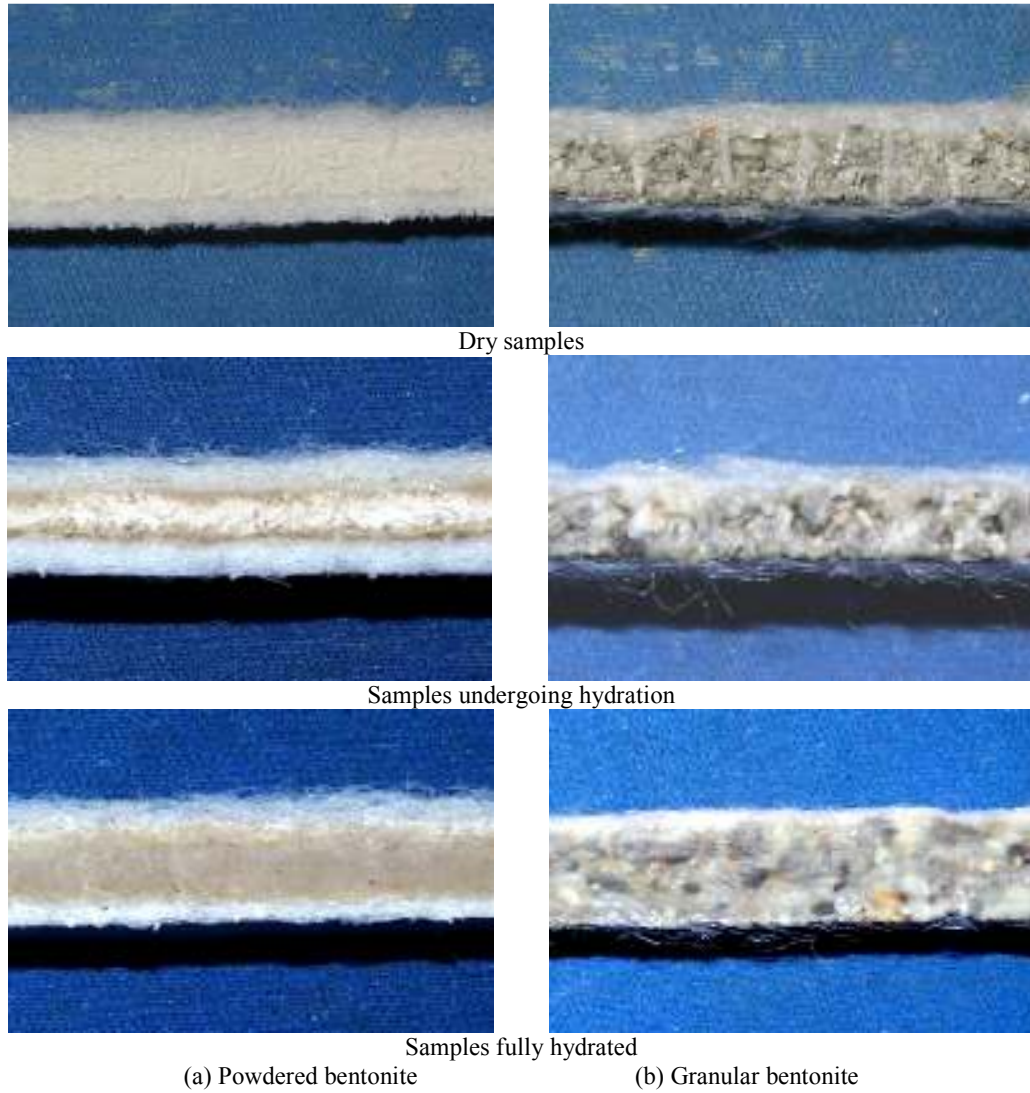


Figure 2. Illustration of hydration mechanisms of powdered and granular bentonite (from Vangpaisal and Bouazza, 2004).

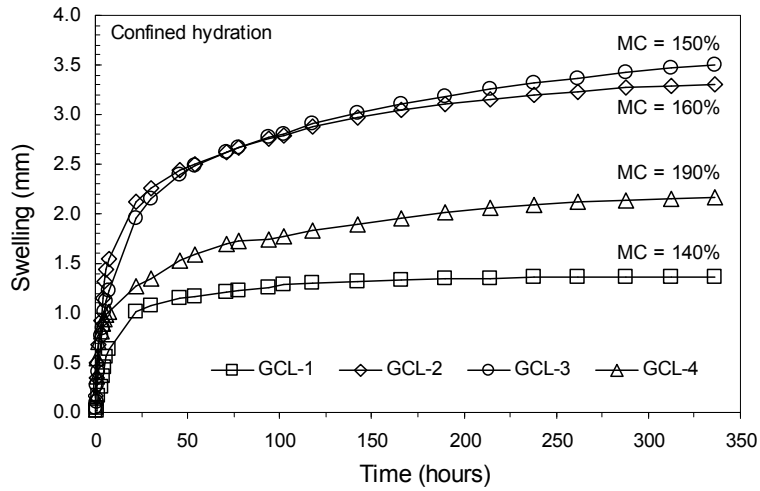


Figure 3 Relation of GCL swell to hydration time, confined hydration (MC= final gravimetric moisture content).

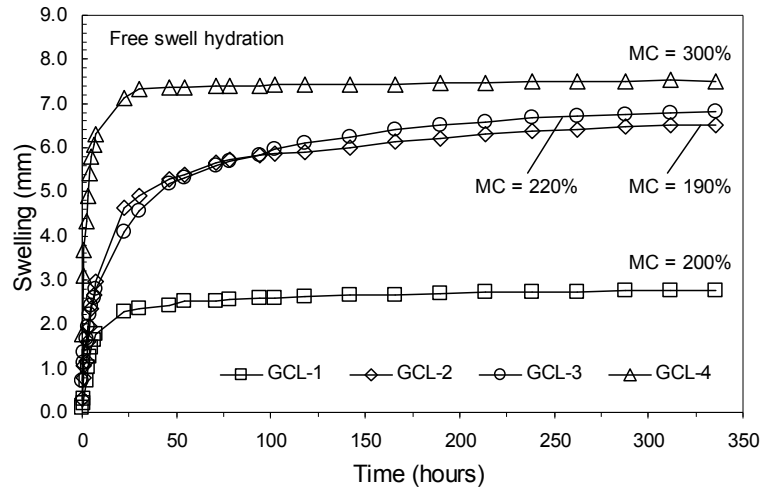


Figure 4 Relation of GCL swell to hydration time, free swell hydration (MC= final gravimetric moisture content)



Figure 5. Hydrated stitch bonded GCL, showing the flat surface for a confined swell hydration (left), and the uneven surface for a free swell hydration (right)

An approach to predict the swelling behaviour of expansive soils using the rectangular hyperbolic law was proposed by Dakshanamurthy (1978), in order to quantify the maximum swelling of a given material. This approach was shown to have a good correlation with the swell kinetics of GCLs (Didier and Comeaga, 1997). The hyperbolic law for GCL swelling is defined as:

$$\Delta H = \Delta H_{\infty} \frac{t}{t_{50} + t} \quad (1)$$

where ΔH is the GCL swelling, ΔH_{∞} is the predicted swelling for an infinite time, t is the elapsed swelling times and t_{50} is the swelling time corresponding to 50% of the total swelling. The hyperbolic law corresponds to a straight line of the plot between $t/\Delta H$ versus t , which is expressed as follows:

$$\frac{t}{\Delta H} = at + b \quad (2)$$

The ΔH_{∞} is obtained from the inverse of the slope of the plot ($\Delta H_{\infty} = 1/a$), and the t_{50} is obtained from $t_{50} = \Delta H_{\infty} b$. The swell characteristic values according to the hyperbolic law are summarised in Table 1. The calculated t_{50} and the measured t_{50} are comparable for both the confined hydration and the free swell hydration conditions. Also presented in the table is the time required to achieve 90% of the total swelling, t_{90} , where the full saturation is assumed.

Table 1 Swell characteristic values of the GCL according to the hyperbolic law.

Parameters	Confined swell hydration				Free swell hydration			
	GCL-1	GCL-2	GCL-3	GCL-4	GCL-1	GCL-2	GCL-3	GCL-4
ΔH_{∞} (mm)	1.42	3.35	3.61	2.18	2.79	6.63	6.94	7.53
t_{50} (hours); calculated	11.1	12.1	20.7	12.3	6.1	9.9	11.2	1.3
t_{50} (hours); measured	10.6	10.0	19.0	10.0	4.5	9.5	13.5	1.3
t_{90} (hours)	100	108	186	110	55	89	101	12

It can be seen that granular bentonite (GCL-3) tended to have slower swell kinetic than powdered bentonite provided that the GCLs had a similar structure. This is because the hydration mechanism of granular bentonite was slower than the powdered bentonite as a hydrated bentonite film was formed around each individual grain (see Figures 1 & 2) and hindered the hydration rate of the dry bentonite core. However, the t_{90} of GCLs containing powdered bentonite and granular bentonite can be achieved in 5 and 8 days of the hydration period, respectively, for both hydration conditions. Interestingly, in the case of free swell hydration, the needle punched GCLs (GCLs 1, 2 and 3) had a slow swell kinetic and achieved 90% of the total swelling after at least 50 hours and up to 100 hours, while it took less than 24 hours for the stitch bonded GCL (GCL-4) to achieve the 90% of the total swelling. This shows that the needle punched fibres have a significant role in inducing internal confining stresses in the GCLs and limit their full hydration and swelling under free swell conditions. This aspect is very important in the event that GCLs get wet prior to application of overburden.

4. HYDRAULIC CONDUCTIVITY, CHEMICAL COMPATIBILITY AND DIFFUSION

The hydraulic performance of GCLs depends in most cases on the hydraulic conductivity of the bentonite. The only exceptions are GCLs containing a geomembrane where the geomembrane is sealed during construction (e.g., with a cap strip). In general, laboratory hydraulic conductivities to water of different types of geotextile supported GCLs vary approximately between 2×10^{-12} m/s and 2×10^{-10} m/s, depending on applied confining stress (Figure 6). The hydraulic conductivity of a GCL is highly dependent on the hydrating conditions and the applied effective stress during permeation. Petrov et al. (1997a) showed that these factors combined with the method of manufacture, water content prior to hydration and mass of bentonite all significantly influenced the GCL thickness and while there was some correlation between hydraulic conductivity and thickness there was a great deal of scatter.

GCLs often are used to contain liquids other than water. In this case, the evaluation of hydraulic conductivity of

GCLs when acted upon by chemical solutions is of a paramount importance. Hydraulic conductivity to the actual permeant liquid is usually assessed via a "compatibility test" where the specimen is permeated with the liquid to be contained or a liquid simulating the anticipated liquid. GCL compatibility with various permeants has been studied by a number of researchers and evaluated for numerous projects (Shan and Daniel 1991; Rad et al. 1994; Ruhl and Daniel 1997; Petrov et al. 1997a, b; Petrov and Rowe 1997; Rowe 1998; Mazzieri et al. 2000; Shackelford et al., 2000; Jo et al. 2001, Kolstad et al., 2004a, b). It should be noted that all studies have concentrated on the short term behaviour of GCLs. The properties of GCL which influence their hydraulic conductivity with liquids other than water; may include: aggregate size, content of montmorillonite, thickness of adsorbed layer, bentonite surface area, exchange cation identity, type and efficacy of beneficiation processes, prehydration and void ratio of the mineral component. On the other hand, the main factors related to the permeant that influence the hydraulic conductivity are: ionic strength, cation and anion valence, viscosity, density and surface tension. When performing these tests, it is important to monitor the chemical composition in permeant influent and effluent and to ensure that sufficient pore volumes (i.e., >10) of the permeant has passed through the sample to ensure that chemical equilibrium has been reached. Furthermore, it is recommended that the height of the GCL be constant before terminating these types of tests. A detailed summary of issues related to GCL short-term chemical compatibility is provided by Rowe (1998).

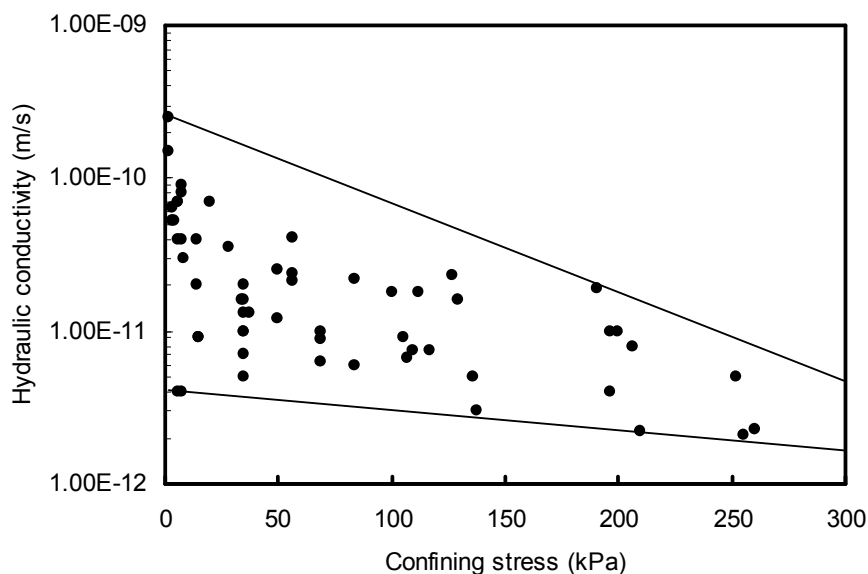


Figure 6. Variation of hydraulic conductivity versus confining stress (from Bouazza, 2002)

A method that has been suggested to prevent alterations in hydraulic conductivity of GCLs is prehydration (Daniel et al. 1993) i.e., when the GCL is hydrated with water. Daniel et al. (1993) found that when partially saturated GCLs were permeated with concentrated hydrocarbons, the hydraulic conductivity was high for a low initial water content (i.e tests with initial water content of 17% and 50%). At water content of 100 % the hydraulic conductivity for the hydrocarbons was close to that of water. They concluded that GCLs would not be affected by chemical permeant liquids, provided that the bentonite component was fully prehydrated (>100%) prior to contact with the hydrocarbon liquid. Vasko et al. (2001) evaluated how prehydration water content affected the hydraulic conductivity of GCLs permeated with divalent salt solutions. Their results are shown in Figure 7, prehydration water content was found to not have any apparent effects on hydraulic conductivity for the intermediate (~0.025M) and weaker (<0.01M) solutions. For the stronger (>0.1M) solutions, however, lower hydraulic conductivity was obtained with higher prehydration water content. The hydraulic conductivity decreased from 1×10^{-6} m/s to 3×10^{-9} m/s as the prehydration water content increased from 9% to 150% and then remained constant as the prehydration water content increased.

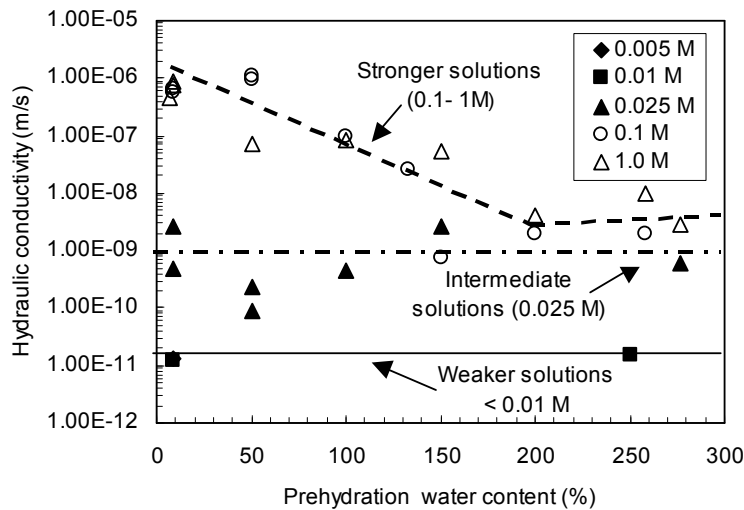


Figure 7. Hydraulic conductivity versus prehydration water content for unconfined GCL samples (modified from Vasko et al. 2001)

Vasko et al. (2001) indicated that the benefits accrued by prehydration with water followed by permeation with a non wetting organic liquid (as obtained by Daniel et al. 1993) are not obtained when the permeant liquid is a wetting aqueous solution. This difference was attributed by the authors to the different hydration mechanisms involved when the GCL is in contact with a wetting and non-wetting liquids. Most organic liquids have varying degrees of miscibility in water, and this will influence how the organic liquid interacts with the bentonite component of the GCL. It follows that if the permeants are miscible in water, the tendency would be for displacement of water from the GCL, regardless of prehydrated conditions. On the other hand for permeants that are poorly miscible in water, prehydration levels are important: while displacement of water by the non standard permeant can occur at unsaturated conditions, at fully prehydrated conditions water will be retained more readily by the bentonite. Another possibility was that the tests conducted by Daniel et al. (1993) were terminated before equilibrium was established.

How uniformly prehydrated the GCL is prior to interaction with contaminants can control its hydraulic performance. In Vasko et al. (2001), a uniform pre-hydration over the entire GCL was achieved by using a filter paper suction method. However, Katsumi et al. (2004)[from Katsumi (2006)] conducted hydraulic conductivity tests on GCLs which were prehydrated by being placed on a compacted soil to simulate field conditions; in contrast, they did not attempt to achieve uniform prehydration. The needle punched GCLs were placed with the woven geotextile in contact with the base soil. This is not consistent with the pre-hydration tests presented by Vasko et al. (2001), who in contrary put the GCLs with the nonwoven geotextile side in contact with the filter paper to ensure uniform pre-hydration over the entire area of the sample. The hydraulic conductivity values obtained by Katsumi et al. (2004) are plotted in Figure 8. The pre-hydration condition provided a hydraulic conductivity that was only 0-1 order of magnitude lower than that obtained under the non-prehydration conditions. The increase in the pre-hydration water content did not necessarily cause a decrease in the hydraulic conductivity, as shown by Vasko et al. (2001). Katsumi et al. concluded that prehydration did not effectively contribute to maintaining a low hydraulic conductivity. We must emphasize here that care should be taken, when comparing the hydraulic conductivity of GCLs to different non-standard liquids, to ensure that the GCL is either fully hydrated or, if not fully hydrated, then to record the hydration level for the particular interaction.

Another important aspect highlighted in these two studies is the magnitude of the hydraulic conductivity values for granular vs powdered bentonite GCLs. The hydraulic conductivity values of prehydrated powdered bentonite GCLs (Katsumi et al 2004) ranged from 4×10^{-9} to 6×10^{-8} cm/s regardless of any prehydration water content for ≥ 0.2 M CaCl_2 concentrations. These hydraulic conductivity values were significantly lower than those obtained for the granular bentonite GCLs permeated with ≥ 0.1 M CaCl_2 shown in Figure 7 (Vasko et al. study). This is probably due to the hydration/swelling processes that the bentonites have experienced when in contact with CaCl_2 permeants. In section 3, it has been shown, for water as permeant, that the hydration mechanism for a

powdered bentonite is different from the hydration mechanism undergone by a granular bentonite. It can be postulated that when in contact with aggressive permeants, the pores between the bentonite grains in the granular bentonite are only partially plugged due to a lower level of swelling, leading therefore to a higher hydraulic conductivity. In contrast, the pores in powdered bentonite are much smaller even when swelling is limited. Consequently the hydraulic conductivity is lower. It is interesting to note that both studies have been conducted at low confining pressures (less than 50 kPa). It is expected that at higher compressive pressures such as encountered in bottom liners of landfills little or no detrimental effect would be observed (Bouazza, 2002). This has been confirmed recently by Thiel and Criley (2005) who conducted hydraulic conductivity tests on partially prehydrated GCLs under high confining stresses. Prehydration took place on native subgrade soils for several weeks. The measured hydraulic conductivity shown in Figure 9 appear to be independent of fluid chemistry and prehydration moisture content at effective stresses greater than 400 kPa, indicating that GCLs subjected to high overburden stresses such as encountered in landfill bottom barriers will result in low hydraulic conductivity even if the GCLs are subjected to leachates containing chemicals which might affect their hydraulic conductivity.

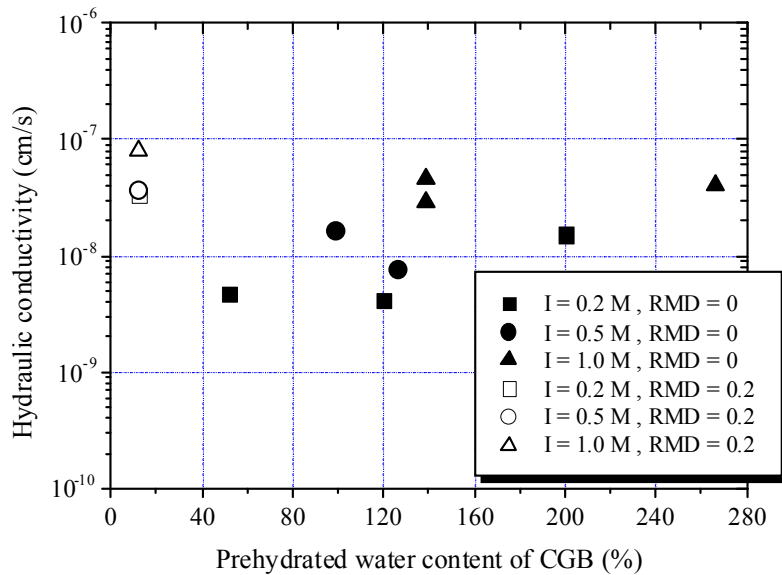


Figure 8. Hydraulic conductivity values versus the prehydration water content (from Katsumi et al.,2004)

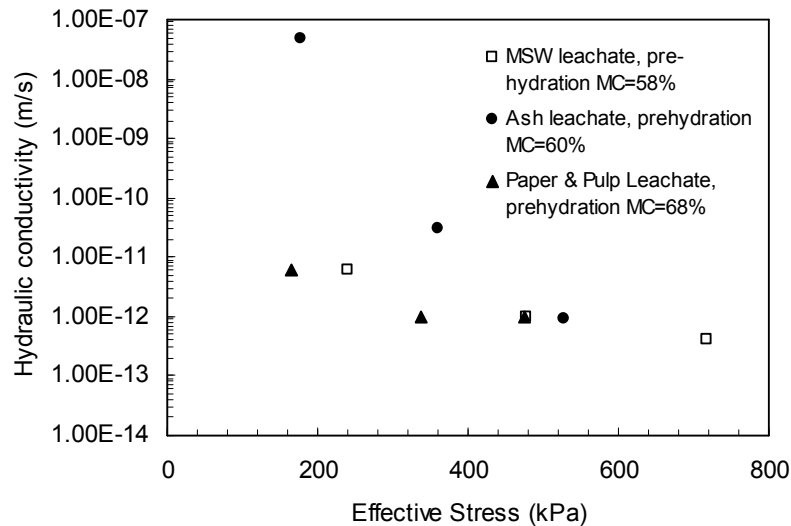


Figure 9. Hydraulic conductivity values versus Effective stress for a partially pre hydrated GCL (data from Thiel & Criley, 2005)

Long-term chemical compatibility of GCLs is another important issue that has received lot of attention (Shackelford et al. 2000; Benson 2001). GCLs have low hydraulic conductivity to tap water because they contain in most cases sodium bentonite. The presence of sodium in the exchange complex permits unlimited or osmotic swelling of the bentonite, which drastically reduces the size of the pores and the volume of the pore space that is actively involved in flow. However, if sodium is exchanged for cations with higher valence (e.g., Ca^{++} or Mg^{++} , which are common in leachates), unlimited swelling does not occur and the bentonite may become orders of magnitude more permeable (Shackelford et al. 2000; Jo et al. 2001). The hydraulic conductivities reported by Jo et al. (2001) for a GCL permeated with different single species salt solutions (0.1 M solutions with divalent or trivalent cations) were approximately 10^{-7} to 10^{-6} m/s. Whereas, the hydraulic conductivity to deionised (DI) water was approximately 2×10^{-11} m/s. Benson (2001) pointed out that at low concentrations, the exchange process occurs very slowly due to mass transfer limitation (actually a diffusion limited phenomenon-the steric-physical- hindrance of penetrating the interlayer is what limits the rate of exchange) that occurs between the bulk pore water and the interlayer water between the montmorillonite layers. The laboratory hydraulic tests on GCL using dilute CaCl_2 solutions reported by Benson (2001) show that after nearly a year of permeation, equilibrium was still not established and the hydraulic conductivity continued to increase gradually (Figure 10). This observation raises the possibility that much longer times will be required for equilibrium to occur in the field.

Diffusion is a chemical process involving mass action migration of a solute from areas of higher concentration to areas of lower concentration even when there is no advective flow of water. The diffusive behaviour of inorganic contaminants through a GCL has been reported recently by Rowe (1998) and Lake and Rowe (2000). Their main findings can be summarized as follows: (1) void ratio and related confining stress have a strong influence on diffusion coefficient; and (2) the diffusion coefficients varies with respect to any modification of the micro-structure of the sensitive mineral component (in particular sodium bentonite). The GCL manufacturing process was found to not significantly affect the diffusion coefficient. However, it is worth noting that Lake and Rowe (2000) indicated that a slight reduction in diffusion coefficient could be achieved when using a thermal locked GCL compared to a non-thermal locked GCL. This is simply due to the increased bonding of the fibres to the carrier geotextile in the thermal locked GCL, which reduces total swelling and thus the bulk void ratio.

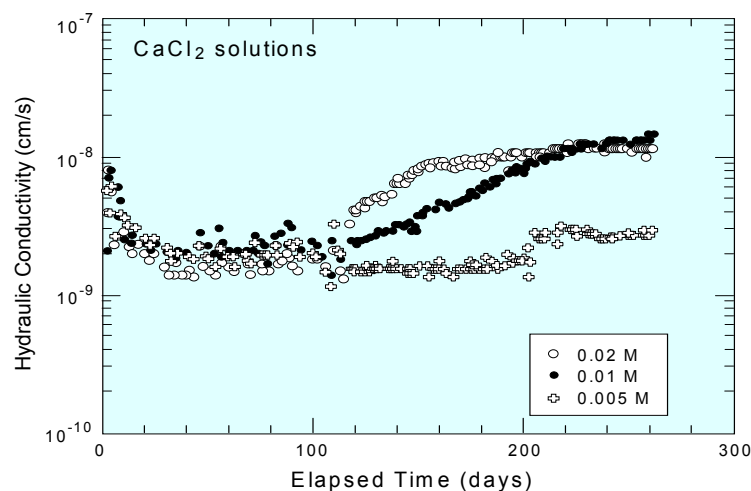


Figure 10. Hydraulic conductivity of a GCL to dilute CaCl_2 (from Benson 2001)

Roque (2001) conducted a series of diffusion tests of inorganic contaminants on a needle punched GCL placed directly on top of a compacted clay liner (CCL) to simulate the case when a GCL is used as an augmentation to a CCL. Some of his results are shown in Figure 11. The effective diffusion coefficients of potassium, zinc and cadmium were found to be 1.5 times, 2.8 times and 2.2 times smaller, respectively, than those obtained from the diffusion tests carried out on the compacted clay liner. This means that these inorganic contaminants were adsorbed to varying degrees onto the bentonite mineral surface. These results suggest that the use of a GCL can retard the depth of diffusive migration of these chemicals. Under these conditions, the use of the GCL in the bottom liner can contribute to the reduction in the CCL thickness.

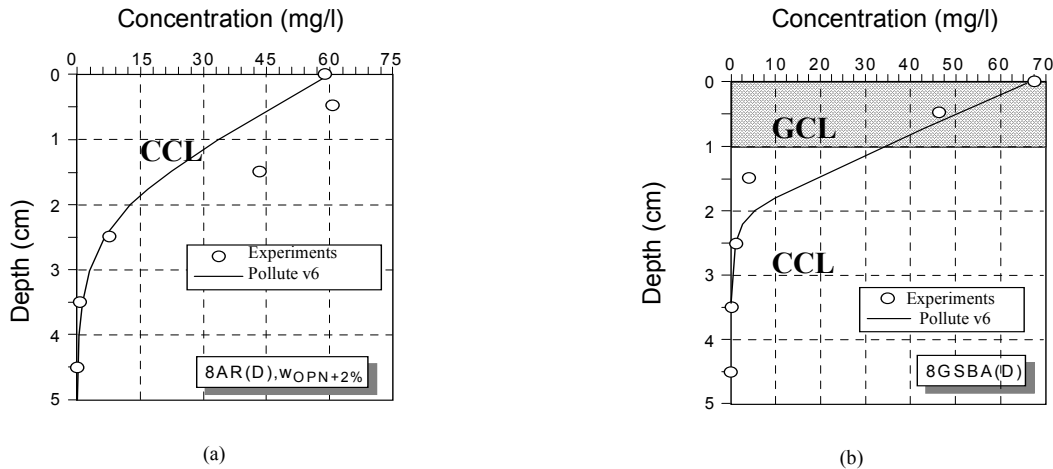


Figure 11. Variation of zinc concentration with depth; (a) compacted clay, (b) GCL + compacted clay: Experimental results and analytical solutions (modified from Roque 2001)

5. WATER POTENTIAL OF BENTONITE

Water potential is a basic hydro-physical soil characteristic that can be described by the relationship between capillary pressure (suction) within the soil and the soil volumetric water content or its degree of saturation. This relationship is also termed as soil water characteristic curve (SWCC) and is the fundamental constitutive relationship governing the behaviour of unsaturated soils (Fredlund and Rahardjo, 1993; Barbour, 1998). The total water potential comprises osmotic potential, matric potential, gravitational potential, pressure potential and overburden potential. However, the matric potential is the largest component in most unsaturated soils. Thus, the water potential normally measured is the matric potential. The knowledge of soil water potential characteristics is necessary for the study of many processes in the soil such as infiltration, drainage, solute movement and water availability for plants. Zhou and Rowe (2003, 2005) emphasized the need to have a clear understanding of the moisture dynamics in the GCL to carry out an accurate modelling of the hydraulic regime in the overall lining system. Thus, understanding of the water potential behaviour of GCLs under unsaturated conditions is very important in the design of cover and bottom barrier landfill systems.

Bentonite has a very high ability to absorb water from the environment, for example from intact soil and from the atmosphere. If the bentonite in a GCL is placed against soil, it may either absorb water from the soil or yield water to the soil, depending on the water potential in the soil and the bentonite as the water moves from high potential to low potential. Pure, free water is assigned zero water potential, and the potential energy of water in the unsaturated soils is in negative values. Dry bentonite has an extremely negative water potential and tends to absorb water from soil until the water potential between the soil and the bentonite is balanced or reaches equilibrium. The presence of thermal gradients from the heated composite liner to the generally cooler surrounding soil, due to decomposition of organic material within the waste, can also induced suction pressure and moisture content changes in the GCLs. The investigation carried out by Southen and Rowe (2005) showed that such thermal gradient have the potential to cause desiccation of the mineral component of GCLs, with potential impacts on long-term performance. As the GCLs are comprised of a thin layer of bentonite bonded to a layer or layers of geotextile, their water potential behaviour will be function of the water potential behaviour of both components (bentonite and geotextile) as well as their bonding method (e.g. needle punching, stitch bonding, adhesive).

A preliminary investigation has been conducted at Monash University on the bentonite component of 4 GCLs. Tests were performed to establish the relation between the moisture content and the water potential of the bentonite component. It needs to be highlighted that very high suctions are needed to characterise fully the GCL water retention, the technique presented herein does not cater for such suctions. However, it can be used as a first step in identifying the bentonite water potential. The water potential of the bentonite component of a GCL was determined using a water potential meter called psychrometer, which contains a thermocouple. The thermocouple is a small electrical thermometer used to measure temperature differences. If the temperature

changes at the junctions, reference junctions and wet bulb junction, current will begin the flow. The voltage measured is proportional to the temperature difference, thus measuring the voltage gives the temperature. The algorithms in the microcontroller use that voltage to compute the water potential of the sample. The water potential of bentonite was measured with the Tru Psi psychrometer. The equipment consisted of a set of sample cups, sample holder equipped with a thermocouple, and a micro-controller. A small amount of hydrated bentonite was put in a sample cup. The sample was then left in an enclosed space allowing the water vapour in the air around the sample to equilibrate. The water potential of the sample and the air were equal after an equilibration time. The relative humidity of the air above the sample was then measured in terms of temperature difference using a thermocouple. The relation between the measured temperature difference and the vapour phase water potential was then computed and the controller gave out the water potential of the sample as potential energy in a unit of mass, such as J/kg, bar (kg/cm²), kPa or head of water.

Water potential tests of the bentonite component of the 4 GCLs (GCL-1, GCL-2, GCL-3 and GCL-4) were performed. The relations between the water potential and the moisture content of all tested bentonite are shown in Figure 12. The water potential or suction of hydrated bentonite was found to range from -35 bar (3500 kPa) to -3 bar (300 kPa) for a moisture content of 40 % to 200 %. The relationships follow the same trend, in which the water potential of bentonite increases (higher negative head) as moisture content decreases. It can be seen that the water potential increases with a higher rate at lower moisture content and the increasing rate is more pronounced as the bentonite becomes drier i.e. lower than 50 %. On the contrary, the water potential varies in a narrow range of -5 bar to -3 bar at high moisture content, i.e. higher than 100 %. When a comparison is made between each type of bentonite, at the same moisture content, bentonite from GCL-4 seems to have slightly higher water potential (higher negative head) than other bentonite tested. This means that if all four dry bentonite samples are placed against moist soils, the bentonite from GCL-4 will absorb water and reach equilibrium with higher moisture content than the other bentonite samples. In other words, if all four bentonite samples with the same initial moisture content are put facing each other, bentonite from GCL-4 will tend to absorb moisture from the other bentonite until it achieves water potential equilibrium.

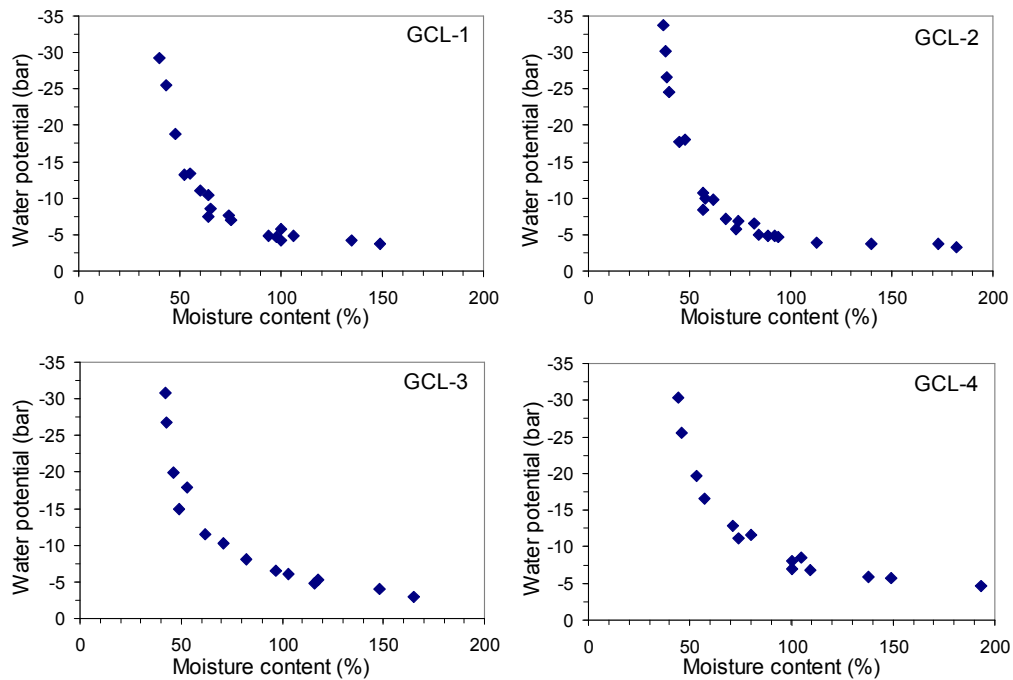


Figure 12. Relations between water potential and moisture content of bentonite component from four types of GCL

In practice, the moisture content of soil in landfill cover systems will change with changing weather due to precipitation or desiccation, whereas in the bottom barrier the change will be due to desiccation caused by thermal gradients. As a result, the GCL becomes vulnerable to changes in the water potential as the soil cover or the compacted clay liner at the bottom barrier, and the GCL equilibrate. Therefore, the water potential can also be used to predict the moisture content of the bentonite in a GCL subjected to different climatic or operating conditions. Furthermore, in order to use the experimental data as a basis for numerical modelling, it is necessary to obtain representative parameters that numerically describe the water characteristic curve. An example of such approach is shown in Figure 13 where the experimental data obtained for the bentonite component of GCL-2 is plotted against results obtained from a one dimensional numerical model (Hydrus 1D) using the modified Van Genuchten equation. The best fit curve using this equation can be developed for different GCL types. However, it is important to develop a testing protocol closer to reality where the GCL sample including the geotextile and fibre components can be assessed since they can affect the water characteristic curve.

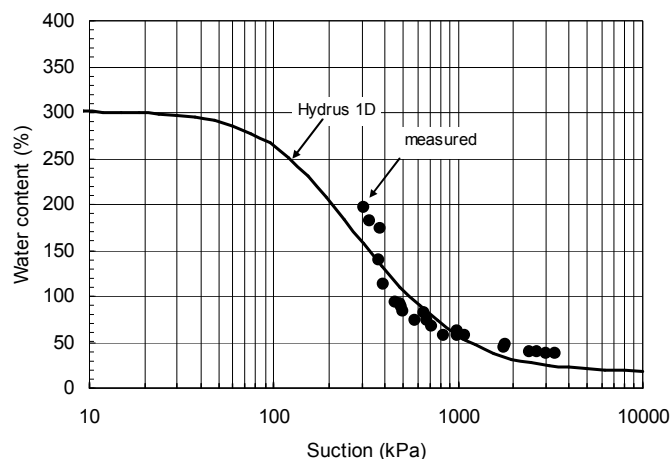


Figure 13. Model prediction for the water characteristic curve GCL-2 bentonite compared with experimental data

6. PUNCTURES, BENTONITE THINNING, INTERNAL EROSION, ION EXCHANGE

GCLs are susceptible to accidental punctures, which might occur during handling and installation. In this respect, their hydraulic performance can be compromised depending on the level of damage incurred. It has been shown that small penetrations or defects can be effectively sealed by the sodium bentonite in the GCL, with a minor increase in the hydraulic conductivity of the damaged specimen compared to intact specimens (Shan and Daniel, 1991, Bouazza et al., 1996, Mazzieri and Pasqualini, 2000). Furthermore, the healing kinetics of open holes up to 30 mm diameter show that only a short time (15 days) is necessary to totally heal the defect (Didier et al., 2000b). More importantly, Didier et al. (2000b) found that the stability of the self healing area depended on the hydraulic head: it was observed that failure of the self healed area occurred when the hydraulic head exceeded 1 m (under a 10 kPa confinement). Although the self healing capacity of sodium bentonite GCLs is high, experimental evidence show this capacity can be impeded if the self healing process is coupled with ion exchange (Lin and Benson, 2000, Mazzieri and Pasqualini, 2000, Bouazza et al., 2006).

A number of case histories related to GCL in-situ defects have been reported in the literature. Mazzieri and Pasqualini (1997) reported on a case where an adhesive bonded GCL was punctured by plant roots, resulting in increased hydraulic conductivity. However, Daniel (2000) pointed out that the source of high hydraulic conductivity was likely to be the root itself, not the seal between the bentonite and the perimeter of the root. This was further confirmed by Didier et al. (2000b) who showed that a very good seal can be obtained around objects inserted in GCLs. Peggs and Olista (1998) describe a case study where a GCL was severely punctured by the subgrade stones and compromised its hydraulic performance, but this was more a design issue rather than a performance issue.

The hydraulic performance of geotextile supported GCLs depends also on the distribution of bentonite mass/area within the material. Once hydrated the bentonite has a very low shear strength, it is possible in this case that stress concentration activities and permanent structural loads may cause the bentonite to squeeze laterally and

lead to a local reduction in thickness which in its turn can cause a higher liquid flux at these locations (Koerner and Narejo, 1995; Fox et al., 1996). To avoid local bentonite displacement, and subsequent possible impact on the hydraulic performance of a GCL, a cover soil of suitable thickness and particle size should be placed over a GCL before it hydrates and before it is subjected to concentrated surface loads. The presence of coarse grained material, such as gravel, overlying a GCL can also be another cause of bentonite migration due to stress concentration. However, it has been observed that this effect on hydraulic conductivity is insignificant even at high confining stress (Fox et al., 1998, 2000). Another potential source of stress concentration is the presence of wrinkles in an overlying geomembrane, these may create a void or area of reduced stress into which bentonite in an underlying GCL could migrate (Stark, 1998). The choice of subgrade is another important consideration for the installation of GCLs. Like the cover soil, the subgrade on which the GCL is installed should be suitable with respect to particle size. Daniel (2000) discusses steps that can be taken to minimize bentonite thinning in GCLs.

The process of internal erosion involves the movement of fine particles due to the presence of a high hydraulic gradient (typical in fluid containment facilities) as for preferential flow paths. Stam (2000) reported a case where abnormal leakage was observed in a GCL lined lake. Excavation of the installation revealed areas of “patchy” bentonite piping through the lightweight nonwoven geotextile of the GCL into the coarse sand subgrade to a depth of 15-20 cm. Recent work by Orsini and Rowe (2001) indicated that at a high gradient, there is potential for piping of the GCLs when used in contact with a pea gravel subgrade. Another scenario, which can be considered is a geotextile supported GCL overlying a leachate collection layer (coarse grained material or geonet). The possible accumulation of bentonite fines in the drainage layer may have a detrimental effect on the hydraulic transmissivity of the drainage layer and lead eventually to the failure of the leachate collection system. Giroud and Soderman (2000) provide a detailed analysis of the mechanisms and consequences of bentonite migration from a GCL. They proposed a criterion for acceptable bentonite migration. The criterion sets the limit for acceptable bentonite migration, into a geonet drainage layer, at 10g/m^2 . At this limit the drainage layer is not significantly affected. Another way of avoiding bentonite loss from geotextile supported GCL is to use an additional geotextile filter between the GCL and the drainage layer (Estornell and Daniel 1992). Installation steps that minimize lateral bentonite may also assist in minimizing bentonite piping, especially in regard to subgrade and oversized particles.

The issue of cation-exchange induced changes in hydraulic conductivity, for GCLs with sodium bentonite, has received much attention recently (Dobras and Elzeas, 1993, James et al., 1997, Melchior, 1997, Lin and Benson, 2000; Shackelford, 2003, Bouazza et al., 2006). This attention stems from the fact that an increase in the GCL hydraulic conductivity (one to two orders of magnitude) has been observed when in contact with calcium rich soils or calcium solutions. These observations are related to GCLs subjected to low compressive pressures (<20 kPa), typical of landfill cover systems. The low confining pressure appears to enable exchange-driven internal clay fabric changes, which result in changes to void ratio and void size, to take place relatively unimpeded. This probably results in a high level of interconnectivity between voids (Likos and Lu, 2006). It is expected that at high compressive pressures such as encountered in bottom liners of landfills little or no detrimental effect would be observed (Daniel, 2000). A detailed summary on ion exchange problems is also given in Egloffstein (2001).

One of the main problems encountered in the post-closure of a landfill is the internal cap distress due to subsidence. Indeed, the heterogeneous waste composition and ageing process (waste biodegradation) can lead to substantial differential settlement of the cover system which in turn may lead to zones of tension cracking. It was shown that GCLs could withstand distortion and distress while maintaining their low hydraulic conductivity (Bouazza et al., 1996; LaGatta et al., 1997).

7. GAS PERMEABILITY AND DIFFUSION

As part of the evaluation process of cover systems, the hydraulic properties of GCLs were considered to be the prime factors. However their performance as gas barriers has recently come under a growing scrutiny. With major environmental concern regarding gas emission, control of landfill gas is becoming an important issue for the protection of public health and safety. In other situations, covers may have to prevent oxygen from the atmosphere to come in contact with reactive materials, such as sulphidic tailings that could otherwise generate acid (e.g., Yanful, 1993; Cabral et al. 2000)

7.1 Advective Gas Flow

In advective flow, the gas moves in response to a gradient in total pressure. To equalize pressure, a mass of gas travels from a region of higher pressure to a lower one. In the context of landfills, the primary driving force for gas migration, especially through cover systems, is pressure differentials due to natural fluctuations in

atmospheric pressure (barometric pumping). Falling pressures tend to draw gas out of the landfill, increasing the gas concentration near the surface layers. Conversely, high or increasing barometric pressure tends to force atmospheric air into the landfill, diluting the near surface soil-gas and driving gas deeper into the landfill (this is a possible explanation on how VOCs can find their way into groundwater). A change in the leachate/water table position or on temperature can also cause pressure differences and lead to gas migration. Recent studies have shown that the gas permeability (or permittivity) of GCLs may vary depending on the manufacturing process, moisture content and the overburden pressure during the hydration process (Didier et al. 2000a; Vangpaisal & Bouazza 2001, 2004; Bouazza et al. 2002). Typical permittivity results versus volumetric water content for needle punched GCLs are shown on Figures 14 and 15. Commercially available GCLs consisting of essentially dry bentonite [powder in GCL1 and GCL2 (with bentonite impregnated into the cover non-woven geotextile layer), and granular in GCL3] sandwiched between polypropylene geotextile layers were used in the investigations, reported by the above authors. It can be observed that the variation of permittivity follows the same trend for both hydration conditions (i.e., confined under 20 kPa and 0 kPa). The permittivity increases with decreasing volumetric water content. Interestingly, at the same volumetric water content, GCL1 and 2 tend to have lower permittivity than GCL3. This is because of the nature of the bentonite in GCL3 (with bentonite in granular form). The hydrated granular bentonite is stiffer, clearly visible as soft grain particularly at the lower level of volumetric water content, than the hydrated powdered bentonite. This indicates the presence of larger inter-granular pore spaces, which provides preferential gas flow paths. The difference in permittivity of GCL3 to GCL 1 and 2 is lower at higher volumetric water content due to the reduction of inter-granular pore spaces when bentonite forms a gel and becomes softer. It is also observed from Figure 14 and 15 that the impregnated bentonite in the non-woven geotextile (GCL2) also contributes to the lower gas permeability, particularly in case of free swell hydration.

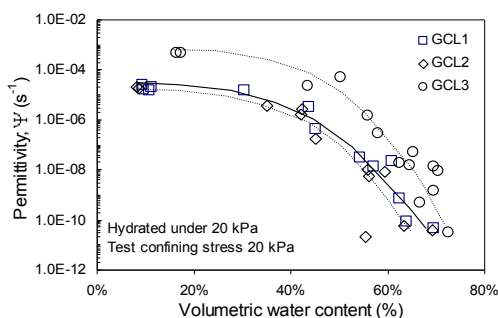


Figure 14. Variation of gas permittivity with volumetric water content for confined hydration (from Vangpaisal and Bouazza 2001).

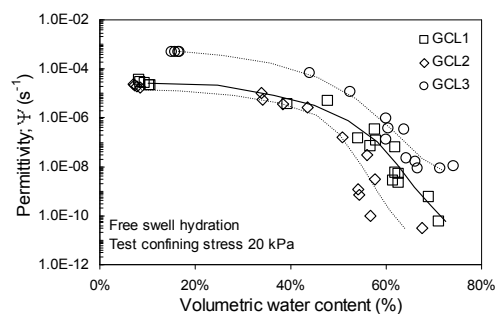


Figure 15. Variation of gas permittivity with volumetric water content for free swell hydration (from Vangpaisal and Bouazza, 2001).

7.2 Diffusive Flow

Gas movement by diffusion occurs due to molecular interactions. When a gas is more concentrated in one region of a mixture more than another, gas will diffuse into the less concentrated region. Thus molecules move in response to a partial pressure gradient or concentration gradient of the gas. Some applications of final covers require special considerations beyond those used for municipal solid waste facilities or capping of contaminated soils. These applications include facilities for mine wastes (e.g., sulphidic mine rock and tailings or uranium mill tailings). Covers for reactive mine waste must preclude ingress of water or oxygen to minimize oxidation of the underlying waste. Traditional principles can be used to design covers that will limit percolation. However, limiting oxygen transport requires special considerations. Oxygen transport can be limited by including a barrier layer that impedes oxygen diffusion. Soil layers with high degree of saturation can limit oxygen diffusion since the liquid-phase diffusion coefficient for oxygen is orders of magnitude lower than the gas-phase diffusion coefficient. In particular, oxygen diffusion decreases as the degree of saturation increases (Yanful 1993). Aubertin et al. (2000), Rahman et al. (2002) and Bouazza and Rahman (2004) illustrated also the importance of moisture content variation on the gas diffusion of GCLs.

The diffusion of gases, such as oxygen, will occur mainly through the air filled pores of the soil with only a small amount occurring in the dissolved phase through the water filled pores. Aubertin et al. (2000) indicated that in a soil with volumetric air content θ_a ($\theta_a = n(1-S_r)$, n = porosity and S_r = degree of saturation), and volumetric content, θ_w ($\theta_w = nS_r$), the porous media diffusion coefficient, D_{pg} , can be expressed as:

$$D_{pg} = \theta_a D_\theta + \theta_w H D_R \quad (3)$$

where D_θ and D_R are the diffusion coefficients for the air and water phases in the porous media, H is the modified Henry's law coefficient ($H=0.03$ for oxygen in an air water system at room temperature). The gaseous diffusion coefficient in soil D_θ is often related to the diffusion of gas through air, D_a . Many studies have been conducted to examine the variation in the ratio D_θ/D_a with the degree of saturation. Rowe (2001) summarized these results and formulated an empirical relationship for gas diffusion through soils. This relationship is given by:

$$D_\theta/D_a = \exp[-1.03 \exp(0.017 Sr)^{1.64}] \quad (4)$$

where the oxygen diffusion through air, D_a , equals $2.06 \cdot 10^{-5} \text{ m}^2/\text{s}$ at 25°C . Figure 16 presents the results of the model proposed by Rowe (2001) along with experimental results collected in various studies. The upper most and lower most values from the compiled results were selected to draw the upper and lower boundaries and these two curves are also presented in Figure 16. Recent laboratory test results obtained by Rahman and Bouazza (2002) are presented in Figure 16 for comparison purposes. The results in the figure show that the laboratory obtained values are significantly lower than those predicted by the model. Most values fall close to the lower boundary. The reasons for such disparities could be due to the fact that the model was developed for uniform porous materials (soils). If different layers are encountered, it is usual to consider equivalent properties. GCL is a composite material and there are uncertainties in distribution of bentonite and homogeneity in moisture distribution even in properly hydrated and cured samples. It is also difficult to consider the equivalent properties of GCL. In any case, a general trend similar to soils has been observed, the ratio D_θ/D_a was found to decrease significantly as the degree of saturation increased. Results obtained by Aubertin et al (2000) and Soltani (1997) are also presented in Figure 16. Soltani (1997) tested three different types of materials at different degree of saturation. It could be seen that the results vary significantly at similar degree of saturation, although they fall within the band drawn from the data sets of Rowe (2001). This is probably due to variability in effective air porosity at high degree of saturation and product characteristics. Results by Aubertin et al (2000) seem to agree with the results obtained by Rahman and Bouazza (2002) on the same type of GCLs.

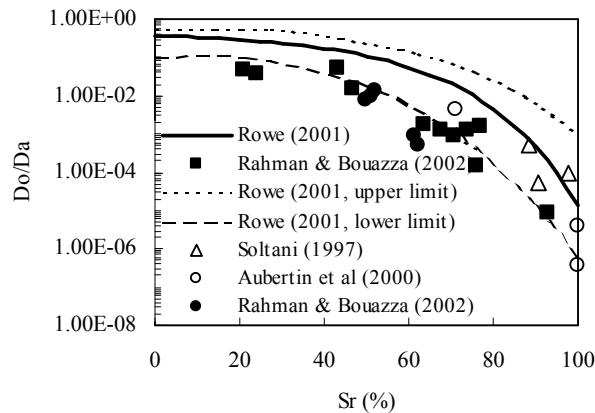


Figure 16. Diffusion coefficient as a function of saturation, model and laboratory results (from Rahman & Bouazza 2002).

8. EQUIVALENCY OF GEOSYNTHETIC CLAY LINERS AND COMPACTED CLAY LINERS

The performance design approach imposes the quantitative evaluation of the equivalence of alternative liners and traditional liners. Therefore, in order to quantify the comparison between GCLs and CCLs, it is necessary to evaluate the following main features and parameters of GCLs which govern pollutant transport (Rowe 2001): (1) hydraulic conductivity of GCLs permeated with non-standard liquids, (2) effect of holes on GCL hydraulic conductivity and (3) diffusion and sorption parameters. Rowe (1998), Shackelford et al. (2000), Lake and Rowe (2000), Bouazza et al. (2002) and Rowe and Brachman (2004) have developed these topics in detailed and comprehensive manner. The comparison of GCL versus CCL in terms of actual performance is today pretty much understood by engineers involved in landfill design, construction, management and regulation.

However, when comparison between different products must be carried out, it is important to keep in mind that it is not possible to generalize about "equivalency" of liner systems since what is "equivalent" depends on what is being compared and how it is being compared (Rowe, 1998). Apart from their own features, the performances of liner systems are related to the contaminant amount, concentration and decay parameters, the aquifer characteristics and its distance from the bottom of the landfill, the efficiency of capping and drainage systems. A qualitative comparison of GCLs and CCLs, provided by different authors referring to different criteria is given in Table 2. The performance of a GCL, for most criteria, should be either equivalent to or exceed that of a CCL. However, in terms of liner applications, the considerations of solute flux and breakthrough time, compatibility, and attenuation capacity favour CCLs. Some exceptions can be made for GCLs that use geomembrane supports instead of geotextiles and when an attenuation layer (AL) is provided.

Table 2. Potential equivalency between geosynthetic clay liners (GCLs) and compacted clay liners (CCLs)
(from Manassero et al., 2000)

Category	Criterion for Evaluation	Equivalency of GCL to CCL			
		GCL Probably Superior	GCL Probably Equivalent	GCL Probably Inferior	Site or Product Dependent
Construction Issues	Ease of Placement	X			
	Material Availability	X			
	Puncture Resistance			X	
	Quality Assurance	X			
	Speed of Construction				
	Subgrade Condition	X			X
	Water Requirements	X			
Contaminant Transport Issues	Attenuation Capacity				
	Gas Permeability			X ⁽¹⁾	X
	Solute Flux and Breakthrough Time				X
Hydraulic Issues	Compatibility	X ⁽²⁾		X	
	Consolidation Water	X			
	Steady Flux of Water				
	Water Breakthrough Time		X		
Physical/Mechanical Issues	Bearing Capacity				X
	Erosion				X
	Freeze-Thaw	X			
	Settlement-Total		X		
	Settlement-Differential				
	Slope Stability	X			
Wet-Dry	X			X	

⁽¹⁾ Based only on total exchange capacity, TEC

⁽²⁾ Only for GCLs with a geomembrane

9. CONCLUSIONS

There is no doubt that geosynthetic clay liners have gained over the past decade widespread popularity as a substitute for compacted clay liners in cover systems or as an augmentation to compacted clay liners in bottom liners of landfills, but they should not be seen as a panacea to all containment problems.

Data available suggests that they have very low hydraulic conductivity to water and they can maintain their hydraulic integrity over the long term. The critical aspects about the service life of the GCL as far as hydraulic integrity is concerned can be related to long term chemical compatibility problems, penetration, localized loss of bentonite, bentonite thinning, piping phenomena and ion exchange. With respect to gas migration, on-going studies suggest that it is dependent on moisture content and types of GCLs. The use of GCLs appears suitable or recommended where important vertical settlements are foreseen, and for the capping of landfills where stresses

are lower and a high degree of flexibility is required. Finally, geosynthetic clay liners, integrated with an attenuation layer can be considered as a possible alternative to compacted clay liners in composite liners. However, a careful comparison must be carried out between the two alternatives on a case by case basis. The actual boundary conditions into the time and space domains, the different pollutant transport phenomena, the contaminant lifespan and the active service life of the composite barrier materials and other landfill components must be taken into account.

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