

**Faculty of Engineering  
Department of Civil Engineering**

**An Investigation into a Bentonite Clay Based Geosynthetic Liner in a  
Caustic Refinery Environment**

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**This thesis is presented for the Degree of  
Master of Philosophy  
of  
Curtin University**

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To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signed.....Date .....

Damian Rolfe,

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## PROJECT DOCUMENTATION SHEET

Title: An investigation into a  
Bentonite clay based geosynthetic  
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### Abstract

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Bauxite residue (red mud) management is a major environmental issue for alumina refineries. The global average for residue storage can cover in excess of 2.1 million square metres per refinery and is increasing annually by 300 to 400 thousand square metres. Residue has the potential to damage surface and groundwater quality due to the residue's high alkalinity. Bauxite residue drying areas (RDAs) need to be designed in a manner that is safe for the population and the natural environment. Currently, RDA construction practice relies on the placement of a minimum of two clay lifts, a constructed low permeability base and an embankment seal that is at least equivalent to a 0.5m depth of mechanically compacted clay with a permeability coefficient of less than  $10^{-9}$  m/sec. This is overlain with a high-density polyethylene (HDPE) geomembrane, as the primary seal against seepage of caustic liquor. In Western Australia it is becoming increasingly difficult to source sufficient clay for future RDA construction.

To continue to meet and improve on current community and environmental standards, this investigation proposes an alternative to the clay lining system. A factory prehydrated geosynthetic liner (GCL) was evaluated in terms of its feasibility and its use in the design of a RDA, which would reduce the dependency on the sourcing of mass volumes of high quality clay from potentially long distances. The investigation also reviews the use of the GCL in a structural application, utilising it as a secondary containment measure under concrete bunds containing alumina process tanks.

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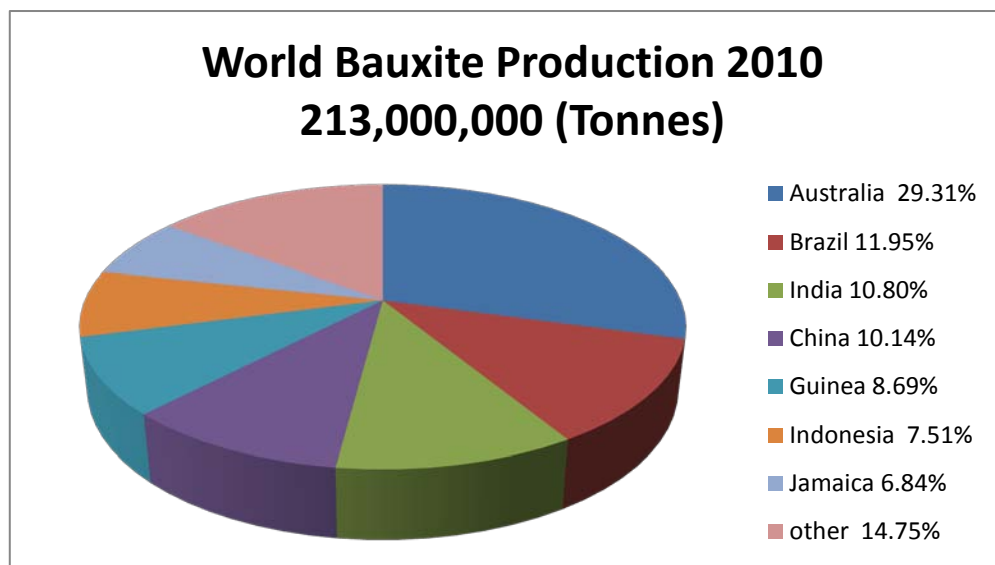
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# 1. INTRODUCTION

## 1.1 Background

Bauxite residue (red mud) is a waste material produced in the process of extracting alumina from bauxite via the Bayer Process. Figure 1.1 below shows the relative bauxite production of main countries in 2010. Approximately 35% to 40% per ton of bauxite, treated using the Bayer Process, ends up as red mud. This equates to more than 85 million tons of bauxite residue generated annually. This red mud is either stored on land in tailing dams (RDAs) or in the ocean near alumina refineries. The residue is highly alkaline and may generate leachates that have the potential to damage surface and groundwater quality if they were able to infiltrate the subsoil. Careful planning for the storage of bauxite residue and for closure of the storage areas is required to minimise the negative impact on the surrounding environment. Research has been undertaken to source and investigate alternative lining systems, due to the increased difficulty of sourcing large volumes of high quality clay for these RDAs, and the significant challenges in terms of revegetating the large clay borrow pits. In this investigation, a factory prehydrated geosynthetic liner (GCL) was evaluated in terms of its feasibility and its use in the design of a residue storage facility.



**Figure 1.1 Bauxite production and the relative proportion of main countries in 2010 (USGS, 2011)**

## 1.2 Aim

The investigation aims to:

- assess the viability of a factory prehydrated geosynthetic lining system
- provide cost estimates to implement the alternative lining system to verify suitability
- provide advice on opportunities for improvement and/or any changed practice of the current lining system
- report on the final findings and make recommendations on improvement opportunities provided by adopting an alternative lining system.

## 1.3 Scope

The scope of this investigation included the construction of seven test cylinders; six of which were individually deconstructed and chemically tested over a period of 470 days. A long-term pressurised testing cylinder was also constructed and monitored for a period of 784 days. Suitable parameters and testing procedures were developed through consultation with representatives of an Australian alumina refinery and Australian GCL distributors. The GCL used in this investigation was a factory prehydrated geosynthetic liner. It was a laminated GCL and not a needle-punched GCL. The cost analysis included only the cost of obtaining the GCL. Other costs obtained were the general costs of obtaining the materials. All assumptions and figures were directly obtained from industry and the GCL distributor.

## 1.4 Method

The method of testing was to expose the samples to a corrosive caustic environment (with an expected PH level of up to pH 13.8), representative of the typical environment in an alumina refinery's RDA. This was achieved by making cylinder test samples with caustic liquor, or residue, confining the top layer of the samples. The samples were visually inspected and photographed, with measurements taken to monitor their integrity over the course of the previously stated time period (see 1.3). The samples remained undisturbed until selected for chemical analysis where selected samples were

deconstructed and tested for Moisture content, pH and Cation Exchange Capacity (CEC).

A long-term test cylinder was pressurised, to represent expected site conditions was constructed. The GCL sample in this cylinder was exposed to the fluids that it was expected to come into contact with, within a RDA.

The data from these two testing procedures was compiled along with the costs of application, to obtain an overview of which method would be more feasible - the use of the GCL or the current method of using a HDPE liner with a clay base.

## 2. LITERATURE REVIEW

This section provides the background and reasoning behind the laboratory work and research presented in this investigation. The literature reviewed relates to the Bayer process and past testing done on different types of GCLs, and it specifically expresses the need for further research into prehydrated GCLs for site-specific applications.

### 2.1 The Alumina Process Typical

To understand the need for RDAs it is important to know how the residue is produced and what processes are involved. A typical method of alumina extraction from bauxite ore is the Bayer process. The Bayer process involves a number of key steps including Bauxite Grinding, Digestion, Clarification, Precipitation and Calcination.

A simplified process flow diagram of the Bayer process can be seen in Figure 2.1.

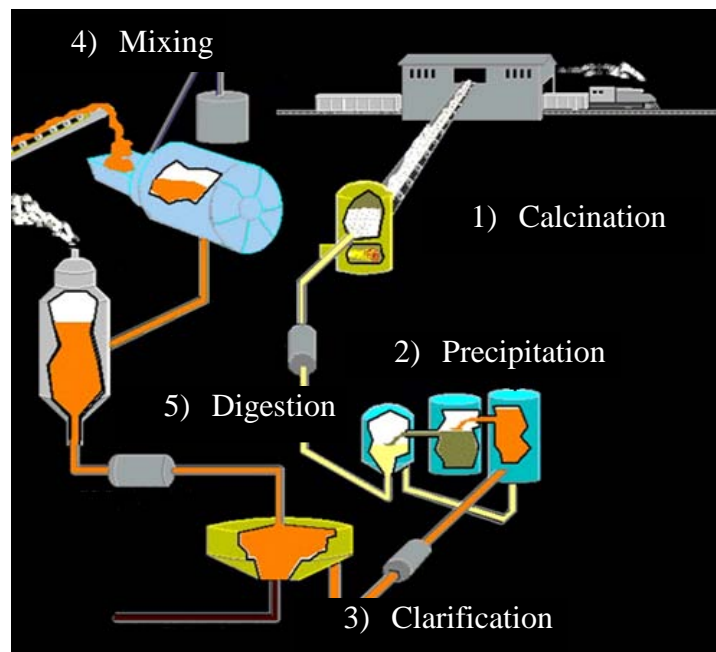


Figure 2.1 Typical Bayer Process

### **2.1.1 Bauxite Grinding and Slurry Storage**

Bauxite is crushed to a particle size of approximately 25mm. It is then passed through Rod Mills to ensure sufficient solid-liquid contact during the digestion phase. This improves the alumina extraction efficiency. A solution of sodium hydroxide (NaOH i.e. caustic soda), bled from a recycled caustic liquor circuit, is added to the bauxite during grinding to produce slurry.

The slurry is pumped to holding tanks prior to the next stage of the Bayer process. The purpose of the holding tanks is to allow for minor interruptions to the ground bauxite supply and to allow the process of desalination (i.e., removal of silicate from the liquor) to commence.

### **2.1.2 Digestion**

The bauxite slurry is pumped from the holding tanks into the digestion units, where additional recycled caustic liquor is added to the ground bauxite slurry. The digestion process removes the hydrated alumina from other insolubles, a process which occurs from the reaction with sodium hydroxide.

The slurry leaving the digestion units contains the alumina in solution (often referred to as green liquor), and other undissolved ore solids. Sand-sized insoluble minerals that have passed through this process unaltered are separated from the slurry and pumped to the RDA. This coarse sand fraction comprises approximately 40% of the residue.

### **2.1.3 Clarification**

The clarification stage of the process separates the fine undissolved ore solids from the green liquor. This is achieved using large clarification vessels (mud thickeners), which allow the undissolved bauxite solids to settle out. These bauxite solids are then passed through a counter-current washing train (mud washers), using water to recover as much of the green liquor as possible. The washed solid from the counter-current washing train is called process residue, or red mud, and is pumped to the RDA.

The overflow stream of the mud washing process is heated and added to a series of tanks with lime slurry. This is known as the causticisation process where a portion of the sodium carbonate that is formed in the liquor is converted to sodium hydroxide. Without causticisation, the refinery would require large quantities of fresh caustic to be constantly added to the liquor for the refinery to remain productive.

#### **2.1.4 Removal of Organic Material**

Organic material is naturally present in bauxite ore and in some of the specialised chemicals added throughout the Bayer process (such as flocculants). This organic matter reacts to form various organic sodium compounds and over time, the level of organic content builds up in the recycled caustic liquor, reducing the efficiency of precipitating alumina tri-hydrate. These organic compounds can also adversely affect the formation of hydrate crystals resulting in the production of alumina with undesirable product quality.

Oxalate (an organic material that primarily exists as sodium oxalate) is concentrated and removed by a sequence of seeding, precipitating, and washing to produce a wet oxalate cake. In the past, oxalate has been oxidised using an oxalate kiln; lime is added to produce a reaction and the oxalate is stored within residue mud or sold to a third party for use in other industrial processes. Most recently oxalate has been stored as sodium oxalate in separately lined impoundments at the residue area, as part of a longer-term oxalate management strategy. The most promising option at present, for organic substance removal, is the biological decomposition of oxalate into harmless by-products such as carbon dioxide and water. Other than oxalate, refineries can use a liquor burner for the removal of organic impurities from the liquor.

#### **2.1.5 Precipitation**

Green liquor is passed to precipitation via a heat exchange process where it is cooled. The heat from the green liquor is transferred to the cool spent liquor (i.e., liquor from which the alumina has been removed) that is returned to the start of the digestion process. The cooled liquor is seeded with crystals of alumina tri-hydrate, which act as the nuclei for precipitation. The liquor is passed through a series of large precipitator

vessels and the alumina tri-hydrate is sorted by size and thickened before being passed to calcinations. The alumina tri-hydrate that is too small or fine for calcination is recycled back to the beginning of precipitation as seed.

### **2.1.6 Calcination**

Calcination involves the use of a two-stage heating process to dry the alumina tri-hydrate. The process drives off the water held during crystallisation, to produce alumina, a fine white powder. This is the final product of the Bayer process.

### **2.1.7 Bauxite Residue**

The material remaining after the alumina has been extracted from the bauxite ore is commonly termed “residue”. The residue consists of a coarse sand fraction and a fine silt fraction. These size fractions are separated as part of the refining process, resulting in an approximate 50:50 sand/ mud split. Prior to leaving the refinery they are recombined in a single pipeline and pumped to the residue drying area. A number of other facilities that support the refining operations are included within the residue complex. These include cooling ponds designed to cool the process liquors from the refinery and to store rainfall runoff water from both the refinery site and residue drying area.

## **2.2 General GCL Performance**

Once an understanding of the alumina refinery process was understood, where the process residue comes from, and the need for RDAs, it was important for this investigation to understand the general performance characteristics of a GCL.

A literature review of a report of a 1995 workshop on geosynthetic clay liners, Hydration of GCLs Adjacent to Soil Layers (David, 1996), helps to identify general performance characteristics. The report details an extensive laboratory testing program that was undertaken to investigate the potential for hydration of a GCL when placed against a compacted soil layer. Three different GCLs were used to evaluate the effects



of hydration time, initial GCL water content, thickness of soil layer and overburden pressure.

The tests were conducted using three commercially available GCL products; one woven and two non-woven. Specimens of GCL with known moisture content were placed in a specially designed test apparatus where a soil with known moisture content was compacted into the base and the GCL was placed on top. The specimen was then loaded with a load plate and allowed to hydrate for a specific amount of time. At the end of the hydration period the GCL was tested for moisture content. The GCL was left in contact with the soil for periods of 5, 25 and 75 days to define the effect of test duration on the hydration of the GCL.

The test results show that the moisture content of all three GCLs increased significantly as a result of contact with compacted sub-grade soil. The increase in GCL water content was significant after only five days of hydration. Over time, GCL water content continued to increase at a decreasing rate.

It was interesting to note that all three GCL products showed relatively similar behaviour. Increases in water content were comparable for the three GCL products despite differences in GCL fabric (i.e., woven vs non-woven) and types of bentonite clay used to manufacture the GCLs.

The report also noted that GCLs will hydrate when placed in contact with sub-grade soils compacted within the range of moisture contents typically found in earthwork construction specifications. This conclusion is consistent with data provided (Daniel, 1993); even for the driest soil (compacted 4% points dry of Optimum Moisture Content, OMC), GCL moisture content consistently increases from initial values in the range of 15 - 20 % up to about 40% within a 100-day period. It should be thus anticipated that even GCLs placed against relatively dry compacted sub-grades will undergo substantial hydration.

Given that long-term GCL shear strengths are insensitive to water content for water content above about 50% (Daniel, 1993), stability analyses involving GCLs placed in

contact with compacted sub-grade soils should be based on hydrated GCL shear strengths.

From reviewing this report, key characteristics of GCLs were identified:

- significant increases in GCL moisture content may occur within a few days of GCL contact with moist soil
- the rate of GCL hydration is initially highest and then decreases with increasing time
- overburden pressure within the range tested (i.e., 5 to 390kPa) did not influence the hydration process, and
- the differences between GCL products tested (i.e., type of bentonite clay and fabric) did not seem to significantly affect the test results.

The paper, Geomembranes for Tailing Impoundments (Beck, 2009), identified that the reasons for employing geomembranes for containment facilities are all based on the reduction of leakage and the resulting reduction in “failure” risk that comes with better containment. The definition of “failure” includes structural failure, environmental contamination and inadequate water supply.

The paper performed a simplified comparative analysis between geomembrane-lined and unlined tailings facilities located on sites with one metre of naturally occurring or compacted clay ( $k=1 \times 10^{-9} m/sec$ ). A summary of the results is seen in Table 2.1.

**Table 2.1 Comparative Analysis**

<b>LEAKAGE RATES (litres/hectare/day)</b>				
<b>Head (m)</b>	geomembrane high quality	geomembrane average quality	geomembrane low quality	clay only (1m)
1	6	37	79	864
5	35	208	446	4,320
10	86	503	1,077	8,640
20	230	1,350	2,894	17,280

The investigation came to the conclusion that if design concerns include environmental degradation, water conservation or reduction of risk, then employing a geomembrane in the design of a tailings or residue storage facility could significantly improve its performance. Constructing a tailings impoundment with a geomembrane can reduce leakage by up to 99%, as illustrated by a quantitative comparative analysis of leakage rates (Table 2.1). In addition, the risk of failure is mitigated, substantially eliminating 75% of the cause of most tailings dam failures. Using average or high quality installation techniques further reduces the risk of failure of the geomembrane liner by at least 30%.

The literature reviewed in this section reported on the benefits of using or omitting GCLs as a liner, but did not look into the different types of GCLs specifically.

### 2.3 Current Testing and Investigations

A refined review into literature that investigated specific types of clay used in the GCLs, defined optimal characteristics as well as the tests to identify them. A review of literature identifying the advantages and disadvantages of GCLs was also undertaken.

Some clay definitions to be noted:

- Bentonite A soft rock composed predominantly of the smectite clay mineral montmorillonite.
- Smectite A group of clay minerals which include dioctahedral smectites such as montmorillonite and nontronite and trioctahedral smectites, for example saponite.

The journal article Bentonite Clay Keeps Pollutants at Bay ( Gates, 2009), notes the increasingly stringent regulation of pollution and waste production worldwide. By using engineered barrier systems, such as GCLs, the contaminants that pose a threat to human and environmental health can be isolated and therefore reduced. The relatively low cost and wide versatility of reactive barriers favours the use of bentonite as an important component in barrier systems.

GCLs now widely replace or augment compacted clay liners and bentonite-soil mixtures in many barrier systems (Rowe, 2001; Bouazza, 2002). A GCL is a low-permeability composite material typically consisting of a thin layer (approximately 10mm) of Na-bentonite which is contained between two geotextiles, held together by either needle-punching or stitching (a reinforced GCL). Alternatively, the bentonite layer might be adhered directly to a geomembrane (a non-reinforced GCL). A GCL is often used with a geomembrane primary liner, and generally its performance (i.e.,  $K^{\text{sat}}$ ) depends on mineral composition and the form of the bentonite, rather than on the type of geotextile or the bonding methods used. The main advantages and disadvantages are shown in Table 2.2.

Low hydraulic conductivity and high confining stress tend to reduce the sensitivity to chemical attack of soil-bentonite and cement-bentonite mixtures, for all bentonite-based barriers. The journal article identified two key aspects - that the most useful bentonite for barrier technology contains at least 70 wt% montmorillonite and that the cation exchange capacity is a measure of the attenuation and exchange of positively charged ions by the negatively charged clay surfaces, and is correlated to layer charge for swelling clays (Churchman, 2006).

The journal article identified the sodium form of bentonite is as the most suitable for promoting swelling, sealing, low hydraulic conductivity and low chemical diffusivity in barrier applications. Some of the useful properties of sodium bentonite are listed in Table 2.3.

The bentonite can also be enhanced through beneficiation, which includes doping with soda ash (sodium carbonate), sodium bicarbonate, or other soluble sodium compounds, then mixing and perhaps grinding. For most engineering applications, a small weight percentage of non-ionic, anionic or perhaps low-charge cationic polymers may be added to enhance wetting, swelling, dispersion and gel formation. Beneficiation generally adds considerably to the final cost (Landis, 2004).

**Table 2.2 Advantages and Disadvantages of GCLs**

(Bouazza A 2002a)

Advantages	Disadvantages
Ease of installation (manageable rolls, less-skilled labour needed; lower costs)	Possible loss of bentonite during emplacement
Very low hydraulic conductivity if properly installed and pre-hydrated	Possible increase of hydraulic conductivity if leachate is incompatible and if not pre-hydrated
Bentonite density is uniform	Low shear strength of hydrated bentonite (for unreinforced GCL)
Can withstand large differential settlement	Possible post-peak shear strength loss
Excellent self-healing characteristics	GCL can be punctured after installation
Not dependent on local soils	Smaller leachate (e.g. dissolved cations) attenuation capacity
Easy to repair, at low cost	Prone to desiccation if not properly installed
Resistant to the effects of freeze-thaw	Greater diffusive flux
Thin liner offers more landfill space	Prone to ion exchange (for GCL with Na <sup>+</sup> -bentonite)
Field hydraulic conductivity testing not generally required	Low-moisture bentonite permeable to gases
Hydrated GCL is an effective gas barrier	Possibly higher long-term flux where thickness decreases under applied normal stresses
Reduced overburden stress on compressible substances such as municipal solid wastes	

**Table 2.3 Useful Properties of Sodium-Bentonite for Waste Containment**

(Bouazza A 2002c)

<b>Predictable cation and metals retention:</b> greater cation exchange capacity – greater retention
<b>High liquid sorption capacity:</b> 250 ml can sorb more than 1 litre of water
<b>Large surface area:</b> 20 grams equivalent to the area of a football field
<b>Excellent swelling and gel-forming properties:</b> increases original volume many times in water
<b>Low conductivity and diffusivity for water and gas:</b> less than 300 microns per year

The journal article states that in reality, performance depends on many factors such as ionic strength, charge on the dissolved ions and the degree of GCL hydration prior to contact with the permeating fluids and chemical diffusion (Bouazza, 2006). The article recommends that while design criteria exist for many bentonite-based barriers, their expected lifetimes have not been rigorously tested for leachate numbers. Well-constructed barrier systems are often assumed to function indefinitely, provided they remain intact, do not dry out and are not exposed to harsh leachates during their life span. Real performance lifetimes are generally unknown, and estimates are highly uncertain. Hydraulic conductivity or diffusion is usually assessed using a compatibility test, where a specimen is permeated with the real leachate or a simulant liquid (Shackelford, 2003).

The journal article concludes with the discussion of bentonite-based barrier systems playing an increasing role in environmental protection. Improved materials have been developed that prevent the migration of many industrial leachates, but strongly acidic and hypersaline wastes present significant challenges that require further research in the evaluation of bentonite performance.

The previous paper (Gates, 2009), noted that cation exchange capacity (CEC) is a characteristic in the performance of the clay material. The investigation was refined to examine the specifics of CEC. For this, the paper Cation Exchange Capacity and Swelling Characteristics of Geosynthetic Clay Liners (Wijeyesekera, 2003) was reviewed.

The paper reports the cation exchange capacities observed for Kaolin and montmorillonite (smectites) after their interaction with sodium chloride and calcium chloride solutions. Rolls of four different types of commercially available liners were anonymously obtained for the paper's investigation, which was part of an ongoing research project.

Cation exchange is identified as a fundamental electrochemical soil property and it is a particularly significant aspect of the behaviour of clay soils. CEC is the ability of soils to retain cations. The physical and chemical behaviour of soils can be related to CEC (Wilding, 1966; Yuan, 1967; Wright, 1972; Drake 1982). CEC increases with the proportion of the montmorillonite and its interlayering enhances its potential to adsorb many layers of water.

The cation exchange capacity of smectites is quite high, ranging from about 75 to 125  $\text{cmol kg}^{-1}$ . This high exchange capacity is due almost solely to permanent charge derived from the aligning of atoms. Variable charge due to broken edge effects commonly amounts to no more than 5  $\text{cmol kg}^{-1}$ . Because of their tendency to disperse when saturated with sodium (Na), and the resultant low permeability of the dispersed clay mass, Na saturated smectites are commonly used as liners for waste disposal sites, dams, lakes, and canals. When wetted, they disperse and swell, producing an almost impermeable liner for the landfill. This low permeability is desired in order to prevent heavy metals, organic wastes, and water itself from leaching out of the system and into the soils and sediments beneath (Borchardt, 1989).

From the test results, the paper concludes that CEC increases with the proportion of the montmorillonite, and its interlayering enhances the potential to adsorb many layers of water. Clays with a higher value CEC have the advantage of greater sacrificial space for cation exchange and accordingly CEC is useful as a GCL performance evaluator. Further, it is further useful in evaluating the response to changes in CEC under hostile chemical environments.

It should also be noted that bentonites treated with stabilising agents and factory prehydrated - are a potential improvement on obtaining clay infills with a high CEC that lose comparatively less of the CEC in hostile chemical environments. Factory prehydration avoids the difficulties of onsite hydration of dry GCLs which can substantially reduce the efficiency of liners that are initially dry.



Having investigated exactly what CEC is, and its benefits, this investigation was then further refined to review literature which examined how much cation exchange is beneficial for tailings dams and what other indicators would optimise dam design.

Guyonnet, (2009) published Performance-based indicators for controlling geosynthetic clay liners in landfill applications. The paper produced the results of a project aimed at identifying performance-based indicators that can be used by landfill operators to check the suitability of GCLs for bottom barrier applications. The results also underlined the correlation between CEC and smectite content, the correlation between free swell volume and proportion of exchangeable sodium, and the influence of the bentonite's calcium carbonate fraction on hydraulic conductivity. Several performance-based indicators are selected, in order to provide practical tools for checking the suitability of sodium-bentonite GCLs in bottom barriers applications, and limit values are proposed.

Note that GCL prehydration with a chemically non-aggressive fluid, prior to contact with divalent cation-rich fluids, helps to maintain low values of hydraulic conductivity. Petrov (1997), Rowe (2004), Shackelford (2000) and Jo (2001) stress the importance of allowing for sufficient equilibration time during hydraulic conductivity tests in order to obtain representative hydraulic conductivities.

Guyonnet (2005), investigated the correlation between surface chemistry, microstructure and permeability on a natural sodium-bentonite GCL and a sodium-activated calcium-bentonite GCL. It was found that the natural sodium-bentonite GCL consistently displayed superior hydraulic performance compared to the activated bentonite GCL during oedo-permeameter tests.

The isotopic ratios in this paper are expressed with respect to an international standard; PDB (Pee Dee Belemnite, a fossil belemnite found in the Cretaceous Pee Dee Formation in North Carolina, USA). This method is used routinely in France to check

the natural versus the activated nature of bentonites used in GCLs for landfill applications.

A correlation was observed between the CEC and the smectite content. Such results suggest that CEC might be a useful indicator of smectite content for controlling GCLs in field situations, as it is relatively fast and cheap to implement.

From the results of the project it is expected that for bentonites in GCLs (used in landfill applications in France), the value of CEC proposed in Table 2.4 should guarantee an optimal smectite content of at least 60 wt%.

**Table 2.4 Proposed performance-based indicators for GCLs in landfill applications**

Indicator	Value	Comments
Free Swell Index	$\geq 24 \text{cm}^3/2\text{g}$	This value typically appears in product sheets
Cation Exchange Capacity (CEC)	$\geq 70 \text{ meq}/100\text{g}$	Correlated to smectite content
$\text{CaCO}_3$ content	$\leq 5\%$ weight	This $\text{CaCO}_3$ content has the potential, upon dissolution, to saturate a CEC of $75 \text{ meq}/100\text{g}$ with $\text{Ca}^{2+}$ ions
Carbon and Oxygen isotope analysis	-	If one needs to know the origin of the bentonite

Performance-based indicators, such as those proposed in Table 2.4 may contribute to pulling market quality upwards, by helping landfill operators distinguish between suitable products and products that are unsuitable for landfill barrier applications. As the GCL market is very competitive, it is the opinion of the authors of this paper that such criteria are needed, in order to avoid that fact that some products find their way into landfills for reasons of attractive pricing rather than product quality.

It was noted that in the reviewed paper, the leachates had a pH of only 7.25 whereas in the specific application identified in this investigation, leachates have a pH of up to 13.8 (a far more aggressive leachate). Guyonnet's paper (2005), leads into a final refinement of the literature review.

One such piece of literature specifically investigating the effects of alumina residue leachate on GCLs is Hydraulic Conductivity of Two Geosynthetic Clay Liners Permeated with an Alumina Residue Leachate (Benson, 2008). The paper notes that GCLs are often used as hydraulic barriers in waste containment systems to contain liquids that have markedly different chemical compositions to DI water. Therefore, understanding how the liquid to be contained may affect hydraulic conductivity (K) is an important step in evaluating the suitability of a GCL for a barrier system. In the abovementioned paper, a study is described, where the suitability of two GCLs to contain leachate from an alumina processing residue was evaluated during the design of a residue storage facility at an alumina refinery in Australia.

The residue storage facility comprises a series of large cells where alumina processing residue is stored as high viscosity slurry (>50%). The slurry is pumped into lined paddocks and distributed in thin layers that are exposed to the sun. The sun drying process reduces the water content appreciably, but the residue remains saturated due to its high affinity for water. Liquid draining from the residue is captured by a composite liner system overlaid by a granular leachate collection system. Historically, a 500mm thick compacted clay liner has been used for the soil component of the composite liner. However, suitable and economical clay resources have become scarce. Consequently, alternative barrier materials, including GCLs, are being explored,.

The residue placed in the facility is from the Bayer process, used to produce alumina from ore. The ore is generally a weathered rock or sedimentary deposit of bauxite, which is chemically treated as part of the extraction process. The process results in an alkaline residue with pH levels of 11.5-12.5. Leachate from the residue has high concentrations of Na salts and aluminium complexes as well as a range of trace elements. The leachate used in the test program was collected from the discharge stream at the refinery and sent to the laboratory in sealed one litre polyethylene containers with no headspace. This leachate is believed to have near maximum concentrations, as exposure to air over time in the residue storage facility reduces concentrations due to the precipitation of salts.

Two GCLs (A and B) readily available in Australia were evaluated in this study. GCL A is manufactured in Brisbane, Australia, using locally sourced bentonite. GCL B is manufactured in China using bentonite from a Chinese source that is treated with soda ash. GCL A contained powdered bentonite and GCL B contained granular bentonite.

Hydraulic conductivity tests were conducted on both GCLs in flexible-wall permeameters in general accordance with the procedures in ASTM D 6766. Test specimens having a diameter of 102mm were cut from samples of the GCLs using the method described in (Jo, 2001). All tests were conducted until the termination criteria in D 6766 and D 7100 were met or six months of permeation was completed (whichever occurred first).

From the results, the paper concluded that the permeation by the leachate had a significant effect on the hydraulic conductivity (K) of both GCLs. For the prehydrated GCLs, permeation with leachate caused a decrease in K of GCL A and a large increase in K for GCL B. The reason for the differences in K in the leachate has not yet been determined. However, an important conclusion is that GCLs from different manufacturers can behave differently, and tests should be conducted on the specific GCL being planned for construction.

Prehydration had a significant effect on the K of the GCLs. When the GCLs were not prehydrated, the K was 60-800 times higher than the K of the prehydrated GCLs. When the GCLs were not prehydrated, the K to leachate was higher than the K to tap water. For these GCLs, prehydration is important to achieve low K, when used to contain leachate from alumina residue.

It has been noted that the long-term effectiveness of prehydration has not been evaluated for either of the GCLs which were permeated with alumina processing leachate.

Tests were conducted at different stresses on one of the non-prehydrated GCLs (A) permeated with leachate. Increasing the stress had little effect on the K. Similar tests

were not conducted on prehydrated GCLs. Additional testing is needed to determine if the beneficial effects of stress can be realised for GCLs that are prehydrated.

This piece of literature reviewed only powdered and granular GCLs, not factory prehydrated GCLs. Also noteworthy, is that the leachate was sourced from a United States refinery rather than an Australian one, and the leachate had a pH of only 12.2 and not the higher concentration of 13.8 used in this investigation.

The literature review shows the need for further investigations into the permeation of GCLs, specifically prehydrated GCLs. There is also a need to identify their chemical reactions when permeated with the leachates that they are expected to come into contact with i.e., residue from an alumina refinery in a RDA tailings dam application.

## 2.4 Cost of Tailings dam failures

The risks of tailings dam failures and associated costs (environmental and socioeconomic) have been identified throughout the literature review. Floods from tailings dam failures(Rico, et al, 2008) is one such piece of literature.

The paper identifies several characteristics that make tailings dams more vulnerable to failure than water storage dams:

- embankments formed by locally derived fills (soil, coarse waste, overburden from mining operations and tailings)
- multi-stage raising of the dam to cope with the increase in solid material stored, and effluent ( plus runoff form precipitation) released
- the lack of regulations on specific design criteria
- dam stability requiring continuous monitoring and control during emplacement, construction and operation of the dam
- the high cost of remediation works following the closure of mining activities.

The paper then gave an example of the Los Frailes (Aznalcollar) accident. A tailings dam disaster occurred in April 1998 due to the failure of large-scale sulphide tailings ponds embankments. €152 million in socioeconomic losses were experienced, of which €147 million was spent to correct the negative environmental and agricultural impacts, including restoration of the area's natural resources. €5 million was dedicated to mitigate socioeconomic and social-labour impacts in the affected municipalities. In addition, the region's production structure was affected, which produced a drop in sales from milk producers, farmers and fish industries.

Another more recent failure to be noted was on October 4<sup>th</sup>, 2010, in Hungary, when a reservoir containing pH-13 waste from bauxite mining burst open, releasing 700,000 m<sup>3</sup> of red mud. Eight people were killed, hundreds of people were burned and the failure has been labelled as one of the country's biggest environmental disasters to date. Figure 2.1 below is from Der Standard in Austria.



**Figure 2.2 Hungary Tailings dam failure**

It should be noted that the tailings dam in Hungary had been in operation since the 1940's and did not incorporate any GCL into its construction. A preliminary investigation of the possible cause indicates that the dam foundations were unsuitable.

These articles give some insight into the relative environmental and socioeconomic costs of catastrophic tailings dam failures, and they demonstrate the need for further investigation into the permeability of GCLs, the robustness of which should assist in lowering the risks of these types of failures reoccurring.

### **3. EXPERIMENTAL PROCEDURE**

This section will discuss the testing methods, techniques and processes used to satisfy the aims of this report. All data and tables are provided to ensure clarity and to display important points about the procedure.

#### **3.1 Materials**

The materials used were typical of those expected in an alumina refinery environment for this application, in terms of tailings dams. Materials include the factory prehydrated GCL, mastic, sand and Bayer-liquor. The following is a detailed discussion of each material used in the testing procedures.

##### **3.1.1 Factory prehydrated geosynthetic liner**

The factory prehydrated GCL is a waterproofing membrane used as a containment barrier for the control of liquids in the ground. The waterproofing membrane should comprise of a woven geotextile lower layer, a factory prehydrated natural sodium bentonite core, and a non-woven needle-punched geotextile upper layer in accordance with the BS EN ISO 9001 scheme. The natural sodium bentonite core should be hydrated under factory conditions with liquid polymers, vacuum air extraction and high pressure dye extrusion should be used. The membrane should be delivered to the site as a composite, in a hydrated state, with the bentonite core being of modelling-clay consistency.

##### **3.1.2 Mastic**

Mastic is a weather resistant paste, used to externally seal construction joints and pipe penetrations in concrete structures. It is manufactured in accordance with current BBA accreditation. The mastic should be supplied in 20kg containers. It should be delivered to the site in a dense hydrated state, be impermeable to non-aqueous liquids such as hydrocarbons, and tolerant of high acidic and alkaline conditions.



### **3.1.3 Sand**

The sand used in the testing was sourced from the Civil Engineering laboratories at Curtin University and supplied by a local concrete aggregate company. This was used instead of locally sourced sandy clay from the alumina refineries. This option was taken in order to eliminate the beneficial properties of the clay - the component of lower hydraulic conductivity - from the testing. Using the “Curtin” sand would allow the researchers to limit the hydraulic conductivity performance to the GCL only.

### **3.1.4 Bayer-liquor**

Bayer-liquor, also known as caustic, caustic soda, spent liquor or green liquor, has a pH value of approximately 13.8. The leachate used in the test program was collected from an Australian alumina refinery and was sent to the Civil Engineering laboratory at Curtin University, in sealed 20 litre polyethylene containers and two x 5 litre polyethylene containers with no headspace inside each as a secondary containment. The leachate was believed to have near maximum concentrations, as its storage in containers reduced its exposure to air. This air exposure occurs over time in residue storage facilities and reduces leachate concentrations due to the precipitation of salts.

## 3.2 Testing Procedure

Two testing procedures were developed to satisfy the requirements of this investigation.

By consulting with an Australian alumina refinery, and through the knowledge gained via the literature review, a chemical testing procedure was developed. The aim was to expose the GCL to the typical leachates it would encounter within a RDA. It was also agreed that the chemical testing would look at CEC, moisture content (H<sub>2</sub>O), and pH, to give an indication of the performance of the GCL.

The long-term testing procedure was a modified version of a long-term test cell testing protocol. This protocol is adopted by GCL distributors to measure the permeation through GCLs that are hydrated and permeated with site fluids under site load conditions. In order to replicate the expected conditions in a RDA facility, and to improve the safety of the test procedure, modifications were made to the testing procedure. This was done in consultation with an alumina refinery.

The tests took place in the Civil Engineering concrete laboratory at Curtin University. Due to the high alkaline nature of the Bayer-liquor, with a pH up to 13.8, strict safety precautions were put into place. Curtin University requirements included conducting a Chemical Alert 2 analysis (Curtin University 2009a), and completing a Chemical Risk Assessment Worksheet (Curtin University 2009b). From these procedures it was determined that for the duration of the testing, the testing area would be sectioned off. In addition a danger tap was installed, and the area was located in the vicinity of a safety shower. The shower was located above a drain, suitable for the disposal of materials of over 13pH. Figure 3.1 shows the general arrangement of the work area, highlighting the newly installed safety shower.



**Figure 3.1 Work Area**

### **3.2.1 Cylinders Subjected to Observation and Chemical Testing**

Along with visual inspections, where the cylinders were photographed and notes taken on the chemical testing of the GCL, tests of the top and bottom layers of sand were conducted, to create a cylinder profile over time.

#### **3.2.1.1 *Cylinder Construction***

An inspection of the bulk sample to be tested was conducted. It was noted that there was no disturbance, irregularity, or damage to the sample. However, mould spots were evident but these simply indicated that the sample had remained in storage for some time; the mould would not compromise the integrity of the testing (Figure 3.2). A template with a 200mm diameter was placed on the GCL sample and an outline was marked. The bulk sample was cut to size with a utility knife which was carefully removed with little or no loss of bentonite.



**Figure 3.2 Typical Specimen**

It was agreed that there would be a 150mm lower layer of sand that was to be tamped down 40 times with a 5kg weight in 75mm layers, for optimum compaction. The test specimen was then placed into the cylinder and the top non-woven fabric layer was removed. Mastic was then applied around the edge of the cylinder in an effort to create a seal between the GCL and the cylinder wall Figure 3.3. The non-woven fabric layer was then replaced.



**Figure 3.3 Mastic sealing the edges of the GCL to the cylinder**

A 300mm confining layer of sand was then placed on top of the GCL and tamped down 40 times with a 5kg weight in 75mm layers, for compaction. Following this, the Bayer-liquor was placed into each sample until the top confining layer was fully hydrated (approximately 3 litres for each sample), see Figure 3.4. The cylinders were then sealed with an acrylic plate, using silicone and an industrial strength tap was installed for reinforcement.



**Figure 3.4 Filling of the Cylinders with Bayer Liquor**

### **3.2.1.2 Observations**

Observations were taken 24 hours after the cylinders were constructed. It was noted that liquor was passing along the edges of the cells and this is shown by the discoloration below the GCL, see Figure 3.5.



**Figure 3.5 24 hour Observation**

The reason for this may be attributed to the sand moisture content which could have been very low, thereby absorbing moisture from the mastic. This would have occurred over the 24 hour testing period, where the mastic had time to shrink, leaving small gaps for the liquor to pass through.

The absorption of the liquor was not believed to be a failure of the GCL, but of the bond between the mastic and the cylinder. It was determined that this would be a short-term issue only, and that leakage would cease once the GCL and mastic were rehydrated. To establish if this was the case, the progression of the liquor was marked and documented over the course of the testing.

It was noted that Cylinder 7 was constructed 28 days before being filled with the Bayer-liquor. The gap between construction and use was due to a delay in delivery of this particular cylinder. The gap for cylinders 1, 2 and 3 was five days before liquor placement, and the gap for cylinders 8, 4 and 6 was seven days. From this it would be expected that Cylinder 7, having the most time to dehydrate, would have the highest amounts of Bayer-liquor passing through it before the sample rehydrated; cylinders 1, 2 and 3 would be expected to have the least. This was taken into account during further observations.

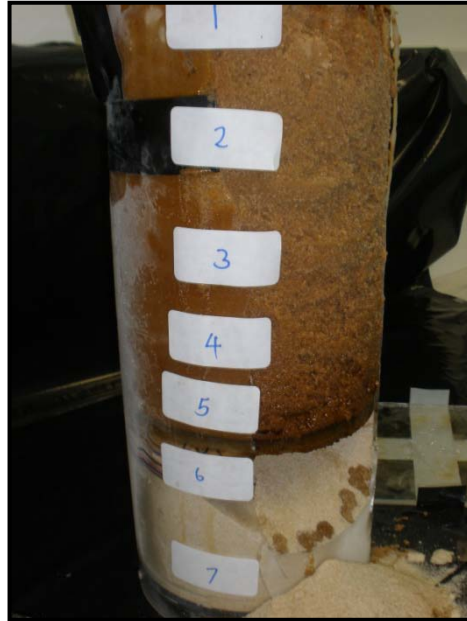
### **3.2.1.3 Chemical Testing Procedure**

Upon delivery to the Chemical Centre, the cylinders were date stamped and then frozen. The cylinders were frozen in order to make the handling and sampling safer and to slow down any chemical reactions so that delays in testing would not have an adverse effect on the given time the cylinders were tested (Figure 3.6).

Once frozen, a section of the cylinder was cut out using an angle grinder, and samples were taken at the top of the column, at 100mm depth, 200mm depth, directly above the GCL, 20mm below the GCL and at the base of the cylinder (Figure 3.7).



**Figure 3.6 Frozen Cylinder**



**Figure 3.7 Sampling from the Cylinder**

Once the samples had been taken, the rest of the cylinder was dismantled and the GCL removed for inspection (Figure 3.8). The GCL was sectioned into quarters and split into two layers, top and bottom (Figure 3.9). The GCL was tested as a whole sample, top half and bottom half. This was to give an indication of how much of the Bayer-liquor was penetrating the GCL.



**Figure 3.8 GCL Remove for Inspection**





**Figure 3.9 GCL with top layer removed**

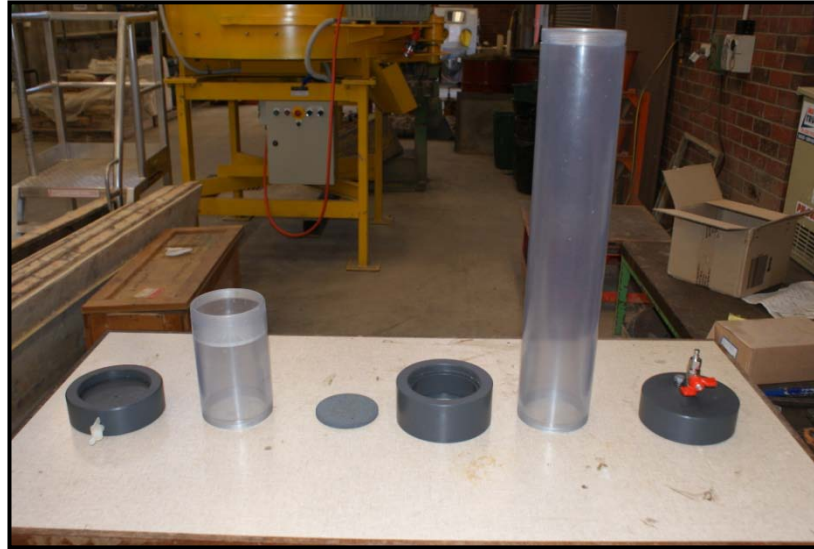
Cylinders 1, 3, 4, 6, 7 and 8 were sent to the Chemical Centre for testing, leaving cylinder 2 for further observations.

### **3.2.2 Long-Term Testing Cylinder**

An outline of the full testing protocol can be seen in Appendix A. For the purposes of this investigation, small variations to the test protocol were made to improve safety. Because of the nature of the Bayer-liquor it was agreed that handling and unsealed exposure would be minimised. This would mean that instead of adding the Bayer-liquor in increments as the sand is being added and compacted, it would all be added at the end stage.

#### **3.2.2.1 Summary of Test method**

- 1.1 The test method involves the hydration and permeation of a 100mm diameter sample of GCL test specimen.
- 1.2 The specimen is set up in a large column, solid wall and permeation apparatus, subjected to a confining stress of 300mm sand.
- 1.3 Saturation and permeation of the test specimen is carried out with the fluids that are/may come into contact with the GCL (Bayer-liquor).
- 1.4 The hydraulic head is to be equal or greater than that expected on site (7m).
- 1.5 The permeability is determined when a state of equilibrium is reached.



**Figure 3.10 Components of Test Rig**



**Figure 3.11 Lower Reservoir and bleed valve**



**Figure 3.12 Sample in Test Rig with Mastic Seal**



**Figure 3.13 Fully Constructed Test Rig**

## 4. RESULTS AND DISCUSSION

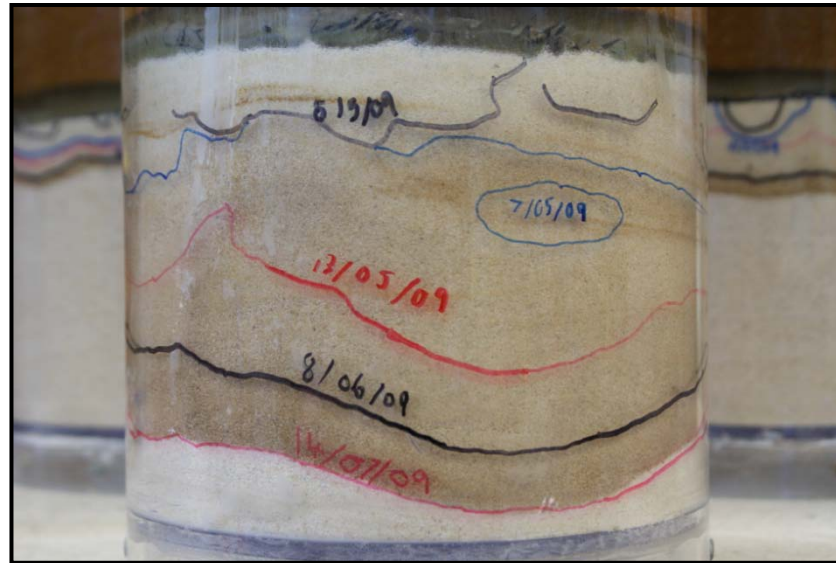
This section will discuss and compare the results that were obtained from the testing undertaken. For the purpose of this section of the investigation, figures and tables shown are representative of cylinders that best represent typical results from the testing. All tables and figures for the cylinder observations and chemical testing in its entirety can be seen in Appendix B.

### 4.1 Observations over Time

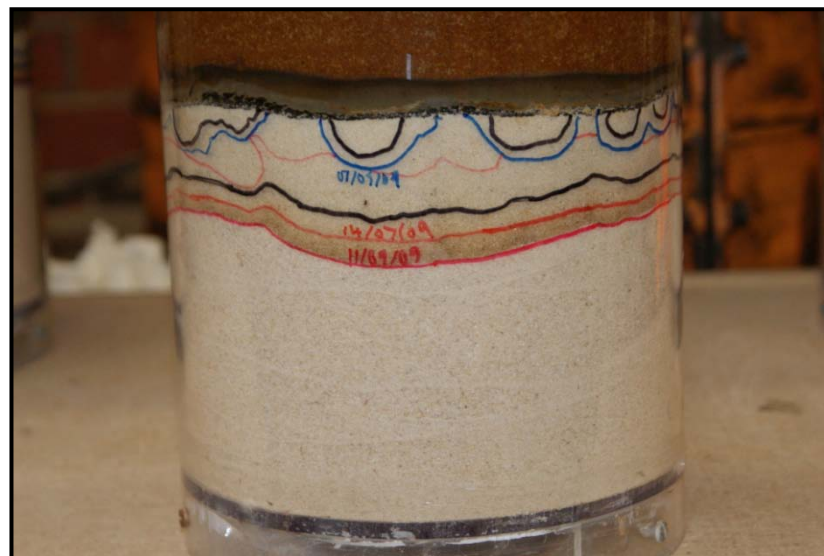
From the initial 24hr observations it was seen that some of the leachate had seeped out around the edges of the cylinders. This was expected, due to the dry sand absorbing the moisture out of the mastic over the time period before the leachate was added. Seepage was expected to cease once the GCL and the mastic had fully rehydrated. It was expected that Cylinder 7 would have the most leachate passing through as it had the longest time period between construction and the leachate being added. The other cylinders were expected to have considerably less leachate pass through to the edges.

After the 24hr observation was marked and dated, follow-up observations were made in one week and then at monthly intervals. As expected, when comparing cylinder 7 (Figure 4.1) and cylinder 3 (Figure 4.2), more of the leachate had passed through and infiltrated the lower layer of sand in cylinder 7 than in cylinder 3.

Colouration of the lower layer of white sand in the two figures should be noted. It can be seen that only a certain amount of leachate had passed through the edges of the cylinders before the GCL and mastic rehydrated as, over time, the colour of the sand directly below the GCL turned back to white and the only true discolouration was at the latest infiltration boundary. It was expected that the leachate would continue to infiltrate into the lower sand layer, but at a decreasing rate i.e., no new leachate would bypass the GCL and it would be absorbed by the sand to an optimum moisture content as it descended. This is confirmed by Figure 4.2 where it can be seen that there is a decrease in the distance of infiltration between observations, even though the time between observations has increased.



**Figure 4.1 Cylinder 7**



**Figure 4.2 Cylinder 3**

The literature review brought to light a concern that the sodium bentonite would not react to the high pH environment and that it would not swell, this being one of the beneficial characteristics of this type of clay. An interesting observation was made regarding several of the cylinders, particularly cylinder 8 (Figure 4.3). Due to the

dryness of the sand, true compaction could not be met. Some of the leachate passing the edges of the GCL had hydrated the sand, and with the suction of the leachate infiltration, the sand particles compacted more. This created an air void between the GCL and the lower sand layer. The GCL did not slide down to fill the void, but due to the reaction to the leachate, it swelled and sealed the edge gaps, eventually supporting some of the weight of the confining layer and the leachate (Figure 4.4).



**Figure 4.3 Cylinder 8**



**Figure 4.4 Cylinder 8 Completely Detached from Lower Layer**

From the observations over the course of this investigation it has been seen that the GCL has shown the characteristics identified in the literature review, even when exposed to a leachate of pH 13.8. This was only a visual inspection and it required the confirmation of the chemical testing.

## 4.2 Chemical Testing results

Reports containing all the data from the chemical testing of the cylinders can be seen in Appendix C. Samples of the sand and the GCL were taken as a control and these are shown in Table 4.1. Typical results from the testing can be seen in Table 4.2.

Note that NSS = Not a Sufficient Sample

**Table 4.1 Control Cylinder**

Sample Description		Blank Cylinder			
Made	4/05/2009				
Received	15/07/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	<1	7.8	0.4	2
Column -2	100mm depth	<1	7.8	0.4	2
Column -3	200mm depth	<1	7.8	0.4	2
Column -4	Top of Barrier	<1	7.8	0.4	2
Column -5	Barrier top half	30	7.9	66	140
Column -6	Barrier Bottom half	30	7.9	66	140
Column -7	Barrier complete	30	7.9	66	140
Column -8	Below barrier middle	<1	7.8	0.4	2
Column -9	Base of column	<1	7.8	0.4	2

From the literature review of Guyonett (2009), a key performance indicator was the CEC and this was seen as having a direct correlation to the smectite content in the GCL. It was recommended that a GCL have a CEC > 70 cmol(+)/kg. From Table 4.1 it can be seen that this GCL has a CEC of 66 cmol(+)/kg which is less than recommended, but it should also be noted that this GCL is a factory prehydrated geosynthetic liner and it could have been subjected to Beneficiation. This includes “doping” the clay with soda

ash (sodium carbonate), sodium bicarbonate, or other soluble sodium compounds. These compounds are added to enhance wetting, swelling, dispersion and gel formation (Landis, 2004). This would mean that the GCL would perform as well as, if not better than the GCLs with a natural CEC >70 cmol(+)/kg and this would be realised in the long-term permeation testing.

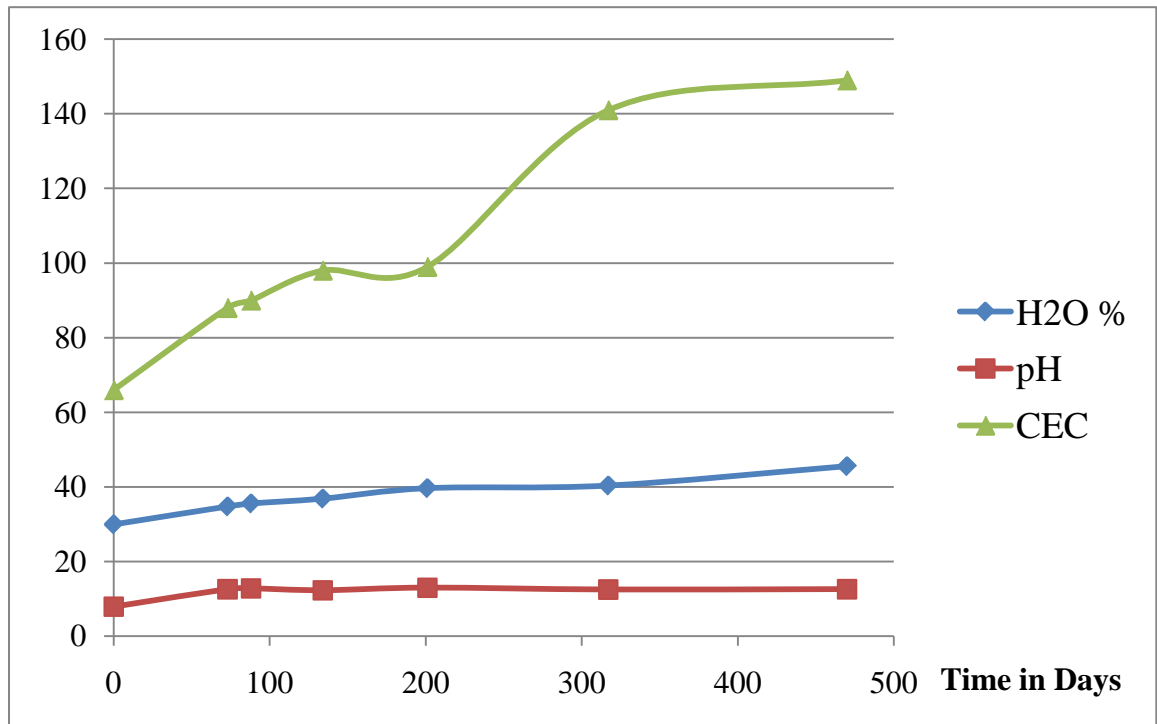
**Table 4.2 Typical Sample Results**

Sample Description		Sample 2 (C7)			
Made	4/05/2009				
Received	31/07/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	11.4	11.8	4	1100
Column -2	100mm depth	13.5	12.1	NSS	1300
Column -3	200mm depth	13.5	12.1	3.5	NSS
Column -4	Top of Barrier	13.4	12.2	4	1200
Column -5	Barrier top half	34.4	12.7	90	3800
Column -6	Barrier Bottom half	32	12.7	90	3700
Column -7	Barrier complete	35.6	12.8	87	3900
Column -8	Below barrier middle	3.9	11.2	<1.0	350
Column -9	Base of column	0.8	10.4	<1.0	86

From the data obtained from the chemical testing, graphs were created to show the changes over time in the cylinder profile in terms of moisture content, pH and CEC. Below, in Graph 4.1 is the profile for the GCL itself over time.



**Graph 4.1 GCL Profile**



As shown in the graph above, the CEC has increased from 66 cmol(+)/kg at day 0 to 149 cmol(+)/kg at day 470. This would indicate an increase in the sacrificial space for cation exchange to occur, and it would lead this investigation to believe that the GCL may be becoming less permeable over time. This can be further realised with the long term permeation test.

The moisture content of the GCL had also increased from 30% day 0 to 45.6% at day 450. This is consistent with David, E (1996), in that the rate of GCL hydration rate is initially high and then decreases over time. It was also noted that a GCL can take from 100 to 175 days to reach 40% hydration.

The pH, as expected, increased from 7.9 on day 0 to 13 at day 470, and has remained at pH 13 consistently since observations at day 201. This can be attributed to the hydrating of the GCL with the leachate.

Graph 4.1 would suggest that the samples were trending towards chemical equilibrium, but had not quite reached it. The pH has remained consistent from early observations

and the trend for hydration has levelled. The trends over time would be expected to level off in terms of the CEC, and if examined over a long enough period of time the CEC would be expected to decrease. How long this would take should be realised through further investigation.

### 4.3 Long Term Permeation Testing

Once the long-term test cylinder was constructed, it was allowed to sit for 48 hours without any pressure in order to allow the GCL sufficient time to hydrate. The pressure was then increased to 35 kpa (3.5m head pressure) for one week, then increased to 70 kpa (7m head pressure) for 180 days, then increased to 105kpa (10.5m head pressure) for a duration of 595 days of testing. Observations were made approximately every 60 days for 180 days Figure 4.5. and then periodically over the 595 day duration.



**Figure 4.5 Observations at 120 Days**

Using the permeation equations in Appendix A and the data collected, the amount of leachate passing was calculated in metres per second (Table 4.3).

The permeation,  $q$  [ $m^3/m^2/s$ ] is calculated as follows:

$$q = \frac{v}{At} \quad (\text{eq 1})$$

where,

$V$  is the quantity of flow taken as the average of inflow and outflow [ $m^3$ ]

$A$  is the cross-sectional area of nominal diameter of the specimen [ $m^2$ ]

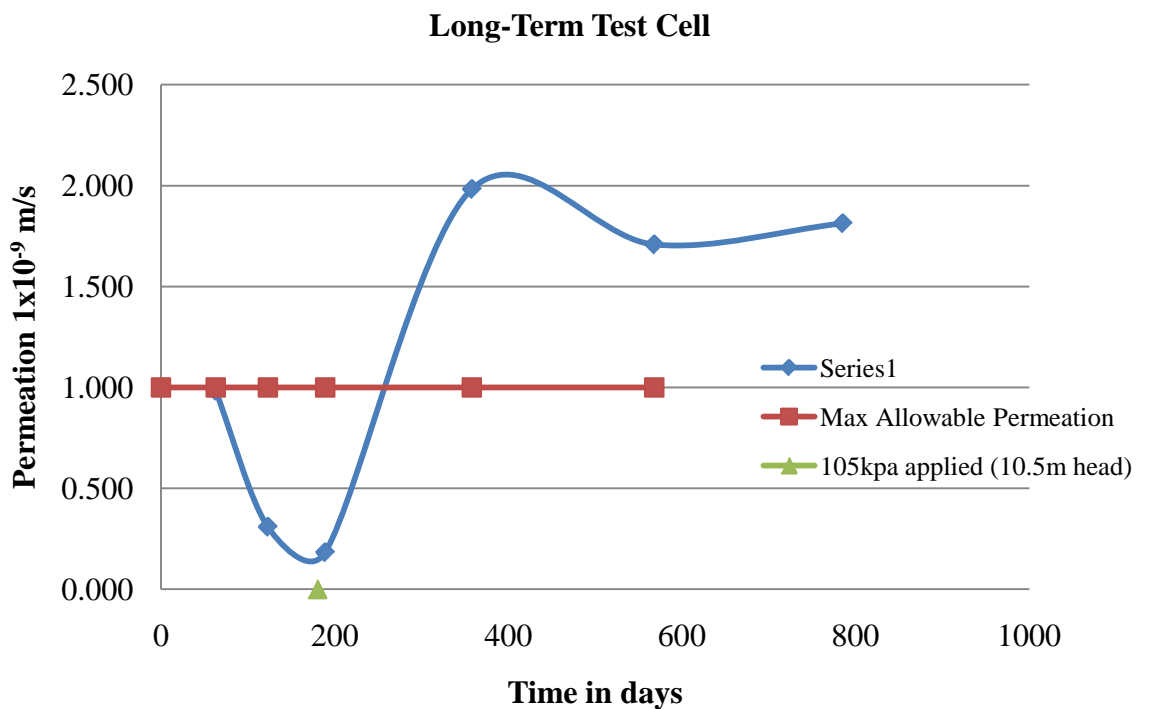
$t$  = interval of time, in seconds, over which the flow occurs

**Table 4.3 Observations**

Observation	A m <sup>2</sup>	V m <sup>3</sup>	t sec	q m/s
1	8.17E-03	4.23E-05	5.27E+06	9.83E-10
2	8.17E-03	1.31E-05	5.18E+06	3.09E-10
3	8.17E-03	8.50E-06	5.70E+06	1.82E-10
4	8.17E-03	2.37E-04	1.46E+07	1.98E-09
5	8.17E-03	2.53E-04	1.81E+07	1.71E-09
6	8.17E-03	2.78E-04	1.87E+07	1.81E-09

The results in Table 4.3 were then graphed in Graph 4.2 and compared to the maximum allowable permeation for this investigation, of  $1 \times 10^{-9}$  m/s. This is equal to the maximum allowable permeation of the high quality conventional clay currently in use.

**Graph 4.2 Long-Term Permeation Observations**



From the results shown in the above graph, it can be seen that the GCL had become less permeable when exposed to the leachate under a constant pressure of 70 kpa. This is confirmed by an increase in CEC, and is shown by the results of the visual observations

of the sample swelling, and the chemical testing. The graph also shows that the sample has yet to reach equilibrium. Shackelford (2000) and Jo (2001) stress the importance of allowing for sufficient equilibration time during hydraulic conductivity tests, in order to obtain representative hydraulic conductivities.

Once the time period was observed, the stress was increased to 105 kpa. From 185 days onwards, it can be seen that the permeation increased to above the maximum allowable that was set for this test. The trend appears to have peaked just above  $2 \times 10^{-9}$  m/s and over time, levels to around  $1.8 \times 10^{-9}$  m/s. It was expected that the leachate passing through would further decrease, similar to the results obtained by Benson (2008), where two different GCLs under similar test conditions were observed. However, as seen here, this was not the case.

From the tests so far, the GCL has been identified as showing the characteristics typical of sodium bentonite that make it the most suitable for promoting swelling, sealing, low hydraulic conductivity and low chemical diffusivity in barrier applications.

## 5. FEASIBILITY STUDY

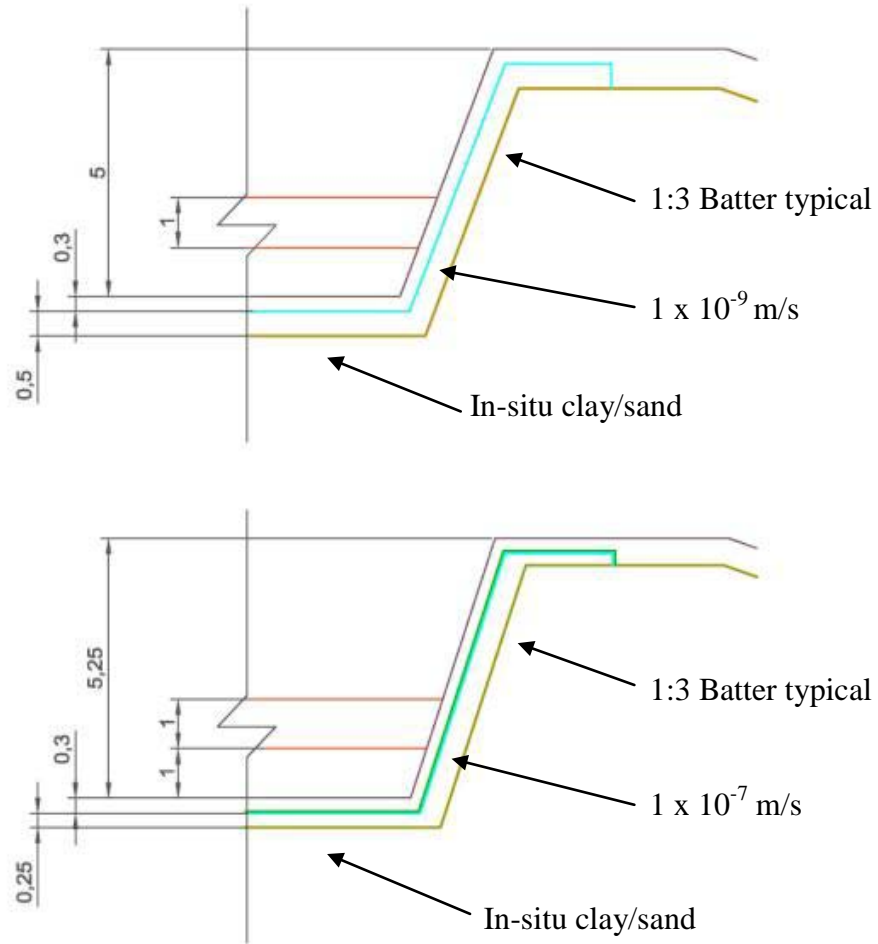
This section identifies the typical design of materials currently adopted by alumina refineries today, and proposes future changes in design. It also gives simple cost estimates of materials but does not include construction costs. All prices stated in the investigation were obtained from industry representatives of GCL distributors and alumina refineries during 2009. Prices would be subject to change dependent on the economic climate. Other viable applications of the GCL are also identified in this section.

### 5.1 Proposals and Applications

Currently the design for tailings dams (RDAs), as seen in Figure 5.1 (Top) includes a 0.5m layer of high quality clay with a hydraulic conductivity typically of  $1 \times 10^{-9} m/s$ , followed by a high-density polyethylene geomembrane (HDPE) and a 0.3m confining layer of locally sourced sand. The residue is then placed in 1m layers on the top for typically five lifts with another dam being constructed on top of that.

As identified previously in this investigation, in Western Australia it is becoming increasingly difficult to source sufficient high quality clay for future RDA construction. With increasing haulage distances and the environmental impacts of large clay borrow pits, it is difficult to continue to meet and improve upon current community and environmental standards. One possible answer is to investigate and produce an alternative lining system design.

The proposal of an alternative tailings dam design, as seen in Figure 5.1 (Bottom), would include a 0.25m layer of medium quality clay with a hydraulic conductivity typically of  $1 \times 10^{-7} m/s$ , followed by the application of a factory prehydrated geosynthetic liner (as investigated), with a hydraulic conductivity equal to or better than that of the previously mentioned high quality clay. A Hdpe liner would be added, then a 0.3m confining layer of locally sourced sand. It should be noted that the decrease in thickness in the lowest clay layer would increase the total volume of the tailings dam.



**Figure 5.1 Current Tailings Dam Design (Top)**  
**Proposed Tailings Dam Design (Bottom)**

## 5.2 Hypothetical situation

As previously stated in this investigation, RDAs are increasing in size by 300 to 400 thousand square metres annually. Therefore it is the purpose of this feasibility study to identify the costs of producing a 400,000 m<sup>2</sup> RDA. This will be done by utilising both the currently adopted design (option A) and the proposed design (option B) and then comparing the two.

The term *haulage* is identified as the distance from the RDA to the sourcing clay borrow pit.

Prices used in this feasibility study were as follows:

High quality clay long haulage (>3km<50km)	\$15/m <sup>3</sup>
High quality clay short haulage (<3km)	\$9/m <sup>3</sup>
Medium quality clay long haulage	\$8/m <sup>3</sup>
Medium quality clay short haulage	\$5/m <sup>3</sup>
Hdpe geomembrane	\$15/m <sup>2</sup>
Factory prehydrated geosynthetic liner	\$17/m <sup>2</sup>

Volumes calculated from hypothetical situation are show in Appendix D.

It should be noted that the cost of the 0.3m locally sourced sand layer has not been included as in both options as it remains the same. The decrease in thickness in the lowest clay layer in option B increases the RDAs total volume capacity by 5%. This increase in storage has a positive effect in relation to the price of the RDA as it is roughly estimated that every 10,000 m<sup>2</sup> is worth \$1 million.

In calculating the area of GCL required it was assumed that the GCL would be supplied in 2.5m wide lengths. The 150mm lapping required to connect parallel rolls was also included.

From the volumes calculated in Appendix D, and the prices stated above, the following cost estimates have been obtained.

**Table 5.1 Initial Analysis**

HDPE Inclusive		
Totals	option (A)	option (B)
Long Haulage	\$8,205,156	\$11,112,262
Short Haulage	\$7,588,324	\$10,775,624

Table 5.1 shows that even with the increase in capacity of the RDA option (A) the currently adopted design has the potential to be cheaper.

It should be noted that \$17/m<sup>2</sup> for the GCL is the upper bound in terms of pricing. A typical lower bound value for the GCL would be \$10/m<sup>2</sup> and this has been incorporated into the figures in Table 5.2. It can be seen that the currently adopted design still has the potential to be cheaper, but the proposed design is considerably closer.

**Table 5.2 Lower Bound GCL**

HDPE inclusive option B lower bound		
Totals	option (A)	option (B)
Long Haulage	\$8,205,156	\$9,553,976
Short Haulage	\$7,588,324	\$9,385,657

Even though the current design would appear to be the more feasible option, the situation may arise where no high quality clay can be sourced. Having confidence in the viable GCL option would mean that tailings dams could be constructed in areas where it was not possible to do so in the past.



With further testing and observations of the permeation and chemical reactions of the factory prehydrated geosynthetic liner, confidence in its ability to stop leachates from infiltrating the ground and water sources may become high enough to omit the Hdpe liner. A sensitivity analysis of this situation can be seen in Table 5.3 (Upper Bound) and Table 5.4 (Lower Bound).

**Table 5.3 Sensitivity Analysis Upper Bound**

HDPE inclusive in option A only		
Totals	option (A)	option (B)
Long Haulage	\$8,205,156	\$6,000,336
Short Haulage	\$7,588,324	\$5,832,017

**Table 5.4 Sensitivity Analysis Lower Bound**

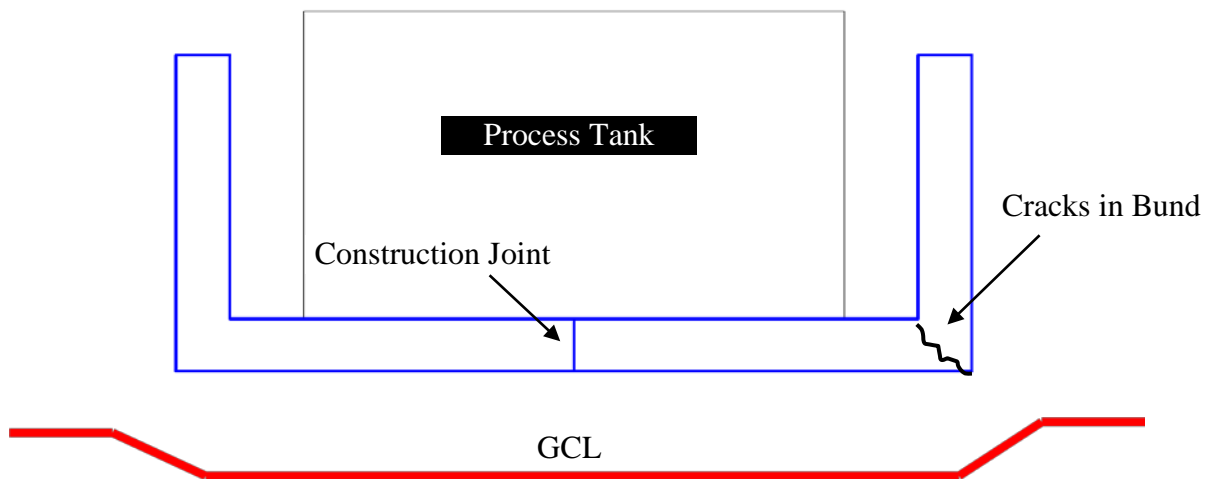
HDPE inclusive in option A only, option B lower bound		
Totals	option (A)	option (B)
Long Haulage	\$8,205,156	\$2,890,901
Short Haulage	\$7,588,324	\$2,722,582

It is the belief of the investigators that if a more technical feasibility study were to be conducted, inclusive of construction costs, the proposed design would be likely to be more cost-effective.

If confidence in the GCL were to increase over time, to such an extent that the Hdpe liner could be omitted, it would prove to be of additional benefit in making the proposed design more feasible. This can be attributed to the lower installation costs of the GCL as it does not require highly-skilled labour to install. There would also be an increase in construction speed as a thinner layer of clay could be used for compaction and preparation in the base.

### 5.3 Secondary Containment

This investigation identifies that tailing dams for RDAs are not the only viable application of the GCL in a Caustic refinery environment. It could also be used in a refinery in a structural capacity as secondary containment under concrete bunds containing alumina process tanks, as show in Figure 5.2.



**Figure 5.2 Secondary Containment**

One of the design issues with concrete bunds in alumina refinery environments is that due to the large coverage areas, they require construction joints to be included in the design. With exposure over time to the Bayer-liquor these construction joints often erode and the liquor passes through the joints and leaches into the ground. Another avenue for the escape of Bayer-liquor through the concrete bunds is by leaching through cracks created through the general wear and tear of plant operations. In this situation the GCL could be place underneath the concrete bund with a 300mm confining layer of soil on top and it would remain there for the duration of the asset life. Once the asset is decommissioned, any Bayer-liquor that had breached the concrete bund would be contained in the soil between the bund and the GCL. This soil could be reclaimed once the asset was demolished and transported to an RDA. This application would decrease the negative impact of the refinery on the surrounding environment.

## 6. CONCLUSION AND RECOMMENDATIONS

This thesis investigated the performance of a factory prehydrated GCL in terms of its hydraulic conductivity and chemical reactions in a Caustic refinery environment. It would appear that even though the initial CEC of the GCL was 66 cmol(+)/kg lower than the recommended 70 cmol(+)/kg, the hydraulic conductivity was similar to that of the GCLs with a higher initial CEC. It would seem that the stabilising agents and the factory prehydration of the GCL have proven to be beneficial. It should be noted that bentonites treated with stabilising agents and factory prehydrated GCLs would appear to be an improvement on obtaining clay infills that perform well under hostile chemical environments.

Although the initial results are promising, they are still only short-term results in terms of the asset life of a permanent residue facility. Indications from this investigation are that the trends will level out and achieve chemical and hydraulic equilibrium over time.

Based on the limited and relatively short-term data, initial indications express that a factory prehydrated GCL has the potential to replace the high quality clay required in the construction of tailings dams. However, at this stage of the investigation, omission of the HDPE liner in conjunction with the GCL is not recommended unless sufficient data is collected to raise the confidence in the GCLs low hydraulic conductivity.

It is recommended that the investigation be extended by conducting further observations and chemical tests on the remaining test cylinder. It is also recommended to return the confining stress of the long-term test permeation test cylinder back to 70kpa and conduct further observations. A more detailed technical feasibility study should also be conducted, inclusive of the construction costs of the tailings dam application and the structural application of secondary containment.

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## 8. APPENDIX A

### 8.1 Significance of use

- 8.1.1 This test method subjects the GCL specimen to actual site fluids and material. Efforts to match actual site flow conditions are made.
- 8.1.2 This test method may be incorporated as part of a full assessment of actual site flow conditions.
- 8.1.3 The test method does not provide a value of hydraulic conductivity, although hydraulic conductivity can be determined in a manner similar to the method described herein. A measurement of the thickness of the sample is needed for the determination of hydraulic conductivity.
- 8.1.4 This test method may be continued over time and used in the assessment of long-term performance in terms of permeability.
- 8.1.5 This test method provides an indication of site/specimen compatibility with respect to permeability.

### 8.2 Apparatus

- 8.2.1 *Hydraulic System* - Constant head systems may be utilised provided they meet the criteria outlined as follows:
- 8.2.2 *Constant Head* - The system shall be capable of maintaining constant hydraulic pressure to within  $\pm 5\%$  and shall include means to measure the hydraulic pressure to within the prescribed tolerance. In addition, the head loss across the test specimen must be held constant to within  $\pm 5\%$  and shall be measured with the same accuracy or better. Pressures shall be measured by a pressure gauge, electronic pressure transducer, or any other device of suitable accuracy.
- 8.2.3 *Flow Measurement System*- The inflow volume shall be measured unless the lack of leakage, continuity of flow, and cessation of consolidation or swelling can be verified by other means. Flow volumes shall be measured with a graduated accumulator, graduated pipette, vertical standpipe in conjunction with an electronic pressure transducer, or other volume-measuring device of suitable accuracy.



- 8.2.4 *Flow Accuracy* – Required accuracy for the quantity of flow measured over an interval time is  $\pm 5\%$
- 8.2.5 *Permeameter Cell Pressure System* – The system for pressurising the permeameter cell shall be capable of applying and controlling the cell pressure to within  $\pm 5\%$  of the applied pressure. However, the effective stress on the test specimen shall be maintained to the desired value with an accuracy of  $\pm 5\%$ . The device for pressurising the cell may consist of a reservoir connected to the permeameter cell and partially filled with de-aired water, with the upper part of the reservoir connected to a compressed gas supply or other source of pressure. The gas pressure shall be controlled by a pressure regulator and measured by a pressure gauge, electronic pressure transducer, or any other device capable of measuring to the prescribed tolerance. A hydraulic system pressurised by deadweight acting on a piston or any other pressure device capable of applying and controlling the permeameter cell pressure to the tolerance prescribed in this paragraph may be used.
- 8.2.6 *Permeation Cell* – The permeation cell consists of a large upper column to facilitate confining material, attached to a lower column which holds the specimen configuration. The cell contains an upper cap which contains an inlet pressure port and a bleed valve. A schematic detail of the cell is shown in Figure 3.10.
- 8.2.7 To allow for the evaluation of hydraulic conductivity, measuring devices may be attached to the cell. These may be in the form of a graduated optical, mechanical or electronic device. The device used for the assessment of thickness or change in thickness should be such that flux parameters are not affected. Where deformations in the sample are measured, the instrument used should be suitable for providing an accuracy of 0.3mm or better and have an adequate travel range.
- 8.2.8 *Specimen Assembly* – The specimen assembly is to be as per Figure 3.10. Firstly the perforated plate is to be placed in the lower cell assembly. A 100mm diameter porous stone is then to be placed onto the perforated plate. A 100mm diameter specimen shall be laid onto the porous stone.
- 8.2.9 *Confining Material* – The confining load shall be provided by material that is representative of that to be used on site. This material should be representative both chemically and in terms of particle distribution. The density of the material

used should be within  $\pm 5\%$  of the actual site confining material. The height (300mm) of the confining material in the test rig should be within  $\pm 5\%$  to that of the actual site confining material.

- 8.2.10 De-airing of the confining material is to be achieved by presaturation with the site permeant for a minimum period of one hour prior to placement in the test rig. Care should be taken not to cause particle segregation during this process.
- 8.2.11 The confining material is to be carefully placed in 10 layers as described herein.
- 8.2.12 *Porous Plate* – The porous plate shall be of silicon carbide, aluminium oxide, or other material that is not degraded by the specimen or permanent liquid. The porous plate shall be free from cracks and have a regular smooth surface.
- 8.2.13 The porous plate shall have a diameter of no greater than 100mm and no less than 98mm. The porous plate shall be sufficiently rigid and have a thickness such that cracking under the specified loading does not occur.
- 8.2.14 The porous plate shall have a substantially greater hydraulic conductivity than that of the specimen such that it does not have a noticeable effect on the levels of flow.
- 8.2.15 *Filter Paper* – Filter paper shall be used to prevent the clogging of the porous plate from sediments during testing. The hydraulic conductivity of the filter paper shall be substantially greater than that of the specimen such that it does not have a noticeable effect of the levels of flow. One or more sheets of filter paper may be used. The type of filter paper recommended is Whatman No. 1 (or equivalent), that has a particle retention capability greater than  $11\mu\text{m}$ .
- 8.2.16 *Device for measuring dimensions of the specimen* – The device used for the measurement of the specimen shall be accurate to 0.3mm. The readings should be taken in such a manner as not to disturb the sample.
- 8.2.17 *Temperature Control* – The temperature at which the test is conducted should represent that to which the GCL is exposed during its working life. For each test the temperature should not vary by more than  $\pm 3^\circ\text{C}$ .
- 8.2.18 Where only one test is conducted, the temperature selected should be within  $\pm 5^\circ\text{C}$  of the average worst-case temperature. For hot countries this would be an average of the maximum expected seasonal temperatures at ground level (level of GCL below confinement). For cold climates this would be an average of minimum seasonal temperatures at ground level (level of GCL below

confinement). Where large seasonal temperatures variances are expected, a minimum of two tests is required, with the max/min expected ground (at GCL level) temperatures used.

### **8.3 Permeant**

- 8.3.1 The permeant shall consist of a titrate or fluid representative of that to which the GCL is to be exposed, as well as the fluid to which the GCL could become exposed. Where concentrations of the site fluid to which the GCL is to be exposed change over time, the most onerous concentration should be used. Where fluid concentrations to which the maximum the GCL may become exposed cannot be sourced from site, a representative synthetic fluid may be used.
- 8.3.2 The permeant fluid should be de-aired. The method of de-airing should be either by forceful agitation of the fluid in an agitator attached to a vacuum source, or by spraying a fine mist of fluid into an evacuated vessel attached to a vacuum source.

### **8.4 Test Specimen Preparation**

- 8.4.1 Inspect the bulk GCL sample to be tested and record any disturbance, irregularity, or damages. Choose a representative section of the GCL sample to obtain the specimen for testing.
- 8.4.2 Place a template with a known area on the selected section.
- 8.4.3 Using a sharp utility knife, or another suitable instrument, cut the bulk GCL sample to the exact size of the templates. Carefully remove, with little or no loss of bentonite, and weigh the cut GCL sample. The weight of the GCL sample and the area of the template could be used to provide an estimate of the mass per unit area of the GCL sample.
- 8.4.4 If necessary, utilising a squirt bottle with a long nozzle and filled with the permeant of interest, wet the edges of the GCL sample to prevent bentonite loss during further handling and specimen preparation.
- 8.4.5 Carefully place the GCL sample on a flat smooth surface.

- 8.4.6 Place a 100 mm diameter disc at the centre of the GCL sample. With a thin marker, trace around the disc directly onto the GCL backing.
- 8.4.7 Remove the disc. Using a sharp utility knife, or another suitable instrument, cut through the traced line and into the upper GCL backing. Depending upon the type of geotextile backing, heated fine-pointed soldering irons or carpet knives have been successfully used for this purpose.
- 8.4.8 Utilising a squirt bottle with a long nozzle, apply the permeant of interest on the cut line. Allow the bentonite to become wetted for 2 to 5 min, if required, to prevent any loss of bentonite.
- 8.4.9 Using a sharp pair of scissors or another suitable instrument, cut through the bentonite and lower geotextile backing on the cut line. Add the permeant of interest to the exposed bentonite, if required, to prevent any loss of bentonite.
- 8.4.10 Examine the exposed edge of the specimen to verify that geotextile fibres from the upper and lower geotextile backings are not connected, the edge of the geotextile backing may be slightly trimmed using a pair of sharp scissors.
- 8.4.11 The diameter of the specimen shall be not less than the diameter of the disc and no greater than 102mm.

## **8.5 Procedure**

- 8.5.1 *Base Rig Assembly*- Apply a thin coat of silicon high-vacuum grease to the base plate rubber seal and place the rubber seal into the groove provided in the base plate. Attach the lower cell assembly by screwing it onto the base plate.
- 8.5.2 *Sample Configuration and Placement*- Place the perforated plate into the lower cell assembly such that it is flush with the hunch provided Figure 3.11. Place a porous plate, saturated for 24 hours with the permeant of interest, onto the perforated plate. Place onto the porous plate a 100mm diameter filter paper, which has been saturated for 24 hours with the permeant of interest. Carefully place the prepared GCL specimen onto the filter paper. Ensure that the GCL specimen is sitting flush and that the edges of the specimen have not been damaged during placement. Ensure that the orientation of the specimen is as per

that on site, with the correct covering geotextile uppermost. The edge of the GCL specimen to the cylinder should be sealed by a mastic, see Figure 3.12.

- 8.5.3 Add a layer of approximately 5mm of permeation to the specimen.
- 8.5.4 Over a period of a few minutes, apply 2 x 50 mm layers of confining material onto the specimen. Each layer is to be carefully levelled with a flat edged-levelling bar, in such a manner that no excessive void formations occur. During the levelling of the layers with the levelling bar, each layer should not be penetrated by more than 15mm. At no point during the placement of the confining material should the specimen be disturbed. Subsequent to the placement of each layer, permeation fluid is to be added, such that each layer is capped with a minimum of 0.5mm and a maximum of 3mm of permeation fluid.
- 8.5.5 *Conjoining Ring and Upper Cell Assembly-* Thoroughly clean the thread in the lower cell assembly. Apply thin coats of silicon high-vacuum grease to the conjoining ring rubber seals and place the rubber seals into the groove provided in the conjoining rings. Attach the conjoining ring to the lower cell assembly. Then attach the upper cell assembly to the conjoining ring Figure 3.13.
- 8.5.6 *Application of Remainder of Confining Material and Permeation Fluid-* Over a period of 16 minutes, apply 8 x 50 mm layers of confining material onto the specimen. Each layer is to be carefully levelled with a flat edged-levelling bar, in such a manner that no excessive void formations occur. During the levelling of the layers with the levelling bar, each layer should not be penetrated by more than 15mm. At no point during the placement of the confining material should the specimen be disturbed. Subsequent to the placement of each layer, permeation fluid is to be added such that each layer is capped with a minimum of 0.5mm and a maximum of 3mm of permeant fluid which should be brought to a level of 50mm from the top of the upper cell assembly.
- 8.5.7 *Placement of Upper Cap and De-airing-* Thoroughly clean the thread in the upper cell assembly. Open the bleed valve on the upper cap. Apply a thin coat of silicon high-vacuum grease to the upper cap rubber seal and place the rubber seals into the groove provided in the upper cap. Attach a toxic interface chamber to the permeation port valve in the upper cap.
- 8.5.8 Close the inlet valve and open the bleed valve and allow a settling time of 24 hours.

- 8.5.9 *Permeation*- Apply a 2m pressure head through the toxic interface chamber to the specimen.
- 8.5.10 *Termination Criteria* - Continue the test for a minimum of seven days. Assess the inflow gradient for deviations. When a linear flow gradient is achieved after the prescribed seven days, at least three readings are to be taken over an eight hour period. Steady state is deemed to have been satisfied when these readings do not vary by more than 3% on a linear flow gradient.
- 8.5.11 On completion of the test, the applied head (2m) pressure source should be removed and all valves closed. The rig should then be stored in an environment similar to that of the GCL on site (temperature and light).

## 8.6 Calculation

Calculate the permeation,  $q$  [ $m^3/m^2/s$ ] as follows:

$$q = \frac{v}{At}$$

where,

$v$  is the quantity of flow taken as the average of inflow and outflow [ $m^3$ ]

$A$  is the cross-sectional area of nominal diameter of the specimen [ $m^2$ ]

$t$  = interval of time in seconds over which the flow occurs

## 9. APPENDIX B

### 9.1 Cylinder One Observations



Figure 9.1 Cylinder One 07/05/2009

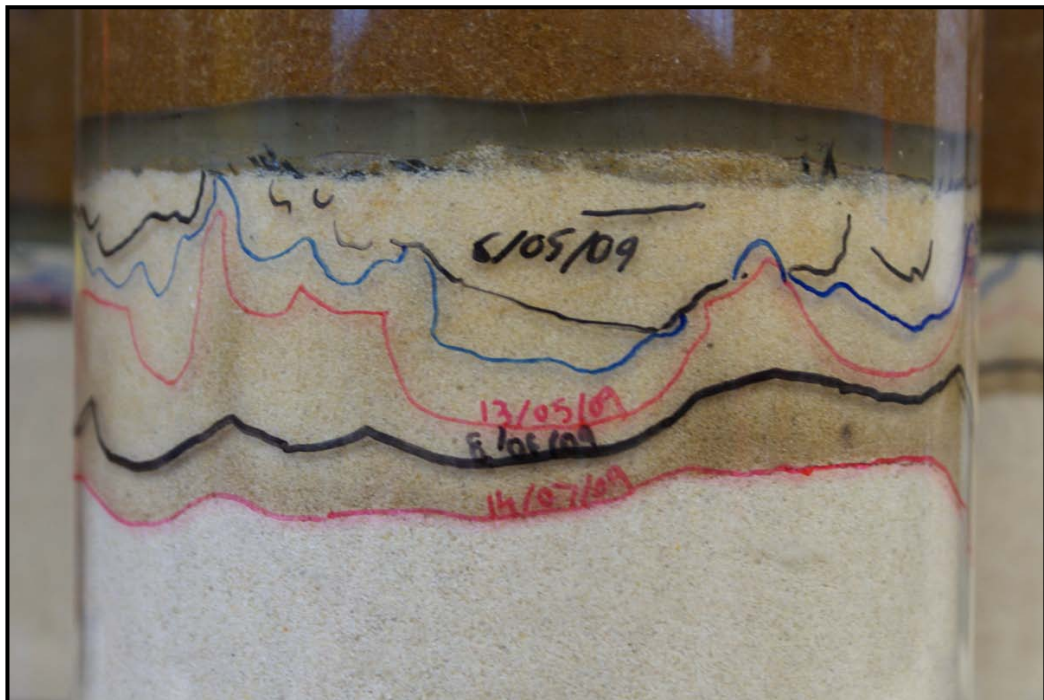


Figure 9.2 Cylinder One 14/07/2009

## 9.2 Cylinder Two Observations



Figure 9.3 Cylinder Two 07/05/2009

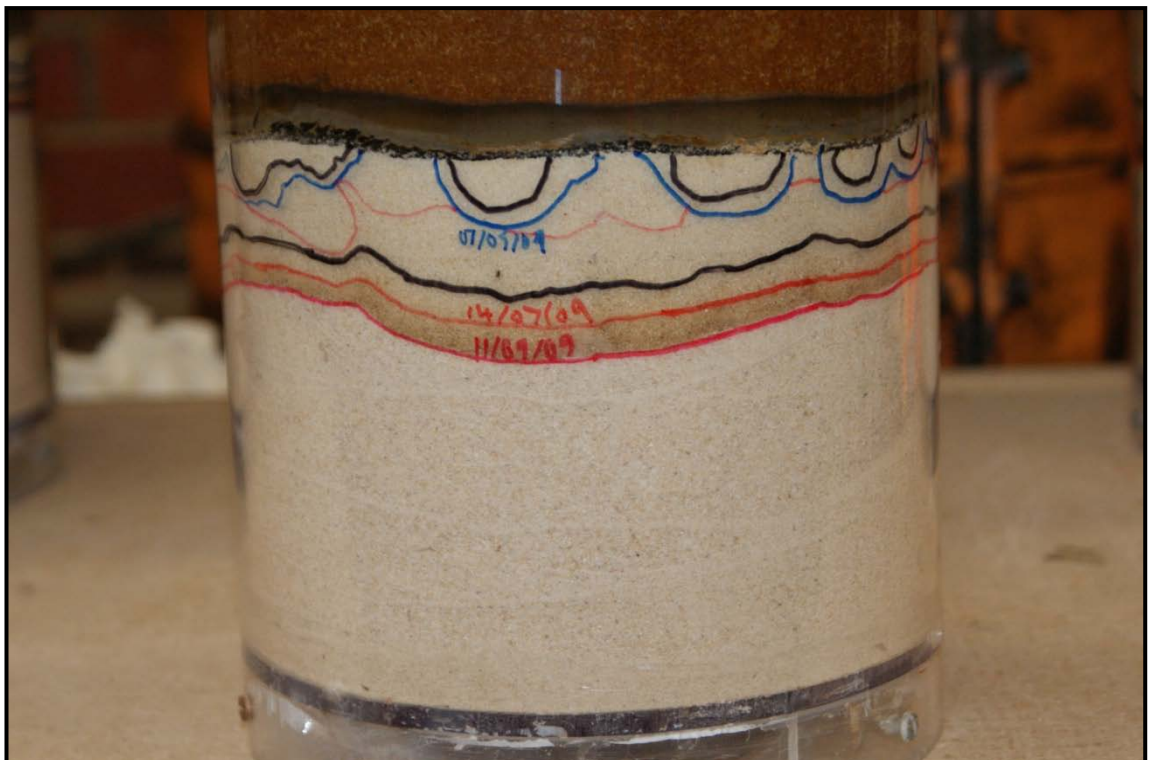


Figure 9.4 Cylinder Two 11/09/2009



### 9.3 Cylinder Three Observations



**Figure 9.5 Cylinder Three 07/05/2009**



**Figure 9.6 Cylinder Three 11/09/2009**

## 9.4 Cylinder Four Observations



Figure 9.7 Cylinder Four 07/05/2009

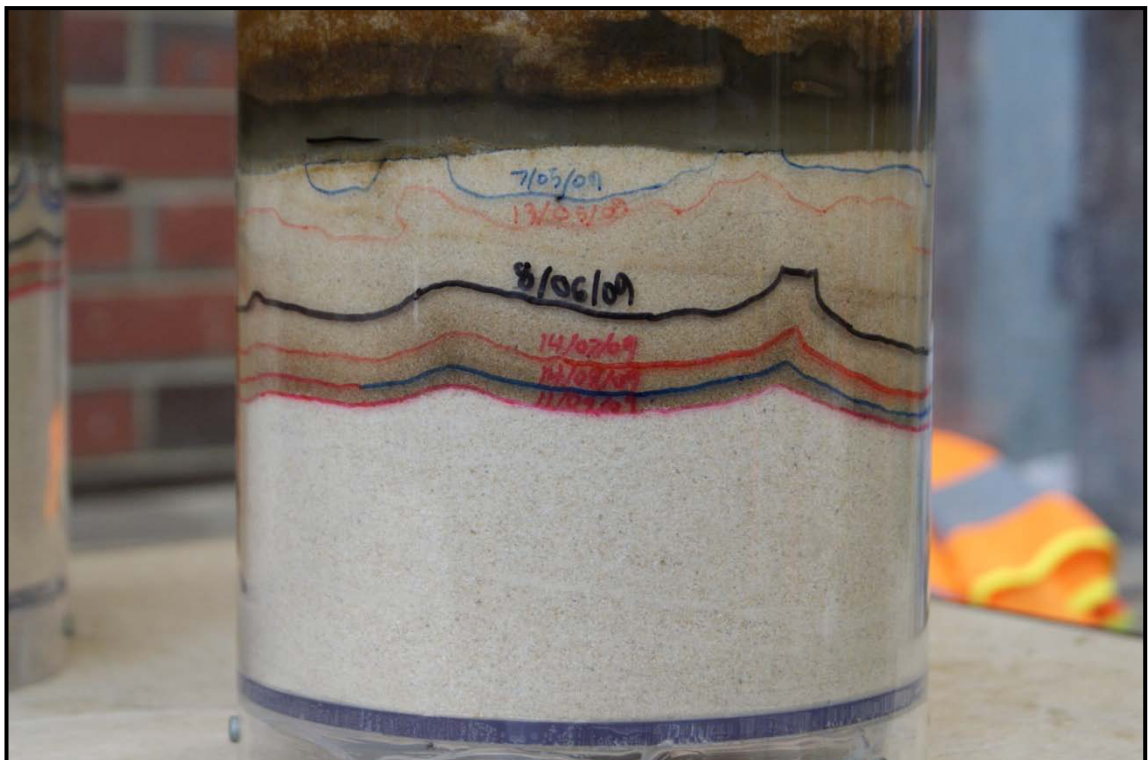


Figure 9.8 Cylinder Four 11/09/2009

## 9.5 Cylinder Six Observations



Figure 9.9 Cylinder Six 07/05/2009

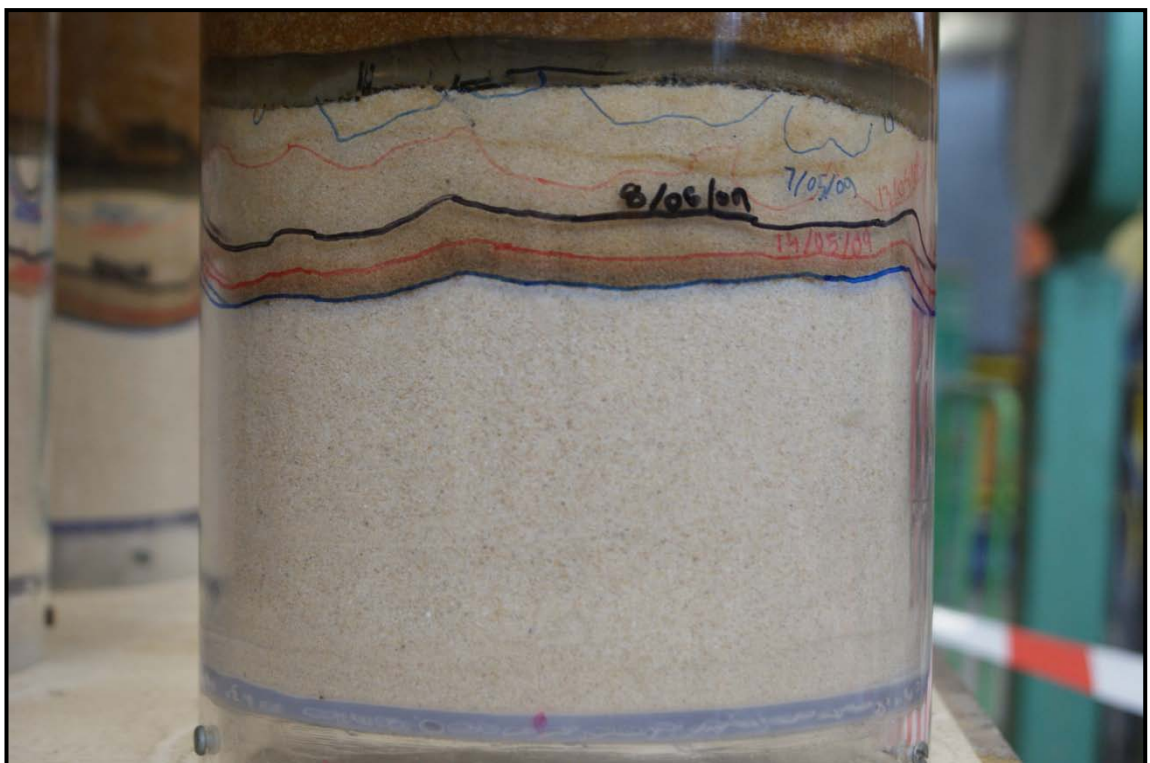


Figure 9.10 Cylinder Six 18/08/2009

## 9.6 Cylinder Seven Observations



Figure 9.11 Cylinder Seven 07/05/2009

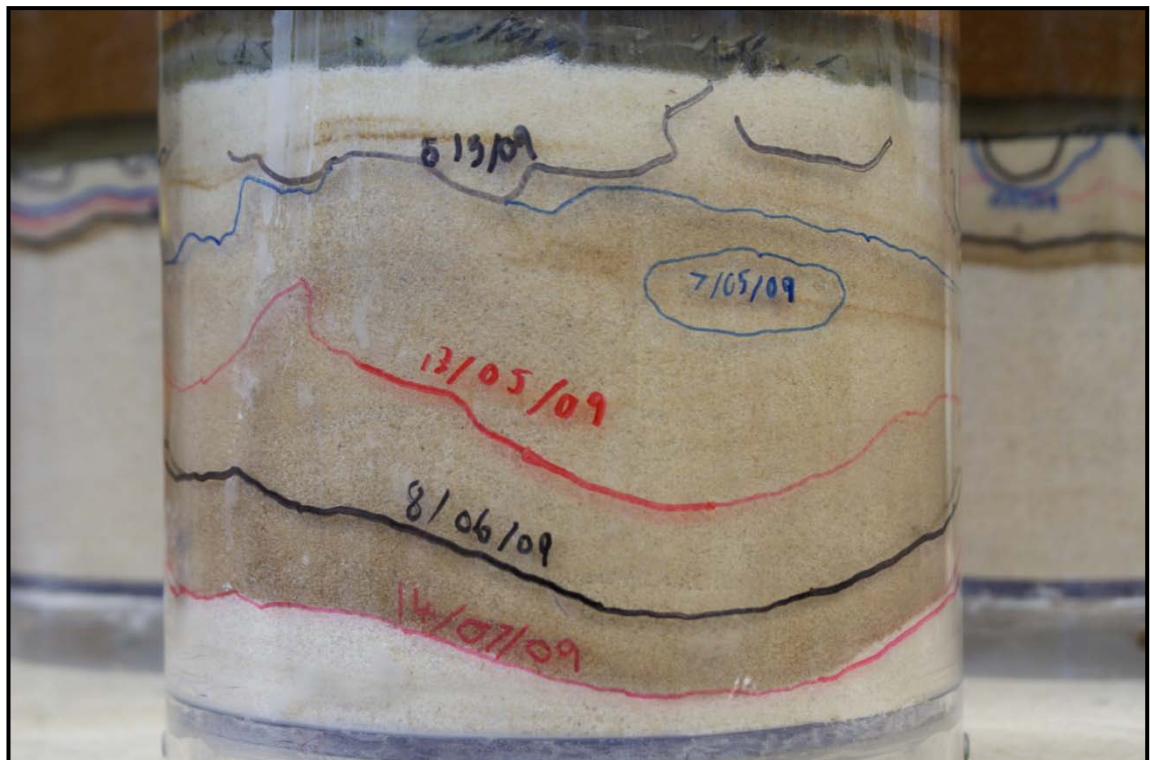


Figure 9.12 Cylinder Seven 14/07/2009

## 9.7 Cylinder Eight Observations



**Figure 9.13 Cylinder Eight 07/05/2009**



**Figure 9.14 Cylinder Eight 11/09/2009**

## 9.8 Observations all Cylinders



Figure 9.15 All Cylinders 07/05/2009



Figure 9.16 All Cylinders 08/06/2009



**Figure 9.17 11/09/2009**



**Figure 18 23/03/2010**



**Figure 19 23/03/2010**





**Figure 20 23/03/2010**



**Figure 21 23/03/2010**



**Figure 22 23/03/2010**

## 10. APPENDIX C

**Table 10.1 Control Cylinder**

Sample Description		Blank Cylinder			
Made	4/05/2009				
Received	15/07/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	<1	7.8	0.4	2
Column -2	100mm depth	<1	7.8	0.4	2
Column -3	200mm depth	<1	7.8	0.4	2
Column -4	Top of Barrier	<1	7.8	0.4	2
Column -5	Barrier top half	30	7.9	66	140
Column -6	Barrier Bottom half	30	7.9	66	140
Column -7	Barrier complete	30	7.9	66	140
Column -8	Below barrier middle	<1	7.8	0.4	2
Column -9	Base of column	<1	7.8	0.4	2

**Table 10.2 Cylinder 1**

Sample Description		Sample 1 (C1)			
Made	4/05/2009				
Received	15/07/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	9.2	11.4	1.7	730
Column -2	100mm depth	11.8	11.8	3	1000
Column -3	200mm depth	13.1	11.8	3.1	1000
Column -4	Top of Barrier	13.4	12	3.5	1000
Column -5	Barrier top half	37.5	NSS	NSS	3600
Column -6	Barrier Bottom half	34.6	12.7	NSS	3400
Column -7	Barrier complete	34.8	12.6	88	3600
Column -8	Below barrier middle	3.4	10.7	0.82	300
Column -9	Base of column	<1	7.1	0.29	1

**Table 10.3 Cylinder 7**

Sample Description		Sample 2 (C7)			
Made	4/05/2009				
Received	31/07/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	11.4	11.8	4	1100
Column -2	100mm depth	13.5	12.1	NSS	1300
Column -3	200mm depth	13.5	12.1	3.5	NSS
Column -4	Top of Barrier	13.4	12.2	4	1200
Column -5	Barrier top half	34.4	12.7	90	3800
Column -6	Barrier Bottom half	32	12.7	90	3700
Column -7	Barrier complete	35.6	12.8	87	3900
Column -8	Below barrier middle	3.9	11.2	<1.0	350
Column -9	Base of column	0.8	10.4	<1.0	86

**Table 10.4 Cylinder 6**

Sample Description		Sample 3 (C6)			
Made	4/05/2009				
Received	14/09/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	12.2	11.6	3	1100
Column -2	100mm depth	13	11.6	3	1200
Column -3	200mm depth	13.2	11.5	3	1200
Column -4	Top of Barrier	13.7	12.1	4	1300
Column -5	Barrier top half	34.3	12.2	97	2900
Column -6	Barrier Bottom half	31.2	12.4	98	2600
Column -7	Barrier complete	37.6	12.4	98	
Column -8	Below barrier middle	2	10.7	1	210
Column -9	Base of column	0.5	7.8	<1.0	3

**Table 10.5 Cylinder 3**

Sample Description		Sample 4 (C3)			
Made	4/05/2009				
Received	20/11/2009	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	13	12.6	4	1500
Column -2	100mm depth	12.6	12.6	4	1400
Column -3	200mm depth	12.9	12.6	3	1600
Column -4	Top of Barrier	14	12.7	3	1700
Column -5	Barrier top half	34.2	13.1	85	4300
Column -6	Barrier Bottom half	30.3	13.1	90	3900
Column -7	Barrier complete	39.7	13	97	NSS
Column -8	Below barrier middle	0.2	8.8	1	400
Column -9	Base of column	0.3	9.4	1	1200

**Table 6 Cylinder 4**

Sample Description		Sample 5 (C4)			
Made	4/05/2009				
Received	16/03/2010	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	17.9	11.8	7	1500
Column -2	100mm depth	12.6	11.5	4	1100
Column -3	200mm depth	12.8	11.8	3	1100
Column -4	Top of Barrier	11.8	12.2	4	1300
Column -5	Barrier top half	39.3	12.1	134	3300
Column -6	Barrier Bottom half	42.2	12	139	3500
Column -7	Barrier complete	40.4	12.5	141	3700
Column -8	Below barrier middle	2.4	10.5	1	230
Column -9	Base of column	0.1	9.3	0.9	17

**Table 7 Cylinder 8**

Sample Description		Sample 6 (C8)			
Made	4/05/2009				
Received	16/08/2010	H2O	pH	CEC	EC
		%		cmol(+)/kg	mS/m
Column -1	Top of column (surface)	3.5	11.3	2	340
Column -2	100mm depth	3.6	11.5	2	370
Column -3	200mm depth	14.6	12.2	4	1300
Column -4	Top of Barrier	14.5	12.2	4	1400
Column -5	Barrier top half	48.6	12.2	149	4500
Column -6	Barrier Bottom half	43.8	11.4	148	3800
Column -7	Barrier complete	45.6	12.4	149	4300
Column -8	Below barrier middle	3.2	11.3	2	330
Column -9	Base of column	5.1	11.5	3	490

## 11. APPENDIX D

Materials	Long Haulage (>3km) \$/m <sup>3</sup>	Short Haulage (<3km) \$/m <sup>3</sup>
High quality clay	15	9
Med quality clay	8	5

High quality clay Volume m <sup>3</sup>	\$15 /m <sup>3</sup>	\$9/m <sup>3</sup>
1.03E+05	\$1,542,081	\$925,249

Med quality clay Volume m <sup>3</sup>	\$8 / m <sup>3</sup>	\$5/ m <sup>3</sup>
5.61E+04	\$448,851	\$280,532

Geosynthetic liner Area m <sup>2</sup>	\$17 / m <sup>2</sup>	\$10 / m <sup>2</sup>
4.44E+05	\$7,551,485	\$4,442,050

HDPE Area m <sup>2</sup>	\$15 / m <sup>2</sup>
4.44E+05	\$6,663,075