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Forensic Examination of Field GCL Performance in Landfill Capping and Mining Containment Applications

J Buckley. Geosynthetic Centre of Excellence, Gold Coast, Australia. j.buckley@geofabrics.com.au
W P Gates. Smectech Research Consulting, Melbourne, Australia. gateswp@smectech.com.au
D Gibbs. Geosynthetic Centre of Excellence, Gold Coast, Australia. d.gibbs@geofabrics.com.au
F Gassner. Golder Associates, Melbourne, Australia. fgassner@golder.com.au

ABSTRACT
Geosynthetic Clay Liners (GCL's) have been used in landfill capping and mine containment applications in the Australian environment over the last 14 years. Their use as hydraulic / gas barriers has been accepted by regulatory authorities and design engineers over this time.

The aim of this paper is to evaluate the field performance of GCL's in terms of hydraulic performance, changes to bentonite mineralogy and physical characteristics. While GCL index properties are appreciated by designers, the performance of GCL's under Australian environmental conditions requires further research to ensure these characteristics provide the desired environmental safety margin. This paper outlines a study of the in-field performance of GCL's exhumed from landfill capping and mine containment sites around Australia.

1. INTRODUCTION

Most GCL's consist of a layer of sodium bentonite clay secured between two layers of geotextiles. The primary function of the bentonite component is to limit the migration of fluids (Bouazza et al., 2006). The geotextile component is essentially (i) the carrier / reinforcement network which allows the placement of a uniform barrier layer of processed bentonite (generally ~3-6mm thick) (ii) a physical network that provides internal confining stress to restrict free swelling and (iii) a reinforcement to improve hydrated internal shear strength characteristics.

The development of GCL's has been driven primarily from two points of reference. Firstly, as an alternative to compacted clay liners, which are normally only specified in terms of thickness and hydraulic conductivity. Secondly, development derived from quality control testing carried out by GCL manufacturers. This type of testing requires fast testing turn around and confirms that product quality remains within manufacturing tolerances. The reliance on manufacturing test procedures derived from the textile industry has resulted in a specification focus on strength performance attributes, which in most cases are of secondary importance to the necessary hydraulic performance of the product. To date, little attention has been paid to evaluation of GCL performance in service.

In Australia, there exists a knowledge gap in the behaviour of GCL's in the field. The main reasons for this are difficulties associated with accessing sites for exhumation and industry acceptance that the key GCL performance parameters are geotextile related. This paper outlines an exhumation program of GCL's from landfill capping and mining tailing pond applications within Australia and presents results from selected sites in various states around the country. The aim is to relate manufacturing specification parameters to in-field attributes of GCLs, which will provide a basis to improve both GCL performance and testing.

These results may be used by designers to gauge GCL performance for similar applications. Recommendations as to bentonite specifications required within a GCL can be made based on the findings to provide designers with confidence in the performance of the liner system.

2. BACKGROUND

The stages of the GCL exhumation program are as follows:

- Investigate critical performance parameters such as GCL hydraulic conductivity, bentonite mineralogy and GCL moisture content
- Examine cover soil and subgrade soil characteristics, in particular, moisture content, physical and chemical properties, and mineralogy
- Analyse and compare results from different sites with varying soil type / mineralogy, rainfall environment and time in service
- Develop recommendations for designers to take into account on-site parameters which could affect long-term performance of GCL's in the field.

Site selection for each exhumation was influenced by factors such as age of installation, average annual rainfall and accessibility of GCL, and sites were selected in different states within Australia. The details of each site are shown in Table 1.

Table 1. Details of GCL exhumation sites

Site	Exhumation date	State	GCL grade[1]	Year constructed	Type of installation	Mean annual rainfall (mm)[2]
WA-1	Feb 08	WA	Type 2	2002	Landfill cap	785
QLD-1	Aug 09	NTH QLD	Type 3	Sep-2001	Landfill cap	4235
WA-2a	May 09	WA	Type 2	May-2006	Mineral processing recovery dam	447
WA-2b	Sep 09	WA	Type 2	May-2004	Mineral processing settling dam	447
SA-1	Feb 10	SA	Type 3	Jul-2000	Cellulose waste Cap	705
NSW-1	Feb 10	NSW	Type 1	2000 / 2001	Landfill Cap	1502

[1] GCL grades are described below:
Type 1 GCL - carrier = woven geotextile, cover = non-woven geotextile, dry bentonite mass = approx 3.6kg/m^2
Type 2 GCL - carrier = woven geotextile, cover = non-woven geotextile, dry bentonite mass = approx 4.0kg/m^2
Type 3 GCL - carrier = woven/non-woven composite, cover = non-woven geotextile, dry bentonite mass = approx 3.7kg/m^2

[2] Mean annual rainfall is based on the average of all historical rainfall data at the station nearest to the site

2.1 Climatic conditions

Australia's climate is dominated by the dry, sinking air of the subtropical high pressure belt which moves north and south with the seasons. This causes the rainfall pattern over Australia to be strongly seasonal and helps to define the main climate regions shown below in Figure 1. (Bureau of Meteorology, 2009)

Figure 1. Australian major seasonal rainfall zones (courtesy Australian Bureau of Meteorology website, 2009)

The GCL exhumation sites are situated in distinctly different seasonal rainfall zones, as follows:

- SITES WA-1, WA-2a and WA-2b
  - Situated in sub-tropical Western Australia
  - Winter dominant rainfall
  - Marked wet winter and dry summer
- SITE QLD-1
  - Situated in tropical North Queensland
  - Summer dominant rainfall
  - Marked wet summer and dry winter
- SITE SA-1
  - Situated in SE South Australia
  - Winter rainfall
  - Wet winter and low summer rainfall
- SITE NSW-1
  - Situated in Central Coast, New South Wales
  - Uniform rainfall
  - No defined wet or dry season
  - Median annual rainfall ≥ 350mm

The above rainfall zones have the most diverse rainfall conditions in the Australian Bureau of Meteorology classifications. A graph of historical rainfall for each site, from 1998 to 2009, is shown in Figure 2.

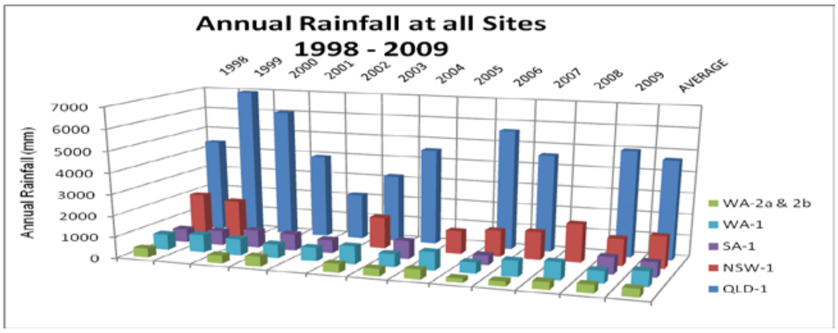

Figure 2 – Annual Rainfall at each Exhumation Site from 1998 to 2009

2.2 Age of site

Research by Meer and Benson (2007) has stated that Ca for Na exchange within cover GCLs can occur within 5 years in temperate North America. The ages of the exhumation sites in Australia varied between 3 to 9 years and all exhumation sites were selected on the basis that any potential cation exchange had occurred in a minimum of 3 years.

2.3 Site final use

2.3.1 WA-1

Site WA-1 consists of a single GCL used as a primary cap for a municipal solid waste installation in Western Australia. The GCL was overlain by approximately 0.50 m of sandy cover soil. A similar material was placed as a blinding layer underneath the GCL. The landfill cap drained into a series of valley drains. The primary function of the GCL is to mitigate rainfall infiltration into the underlying landfill cell, thereby reducing generation of leachate and the costs associated with its management and disposal.

2.3.2 QLD-1

The GCL at QLD-1 was also installed as a primary cap for a regional solid waste installation in North Queensland. The cover soil overlying the GCL consisted of a 0.40 m thickness of a sandy loam mixed with sugar cane ash. A decomposed granite (mixture of sand / fine gravel) bedding layer was originally placed under the GCL. The function of the GCL is also to reduce infiltration into the landfill cell, in a very high rainfall area.

2.3.3 WA-2a and WA-2b

The application for the GCL at WA-2a and WA-2b is for a secondary containment dam liner for mineral processing tailings, installed under a HDPE geomembrane, to form a composite liner. The subgrade soil below the GCL consists of poorly graded, clayey sand. Confinement of the lining system is from the tailings themselves, with the chemical composition of the liquor as follows:

Table 2. Chemical composition of liquor at WA-2a and WA-2b

Property	Value	Units
TSS	38.5	mg/L
TDS	22863	mg/L
EC	32.4	mS/cm
Ca	798	mg/L
Mg	69.4	mg/L
Na	1397.8	mg/L
SO_4	416	mg/L
pH	6.6	pH
Cl	10595	mg/L

This liquor with the above TDS (total dissolved salts), TSS (total soluble salts) and EC (electrical conductivity) levels is best described as saline brine, with an ionic strength of ~0.2M, calculated based on the analyses reported. Chemical compatibility testing with the GCL bentonite and this liquor was conducted some time prior to installation of the GCL at site WA-2b. This testing produced favourable results, which constituted a pre-approval for supply of the GCL with this bentonite for future installations.

2.3.4 SA-1

The function of the GCL at site SA-1 is to form a primary cap over wood processing waste, thereby limiting rainfall infiltration into the waste body and minimising methane gas generation. The site location in South Australia typically experiences higher rainfall than the rest of the state. The GCL was immediately overlain by 0.20 m of drainage sand, then 0.40 m of clay and 0.30 m of topsoil, totalling 0.90 m of cover material. The subgrade material consists of predominately fine-medium sand.

2.3.5 NSW-1

At NSW-1, the GCL is used as a primary cap over a large municipal waste installation which has been developed into recreational playing fields. NSW-1 is situated in an environmentally sensitive area being in close proximity to a major watercourse. The cover material consists of 0.20 m of weathered coal-stone / sandy gravel directly above the GCL, overlain by 0.30 m of topsoil. The subgrade is a gravelly sand material, similar in nature to the overlying coal-stone.

2.4 Nature of bentonite

The sodium bentonite powder used at all sites was designated as a civil engineering grade, Wyoming-type bentonite with the following index properties:

Table 3. Sodium Bentonite Specified Values

Property	Value	Units
Typical physical properties		
Dry screen (passing 75µm)	80	%
Wet screen (retained 75µm)	2	%
Bulk density	0.9	t/m^3
Liquid limit	500	%
Moisture content[1]	10	%
Cation exchange capacity	85	meq/100g
pH	9	-
Typical chemical analysis		
SiO_2	63.8	%
Al_2O_3	13.6	%
Fe_2O_3	2.8	%
Na_2O	2.3	%
MgO	2.0	%
CaO	0.2	%
K_2O	0.2	%
TiO_2	0.3	%
LOI (Loss on ignition)[2]	14.8	%

[1]Moisture content is the water content after oven drying.
[2]LOI is the water content after melting in flux (~1100°C).

3. TESTING

The sampling of exhumed GCL was generally carried out in accordance with ASTM D 6072 (2009).

Independent laboratories provided detailed mineralogical and chemical analyses of both the bentonite within the GCL and surrounding soils, which were carried out in order to identify any changes that may have occurred and to better evaluate the impact that these changes may have on the long term performance of the GCL. These analyses included: Major elements by X-ray Fluorescence (XRF), total metals by ICP-AES (inductively coupled argon plasma atomic absorption spectrometry) on acid-digested extracts; soluble cations and anions by ICP-AES on 1:5 soil-water extracts; exchangeable cations by ICP-AES using the ammonium displacement method (Rayment and Higginson 1992); pH, total soluble salts and total alkalinity on 1:5 soil-water extracts; total Cl using colorimetric methods on acid digested extract; total dissolved salts and EC on a saturated paste extract; particle size analysis by sieving and hydrometer methods. All methods followed standard, internationally recognized methods (e.g. AS, ASTM, APHA, USEPA, NEMM) or methods developed in-house in the absence of documented standards.

Hydraulic and physical testing was carried out by in-house laboratories on the exhumed GCL, as follows.

3.1 Exhumed GCL specimen preparation

Each exhumed GCL bulk sample was cleaned of adjacent soils. From each bulk sample, 10 x (90mm x 150mm) specimens were cut for mass per unit area (MPUA), thickness and moisture content analysis and 10 x 100mm diameter specimens were cut for hydraulic conductivity analysis. Bentonite was extracted from remaining specimens for swell index, specific gravity and the qualitative/quantitative analyses.

3.2 Hydraulic conductivity analysis

Generally, three specimens from each site were tested in accordance with ASTM D 5887 (2009), Method C (Falling Head, Rising Tailwater) and hydraulic conductivity results determined using Appendix X2. A Trautwein M100000 Pressure Control Panel, with triaxial cells and bladder accumulators was used.

Specimens for hydraulic conductivity measurements were carefully selected based on mass and uniformity of bentonite distribution, ensuring specimens were as close to representative as possible. In most cases, a combination of low swell index results and bentonite migration, due to the cutting method in GCL's, with increased moisture contents, resulted in a reduction of bentonite thickness around the edge of each specimen. Where necessary, to minimise sidewall leakage during analysis, the top and base geotextile layers around the circumference of each specimen were separated, wetted with DI water and then edge-rolled with dry bentonite powder of similar quality to the bentonite within the GCL.

3.3 Swell index and specific gravity analysis

A single test was performed on each sample for swell index and, where possible, specific gravity, using bentonite extracted from corresponding specimens. Swell index was performed in accordance with ASTM D 5890-06 and specific gravity was performed in accordance with ASTM D854-06. Bentonite was hydrated, collected, dried, ground and then sieved.

4. RESULTS AND DISCUSSION

The chemical composition analyses showing the exchangeable cation concentrations of the leachate from the cover and subgrade soils for each site are shown in Table 4.

Table 4. Chemical properties of the subgrade and cover soil materials exhumed

Properties of Soil Leachate	WA-1		QLD-1		WA-2a	WA-2b	SA-1		NSW-1	
	Sub[1]	Cov[1]	Sub	Cov	Sub	Sub	Sub	Cov	Sub	Cov
Exchangeable Calcium (meq/100g)	1.9	7.7	1.0	3.1	3.7	4.2	20.9	2.9	11.5	7.9
Exchangeable Magnesium (meq/100g)	0.2	0.5	0.1	0.4	1.4	3.0	1.2	0.9	4.5	3.0
Exchangeable Sodium (meq/100g)	0.2	0.2	<0.1	<0.1	2.2	1.0	1.4	1.4	9.7	12.3
RMD (Ratio of Sodium to Calcium / Magnesium) ($M^{1/2}$)	0.04	0.02	0.02	0.01	0.26	0.10	0.08	0.19	0.66	1.01

[1]Sub=subgrade, Cov=cover

Changes to the major base cation composition (as oxides from ignited samples) of the bentonite samples was used to infer changes to the total calcium, magnesium and sodium contents from the exhumed GCL for each site. These are shown in Table 5. Also shown is the percentage of exchangeable sodium retained within the bentonite following exhumation.

Table 5. Chemical composition of exhumed GCL bentonite

Properties of Exhumed Bentonite	Ref. Samp. – Jul 06	Ref. Samp. – Feb 07	Spec – Jul 01	WA-1	QLD-1	WA-2a	WA-2b	SA-1	NSW-1
Calcium Oxide-CaO (%)	0.46	0.56	0.2	1.61	1.71	0.66	1.33	1.73	1.21
Magnesium Oxide - MgO(%)	2.15	2.17	2.0	2.09	1.98	2.20	2.32	2.19	2.14
Sodium Oxide – Na_2O(%)	2.37	2.60	2.3	0.66	0.70	1.69	1.05	0.37	1.64
Exchangeable Sodium - Na (%)	84.2	N.T.	N.T.	N.T.	0.6	43.3	20.8	1.5	38.3
Cation Exchange Capacity (meq/100g)	62	N.T.	85	N.T.	64	65	69	64	80

The results for exhumed GCL properties such as GCL moisture content, hydraulic conductivity and swell index compared to cover soil and bentonite properties are summarised in Table 6.

Table 6 – Exhumed GCL properties compared with cover soil and bentonite characteristics

Properties of Exhumed GCL	GCL Spec Values	WA-1	QLD-1	WA-2a	WA-2b	SA-1	NSW-1
GCL Moisture Content (%)	15	35.0	54.5	20.5	56.1	113.6	86.5
Swell Index (mL/2g)	27	7	5	21	13	6	18
Hydraulic Conductivity (m/s)	$3x10^{-11}$	$5.6x10^{-11}$	$5.3x10^{-8}$	$2.1x10^{-11}$	$2.9x10^{-10}$	$3.0x10^{-10}$	$2.2x10^{-11}$
Cover Soil RMD ($M^{1/2}$)	N/A	0.02	0.01	0.26[1]	0.10[1]	0.19	1.01
Bentonite Exchangeable Na (%)	N.T.	N.T.	0.6	43.3	20.8	1.5	38.3
Root Penetration	N/A	N	Y	N	N	N	N

[1]WA-2a and WA-2b RMD results are for subgrade soil, GCL covered with geomembrane

4.1 WA-1

As shown in Table 4, the exchangeable divalent cation (ie. calcium and magnesium) levels in the cover soil at WA-1 were higher than the corresponding properties in the subgrade soil. The exchangeable monovalent (ie. sodium) levels for both soils were relatively low compared to the exchangeable calcium and magnesium levels. Therefore, there is a higher risk of calcium for sodium cation exchange occurring in the bentonite within the GCL due to transport of soluble divalent cations, which is also reflected in the RMD values. The RMD (ratio of monovalent to the square root of the sum of divalent cations) values reported in Table 4 reflect the capacity of leachates in equilibrium with the soil material to initiate cation exchange within the bentonite in the GCL. RMD values ≤0.07M $^{1/2}$ are considered to present a high risk of loss of sodium saturation in sodium-bentonites, whereas less significant changes are observed for RMD values ≥0.14 $M^{1/2}$ (Benson and Meer, 2009). Therefore, low RMD values, particularly for the cover soil, can have a significant impact on GCL hydraulic conductivity and swelling performance, especially where there is potential for wet-dry cycling. The RMD value for the cover soil at WA-1 was significantly lower than the limit of $0.07M^{1/2}$, indicating a high potential of calcium for sodium exchange in the GCL.

The exhumed bentonite at WA-1 had a significantly lower total sodium content than the combined total calcium and magnesium levels, as shown in Table 5. Also, the WA-1 total sodium is significantly lower than the bentonite specification and reference sample total sodium values. This, combined with the increase in WA-1 total calcium and magnesium compared to the specification and reference values, would indicate that sodium is being replaced by calcium and magnesium, within the bentonite exchange complex. Also, this could be influenced by both high calcium loading in the cover soils and higher total calcium levels in the original bentonite.

The WA-1 exhumed GCL results in Table 6 show that, even though calcium for sodium exchange has occurred and the swell index is below specification, the hydraulic conductivity is within an order of magnitude of the GCL specification value. Even though the rainfall for the year preceding the exhumation (2007 = 735mm) was close to average, the GCL moisture content was relatively low at WA-1 and was below the value of 85% mentioned by Meer and Benson (2007). To reiterate their findings, GCL's with field moisture contents below 85% are more susceptible to the combined detrimental effects of cation exchange followed by desiccation, generally resulting in higher GCL hydraulic conductivities. GCL's with field moisture contents above 100% generally maintained lower hydraulic conductivities, and in some instances, within specification limits. Gates (2008) estimated the hydraulic conductivity of a GCL with a water content of 50%, in contact with leachate from WA-1 cover soil material to be up to $4x10^{-11}$ m/s. This result closely approximates the measured WA-1 hydraulic conductivity, albeit at a lower GCL moisture content. No plant roots were visible in the exhumed GCL sample.

Therefore, at site WA-1, the combined effect of the calcium for sodium exchange in the bentonite and moderate potential for wet-dry cycling, due to the shallow, sandy cover soil and the low GCL moisture content, does not appear to have significantly affected the GCL hydraulic performance, even after approximately 6 years in service at time of exhumation.

4.2 QLD-1

The cover soil RMD at QLD-1 is the lowest of all the exhumation sites, as shown in Table 4. This is caused by the immeasurably low level of exchangeable sodium combined with the much higher exchangeable calcium content in the cover (and subgrade) soils. The exchangeable sodium content for the exhumed bentonite, shown in Table 5, is the lowest of all sites and these results indicate that bentonite in the GCL's from the QLD-1 site would have the most severe calcium for sodium exchange. The GCL moisture content at QLD-1, shown in Table 6, appeared to be low in light of the high average rainfall experienced at the site. However, the month of the exhumation (August) is typically one of the drier months in this region. The cover soil at QLD-1 consists of a 50/50 loam / sugar cane ash mixture and is relatively free draining. The fact that the site is contoured and well drained could also have limited the infiltration of rainwater into the GCL.

Compared to all exhumation sites, as shown in Table 6, the swell index result for QLD-1 is the lowest and the hydraulic conductivity result is the highest. The hydraulic conductivity value is just over 3 orders of magnitude higher than the specified hydraulic conductivity. The low RMD value and low exchangeable sodium of the exhumed bentonite can partly account for the significant increase in GCL hydraulic conductivity and very low swell index; however, other issues may be contributing to the poor hydraulic performance. The bentonite in the QLD-1 sample had a distinctive appearance unlike any of the other exhumed bentonite samples; consisting of a granular texture with an organic "waxy" coating on the individual granules, possibly caused by the high organic content of the sugar cane ash used in the cover soil. Therefore, further investigation is warranted at this site, involving a compatibility test with pristine GCL in contact with a leachate collected from an elution test with the site cover soil and rainwater.

The exhumed GCL samples from QLD-1 were also observed to have significant amounts of root penetration through the entire thickness of GCL. The cover soil thickness was approximately 400 mm and the landfill cap was planted with a variety of running Couch grass. As previously mentioned, the site is well drained and is located in a very high rainfall area with an average annual rainfall over 4 metres.

4.3 WA-2a

There was no cover soil present at site WA-2a as the GCL was directly overlain by a geomembrane. The RMD value of the subgrade soil, shown in Table 4, is above Benson and Meer's (2009) recommendation of 0.14 $M^{1/2}$ and the results from Table 5 indicate that there is a high percentage of exchangeable sodium remaining in the exhumed bentonite. Therefore, calcium for sodium exchange appears not to have occurred within the bentonite at this GCL installation. The exhumed GCL at this site had the lowest moisture content of all sites, but the swell index was the closest to specification of all sites and the hydraulic conductivity was below the specification value. The GCL at WA-2a has the best hydraulic performance of the program; however, the age of the installation is only 3 years and thus may warrant further investigation after more years of service.

4.4 WA-2b

As for WA-2a, the GCL at site WA-2b was directly overlain by a geomembrane. The subgrade soils' RMD value, shown in Table 4, is above Benson and Meer's (2009) lower cation exchange limit of 0.07 $M^{1/2}$ and Table 5 shows that there is a moderate percentage of exchangeable sodium remaining in the exhumed bentonite. The total calcium (Table 5) level in the exhumed bentonite is slightly higher than the total sodium level, indicating some calcium for sodium exchange. As shown in Table 6, the GCL moisture content was higher than previous sites, but lower than Meer and Benson's (2007) limit of 85%. Also, the swell index and hydraulic conductivity of the exhumed GCL were outside of the specification with the GCL hydraulic conductivity one order of magnitude higher. In light of the above results, it appears that calcium for sodium exchange has started to occur after 5 years of service and has moderately affected the GCL hydraulic performance.

4.5 SA-1

The cover soil RMD for SA-1, as shown in Table 4, is above 0.14 $M^{1/2}$, indicating limited potential for calcium for sodium exchange. However, Table 5 shows that the bentonite exchangeable sodium is quite low and the bentonite calcium and magnesium oxide contents are significantly higher than the sodium oxide content, indicating a certain level of calcium for sodium exchange. The cover soil system at SA-1 is comprised of multiple soil layers and, over the $9^1/_2$ year service period, there could have been a contribution from the upper layers to the measured calcium and magnesium load in the GCL bentonite. The GCL moisture content for SA-1, shown in Table 6, is the highest of all the exhumation sites and is above Meer and Benson's (2007) value of 100% for optimal GCL hydraulic performance, which is surprising since the site has the second lowest average rainfall. The swell index is relatively low and the GCL hydraulic conductivity is one order of magnitude higher than the specification. Therefore, the above results show that the calcium for sodium exchange occurring in the bentonite has had a moderate effect on the hydraulic performance of the GCL.

4.6 NSW-1

As shown in Table 4, NSW-1 has the highest cover soil RMD of all the exhumation sites. The exchangeable sodium content in the cover soil is high and the exhumed bentonite exchangeable sodium content is correspondingly high, as shown in Table 5. From these results, it would appear that calcium for sodium exchange has not occurred in the exhumed GCL bentonite and the potential for it to occur is low. The moisture content of the GCL, as shown in Table 6, is above Meer and Benson's (2007) limit of 85%, but lower than the value for optimal performance of 100%. The average rainfall at this site is higher than most of the other sites. The swell index result is approximately $^2/_3$ of the specification value, but the GCL hydraulic conductivity is lower than the specification. After 9 years of service, the hydraulic performance of the GCL at NSW-1 is effective and calcium for sodium exchange within the bentonite has not occurred.

5. CONCLUSIONS

A summary of the results of the exhumations and the potential for calcium for sodium exchange within the bentonite is shown in Table 7.

Table 7 – Summary of GCL exhumation results

Properties of Exhumed GCL	WA-1	QLD-1	WA-2a	WA-2b	SA-1	NSW-1
GCL Moisture Content (%)	Low	Low	Low	Low	High	Med
Swell Index (mL/2g)	Low	Low	High	Med	Low	Med
Hydraulic Conductivity (m/s)	Low	High	Low	Med	Med	Low
Cover Soil RMD ($M^{1/2}$)	Low	Low	High[1]	Med[1]	High	High
Calcium for Sodium Exchange	Severe	Severe	None	Mild	Mild	None
Root Penetration	N	Y	N	N	N	N

[1]WA-2a and WA-2b RMD results are for subgrade soil, GCL covered with geomembrane

From the above results, it appears that GCLs with superior field hydraulic performance, ie. low hydraulic conductivity, are characterised by the following:

- high in-situ moisture content
- high cover soil RMD
- low risk of bentonite calcium for sodium exchange

There was no relationship between bentonite swell index and hydraulic performance and, hence, this index should not be relied upon to assess field GCL hydraulic performance.

Suggested measures to limit the detrimental effects of cation exchange, desiccation and root penetration on GCL performance include:

- Avoid GCL cover soils with high calcium / magnesium contents in landfill caps

- Collect mineralogical analysis of cover and subgrade soils, prior to consideration for construction
- Measure soil leachate soluble and exchangeable cations of cover and subgrade soils, prior to construction
- Use plastic laminated GCL product with butyl tape jointing system in thin landfill cap applications or where high root penetration potential exists
- Ensure hydration of subgrade soil with fresh water to enable pre-hydration of GCL
- Limit vegetation above GCL to species with non-aggressive root systems

Further research into GCL field performance includes:

- Elution tests with QLD-1 cover soil and rainwater mimicking site conditions, as per a modified version of the column test method described in Meer and Benson (2007). The modifications include a larger diameter permeameter and site-specific compaction and rainfall criteria to determine leachate characteristics, such as ionic strength and RMD values.
- Compatibility tests with leachate from above elution test with pristine GCL over 3 to 6 month period
- Exhumations at sites in Victoria, south-east Queensland and potentially other sites.

REFERENCES

ASTM D 5887. (2009). Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter. *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, USA.

ASTM D 5890. (2006). Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners. *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, USA.

ASTM D 6072. (2009). Standard Guide for Obtaining Samples of GCL's. *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, USA.

Australian Bureau of Meteorology website. (2009). Commonwealth of Australia.

Benson. C.H. and Meer. S.R., (2009). Relative abundance of monovalent and divalent cations and the impact of desiccation on geosynthetic clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 135, no. 3, 349-358.

Bouazza, A., Gates, W.P. and Abuel-Naga, H. (2006). Factors impacting liquid and gas flow through geosynthetic clay liners. Geosynthetics – Recent Developments. Commemorating Two Decades of Geosynthetics in India, Indian International Geosynthetics Society, New Delhi, Chapter 9: 119-146.

Gates, W.P. (2008). Independent Report – WA-1 cover and sub-grade soil analysis. SmecTech Research Consulting.

Gates, W.P., Bouazza, A. and Churchman, G.J. (2009). Bentonite clay keeps pollutants at bay. *Element*s, 5, 105-110.

Meer, S.R. and Benson, C.H. (2007). Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 133, no. 5, 550-563.

Rayment, G.E. and Higginson, F.R. (1992). *Australian laboratory handbook of soil and water chemical methods*. Inkata press, Melbourne, Victoria, Australia, 330p.

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