13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Operational and construction impacts on GCL performance in TSFs

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ABSTRACT: Lining of Tailings Storage Facilities (TSFs) with a low permeability engineered product may be required in the design and construction of new facilities and as a remedial measure for existing storages. TSF lining is used to reduce environmental harm by controlling diffusive contaminant migration from the storage into underlying groundwater aquifers. Assessment of the performance of Geosynthetic Clay Liners (GCL) used as a remedial lining measure to an existing TSF structure (Site A) and as a base liner to a new TSF (Site B), both at copper mines in North Queensland, has been carried out. The assessment included testing of key index parameters on exhumed samples of GCLs from each site, to compare pre-installation and post-installation conditions. The assessment indicates that site chemistry and hydration conditions during placement of the GCL, as well as operation of the TSF can have an impact on the mineralogical properties of bentonite, yet hydraulic performance has not been materially impacted. It can be inferred that initial predictions of GCL performance based on index testing alone may not reflect field conditions, and greater emphasis on project specific testing, GCL placement and soil confinement, should become a key consideration for liner design.

1 INTRODUCTION

The use of Geosynthetic Clay Liners (GCL's) for Tailing Storage Facility (TSF) lining has increased in the past decade and has resulted in greater understanding on the chemical compatibility between bentonite mineralogy and mine liquors (Hornsey et al. 2010). The ability of GCL to maintain manufacturer-specified performance parameters when exposed to strongly alkaline, acidic or highly ionic/saline liquors is considered to be limited based on theoretical prediction or estimation of GCL performance characteristics under these conditions (Gates et al. 2010; Bouazza et al. 2006).

This paper sets out to assess the performance of GCL's used to line TSFs at two copper mine sites located in North Queensland, Australia, with particular consideration to bentonite mineralogy of the GCL, mineralogical analysis of key cations in the boundary soils, and chemistry of the site liquors. During the design process, a desktop analysis was conducted to model GCL hydraulic performance expectations, with results compared to testing carried out on actual materials exhumed from both sites. A review of conditions during construction and climate over the exposure period was also evaluated.

2 CASE STUDY DESCRIPTION

2.1 *Site A*

2.1.1 *Initial design considerations*

Remedial works were prompted due to seepage migration, typically surface expression and groundwater contamination, detected beyond the limits of the TSF. The migration pathway through an upper alluvium horizon occurring beneath perimeter embankments was identified. A GCL was chosen to line the upstream face of the perimeter embankments extending to intersect the underlying mudstone some 4m beneath the original ground surface.

As part of the design scope for the remedial works, a desktop analysis was carried out to estimate GCL hydraulic performance based on bentonite compatibility with the site tailings liquor. SmecTech Re-search Consulting reported that the tailings liquor, characterised by low RMD (effectively the root ratio of monovalent to multivalent cations) and elevated ionic strength, would likely lead to significant cation exchange within the sodium bentonite and subsequent hydraulic performance loss (Benson & Meer 2009) of up to two orders of magnitude. The analysis assumed a 3m operating head with the leachate in full equilibrium with the tailings (worse case to generate Na-bentonite exchange for Ca).

A key consideration to reduce performance loss was saturation of the GCL using "potable water" prior to contact with tailings liquor. Even partial hydration has shown positive impacts on bentonite hydraulic performance linked to confining stress. (Daniel et al. 1993, Petrov & Rowe 1997) and it was considered that a one order of magnitude reduction in permeability loss could be achieved using this approach. However due to incompatibility of leachate with the GCL, the convective flux resulting from a 3m head would result in behaviour akin to direct hydration from the tailings liquor over the short term. On balance, the potential permeability loss under these conditions was deemed acceptable to achieve effective design outcomes.

2.1.2 *Installation conditions*

Tailings that had previously been placed within the storage against embankments were excavated to provide access for placement of the GCL (Figure 1a). The tailings in excavated areas were well drained and consolidated, assisted by ambient conditions at the site over the period of deposition, as well as the method of tailings placement. After placement, materials sourced from onsite borrow comprising sandy gravelly clay, was placed as a cover/confining layer.

It was decided that prehydration of the GCL with "potable water" would not be undertaken as part of the installation works, with uptake from the subgrade under confining stress, and hydration undertaken post installation (during operation) with primarily tailings liquor. Previously excavated tailings were backfilled against the cover material placed over the GCL to rapidly increase the confining stresses.

2.2 *Site B*

2.2.1 *Initial design considerations*

Geotechnical investigation work for the TSF, undertaken as part of design, identified that the underlying geology comprised highly fractured, high permeability basement, particularly in the upper 3 to 4m of the profile. These conditions prompted engineered seepage controls. TSF lining using GCL was selected given the limited local clay availability. GCL was preferred to a PE geomembrane due to the relative ease of installation at an isolated site. SmecTech Research Consulting was again engaged to conduct a desktop analysis, but for this case the focus was to assess compatibility between the GCL bentonite (post-hydration) and leachate generated from the natural subgrade and materials proposed for the GCL confining soil layer. The initial hydration was assumed to occur by exposure to the tailings liquor that was alkaline pH and therefore considered relatively compatible to hydraulic performance.

Analysis of test results indicated that high calcium (Ca+) and magnesium (Mg+) contents in both subgrade and cover, and low RMD values, would likely cause significant cation exchange within 2 years, but the low ionic strength of the hydrating leachate would result in good initial gel formation. It was estimated that a reduction in permeability of at least one order of magnitude could be expected.

A design recommendation due to the long-term presence of calcium carbonate in both the subgrade and waste rock cover material, was to consider buffering the cover soil by "dosing" with a soda-ash or sodium carbonate material to increase the ratio of Na cations to Ca. Such treatment would raise the RMD value and the pH, conducive to better hydraulic performance but was not adopted as it was felt that ensuring good initial gel formation by understanding the hydrating leachate would be more critical.

A further compatibility report was conducted by SmecTech on the acidic and saline S-Dump process water that would likely present as the worst case hydrating leachate onsite. The low RMD and high ionic strength of these liquors would likely cause greater issue than the tailings liquor itself and an expectation of full cation exchange of Ca for Na would be expected within months, with at least an order of magnitude change in hydraulic conductivity and close monitoring for this potential would need to be carried out onsite.

2.2.2 *Installation conditions*

Impoundment floor preparation comprised conditioning and compaction of insitu sequences to form a profiled and smooth subgrade for placement of the GCL (Figure 1b). Due to changes in the material borrows during construction, the specified grading for cover material was not able to be achieved, Figure 2a shows a grading for this material, indicating that up to 40% by weight was greater than the specified maximum particle size of 32mm. Given the well graded nature of the material, the change in specification was permitted. The thickness of the cover soil material was increased from 300mm to 500mm and end-dump placed as Figure 2b.

It was decided that prehydration of the GCL using "potable water" would not be undertaken as part of the installation works, with hydration undertaken post-installation through rain water, process water and tailings liquor. Typical process water quality comprised low pH (2-3) and high conductivity (>10 mS/cm), while the tailings liquor comprised alkaline pH. It is noted that the S-Dump process water was transferred to the TSF as an emergency measure from existing site storages during the initial wet season prior to tailings production. The process water hydration coverage would have been no more than 30% of the full storage area but would likely present as the key GCL hydrating leachate in these areas.

Figure 1a. GCL installation at Site A

Figure 1b. GCL installation at Site B

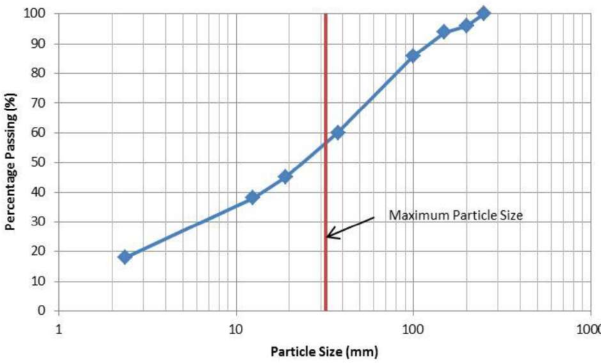


Figure 2a. Site B cover material PSD

Figure 2b. Site B cover material as placed

2.3 *GCL exhumations*

The opportunity to examine the performance of GCL used at Sites A and B was presented during dam surveillance works carried out three years after initial GCL placement. At this time, access to areas of GCL was made available by the operators for exhumation purposes. The overall objective of GCL exhumation was to undertake laboratory testing on samples recovered with a view to assessing any deterioration in GCL characteristics on exposure to operating conditions.

2.4 *Site A*

A sample of GCL was exhumed at Site A. Access to exhumation of a sample at depth was limited due to the thickness of tailings material, with the sample being retrieved within 2m from the surface of the tailings. The condition of the sample exhumed is shown in Figure 3.

It is considered that whilst the GCL had been in place for some 3 years, covering with tailings in the location of the exhumation would have been limited to a year. The GCL appeared to be well hydrated at the time of exhumation, indicated by the extent of swelling, with no indication of saturation of the underlying embankment soils that would have been caused by seepage through the GCL. The thickness of cover soil above the GCL was approximately 1m.

Figure 3. Site A GCL condition at exhumation

2.5 *Site B*

A sample of GCL was exhumed from Site B by site personnel, coinciding with a works campaign to raise the TSF. The exact depth of tailings cover in the area of exhumation was not recorded, but is estimated to be between 2m and 4m. The condition of the GCL received by the laboratory after sample removal is shown in Figure 4. It is considered that the GCL and cover materials would have been covered with tailings for a minimum of 2 years. Given the condition of the sample recovered, it is possible that full hydration of the sample had not occurred, indicated by the limited extent of swelling.

In addition to the exhumed sample, a sample of process water with similar properties to that transferred to the TSF during the early life was provided to the laboratory. The process water was used to hydrate the laboratory GCL sample to provide a comparison between the exhumed sample and possible worst case hydration conditions.

Figure 4. GCL Laboratory sample from site

2.6 *Potential concerns with performance*

Concerns with the installation conditions and long-term performance of the GCL at both sites includes:

- reduction in hydraulic conductivity from hydration with tailings liquor and not potable water,
- the impact of increasing effective stress applied to the GCL during the project life, and it's impact to reduce cation exchange potential and impact on subsequent hydraulic performance.

Hornsey et al (2010) indicates that leachates from copper waste rock or ore can impact on GCL by loss of clay gel and increased permeability due to low pH, elevated sulphate and high copper concentrations.

When hydrated by acidic solutions, Liu et.al (2015) summarized the GCL research to date that shows an expected loss of bentonite swelling properties leading to increased hydrated void ratio and subsequent decreasing hydraulic performance.

Studies undertaken in extreme acidic conditions (defined as pH < 3), Kolstad et al. (2004), Shackelford et al. (2010) and Liu et al. (2013, 2015) reported decreases in key bentonite properties (Fluid Loss, Liquid Limit and Swell Index) and subsequent loss of hydraulic performance greater than three orders of magnitude $10^{-11}ms^{-1}$ to higher than $10^{-8}ms^{-1}$.

Liu et al (2015) identified the potential performance benefits of prehydration with deionized (DI) water (140%) and increasing effective stress. In this study there was a strong correlation between index bentonite parameters for Liquid Limit and Swell Index to hydraulic performance with low pH liquors.

In simple terms, these results may simply be a reflection of bentonite Cation Exchange Capacity (CEC) and the potential for sodium to be replaced by divalent cations; in particular calcium (Ca2+). This exchange causes changes in standard soil geochemistry, and in the case of bentonite, can modify crystal-line structure by reducing inter-particle forces to cause collapse of double diffuse layers, reducing swelling potential and increasing permeability.

Traditional research to measure this has focused on index tests comparisons for Swell Index, Fluid Loss and permeability rather than quantitative analysis of cations in the bentonite. The opportunity that presented was to link traditional index testing com-parisons to testing of bentonite mineralogy and quantitative measures of cation exchange, post-exposure.

3 LABORATORY TESTING

Testing of the exhumed GCL samples from Sites A and B was undertaken by the Geosynthetic Centre of Excellence and CSIRO laboratories, with an aim to compare bentonite properties at point of manufacture, to properties post-exposure and assessment of GCL hydraulic performance when hydrated with both DI water and tailings process liquor.

3.1 *Test regime 1*

The initial round of testing compared basic bentonite performance properties of Swell Index, Fluid Loss and Moisture Content. Swell and Fluid Loss testing is carried out with DI water during the GCL manufacturing process to establish bentonite qualitative controls. The Fluid Loss test has shown the best correlation with GCL permeability, but both tests provide an indication as to potential bentonite mineralogical changes post-site exposure. Testing was also carried out on bentonite hydrated with the process water for Site B to observe any correlation.

GCL moisture contents of exhumed samples were calculated to establish the degree and potential mechanisms of GCL hydration, and results summarised in Table 1.

Table 1: Initial Laboratory Results

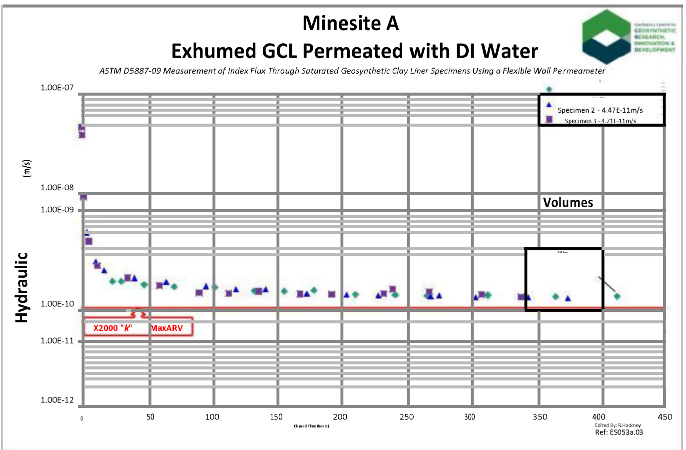
Sample description	Properties		
	Swell index (mL/2g)	Fluid loss (mL)	Moisture content (%)
Site A			
Exhumed sample	14.0	39.3	79.4
MQA properties	>24	<15	< 12
Site B			
Exhumed sample	10.2	49.4	54.5
Hydration with process water	9.9	103.1	10.2
MQA properties	>24	<15	< 12

3.2 *Test regime 2*

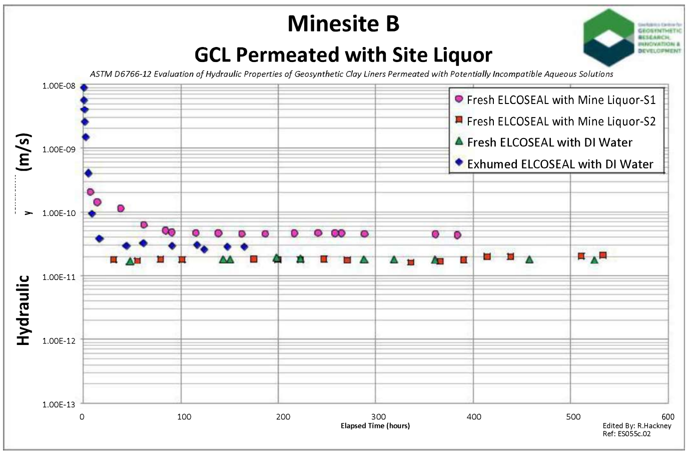
The key property of the GCL to understand in design is permeability over an extended period. Index testing during the GCL manufacturing process was carried out to ASTM D5887, which is a hydraulic performance evaluation of the GCL when hydrated with DI water over a relatively short timeframe (equilibrium generally less than 2 weeks). To establish a performance benchmark, exhumed samples on both sites were hydrated with DI water to observe any performance loss. Furthermore, newly manufactured GCL samples with the same bentonite source as used for Site B were hydrated with Site B process waters transferred to the TSF to observe resulting hydraulic performance in Table 2.

Table 2. Hydraulic conductivity/permeability results

Sample	Hydration solute	Test duration	Manufacturing specification (ms^{-1})	Measured hydraulic conductivity (ms^{-1})
Site A – Exhumed specimen 1	DI water	415 hours	3.0 x 10^{-11}	4.75 x 10^{-11}
Site A – Exhumed specimen 2	DI water	375 hours	3.0 x 10^{-11}	4.47 x 10^{-11}
Site A – Exhumed specimen 3	DI water	340 hours	3.0 x 10^{-11}	4.71 x 10^{-11}
Site B – Exhumed specimen 1	DI water	170 hours	4.0 x 10^{-11}	2.74 x 10^{-11}
Site B – Manufactured specimen 1	DI water	520 hours	4.0 x 10^{-11}	1.80 x 10^{-11}
Site B - Manufactured specimen 2	Process liquor	390 hours	4.0 x 10^{-11}	3.0 x 10^{-11}
Site B – Manufactured specimen 3	Process liquor	530 hours	4.0 x 10^{-11}	2.1 x 10^{-11}



Site A. Hydraulic conductivity curves of exhumed samples with DI water



Site B. Hydraulic conductivity curves of exhumed samples with DI water and hydration of off-shelf GCL with tailings process liquors

3.3 *Testing regime 3*

The final round of testing on exhumed GCL samples for both sites was carried out at CSIRO to review changes in bentonite mineralogy from site chemistry applicable to both sites. The key aims were to measure montmorillonite and carbonate content of the bulk bentonite, <0.5µm fraction by quantitative X-ray diffraction (XRD) analysis, particle size by 75µm dry sieve, <0.5µm and <0.2µm fractions by centrifugation, total and reactive carbonate content by hydrochloric and acetic acids, XRF chemical analysis of <0.2µm fraction for layer charge and layer charge distribution, CEC of bulk samples by methylene blue, Ba exchange with XRF analysis and CEC and exchangeable cations by NH4+ exchange. A control sample of GCL with as-manufactured bentonite was tested in conjunction for result comparison. The key outcome of testing was observable changes in CEC, Table 3.

Table 3. CEC results for new GCL and exhumed samples

Exchangeable cations and CEC by NH4+ method (as received)						
Sample ID	Exchange cations pH 8.5					CEC
	Ca cmol(+)/kg	Mg	Na	K	Total	(NH4)
New GCL	0.4	4.9	62	1.9	70	55
Exposed site A	32	26	29	0.89	88	67
Exposed site B	35	33	3.3	1.2	72	70

4 INTERPRETATION OF RESULTS

Initial design assumptions based on desktop analysis indicated that the exposure conditions of GCL at both sites would result in a minimum of an order of magnitude change in permeability/hydraulic conductivity to the GCL liner through cation exchange. The results of the CEC testing in Table 3 on the exhumed samples and new GCL indicates that significant cation exchange of Na for Ca/Mg has occurred as predicted.

In addition, the testing indicates there has also been significant detrimental changes to Swell and Fluid Loss performance for both site GCLs.

The results of hydraulic conductivity testing for the samples indicates no significant changes to hydraulic performance as a result of the CEC or the changes to Swell and Fluid Loss performance as would be expected.

It is noted that site stresses are substantially below conditions (200kPa+) where significant benefit for bentonite compatibility to low pH liquors is achieved (Liu et al 2015), and lower than those that have been observed to achieve consolidation enhanced membrane behaviour of GCLs (Kang & Shackelford 2011).

Moisture contents measured on both sites likely suggest minimal hydration from the subgrade under low effective stresses, and are more reflective of values where hydration occurs by leachate under high effective stress. The extent of cation exchange also indicates that significant hydration has occurred through the depth of the bentonite layer within the GCL, not simply as wetting fronts on top and bottom with a dry internal layer, which can be observed with powered bentonites (Bouazza et al. 2006).

5 CONCLUSIONS

The results suggest that theoretical/laboratory-based prediction of chemical compatibility between GCL bentonites and site soils or liquors may be a conservative model if it does not consider the impacts of tailings placement, solids content, and project confining stresses.

The GCLs installed at both these sites were expected to observe significant bentonite cation exchange that would result in a minimum one order magnitude increase in permeability.

Bentonite testing demonstrated that significant cation exchange has occurred, but only a minimal increase in permeability has been observed.

Factors likely to impact this include hydration under normal stresses in excess of index testing, and prediction of hydraulic performance based on acting heads that do not consider confinement provided by tailings solids contents.

The opportunity for future liner design is to undertake project testing to greater reflect site conditions. This will allow greater understanding of GCL "membrane" behaviour due to confinement and mechanisms of hydration that lead to improvements in contaminant flux (Kang & Shackelford 2011).

As such an understanding of the effects of onsite placement and GCL confinement conditions is critical to estimate long term performance of GCL and provide a better understanding of long term GCL liner performance in Tailings Storage Facilities.

ACKNOWLEDGEMENTS

The authors thank the Geosynthetic Centre of Excellence for their role in exhumation of samples, laboratory analysis and interpretation of results, Dr Will Gates from SmecTech Research Consulting and Mr. Mark Raven and Dr. Peter Self the team at CSIRO Land and Water Laboratories in Adelaide.

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