Compacted Clay Liners vs. Geosynthetic Clay Liners: Key Considerations for Designers

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Abstract

There are several advantages to using Geosynthetic Clay Liners (GCL's) in lieu of Compacted Clay Liners (CCL's) as part of a composite barrier system design, that are often highlighted by manufacturers of such products as part of their literature and promotional materials. As designers, it is crucial to understand what assessments need to be undertaken and considered when choosing to use GCLs or CCLs, and what their limitations are, especially in the context of the South African Norms and Standards for Disposal of Waste to Landfill (*Government Notice R636 of 2013)*.

This paper will i) provide an overview of the relative challenges when choosing to use either a GCL or CCL as part of a barrier system design and ii) provide an explanation of the design considerations that need to be taken into account when designing with both, and in what situations both liners are most suited. Examples from the author's own design experience will be referenced and used to assist in guiding the understanding of the complexities that need to be considered by designers.

Keywords: *Geosynthetic Clay Liner, Compacted Clay Liner, Design Considerations, GN 636, Compliance*

1 Introduction

Waste disposal facilities are required to incorporate a containment barrier system that has been adequately designed according to the waste type a facility is licensed to receive as per the *National Norms and Standards for Disposal of Waste to Landfill (Government Notice R636 of 2013 (*herewith referred to as "Norms and Standards" or GN 636*)* in terms of the National Environmental Management: Waste Act (NEM: WA).

In terms of the Norms and Standards, the minimum engineering design requirements for containment barriers for Class A, Class B, and Class C facilities all require the inclusion of a Compacted Clay Liner (CCL) as part of a composite lining system in combination with a Geomembrane (GMB) acting as a barrier to pollution migration and to ensure containment is achieved.

GN 636 allows for minimum engineering design requirements to be substituted with "alternative elements of proven equivalent performance which has been considered, such as the replacement of clay components with geomembranes or geosynthetic clay liners". In addition, the design engineer needs to give "consideration of the compatibility of the liner material with the waste stream, in particular noting the compatibility of natural and modified clay soils exposed to waste containing salts".

Due to the relative ease and speed of construction as well as lower relative cost when a suitable clay source is scarce, designers of containment barrier systems often substitute the standard 600 mm thick CCL (for Class A and B Primary Barriers) and 300 mm thick CCL (Class C Primary Barriers), and 200 mm thick CCL (Class A secondary barrier) with a geosynthetic clay liner (GCL).When such an alternative is proposed, the onus is on the design engineer to prove the equivalent or better performance of the GCL product proposed to the CCL it is intended to replace. Other substitutions can also be considered by designers, such as the replacement of the CCL with bentonite enriched soils as long as it can be proven that it provides equivalent performance to that of the CCL being replaced.

There are many factors which can influence the choice that a designer needs to make when considering the design of a basal lining system. These include the specific site where a waste disposal facility is being planned, the waste stream constituency and material availability amongst others.

This paper will attempt to provide an overview of the key consideration that need to be taken when using a CCL, as well as when contemplating using an alternative such a GCL. It will further elaborate on evidence needed or testing required to prove that the alternatives can provide equivalent performance to that of a CCL, as well as perform the containment function that is required of it. Reference will be made to a particular landfill design project that the author was involved in where a GCL was specified as an alternative to a CCL as part of the primary liner in a Class B facility design and a Class A design where a CCL was evaluated for use to illustrate the design process undertaken, and considerations taken when choosing to use either solution.

2 Compacted Clay Liners

CCLs are used in conjunction with a HDPE GMB to form a composite liner, which is the standard requirement for Class A, Class B and Class C lining systems as per the Norms and Standards (DEA, 2013). Class A barriers, in contrast to Class B and Class C lining systems, require two separate hydraulic barrier layers including a primary barrier consisting of a 2 mm thick HDPE Geomembrane overlying a minimum 600 mm thick CCL, as well as secondary barrier consisting of a 1.5 mm thick HDPE geomembrane overlying a 200 mm thick CCL. Class B lining systems only require a single hydraulic barrier layer, which is to the same standard as the primary barrier in the Class A system, except that only a 1.5 mm thick HDPE GMB is required and not a 2 mm thick GMB. The hydraulic barrier layer for a Class C liner is a further devolvement of the Class B barrier, by making the CCL only 300 mm thick compared to the 600 mm required for Class B.

As the Class of lining system required is directly related to concentration of contaminants in the waste stream, the reduced thickness of HDPE GMB and CCL in each system is in direct response to the lower concentrations of contaminants that can be expected in the waste that is being disposed in the waste management facility.

In the author's experience, it is often the perception that because CCL's are the specified requirement in terms of the Norms and Standards, that CCL's can be considered the safe choice, which the Regulator will not be able to reject. As such, there is no need to spend significant time considering and proving the performance of the CCL in the specific application and for the specific waste stream, provided that the material intended for use as a CCL can achieve the necessary hydraulic conductivity requirement of 1×10^{-7} cm/s for Class A and Class B facilities and 1×10^{-6} cm/s for Class C facilities as per the Guideline for Landfill Barrier Liner Design (DWS, 2021*)*. This often leads to designers, taking samples of several clay sources and ordering a series of geotechnical laboratory tests, in particular Falling Head Permeator testing on remoulded samples at a density of between 95-98% Standard Proctor density. When these test results come back favourably, or very close to the requirement of 1×10^{-7} cm/s for Class A or Class B facilities (or 1×10^{-6} cm/s for Class C), the designer continues with the design and undertakes seepage assessments assuming these values to be representative of the on-site performance of the CCL.

Some designers will provide - in addition to the above - a detailed construction methodology requirement in their Construction Quality Assurance (CQA) document including requirements for the CCL to be constructed in 150 mm thick lifts, as well as limit crack development on the surface of the CCL prior to placing the GMB. In-situ density testing will also be specified as a requirement on the completed surface. The design is completed with confidence that the above processes have adequately covered the specification of the use of a CCL in a basal lining design.

The above is a dangerous approach, but one far too often seen in industry when making use of CCL's in basal lining applications. To avoid being placed in this position, designers need to understand the key factors to consider when utilising a CCL that need to be controlled to avoid the risk of an underperforming hydraulic barrier layer being constructed.

The main factors include:

a) making a fair assessment of the in-situ hydraulic conductivity or CCL performance at design stage,
b) limiting crack formation in the CCL, and
c) ensuring intimate contact with the overlying GMB.

Without the above issues being addressed properly throughout design and construction stage, the chances of having an underperforming hydraulic barrier when using a CCL are high.

The focus of this section will be on highlighting a case study where a) above is assessed in more detail. While b) and c) are important, they are fairly well understood and managed by good construction control and monitoring on site when deploying the GMB and limiting wrinkle formation. Advances in Electronic Leak Location and other survey methods have also assisted in ensuring that areas with low intimate contact are more easily identified and rectified during construction.

2.1 Evaluating In-Situ Hydraulic Conductivity at Design Stage

The Guideline for Landfill Barrier Liner Design (DWS, 2021) is clear that the maximum outflow rates of a CCL once installed must not exceed 1×10^{-7} cm/s for Class A and Class B facilities, or 1×10^{-6} cm/s for Class C facilities. The guidelines further suggest that this performance must be evaluated by use of in-field assessment tools such as the Double Ring Infiltrometer or alternatively, the Guelph permeameter test and must be undertaken on the completed layer. For designers, short of undertaking a trial pad ahead of construction stage with the materials they are considering for use in the design, it is very difficult to have certainty ahead of construction that the intended materials can perform as required.

Use of Falling Head Permeameter testing on remoulded samples at the required levels of compaction and moisture content are a good starting point to evaluate whether a material can potentially perform to hydraulic conductivity requirement. However, the key difference between this test and the field test is that the Falling Head Permeameter makes use of a fully saturated sample, and also has very little opportunity to crack. As such, the test results give an upper limit of potential performance rather than a lower conservative assessment that is reflective of actual field conditions and variabilities and challenges associated with constructing and forming such a layer on a large-scale basis.

During the design phase of a Class A Cell in 2023, the author had a unique opportunity to have a number of trial pads constructed using varying silt and clay materials that were indigenous to the development site, and which the Facility Owner wished to evaluate for potential use in construction of the next phases of the facility. A detailed testing regime was specified to allow comparison between testing methods, with particular focus on comparing controlled laboratory testing to in-situ field testing of a completed 600 mm CCL Layer in order to identify whether materials available on site were suitable for use in the construction of the liner.

Three separate trial pads were constructed from material referred to as; a) Layer A Material, b) Layer B Material, and c) Layer C Material in Tables 1,2,3,4 below. From each of the trial pads, disturbed samples were taken for Falling Head Permeameter Testing after remoulding in the laboratory. Undisturbed samples were also taken from the constructed CCL layer and tested using a Falling Head Permeameter for comparison purposes, although results were not significantly different between these tests. In-Situ Testing was also completed on each of the three trial pads, including Double Ring Infiltrometer Testing as well as Guelph Permeameter Testing. Samples were also taken for Grading, Plasticity Index (PI) and moisture content assessment. Density and moisture content were also carefully monitored at the time of testing.

The results of tests undertaken are presented in Table 1 to 4 below. Table 1 indicates the permeability and infiltration rates measured for each trial pad in cm/s for both laboratory and in-situ testing. Table 2 is a reproduction of Table 1 but setting the Falling Head Permeameter test result as the basis for comparison to clearly illustrate the order of magnitude difference in permeability/infiltration rate. Table 3 gives an indication of the difference in calculated effective seepage rates between the same primary composite liner design, with the only difference being the material used for constructing the CCL to illustrate the impact of the measured hydraulic conductivities on the final design. Finally, Table 4 provides data on the actual and optimum moisture content measured after construction of each trial pad and highlights the difference between actual measured and optimum for consideration in context of the maximum dry density achieved and the hydraulic conductivity performance.

It is clear from Table 1, that all three materials did not meet the 1 x 10^{-7} cm/s hydraulic conductivity requirement, with Material C being the closest to this value. Table 2 indicates that the difference between the laboratory and in-situ assessments for hydraulic conductivity varied between 1 to 2 orders of magnitude (i.e. 10 to 100 times) for Layer A and B, and less then 1 order of magnitude for Layer C.

The impact of this difference on the seepage calculations for the primary composite liner resulted in an effective difference in seepage rates of between 403 m^3/day/ha and 7 860 m^3/day/ha. For Material B and Material C, this difference can be calculated between 344 m3/day/ha to 3316 m^3/day/ha and 302 m3/day/ha to 1764 m^3/day/ha, respectively as indicated in Table 3. In a sensitive geohydrological environment, this difference alone could make a site unviable.

Table 1. Comparative Permeability Assessments for Materials Used to Construct Trial Pads

	Permeability	**Infiltration**		**Field Compaction**
	Falling Head	**Double Ring**	**Guelph**	
	(cm/s)	(cm/s)	(cm/s)	(%)
Material A	6.0E-7	1.0E-5	1.7E-5	94.60
Material B	5.0E-7	5.4E-6	6.5E-6	104.10
Material C	4.3E-7	2.6E-6	3.2E-6	101.95
	At 94.5% Compaction	At Field Compaction		

Table 2. Difference Factor between Comparative Permeability Assessments from Table 1

	Permeability	**Infiltration**		**Field Compaction**
	Falling Head	**Double Ring**	**Guelph**	
	(--)	(--)	(--)	(%)
Material A	1.00	17.06	27.58	94.60
Material B	1.00	10.83	12.93	104.10
Material C	1.00	6.10	7.52	101.95
	At 94.5% Compaction	At Field Compaction		

Table 3. Difference in Seepage Rate for Class A design based on Table 1 values

	Permeability	Infiltration		Field Compaction
	Falling Head	Double Ring	Guelph	
	(ℓ/ha/day)	(ℓ/ha/day)	(ℓ/ha/day)	(%)
Material A	403	4877	7860	94.60
Material B	344	2810	3316	104.10
Material C	302	1467	1764	101.95
	At 94.5% Compaction	At Field Compaction		

A crucial observation from the data presented in Table 1, 2, 3 above is the sensitivity of the materials to the level of compaction. The data suggests that the higher the variance in the achieved compaction, then the higher the variance in hydraulic conductivity between field and in-situ testing methods. Investigating this phenomenon further, it became clear that the moisture content at which the compaction is achieved, is of greater importance (see Table 4 below). While Material B achieved a moisture content much closer to Optimum Moisture Content (OMC) than Material C, Material C had an in-situ moisture content wet of optimum.

When evaluating hydraulic conductivity performance (see Table 2), the in-situ measurements for Material C was the closest to the Falling Head Permeameter result, even though Material B had an actual moisture content closer to OMC then Material C. The above observations suggest that to achieve the best possible in-situ performance, a clay material needs to be compacted as close as possible to 100% Maximum Dry Density (MDD) and at OMC. However, it is also important, that the compaction occur wet of optimum rather than dry of optimum to limit hydraulic conductivity variances between field and laboratory measurements to less than 1 order of magnitude.

Table 4. Differences between Actual Moisture Content and OMC for different material tested

	Relative Compaction	Moisture Content		Variance	
		Actual MC %	OMC	AMC to OMC	DIFF
	(%)	(%)	(%)	(%)	(%)
Material A | 1	96.93	30.80	25.10	5.70	22.71
Material A | 2	93.80	35.20	25.10	10.10	40.24
Material B | 3	105.36	14.60	16.10	-1.50	-9.32
Material B | 4	102.84	16.00	16.10	-0.10	-0.62
Material C | 5	103.16	14.90	14.50	0.4	2.76
Material C | 6	100.74	16.80	14.50	2.30	15.86

While most designers appreciate the need for compaction and moisture content to be correct, it can be overlooked as a cause of potentially poor hydraulic conductivities being achieved in the field. Research by Benson et al. (1999) investigated the quality and performance of construction of more than 85 CCLs, over a period of time. Only 26% of them achieved the required 1 x 10^{-7} cm/s specification. In addition, Benson et. al (1999), as a finding of their research, state that to achieve a consistent performance of a CCL, specifications should move away from simple index properties, hydraulic conductivity requirements and percent compaction, and rather focus on ensuring compaction is primarily wet of the line of optimums as illustrated by Figure 1 below.

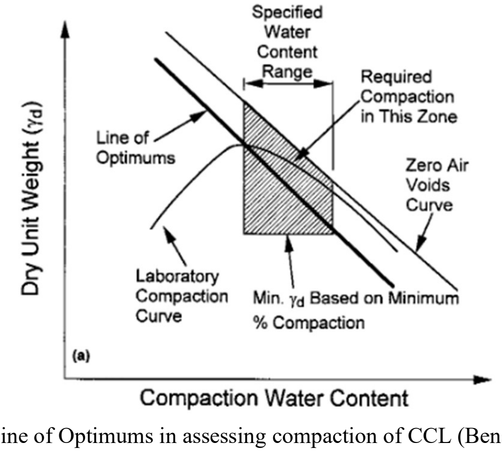

Figure 1. Line of Optimums in assessing compaction of CCL (Benson et al., 1999)

It also clear from the above testing, how the Falling Head Test, can lead to large overestimates of performance.

The reason for this difference can be attributed to the fact that the Falling Head Test fully saturates the sample prior to testing, while the in-situ testing methods are tested at the in-situ moisture content. When measuring such low permeabilities, it takes very little water absorption into the CCL before it can have a significant impact on the reported hydraulic conductivity. As such, this supports the argument that the in-situ tests such as the Double Ring Infiltrometer and Guelph Permeameter measure infiltration, rather than steady state permeability or hydraulic conductivity. The definition and understanding of these terms with respect to the regulations therefore becomes crucial to meeting the Norms and Standards requirements.

It does however make logical sense that before contaminated liquids can be conveyed through the CCL, the CCL layer would need to become saturated first, and therefore perhaps the Falling Head Permeameter test result is a fairer reflection of steady state hydraulic conductivity of the barrier layer over its design life. In contrast however, the in-situ test methods give a far more accurate reflection of crack formation and construction quality then the Falling Head test, which is arguably the main driver of CCL performance. A middle ground perhaps is the localized saturation of the CCL post-construction of the layer and undertaking either of the in-situ test evaluations to get the most reflective measure of in-situ performance of the layer.

This is an argument that needs to be considered further within industry and with the Regulator in order to develop a certainty of approach when undertaking and reviewing these results, rather than taking a hardline on a certain value for compliance.

Therefore, at design stage, it is important that designers are cognizant of the above issues and make appropriate allowances depending on the type of testing undertaken on materials to prove performance.

3 Comparison to Geosynthetic Clay Liners

GCLs are one possible geosynthetic substitution for a CCL as part of a composite lining system design. GCL's are particularly economically attractive for sites where there are no natural sources of suitable clay on site or in close proximity, and also take far less time to install than an equivalent CCL layer. As such, they are a popular choice by designers when needing to replace a CCL as part of a basal lining design in terms of the Norms and Standards.

Acknowledging the many advantages of GCL's, they are not straightforward to design with, as there is an inherent obligation by the designer to prove that the GCL can perform to an equivalent standard as the CCL it is replacing. In this regard, there are a number of considerations that a designer must take into account to ensure that a GCL will be able to perform over its full life cycle within the basal lining system which could be anywhere between 30-120 years depending on the waste stream and disposal period.

Some of these considerations include:

a) Waste stream compatibility with GCL constituents,
b) Proving equivalent hydraulic conductivity performance accounting for a) above

Waste stream compatibility can be assessed at the preliminary stage by undertaking indicator testing, including Free Swell Index testing using a leachate permeant, as well as leachate chemical assessments in terms of ratio of monovalent to divalent cations (RMD) and Ionic Strength (IS) values. These indicators can give a preliminary indication of whether compatibility issues can be expected, and whether consideration should be given to reducing the effective hydraulic conductivity of the GCL in the design calculations to account for chemical compatibility issues with the leachate. An explanation and example of the indicator assessments above is explained in more detail in Mawer & Steyn (2023).

For the particular Class B cell being used as an example in Section 3.1 below, the above assessments were undertaken on the candidate GCL (4500 g/m^2 powdered sodium bentonite) that was considered for the design. Initially, the Free Swell Index results showed reduced swell performance, and RMD and IS values which indicated that the IS was high at 0.107 M, which is attributed as the reason for the low swells in bentonite based on research by Meer and Benson (2009).

The specialist leachate chemical assessment recommended that it would be fair to expect a reduced hydraulic conductivity in the order of 1 x 10^{-9} cm/s, which was 2 orders of magnitude less than the manufacturer's rated performance.

3.1 Equivalent Performance

For the same Class B design referenced above, based on the Minimum Requirements for Disposal of Waste to Landfill (1998), the maximum permissible hydraulic conductivity for a CCL in a Class B Barrier System was required to be 1 x 10^{-6} cm/s using double ring infiltrometer testing on the completed layer on site. The above design preceded 2021 guidelines from DWS being finalised and published hence the reduced hydraulic conductivity requirement.

However, as it was not possible to re-create such a test using a GCL on site effectively at design stage, it was decided to prove equivalence by comparing the theoretical seepage rate calculated in terms of Rowe (2012) formulations for the designed lining system, with a) using a 600 mm thick CCL with hydraulic conductivity of 1 x 10^{-6} cm/s and; b) using a GCL with reduced performance and all other parameters kept the same. Both calculations were undertaken using an assumption of 1 hole per ha aligning with an interconnected wrinkle length of 150 m, and a wrinkle not being more than 0.2 m in width based on undertaking good construction quality assurance on site during construction. A summary of design parameters is indicated in Table 5.

The Client's preferred 4 500 g/m^2 powdered sodium bentonite GCL product was assessed having a rated hydraulic conductivity of 2.0 x 10^{-11} cm/s, using de-aired and deionized water as a permeant under a head of 0.300 m. The GCL (under ideal conditions) is theoretically 50 000 less permeable than the CCL but has a significantly smaller flow path in terms of the seepage calculations undertaken. In addition, possible leachate compatibility concerns with the GCL needed to be accounted for as part of the calculation.

Table 5: Parameters used in GCL vs. CCL equivalence calculation.

Parameter	**600 mm CCL Design**	**GCL Design**
CCL/GCL Thickness (mm)	600	4.5
Hydraulic Conductivity (cm/s)	1 x 10^{-6}	2.0 x 10^{-11} (2.0 x 10^{-9})
Geomembrane Thickness (mm)	1.5	1.5
Lined Area (m^2)	15 200	15 200
Head on Liner (m)	0.3	0.3

In order to account for a potential reduced performance of the GCL, the hydraulic conductivity of the GCL was adjusted in the seepage calculations when evaluating equivalence with a CCL. Based on the outcomes of the chemical compatibility study, it was decided to reduce the rated hydraulic conductivity of the GCL by 2 orders of magnitude, making the hydraulic conductivity of the GCL 2 x 10^{-9} cm/s rather than 2 x 10^{-11} cm/s rated by the manufacturer as can be seen in Table 6 below.

Table 6. Results of CCL vs. GCL Seepage assessment to prove equivalence in performance.

Parameter	**600mm CCL Design**	**GCL Design**
L (m) =	150	150
k_L (m/s) =	1.0E-8	2.0E-9
Q (m^3/s/ha) =	1.3E-5	5.4E-6
Q (ℓ/ha/day) =	**1 128**	**469**

The results of the assessment indicate that the GCL – even accounting for reduced performance – was able to at least have an equivalent if not better seepage rate (469 ℓ/ha/day), than the CCL (1 128 ℓ/ha/day), excluding any consideration of installation damage or other construction related defects. This illustrated that a GCL can be a viable replacement for a CCL, if due consideration is taken for possible leachate compatibility effect, which was accepted by the Regulator during the design approval process, albeit with some specific conditions during construction to illustrate this performance.

To address these concerns, Mawer & Steyn (2023), indicate how a Flexible Wall Permeameter test was undertaken to prove performance of the same GCL referenced above using leachate as the permeant. Ten repeats of the test were undertaken, and the average value of hydraulic conductivity was within 5% of the rated hydraulic conductivity of the manufacturer (2 x 10^{-11} cm/s) even when hydrated and permeated with a leachate sample.

4 Conclusion

The aim of this paper was to highlight the factors that need to be considered when designing with CCL and GCL's as part of a containment barrier design, as well as the different factors that may impact on the performance of both liners when used in a composite barrier system.

The factors influencing the long-term performance of CCLs were highlighted using a case study undertaken by the author on a series of trial pads using different silt and clay materials on a particular Class B facility that was designed. Material A, B and C were compacted as close as possible to 98% MDD and OMC as per DWS (2021) guidelines, and then evaluated for hydraulic conductivity performance through laboratory testing as well as in-situ infiltrometer testing. The results indicated a clear variance between laboratory testing and in-situ field test results, in the order of 1 to 2 magnitudes in favour of the laboratory testing, which raises concern of possible reduced performance if the design was based on laboratory test results from remoulded candidate samples of clay material. In addition, it was observed that the closer to 100% MDD and OMC each trial pad was prepared, the closer the in-field hydraulic conductivity was to the laboratory test result, however being compacted wet of optimum rather than dry of optimum was observed to be of more importance. This was aligned with research by Benson et. al (1999) who suggested that to achieve a consistent performance of a CCL, focus should be placed on ensuring compaction is primarily wet of the line of optimums as illustrated in Figure 1.

It was shown that when considering the use of a GCL product as a substitution for a CCL, that potential reduced performance due to leachate chemical compatibility effects needs to be accounted for. This can be evaluated at a preliminary design stage by undertaking indicator testing such as Free Swell Index testing and leachate chemistry assessments. A method for equivalent performance evaluation between GCL and CCL was also presented by using a comparative seepage calculation approach. A case study was also presented of a design undertaken by the author which showed that a GCL product, even after accounting for reduced performance was able to outperform the standard CCL design applicable to the Class B facility being considered.

Key References

Benson, C.H., Daniel, D.E., Boutwell, G.P. 1999. Field Performance of Compacted Clay Liners. Journal of Geotechnical and Geoenvironmental Engineering. May 1999 Edition. ISSN 1090-0241/99/0005-0390-0403

Department of Water Affairs & Forestry, 2nd Edition, 1998. “Waste Management Series. Minimum Requirements for Waste Disposal by Landfill”. Pretoria, South Africa.

Department of Environmental Affairs: Republic of South Africa. 2013. National Norms and Standards for Disposal of Waste to Landfill. Issued under Government Gazette 36784 No. R 636 of 23 August 2013.

Department of Water and Sanitation: Republic of South Africa. 2021. Guideline for Pollution Control Barrier System Design. Issued under Government Gazette 36784 No. R 636 of 23 August 2013.

Mawer, BW; Steyn, L. 2023. Assessing Geosynthetic Clay Liner (GCL) Equivalence To Compacted Clay Liner (CCL) Including Chemical Compatibility With Site-Specific Leachate. Proceedings of Landfill and Waste Treatment Group Conference 2023. Cape Town, South Africa.

Meer, S and Benson, C., “Relative Abundance of Monovalent and Divalent Cations and the Impact of Desiccation on Geosynthetic Clay Liners” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, March 2009.

R. K Rowe.2012. Short- and long-term leakage through composite liners. The 7th Arthur Casagrande Lecture