SWELL INDEX TESTING OF GCL CLAY COMPONENTS FOR COMPATIBILITY TESTING WITH LEACHATES

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SUMMARY:

The free swell index test was used to determine the swelling characteristics of several GCLs' clay components when exposed to site specific leachates. The test results show that, depending on the leachate, the free swell of the bentonite can be reduced by a factor of 5 or more, which correlates to an increase in hydraulic conductivity of four to five orders of magnitude.

1. INTRODUCTION

The use of geosynthetic clay liners (GCLs) in landfill and hazardous lagoon liner applications is often based on the assumption of guaranteed long-term performance of the GCL as a hydraulic barrier without any sound compatibility testing to support this assumption. Some recent projects involving aggressive leachates with high concentrations of polyvalent cations have highlighted the need to ensure the compatibility of the clay component of the GCL with the site specific leachate, specifically to ensure that there are no significant changes in the hydraulic conductivity of the clay when permeated with the leachate.

The body of literature on this topic is substantial. However most work investigates the performance of GCLs in their complete form, establishing the effects of both weak and strong inorganic solutions comprising monovalent and divalent ions, the effects of strongly basic and acidic solutions, and the effect of prehydration. The author came across only two papers (Kolstad et al. 2004a; Lee et al. 2005) which sought to establish surrogate index tests on the bentonite itself as a litmus test for the suitability of the GCL in a particular application.

Compatibility testing on GCLs is usually in the form of long-term permeability tests in which the liquid of interest is passed through the GCL until all chemical changes to the bentonite have taken place and the system is said to have reached equilibrium. While no consensus on definition of chemical equilibrium has been reached, the condition is usually said to have been achieved when parameters such as the electrical conductivity, concentrations of certain ions (for example Cl^- and Ca^{2+}), and pH measured in the influent and effluent solutions are within preset limits. Typical margins are 1.0 ± 0.1 for EC (Lee et al. 2005) and approximately 1% for pH (Ruhl & Daniel, 1997). An additional criterion sometimes used is at least 2 pore volumes of flow (pvf). (Jo et al. 2005) found that using the ratio of flow rate of the influent and effluent and a steady state of hydraulic conductivity (i.e. the criteria stipulated in ASTM D 5085 and D 6766) are not sufficient termination criteria, as the reported hydraulic conductivity may be 2-13 times lower than the actual long-term hydraulic conductivity. These authors continued their tests for as many as 686 pvfs and 2.5 years.

Usually the hydraulic conductivity of the GCL reduces over time, as the bentonite undergoes ion exchange with the permeant. However tests of this kind may take many pore volumes of flow (200 or more) and many years to reach the equilibrium state, before which only unreliable predictions regarding the GCL performance can be made (Jo et al. 2005). It is therefore usually impractical to perform these tests over the period allowed for design of a new waste facility, if any meaningful information is to be acquired.

An alternative, short-term compatibility test involving free swell index testing of the clay component of the GCL was used by Jones & Wagener as an indication of compatibility. Swell index testing is routinely carried out by GCL manufacturers as a QA measure before shipment of the finished product. However, the standard method (ASTM D5890) is performed with de-ionised water. Jones & Wagener performed testing with site specific leachates and the bentonite component of several commercial GCLs as well as attapulgite clay. The test results can be used to make tentative predictions of the long-term performance of the GCL by consulting the body of research and literature correlating the swell index of bentonites to long-term hydraulic conductivities in GCLs. Lee et al. (2005) and Kolstad et al. (2004a) are two such papers.

2. THE EFFECT OF LEACHATES ON HYDRAULIC CONDUCTIVITY OF GCLs

The low hydraulic conductivity of bentonite clay is due to its ability to swell. When hydrated in dilute solutions the interlayer region of a montmorillonite particle expands, which is manifested at the macroscopic scale as swelling. The water associated with the interlayer expansion is very tightly bound and is practically immobile. Very little void space is available for flow, which results in a low hydraulic conductivity.

Without going into too much detail regarding the electrically charged nature of clay particles and the associated double layer of ions, factors that cause the hydrated radius of the particle to decrease are the presence of divalent or polyvalent ions, and elevated ionic concentration. In the first case this results in cation exchange in which the higher valence ions replace monovalent ions (e.g. Ca^{2+} replacing Na^{+}). pH of the permeant is a further factor affecting swell.

Figure 1 illustrates the effect ionic strength and relative abundance of monovalent and divalent ions (abbreviated as RMD) has on swell. RMD is the ratio of concentrations of monovalent and divalent cations in the permeant solution and is zero when the solution contains only divalent ions and is infinite when all monovalent.

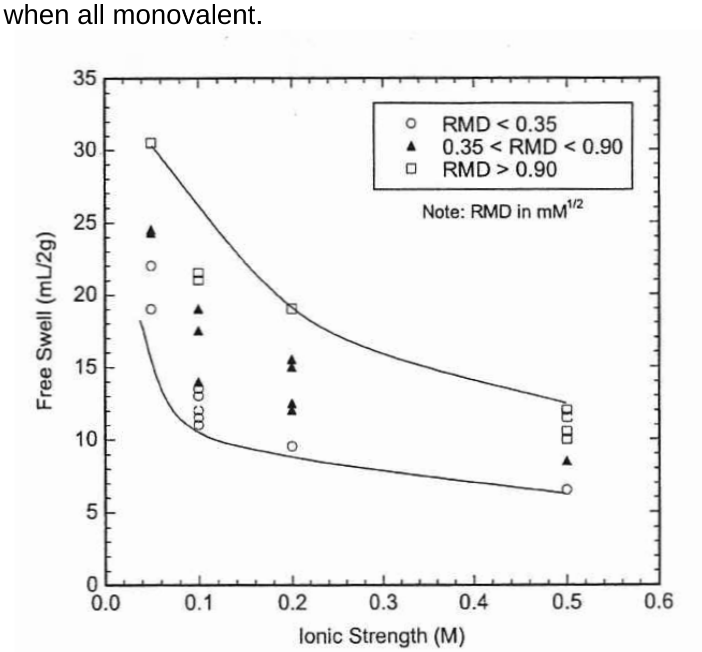

Figure 1 Free swell of bentonite as a function of ionic strength for low, intermediate, and high relative abundance of monovalent and divalent cations. From Kolstad et al. (2004a)

Increases in hydraulic conductivity of GCLs by several orders of magnitude over that achieved when permeated with tap water through the action of ion exchange (inorganic solutions) are abundantly reported in the literature. Many researchers (Ruhl & Daniel, 1997; Jo et al. 2004; Jo et al. 2005; Kolstad et al. 2004b; Lee et al. 2005) report increases in hydraulic conductivity of 5 orders of magnitude when exposed to a strong $CaCl_2$ solution.

While it may seem desirable to test a GCL with a conservatively aggressive synthetic leachate, it is important to use the actual leachate that will be encountered on site (although for obvious reasons this may not always be possible). Ruhl & Daniel (1997) describes how a simulated MSW leachate increased the hydraulic conductivity of a GCL by 4 orders of magnitude, while the real leachate had little to no effect on the long term hydraulic conductivity.

As already discussed, the time taken for increases in hydraulic conductivity to manifest due to exposure to aggressive leachates can be on the order of hundreds of pore volumes of flow (pvfs) and hundreds of days. As a result, tests are often terminated prematurely and the long term performance of the GCL is often overstated.

The issue of pre-hydration has been explored as well. Jo et al. (2004) found that prehydrated bentonite had permeability an order of magnitude lower and a greater water content than a non-prehydrated bentonite even though Ca-for-Na exchange was essentially complete. Kolstad et al. (2004b) found that a GCL where the bentonite was prehydrated at the manufacture stage was 5 orders of magnitude less permeable than a conventional GCL, but this may have been due in part to its higher dry mass per square metre (6.0 kg/m^2 as opposed to 4.3 kg/m^2). Although pre-hydration clearly has benefits, its effects can not last indefinitely and after an initial period of good performance the GCL will ultimately become compromised.

The literature abounds with data and reports of changes in hydraulic conductivity with an almost bewildering array of references to monovalent ions, divalent ions, different ratios of these ions, with concentrations of these solutions reported in mMol or mg/l, tests done at different hydraulic gradients, terminated after different amounts of pvfs using different bentonites conducted in different permeameters under different effective stresses. It quickly becomes very difficult to make any kind of judgement for one's particular case based on past results. Additionally, as borne out in Kolstad et al. (2004a), it is essential to test under site specific conditions. The most reliable route to a meaningful answer is to undertake compatibility tests oneself, but as we know this course can take many years to provide answers. However what one CAN do is a surrogate compatibility test.

3. INDEX TESTING AS SURROGATE COMPATIBILITY TESTING

The underlying premise of surrogate compatibility tests is that physicochemical changes that alter index properties of the clay also cause a change in hydraulic conductivity.

As already stated, free swell index tests using leachate instead of DI water is not a new idea. Several researchers have performed such tests (Egloffstein et al. 2002; Jo et al. 2004; Kolstad et al. 2004a; Kolstad et al. 2004b; and Lee et al. 2005). However, only Lee et al. (2005) and Kolstad et al. (2004a) correlate various index properties of a bentonite with hydraulic conductivity, including free swell index, sedimentation volume, and liquid limit.

These two studies established that the use of index properties is valid for quickly determining the effect of a particular leachate on the hydraulic conductivity of the GCL. Kolstad et al. (2004a) even went so far as to develop an equation relating RMD (the ratio of concentrations of monovalent and divalent cations in the permeant solution) and ionic strength (I) to hydraulic conductivity. However this formula is only valid for a limited range of I and RMD and only at an effective stress of 20 kPa.

Egloffstein et al. (2002) suggest that the swell index test is inferior to sedimentation volume for determining the quality of the bentonite. Correlations between sedimentation volume and hydraulic conductivity are given in Lee et al. (2005). These authors suggest exactly the opposite i.e. that swell index is better than sedimentation volume, and also that liquid limit is a better indicator than sedimentation volume. These assertions are based on the "smoothness" the curves established in the testing program, which illustrate the relationship between hydraulic conductivity and the relevant index property. It is the author's opinion that a swell test is easier to perform than the two alternatives.

It is on the back of the work of Kolstad et al. (2004a) and Lee et al. (2005) that the present work is based. Figures 2 and 3 from these two papers respectively give graphical correlations between swell index and hydraulic conductivity. Note how the hydraulic conductivity dramatically increases with decreasing swell index.

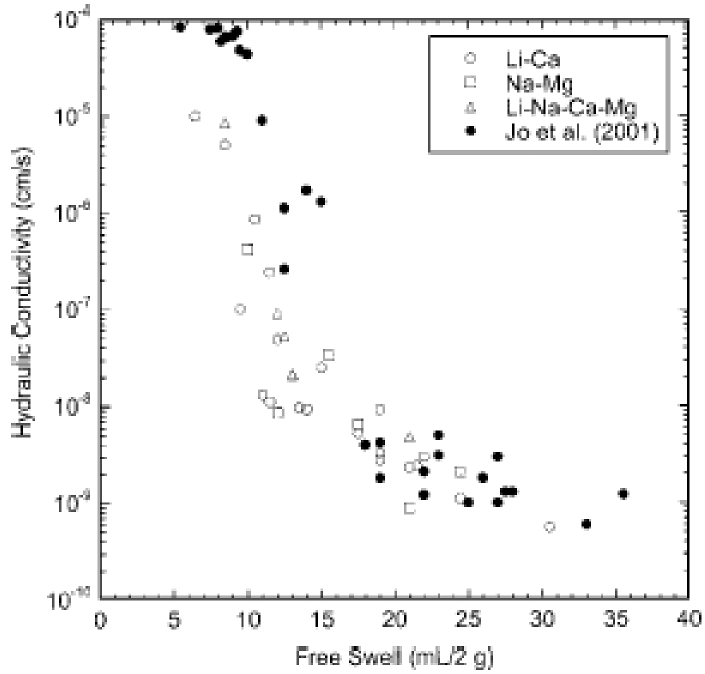

Figure 2. Hydraulic Conductivity of GCL as a function of free swell of bentonite from Kolstad et al (2004a)

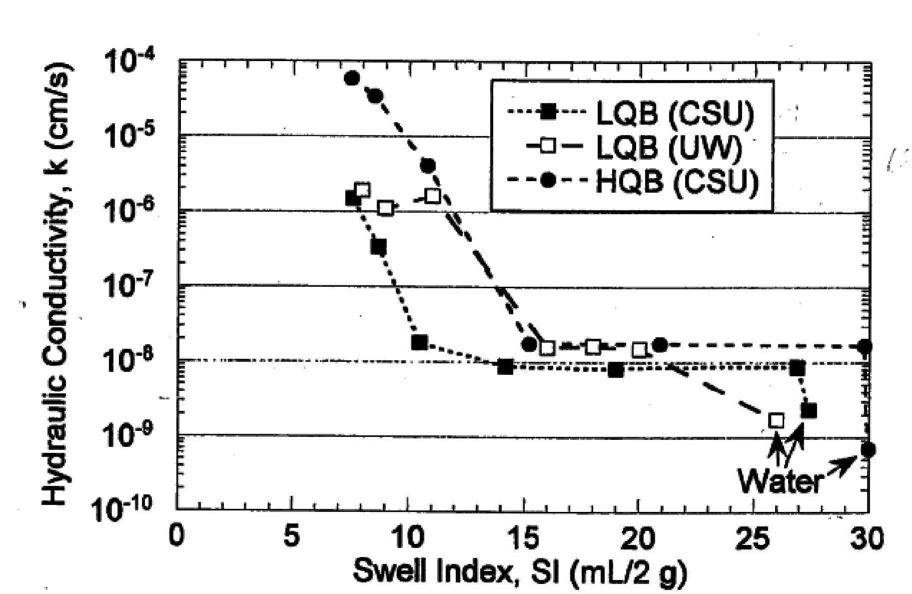

Figure 3. Hydraulic Conductivity of GCL as a function of free swell of bentonite from Lee et al (2005)

4. MATERIALS AND METHODS

The testing programme carried out by Jones & Wagener consisted of determination of the swell index of the bentonite component of three GCLs as well as two attapulgite clays by a standard test method specified in ASTM D5890. This test method is the very same one used by GCL manufacturers as a Quality Assurance measure before manufacture of the final GCL product. However, in the commercial application of the test de-ionised water is used to determine the swelling characteristics of the clay.

Swell Index is measured in units of ml/2g. Bentonite acceptable for use in GCLs must have a swell index of 24 ml/2g or more.

A brief description of the swell index test is as follows:

1. 90ml of the reagent water is added to a measuring cylinder having its 100ml mark at approximately 180mm height.
2. 2.0g of oven dried bentonite or attapulgite having 100 % of the grains smaller than 150 μm and 60% of the grains smaller than 75 μm is added to the reagent water in 0.1g increments. The grains are allowed to hydrate and settle for a minimum period of 10 minutes before the next increment is added. The addition of each increment must be over the whole surface of the water and must take at least 30 seconds to perform.
3. The cylinder is topped up with more reagent water to the 100 ml level.
4. The swell index is measured 16 hours after the final increment of clay is added. The index is measured in ml/2g. Any low-density flocculated material above the settled clay is ignored for this measurement.

A full description of the method is available in ASTM D5890.

4.1 Leachates

Four leachates from various industrial and mining plants were tested. Two leachates were from a vanadium mine, respectively from an effluent dam (hereafter referred to as “scrubber”) and a heap leach pad (“calcine”). These two leachates are very different from one another particularly in terms of pH and cation concentration. However both have elevated levels of cations. The third leachate is return water from a coal fines dam (“colliery”), and the fourth leachate can be described as a saline brine with some heavy metals originating from a chrome processing plant (hereafter referred to as “chrome”). A control set of tests using de-ionised water was also conducted.

The constituents of the leachates are given in Table 1. The mineral composition of potable mineral water is given for comparison.

In terms of readily exchangeable cations, the “scrubber” is extremely aggressive, having high concentrations of Ca, Na, K and Mg. Also of note is its low pH. The “chrome” leachate is very similar to the “scrubber” having a similar level of total dissolved salts and pH. Unfortunately no information is available on the Na and K concentrations of “chrome”, but the Ca concentration is very close to that of “scrubber”.

Table 1 Leachate Qualities

Values in mg/l	**Scrubber**	**Calcine**	**Colliery**	**Chrome**	**Mineral Water**
pH	4.2	10.2	8.0	4.0	7.0
Conductivity (mS/m)	27 190	1 938	495		
TDS at 180 C	166 282	20 694	4 285	> 91 000	111
Alkalinity as CaCO3	<5	5 400	195		85
Chloride as Cl	14 269	239	525	26 169	2
Sulphate as SO4	89 795	6 021	2 095	62 360	2
Silica as Si	97	66		146	
Fluoride as F	959	20	3.5	10.9	0.16
Sodium as Na	37 770	6 172	785		11
Potassium as K	513	26	95		<1
Calcium as Ca	656	12	225	584	15
Magnesium as Mg	1 030	51	115	135	7
Aluminium as Al	637	0.085		271	<0.01
Chromium as Cr	2.29	0.085			
Iron as Fe	1 009	0.177	0.3	1 320	<0.02
Manganese as Mn	32	0.046		163	
Titanium as Ti	1.21	3.6		1.2	
Vanadium as V	375	1 732		28	
Zinc as Zn	3.4	0.034			

4.2 Clay minerals

Three bentonite and two attapulgite clays were tested. The three bentonites are here given the names Bentonite 1, Bentonite 2, and Bentonite 3.

Bentonite 1 is described as a natural sodium bentonite. Bentonite 2 is a granulated bentonite and Bentonite 3 is a polymer activated sodium bentonite. Kolstad et al. (2004b) simply describes activated bentonites as those with large organic molecules that bind to the montmorillonite surface where they act as a prop to hold open the interlayer region in the presence of aggressive liquids, or alternatively bond to the sodium ions in the interlayer space, minimising exchange of the ions with polyvalent ions.

The granulated bentonite was tested in two configurations. The ASTM method calls for 100% of the particle grains to be smaller than 150 μm and 60% of the grains smaller than 75 μm. The granulated bentonite "as received" did not meet this specification, having only 1% of its particles finer than 150 μm. Regardless it was decided to test the bentonite "as received", but also to test the fraction of particles that met the size requirements of ASTM D5890. In order to achieve this the bentonite had to be crushed and only the powder resulting from crushing meeting the particle size requirement was tested. This sample is termed "Bentonite 2 Crushed" in Table 2.

The "as received" granulated bentonite was tested in all leachates despite the possibility that the results would be favourably skewed due to a large amount of the swell being attributable to the size of the granules themselves, which may or may not have become completely hydrated.

A third form of Bentonite 2 was tested in DI water. This was the fine fraction of the uncrushed "as received" granulated bentonite, i.e. the fine particles not bound up in the granules. This fraction did not exhibit sufficient swell in DI water, achieving only 16 ml/2g. This is probably due to this material not being wholly bentonite itself, but rather some sort of filler material. Therefore it was decided not to test this fine fraction with the leachates.

The polymer activated bentonite (Bentonite 3) met the grain size specification. The natural sodium bentonite (Bentonite 1) was very close to meeting the specification, and enough of the fine material was combined to ensure that it did meet the specification prior to testing.

The two attapulgite samples were suitable for testing as received. Attapulgite is not used in GCLs but was tested because of its reported resistance to highly saline environments.

In total 30 swell index tests were performed. Initially the intention was to perform two tests for each combination of leachate and clay in order to reduce experimental error. However it soon became apparent that the results were highly repeatable, and due to the length of time taken for each test it was decided that only one test per combination was necessary. The various clay/leachate combinations that were tested, along with the results are given in Table 2.

5. RESULTS

The results of the swell index tests are given in Table 2.

Table 2 Results of swell index tests. Values in ml/2g

	DEIONISED WATER	COLLIERY	CALCINE	SCRUBBER	CHROME
Bentonite 1	25.5	14.0 13.5	14.0 14.0	3.0 3.5	6.0
Bentonite 2 (Granulated)	24.5 24.5	18.5	19.5	4.0	Not Tested
Bentonite 2 Crushed	19.5	12.5	15.5	3.5	5.0
Bentonite 3	26.0	11.0	20.0	4.0	6.0
Attapulgite 1	5.0	5.0	7.0	4.0	Not Tested
Attapulgite 2	7.0	Not Tested	Not Tested	7.0	8.0

6. DISCUSSION OF RESULTS

All the bentonites achieved the required 24 ml/2g swell in de-ionised water. Interestingly, these bentonites all achieve this by a narrow margin, probably for reasons of economy on the manufacturer's part. In comparison Kolstad et al. (2004b) measured free swell in two commercial bentonites in DI water of 35.0 ml/2g and 35.5 ml/2g.

The granulated bentonite met the required specification of 24 ml/2g swell in DI water in its "as received" form which, it must be noted, does not meet the ASTM particle size specification. However the fine fraction resulting from crushing which did meet the ASTM size requirement failed to meet the 24 ml/2g requirement by quite a large margin, achieving a swell of only 19.5 ml/2g. This is probably due to the collected fine material containing a combination of bentonite clay from the crushed granules, and some of the "filler" material discussed in Section 4.2.

As already discussed, there is doubt over whether the granules in Bentonite 2 hydrate completely when immersed in leachate, or whether an outer layer only is hydrated leaving the inner portion dry. If the latter is the case then the swell of the bentonite would be made up of the volume of the dry part of the granules as well as the hydrated outer layers, in which case the swell would be misrepresented as better than it actually is. Additionally, no data exists correlating hydraulic conductivity with swell of granulated bentonites, making the drawing of conclusions meaningless. However what can be noted is that, in common with the other bentonites, Bentonite 2 undergoes less swelling when exposed to the leachates than when exposed to DI water.

The swells of the clays in the various leachates are not encouraging. The results are relatively straightforward to interpret. By comparing the achieved swell with either Figure 3 or Figure 4, one can immediately get an idea of the impact on the hydraulic conductivity.

As predicted, the “scrubber” leachate was the most devastating, with all bentonites achieving between only 3.0 and 4.0 ml/2g swell. A swell as low as this does not even feature on either of the two correlation graphs, and unquestionably results in a hydraulic conductivity of the order of 10^{-4} cm/s, which is equivalent to that of a fine silty sand. Whether this effect on the clay is due to the extremely high concentration of cations or due to the low pH is not clear, but it is quite apparent that the use of GCLs in contact with this leachate would be totally irresponsible. The same can be said for the “chrome” leachate, where both Bentonites 1 and 3 achieved only 6 ml/2g swell. Bentonite 2 “Crushed” achieved even less at 5.0 ml/2g.

The “colliery” leachate places the hydraulic conductivity inside the ambiguous zone of Figure 4 where Lee et al (2005) reported hydraulic conductivities of between 10^{-8} and 10^{-5} cm/s. One should ideally select Bentonite 1 for use with this leachate (because of its better performance) if no alternative to GCL can be found. On the other hand the “calcine” leachate is best resisted by Bentonite 3 (polymer activated) than by Bentonites 1 and 2 by quite a considerable margin.

At first glance the “calcine” leachate appears to have had the least damaging affect on the clays, where, based on a comparison of their constituents, one would have expected this to have occurred with the “colliery” leachate, particularly with regard to Na in which “calcine” outstrips “colliery” by 6172 mg/l to 785 mg/l. However “colliery” has higher levels of the divalent ions Ca and Mg which may be the defining factor in causing it to be the more aggressive leachate. In actual fact, the two leachates achieve very similar swells in all the bentonites and it is only the result of Bentonite 3 that makes it seem that “calcine” is more benign than “colliery”. It could be that Bentonite 3, being polymer activated, is well suited to resisting the high Na concentrations of “calcine” but not the high concentrations of divalent ions in “colliery”. A similar occurrence is reported in Ruhl & Daniel (1997). These authors state “Not all contaminant resistant bentonites are as resistant to attack as regular bentonites for certain chemicals” Care must be taken to select a contaminant-resistant bentonite to make sure that it is resistant to the specific chemical solution that is of interest. Not all contaminant resistant bentonites are the same.

The performance of the attapulgites is disappointing. Both samples achieved low swells in DI water, but interestingly the swell in some leachates was actually greater than in DI water for two cases (Attapulgite 1 – calcine; and Attapulgite 2 – chrome) although possibly not significantly enough to rule out experimental error. Attapulgite seems relatively insensitive to even these harsh leachates, but lacks the swelling capacity in the first place to make its use in GCLs feasible.

7. CONCLUSIONS

The most obvious conclusion that can be drawn from this work is that GCLs should not be specified for containment of these particular leachates, even one as relatively benign as “colliery”. In general, anything with a swell below 17 ml/2g (if consulting Figure 2) and 15 ml/2g (if consulting Figure 3) should not be deemed suitable for use with the leachates causing that swell. In such cases, compacted clay liners are preferable to GCLs, even though they too are likely to undergo ion exchange and an eventual increase in hydraulic conductivity. However, compacted clay liners have the benefit of having much greater thickness than GCLs (300mm vs

8mm) and so have a kind of “buffering” capacity, thereby taking longer to reach the state of unacceptably low hydraulic conductivity.

This work is not intended to rate the commercially available GCLs against each other, but it does highlight that a bentonite can perform better than others in a certain leachate but worse in another. For example, as discussed earlier, the polymer activated bentonite was the worst performer in the colliery leachate but was the best performer for the calcine leachate.

Also, this paper is not about building experience with respect to specific leachates but rather is meant to highlight that this work can be done simply, cheaply and quickly for each and every case that may come across a designer’s desk. With this tool, one does not need to have an in-depth knowledge of clay chemistry to be able to make an informed decision.

That is not to say that swell testing is a sure fire method. The curves developed in Kolstad et al. (2004a) and Lee et al. (2005) are for particular bentonites and particular leachates. However, there is no disputing the fact that there is a strong inverse relationship between free swell and hydraulic conductivity, no matter what factors play a role in arriving at that swell. These index tests give one an immediate impression of the case at hand, and can categorically rule out the use of GCLs for a particular project where they may otherwise have been specified on the strength of their reputation. Of course there are also the cases where there is some ambiguity, and a range of hydraulic conductivities possible at a certain swell. In these cases one must apply engineering judgement or if cost effectiveness warrants it, pursue further testing.

The benefits over conventional hydraulic conductivity testing have already been discussed in the introductory part of this paper. Of course, there is no substitute for the time-honoured permeability test, but if one is to conduct it properly and obtain a meaningful result, one may have to wait half a year or more.

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