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Swell Index Testing of GCL Bentonites With General And Hazardous Waste Leachates

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ABSTRACT

Recent waste disposal projects involving aggressive leachates have highlighted the need to check the compatibility of GCLs with the site specific leachates. A qualitative determination of leachate-bentonite compatibility can be obtained by performing the standardised test ASTM D5890 to determine the free swell index of the clay component of the GCL using leachate in place of the prescribed de-ionised water. Compatibility of leachates from five general waste and two hazardous waste landfills sites was checked with several bentonites from commercially available GCLs. The free swell of the bentonites was compared to correlations established in the literature to predict long-term order of magnitude changes in the hydraulic conductivity of the GCL. A high standard deviation was noted in the control tests, highlighting product variability. The two hazardous leachates and two of the general leachates produced very low swell volumes, corresponding to high hydraulic conductivities, equivalent to that of a fine sand.

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 or reactive leachates with high concentrations of polyvalent cations have highlighted the need to determine the compatibility of the bentonite in the GCL with the site specific leachate to ensure that there will be no significant changes in the hydraulic conductivity of the clay when permeated with the leachate. In particular, *long-term* compatibility must be established.

1.1 Effect of Electrolyte 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.

The hydrated radius of the clay particle is dependent on the relative abundance of monovalent, divalent or polyvalent ions, and the ionic concentration of the permeating liquid. Generally speaking, the hydrated radius of the particle will be larger when the particle is predominantly surrounded by monovalent ions than when surrounded by divalent ions, and it will be larger when the concentration of ions is lower than when the concentration is higher. pH of the permeant also influences the hydrated radius.

Changes in the hydrated radius can occur due to cation exchange at the interlayer surface. Generally, cations of greater valance and smaller size replace cations of lower valence and larger size. The lyotropic series describes the preference for ion replacement, which is:

$Li^+ < Na^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+}$

Because Na^+ is at the lower end of the series, Na-bentonites are prone to cation exchange when permeated with solutions containing divalent or trivalent ions. Despite this, Na-bentonites are preferred to Ca-bentonites because they have a greater inherent swell.

Note that cation exchange is *not* the only mechanism leading to small hydrated radii. A Na-bentonite particle in a solution of concentrated Na^+ ions will also tend to have a small hydrated radius, even though cation exchange is not occurring.

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 the solution is completely monovalent. The figure clearly illustrates that there is an inverse relationship between free swell and ionic strength, as well as between free swell and abundance of divalent ions.

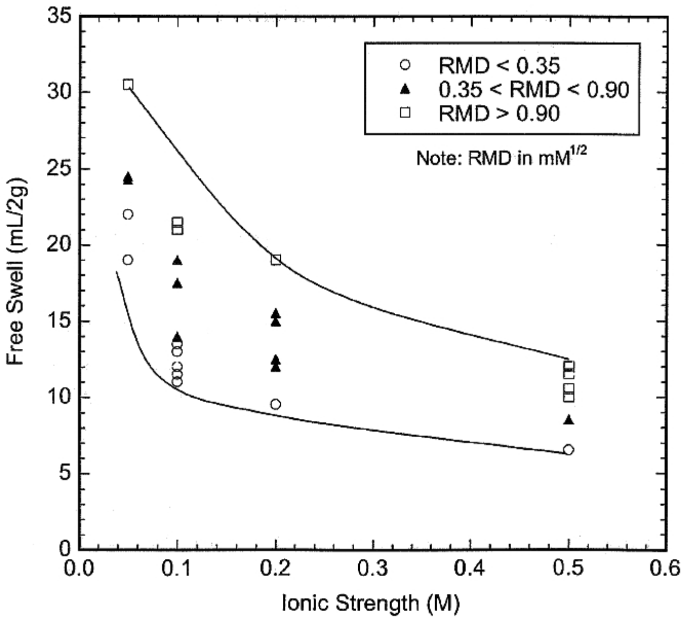

Figure 1 Free swell of bentonite as a function of ionic strength for low, intermediate, and high relative abundance of monovalent and divalent cations. From Kolstad et al. (2004a)

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 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.

1.2 Long-term Compatibility Testing

There is a large body of literature on this topic. However, almost all published work investigates long-term compatibility of the GCL in its complete form by performing conventional hydraulic conductivity tests (methods D 5887 and D 6766) using the leachate that is of interest. Factors that have been investigated include: 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 pre-hydration. Figure 2 is an example of long term hydraulic conductivity testing results, and illustrates how the hydraulic conductivity of a GCL increases with time when permeated with a solution containing divalent ions, in this case Ca^{2+}.

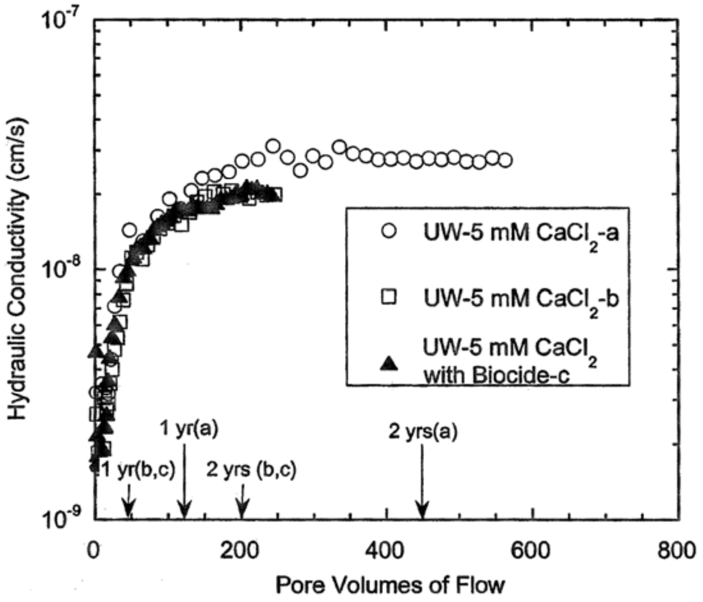

Figure 2 From Jo et al 2005

Apart from the difficulty in eliminating side-wall leakage in these tests, a great many tests are terminated far too early (Jo. et al, 2005). In other words sufficient time and pore volumes of flow (pvf) have not been allowed to occur such that all chemical reactions have reached equilibrium, and therefore an inaccurate result of long-term hydraulic conductivity is obtained.

If tests are terminated before equilibrium is reached, the hydraulic conductivity may be up to an order of magnitude lower than the actual long-term hydraulic conductivity (Jo et al. 2005). Moreover, these authors also found that the criteria stipulated in ASTM D 5887 and D 6766 i.e. the ratio of flow rate of the influent and effluent and a steady state of hydraulic conductivity within prescribed limits, are not appropriate termination criteria, as the reported hydraulic conductivity may be 2-13 times lower than the actual long-term hydraulic conductivity.

Chemical equilibrium is obligatory if the true long-term hydraulic conductivity is to be determined. However the time taken to achieve equilibrium can take as much as 2 years. Additionally no change in hydraulic conductivity may be noted within the whole of the first year. Jo et al (2005) list three long-term hydraulic conductivity studies in which, respectively, the hydraulic conductivity increased by two orders of magnitude over 2.2 years, one order of magnitude over 1.6 years (200 pvf) with no change for the first 220 days (5 pvf), and one order of magnitude over 1.4 years with no change for the first year. It is therefore usually impractical to perform these tests over the period allowed for the design of a new waste facility.

1.3 Index Property Tests as Compatibility Tests

To address the problem of impractically long or otherwise flawed tests as described in Section 1.2, several researchers (Egloffstein et al. 2002; Jo et al. 2004; Kolstad et al. 2004a; Kolstad et al. 2004b & Lee et al. 2005), have tried to establish index tests on the bentonite itself as a rapid method of assessment of compatibility. They have done this by establishing correlations between the index properties of the bentonite and the long-term hydraulic conductivity (using stringent termination criteria) of the GCL when exposed to a particular leachate.

The bentonite index properties tested by these researches are free swell index, sedimentation volume, and liquid limit. The tests have the benefits of being inexpensive, uncomplicated and quick to perform.

Bentonite’s ability to swell is the dominant factor resulting in the low hydraulic conductivity of bentonite clay, thereby making swell index testing suitable as a rapid method for compatibility assurance.

The standard test method ASTM D5890 for swell index testing is routinely carried out by GCL suppliers as a quality assurance measure during manufacture. Swell is reported in units of ml/2g and a value of 24 ml/2g is the minimum required by the Geosynthetics Research Institute (GRI) Standard Specification for GCLs. The test method stipulates using deionised water as the permeant. However it is a simple matter to instead use site specific leachate and to compare the free swell achieved with the correlations determined by Kolstad et al. 2004a and Lee et al. 2005. The correlations determined by these authors are shown in Figure 3 and Figure 4. Note that, despite scatter of the data, hydraulic conductivity increases with decreasing swell index. Also note that these tests were performed under relatively low confining stresses, not greater than 25 kPa.

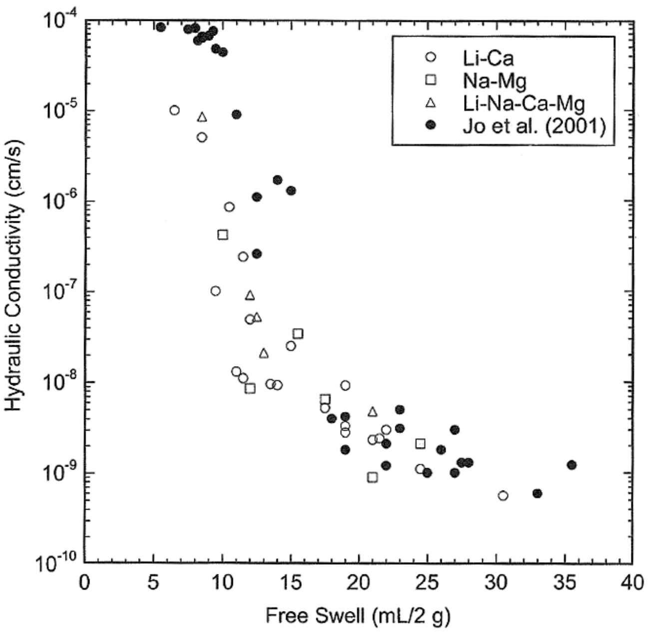

Figure 3 Hydraulic Conductivity of GCL as a function of free swell of bentonite from Kolstad et al (2004a)

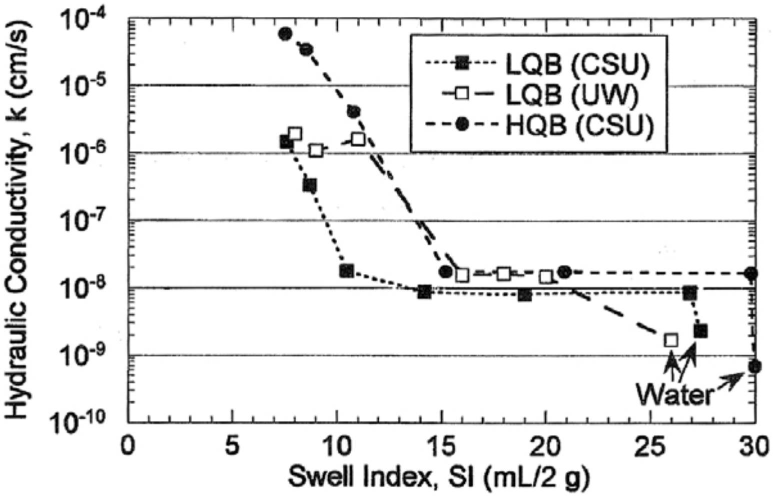

Figure 4 Hydraulic Conductivity of GCL as a function of free swell of bentonite from Lee et al (2005)

The experimental work presented in this paper makes use of these correlations to rapidly assess compatibility of several bentonites with a range of leachates from general and hazardous landfill sites. It must be noted that the correlations shown in Figure 3 and Figure 4 are for particular bentonites and particular permeating liquids. However their usefulness is not diminished for rapid, cost-effective, qualitative compatibility testing.

2. EXPERIMENTAL PROCEDURE

The testing programme carried out for the present work consisted of determination of the swell index of six bentonites when permeated by seven leachates using the standard test method specified in ASTM D5890. This test method is the exact one used by GCL manufacturers as a quality assurance measure.

Swell Index is measured in units of ml/2g. According to GRI-GCL3 (2005), bentonite acceptable for use in GCLs must have a minimum swell index of 24 ml/2g.

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

90ml of the reagent water is added to a measuring cylinder having its 100ml mark at approximately 180mm height. 2.0g of oven dried bentonite 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. The cylinder is topped up with more reagent water to the 100 ml level. 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.

In addition to the leachate tests, control tests were also carried out using distilled water. To keep the identities of the bentonites and the leachates anonymous the leachates were assigned numbers while the bentonites were assigned letters of the alphabet. In total 58 tests were carried out.

2.1 Leachates

Seven leachates from various landfill sites were tested, five from general municipal solid waste (MSW) sites and two from hazardous landfill sites.

In South Africa landfill sites are classified according to criteria set out in the Department of Water Affairs and Forestry's Minimum Requirements for Waste Disposal By Landfill (D.W.A.F, 1998). The criteria are: waste class (**G**eneral or **H**azardous), the size of the waste stream for General Waste (**C**ommunal, **S**mall, **M**edium, or **L**arge), the potential for significant leachate generation for General Waste (**B**$^-$ for insignificant leachate generation or **B**$^+$ for significant leachate generation), and the hazard rating of the waste for Hazardous Wastes (**H** for all categories of hazardous waste or **h** for moderate and low hazard wastes). Thus a large general waste site with a potential for significant leachate generation would be given the designation G:L:B$^+$, and a hazardous waste landfill site permitted to accept all categories of hazardous waste would be given the designation H:H.

Of the 5 general waste leachates tested, 4 were from G:L:B$^-$ sites and one was from a G:L:B$^+$ site. Of the hazardous waste leachates tested, one was from a H:H site and one was from a H:h site.

The basic composition of the leachates is given in Table 1. The leachates were assigned numbers, with the distilled water being given the designation 1 (not shown in the table).

Table 1. Leachate Qualities

Values in mg/l	2	3	4	5	6	7	8
	H:h	GLB-	GLB+	GLB-	H:H	GLB-	GLB-
pH	7.3	7.4	7.4	7.1	7.6	7.1	7.7
Conductivity (mS/cm)	20.4	31.5	2.5	7.5	98.3	4.0	7.9
Sodium as Na	3 444	2 557	244	641	34 580	598	417
Potassium as K	780	2198	37	498	4 339	241	263
Calcium as Ca	85	56	154	123	82	47	16
Magnesium as Mg	113	69	110	266	468	134	36
Aluminium as Al	0.632	0.896	<0.100	<0.100	6.89	<0.100	<0.100
Iron as Fe	3.91	5.49	0.500	0.681	6.84	0.147	0.965
Manganese as Mn	2.14	0.616	8.37	2.03	10	0.101	0.080
Zinc as Zn	0.156	0.227	0.034	<0.025	2.15	0.063	0.026
COD as O_2	3 733	22 133	160	560	44 800	480	1 160

Important to note is the very high level of Na, K and Mg and the high electrical conductivity (EC) of the H:H and H:h leachates and Leachate 3. The table does not show levels of organic compounds such as phenols, benzenes etc although levels of these are certainly high in the hazardous leachates. However, it is the concentration and valence of cations that is of relevance to the swell of the bentonites. These leachates also have high concentrations of Fe, a trivalent ion.

Leachates 4, 5, 7 and 8 are all relatively similar to one another and relatively benign compared to Leachates 2, 3, and 6. Simply by glancing at the values in the table, one might intuitively rank the leachates in order of aggressiveness thus: 6, 3, 2, 5, 7, 8, 4.

In terms of similarity at the landfill, Leachates 2 and 3 should be similar, as although derived from different types of waste, they are both covered with residual granitic soils.

2.2 Bentonites

The bentonites tested were all obtained from commercial sources available in South Africa and are used as the clay component in 3 manufacturers' or suppliers' GCLs. Broadly speaking there are two types of bentonite: sodium bentonites and calcium bentonite, depending on which is the prevalent exchangeable cation. Most bentonites have a mix of sodium, calcium, magnesium and potassium ions. Sodium bentonites have better swelling characteristics than calcium bentonites, with a sodium bentonite expanding 15-20 times its original volume compared to 0-5 times the original volume for Ca-bentonites. In most cases the naturally occurring bentonites are calcium bentonites, and these are normally activated with high concentrations of sodium carbonate to cause the primary calcium ions to be exchanged with the sodium ions, thus resulting in a product with better swelling characteristics. Naturally occurring sodium bentonites exist but are comparatively rare.

Bentonite A is as a natural sodium bentonite from a European supplier.

Bentonite B is a polymer activated sodium bentonite. Kolstad et al. (2004b) 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.

Bentonite C is a granulated sodium bentonite. Although this does not meet the ASTM size specification, having only 1% of its particles finer than 150 μm, it was decided to test the bentonite “as received” 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. The results are included for interest’s sake.

Bentonite D is a powdered bentonite from a South African bulk supplier in the Western Cape. The bentonite in its natural form is a sodium/magnesium material with the main exchangeable cations being Mg^{2+} and Na^{+}, and with auxiliary cations Ca^{2+} (D.M.E Bentonite Report, 2005).

Bentonite E is a powder derived from crushing Bentonite C so that the particle size distribution complies with the ASTM size spec.

Bentonite F is a powdered bentonite from a South African GCL manufacturer.

Bentonite G is an Australian product used in locally distributed GCLs. It is a calcium bentonite that has been activated with sodium carbonate to convert it to a sodium bentonite by cation exchange.

All the bentonite samples met the ASTM particle size requirement, with the obvious exception of the granulated bentonite. The crushed product of this bentonite required sieving to ensure the correct particle size distribution.

2.3 Repeatability

Two bentonite-leachate combinations were selected to establish the degree of repeatability and therefore reliability of the results. These tests were repeated and the result from the two tests compared. The tested combinations were Leachate 2 with bentonite D, and Leachate 5 with bentonite A. The two test results in each case were identical, thus satisfying the authors that the reliability of all test results is satisfactory.

3. RESULTS

The various bentonite/leachate combinations that were tested, along with the results, are given in Table 2. Although the results of Bentonite C (granulated) are included for interest's sake, the range and standard deviations of the results are calculated without this set.

Table 2. Swell Test Results in ml/2g

Leachate Bentonite	Distilled Water (1)	2 H:h	3 GLB-	4 GLB+	5 GLB-	6 H:H	7 GLB-	8 GLB-
A	30	11	5	19	11 &11	3	19	16
B	27	11	6	17	11	3	18	16
C	22	11	4	18	13	1	18	18
D	16	12 & 12	7	12	9	5	12	16
E	20	15	7	19	13	3	20	19
F	22	11	6	12	8	3	12	11
G	25	11	6	20	12	3	20	20
Std Dev	5.0	1.6	0.8	3.6	1.9	0.8	3.8	3.1
Range	16-30	11-15	5-7	12-20	8-13	3-5	12-20	11-20

4. DISCUSSION

4.1 Control Tests

The high standard deviation of the control test results highlights the variability of the results. When tested in distilled water, not all the bentonites achieved the required 24 ml/2g swell. Bentonites C, D, E and F all failed to meet this standard, while the natural sodium bentonite, the polymer enhanced, and the Australian product all exceeded the required standard.

Bentonite C (granulated bentonite) firstly is not applicable to the ASTM method due to its particle size distribution, and secondly probably exhibits a relatively low swell due to incomplete hydration of the granules. 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 C undergoes less swelling when exposed to the leachates than when exposed to distilled water.

Bentonite E is the fine material derived from crushing Bentonite C. It has been proposed based on observations in previous work (Johns, 2007) that the fine fraction of the *uncrushed, as-received* bentonite has a proportion of “filler” material which is not wholly bentonite. It is therefore possible that when crushed, the resulting product is a mixture of bentonite from the granules and filler from the remainder, the proportions of which are such that a low swell may result.

Bentonite D achieved only 16 ml/2g. This is probably a result of its predominant magnesium ion composition giving it inherently lower swell than sodium bentonites.

Bentonite F is of similar origin to Bentonite D which explains its relatively low swell. However this is a significantly better swell than that achieved by Bentonite D.

4.2 Performance in Leachates

Examination of the results given in Table 2 shows the following:

1. The swells resulting from exposure to Leachates 6, 3 and 2 are very low, also having low standard deviations, thus highlighting the very aggressive nature of these leachates and their detrimental effects on the bentonites. By examination of their chemical compositions the relationship between the low swells and the predominant cations and electrical conductivity is clear. In all cases it is either high concentrations of monovalent Na^+ and K^+ ions or the presence of divalent and trivalent ions such as Mg^{2+} and Ca^{2+} that result in the observed low swells. By casual examination of the chemical composition of Leachate 3 one might initially assume that it is fairly benign, but the very high concentration of Fe^{3+} ions (which is on the extreme right on the lyotropic series) suggests ready cation exchange and explains the resulting low swell.

2. There is a well defined relationship between electrical conductivity and swell. The relationship between average swell and electrical conductivity determined from this study is presented in Figure 5. This figure correlates well with Figure 1.

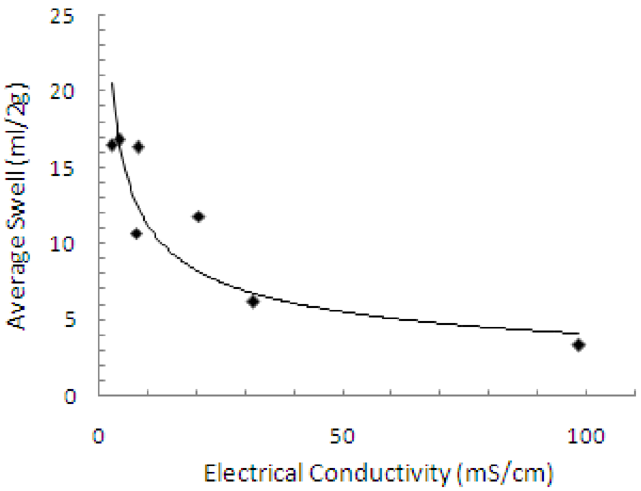

Figure 5 Swell of Tested Bentonites vs Electrical Conductivity of Leachates

3. The expected long-term hydraulic conductivities resulting from exposure to the three most aggressive leachates can be estimated by referring to the correlations determined by Kolstad et al (2004a) and Lee et al (2005) in Figures 1 and 2. The low swells would result in hydraulic conductivities of around 1 x 10^{-4} cm/s, equivalent to that of a fine sand. The results are unambiguous and the usual available benefits from the application of GCLs would not be realised at these sites and their use would be inappropriate.

4. The swells resulting from exposure to the relatively benign and similar leachates 4, 5, 7 and 8 would be expected to be similar and also fairly high. This is indeed true for Leachates 4, 7 and 8, achieving average swells of 16.5 ml/2g, 16.8 ml/2g and 16.3 ml/2g respectively. However, Leachate 5 has an average swell of only 10.7 ml/2g and a low standard deviation and spread of results, possibly due to its higher levels of K and Mg ions. The expected long-term hydraulic conductivities from exposure to these leachates (4, 7 & 8) is 10^{-8} to 10^{-7} cm/s from the Lee and Kolstad correlations, although this swell is on the cusp of a rapidly increasing hydraulic conductivity with lower swells. However, if one looked at Bentonites A , B and G for example, which have higher swells (17-20 ml/2g), the expected hydraulic conductivities would be comfortably around 10^{-8} cm/s. Leachate 5 could result in a hydraulic conductivity of between 10^{-8} cm/s and 10^{-4} cm/s and its use must be considered inappropriate, unless proven otherwise. For example, a factor that may improve its impermeability is a high confining stress.

5. While Bentonite A is one of the best performing bentonites in Leachates 4 and 7 it is not the best performer in Leachate 8. Therefore some bentonites are better suited to certain leachates than others. This emphasises the value of a testing program such as this one, so that the best product can be selected for the design.

5. CONCLUSIONS

It is noted that the curves developed in Kolstad et al. (2004a) and Lee et al. (2005) are for specific bentonites and specific leachates. However, it is indisputable that there is a strong inverse relationship between free swell and hydraulic conductivity, no matter the factors contributing to that swell. These index tests give one a qualitative idea of the performance of a GCL in a particular application, and in some cases can categorically rule out the use of GCLs for that application. The work shows that this is the case for Leachates 2, 3, 5, and 6.

There are also cases where there is some ambiguity, with a range of hydraulic conductivities possible at a certain swell. This is the case for Leachates 4, 7 and 8, depending on the bentonite. The present work looks at the effect of the leachates only and does not take into account the effects of confining stress, prehydration, or physical characteristics of the GCL such as needle punching, all of which will favourably affect the long-term hydraulic conductivity. One might consider the use of GCLs at sites generating leachates such as Leachates 4, 7 and 8 if there were few other practical options, and if performance of the GCL under field conditions could be proven, although the decision to undertake this extra investigative work would require application of sound engineering judgement and a well-defined risk and cost-benefit analysis.

The work shows that certain bentonites do not achieve the GRI standard of 24 ml/2g swell required for quality assurance purposes. If this is due to variability in the product, then this highlights the need to perform third party testing during construction if such a product has been specified.

The work also highlights that certain bentonites are better suited to certain leachates than others. In cases where their application is appropriate, there is an ideal bentonite or GCL for that case. This is supported in Johns (2007).

Another important observation is that one cannot assume that simply because one has a general waste site, one can safely apply GCLs. This is supported by the poor performance of all the tested bentonites in Leachate 3 which is generated at a G:L:B- site.

Finally a main conclusion must be that swell index testing when combined with established correlations is a valuable tool due to its cost-effectiveness, simplicity and the rapidity with which qualitative results can be obtained.

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