Bentonite:Kaolinite Clay Liner

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BENTONITE:KAOLINITE CLAY LINER

ABSTRACT: Conventional geosynthetic clay liners (GCLs) contain bentonite. Since high-quality bentonite is not easily available in Southeast Asia in comparison to kaolinite, an alternative cost-effective method is necessary. The concept of creating a GCL with a bentonite and kaolinite mixture on a biodegradable jute base is discussed in the present paper. The hydraulic conductivity and consolidation behaviour of bentonite: kaolinite mixtures was investigated. It was revealed that at least 30% bentonite was required in the mixture to result in the same decreasing coefficient of consolidation trend with pressure as shown using pure bentonite. The 50:50 bentonite:kaolinite (50:50 B:K) ratio yielded approximately the same hydraulic conductivity, *k*, as pure bentonite; hence, the remainder of the study focused on the 50:50 B:K mixture. For the 50:50 B:K mixture hydraulic conductivity measurements, the following permeants were used: (i) distilled water, (ii) 0.25M calcium chloride, (iii) 0.1M hydrochloric acid, and (iv) 0.1M sodium hydroxide. With the calcium chloride permeant, the hydraulic conductivity of the mixture was found to be in the range of 10^{-10} m/s, whereas the hydrochloric acid and sodium hydroxide permeants yielded values near 10^{-11} m/s. It was also found that the liquid limit and swell index tests carried out on bentonite and the B:K mixture were significantly affected by the presence of a large amount of calcium chloride. A jute-based clay liner was then created with the 50:50 B:K mixture. Its effectiveness in the landfill liner system was investigated for equivalency and was found to be satisfactory when using distilled water as the permeant. The biodegradability of jute and the effect of organic chemicals on the clays are beyond the scope of the present paper.

KEYWORDS: Geosynthetic clay liner, Bentonite, Kaolinite, Hydraulic conductivity, Jute.

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1 INTRODUCTION

One of the major challenges all nations face is the disposal of waste in a safe and environmentally sound manner. To safeguard the ground water and surrounding environment from pollutants originating from landfilled waste, an effective lining system is required in landfills to reduce the pollutant leakage to an acceptably low level. For this purpose, compacted clay liners (CCLs) were used in the early 70s and 80s, and, in recent years, geosynthetic clay liners (GCLs) assume an important role in landfill technology. High-quality bentonite in GCLs contains a high percentage of sodium montmorillonite, which has a hydraulic conductivity in the range of 10^{-11} to 10^{-12} m/s. High swell capacity associated with a very low hydraulic conductivity and diffusion coefficient make this clay suitable as a barrier material in landfills. High-quality bentonite deposits are not easily available, especially in Southeast Asia. On the other hand, kaolinite clay is more abundant; however, it has a larger hydraulic conductivity on the order of 10^{-7} to 10^{-9} m/s. A mixture of the two clays is a probable compromise for satisfying the required lower hydraulic conductivity.

The present paper reports the investigation conducted on bentonite:kaolinite (B:K) mixtures in assessing their relevant geotechnical properties when subjected to a variety of permeants. The complexity and importance of this study are evidenced by the large volume of research already conducted. Gleason et al. (1997) reported that calcium and sodium bentonite both suffered large increases in hydraulic conductivity, *k*, when permeated directly with 0.25M calcium chloride ($CaCl_2$). Ruhl and Daniel (1997) reported that permeation of GCLs with 0.1M hydrochloric acid (HCl) and 0.1M sodium hydroxide (NaOH) resulted in GCLs with high hydraulic conductivity.

The present paper reports the changes observed in consolidation, hydraulic conductivity, and other important index properties with the passage of different inorganic permeants in a B:K mixture used in a new clay liner. A woven jute geotextile was used as the liner base. Both the biodegradability of jute and the effect of organic permeants on the bentonite and kaolinite are beyond the scope of the present paper.

2 BACKGROUND

The purpose of a landfill is to protect the environment through the isolation of waste. To partially accomplish this goal, a top cover is designed to minimise the infiltration of water into the landfill. This water eventually percolates into the waste and supplements the leachate generated within the waste. The landfill bottom liner is designed to contain the leachate and provide a system for leachate removal and treatment.

A typical cover system for a hazardous waste landfill containing a GCL as part of the composite liner, following the United States Environmental Protection Agency (US EPA) guidelines, is shown in Figure 1. The GCL is placed directly beneath the geomembrane (Carson 1995). Under the GCL is a fine-textured soil compacted to 95 to 100% Standard Proctor and wet of the optimum moisture content. For municipal waste landfills, the landfill cover components essentially remain the same.

Figure 2 shows a schematic of a double composite bottom liner for hazardous

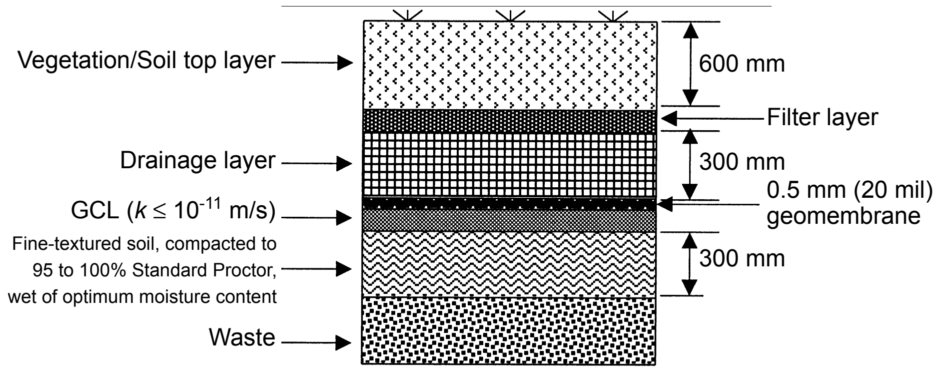

Figure 1. United States Environmental Protection Agency (US EPA) recommended landfill cover design (Carson 1995).

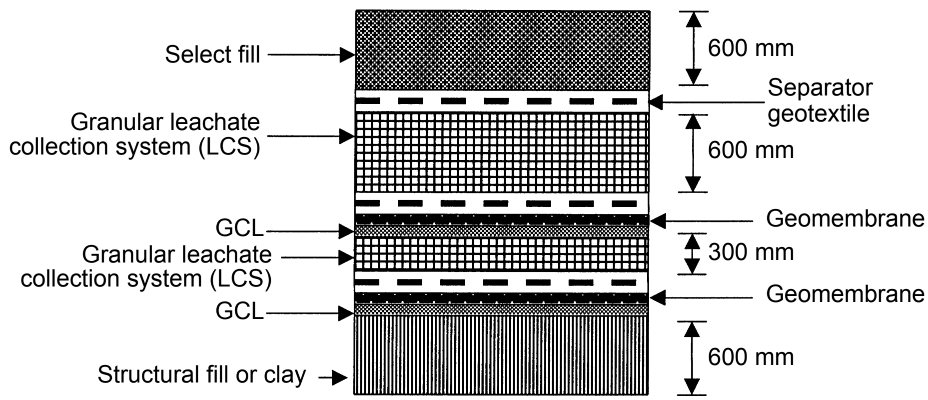

Figure 2. A possible configuration of a landfill double composite liner incorporating GCLs in the bottom liner system for hazardous waste (Carson 1995).

waste landfills. In this case, two geomembranes are used and a GCL is placed under each geomembrane. A 300 mm-thick granular leachate detection system (LDS) is placed between the geomembrane-GCL liners. All the above components are placed on a 600 mm-thick structural fill layer (or clay).

One of the most critical by-products generated by a landfill is toxic leachate, which is produced when the water percolating through the solid waste extracts dissolved material. During the natural degradation of solid waste, other soluble materials are formed, which are enhanced by the soluble materials formed with the action of leachate. The volume of leachate produced depends on the absorption capacity, areal extent, composition and placement of waste, cover material, operation of the landfill, and the amount of recharge water available for infiltration at any particular site (Cheremisinoff and Gigliello 1983). Leachate characteristics are generally highly variable, and it is unlikely that the exact composition of the leachate, which may be associated with a particular landfill at any given time, can be accurately predicted. The leachate characteristics depend on many factors including the material placement, stage of decomposition, chemical characteristics of the percolating water, cover soil, and the soil adjacent to the site. Therefore, the leachate may contain dissolved and suspended organic and inorganic substances as well as products of microbial activity (Cheremisinoff and Gigliello 1983).

Robinson and Luo (1991) reported that concentrations of chloride, sodium, and calcium were 552 to 2,740 mg/L, 217 to 2,100 mg/L, and 22.5 to 42.5 mg/L, respectively, within a pH range of 7.6 to 8.6 in the leachates of Pillar Point Landfill and Ma Yau Tong Landfill in Hong Kong. Leachate generation is a potential problem for tropical areas in Southeast Asia where high precipitation is generally coupled with low evapotranspiration and high ambient temperature. Without properly designed barrier systems this leachate may contaminate the ground water.

In Hong Kong, new environmental policy has led designers to opt for single and composite liners with the depth of waste in the landfill ranging from 30 to 80 m. Depths of 120 to 140 m have also been under consideration (Cowland 1991). The underlying ground varies from jointed rock to soft marine clays. The large amount of summer rainfall in Hong Kong is a major problem during construction, as well as for landfill operation. The high ambient temperature in the region also leads to rapid decomposition of waste causing generation of heat within the landfill, which may deteriorate liner performance and durability. It is very important, therefore, to reduce the potential leakage of leachate into the ground water regime using a high-quality and cost-effective liner system. This paper presents experimental details and salient properties such as hydraulic conductivity and consolidation of B:K mixtures that are proposed to replace the pure bentonite used in clay liners. Shear strength of the mixtures is reported elsewhere (Sinha 2000).

3 MATERIALS

Index properties of the bentonite and kaolinite used in the present investigation are summarised in Table 1. Oven-dried B:K weight ratios of 0:100, 0:90, 20:80, 30:70, 40:60, 50:50, and 100:0 were used; the index properties were measured and are presented in Table 2. Distilled water was used in these determinations. Heating to 105°C is known to reduce the plasticity of bentonite (Grim 1962); however, re-mixing of oven-dried bentonite with distilled water is expected to have a uniform influence over the range of mixtures used in the present study, and, hence, the effect of heating on all the mixtures is considered to be less important.

4 TESTING PROGRAM

One of the main objectives of the consolidation study was to verify the mix ratio that yields nearly identical hydraulic conductivity and consolidation properties of pure ben-

Table 1. Index properties of the bentonite and kaolinite used in the present study.

Item	Standard	Bentonite	Kaolinite
Liquid limit, w_L (%)	ASTM D 4318	465	74
Plastic limit, w_P (%)	ASTM D 4318	41	34
Plasticity index, I_P (%)	ASTM D 4318	424	40
Specific gravity, G_s	ASTM D 854	2.77	2.64
Silt (2 to 74 μm) (%)	ASTM D 422	22	13
Clay (< 2 μm) (%)	ASTM D 422	78	87
Cation exchange capacity (meq/100 g)	----	88	5

Table 2. Index properties of the bentonite:kaolinite mixtures used in the present study.

Bentonite:kaolinite ratio (B:K)	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Plasticity index, I_P (%)	Specific gravity G_s
100:0	465.0	41.0	424.0	2.77
50:50	243.0	28.5	214.5	2.71
40:60	187.0	27.4	159.6	2.70
30:70	150.5	26.5	124.0	2.69
20:80	118.5	25.3	93.2	2.67
10:90	99.5	27.4	72.1	2.65
0:100	74.0	34.0	40.0	2.64

tonite. Since measuring the hydraulic conductivity of clay takes a long time, values were measured using one-dimensional consolidation tests, which were subsequently compared with direct measurements. In addition, the hydraulic conductivity is dependent on the effective stress (and void ratio); hence, it is important to know the effective stress during consolidation to determine the hydraulic conductivity.

4.1 One-Dimensional Consolidation Tests

One-dimensional consolidation tests were carried out on clay mixtures remoulded at the liquid limit with distilled water to determine the change of consolidation properties with the addition of increased amounts of bentonite. Specimens were consolidated in stainless steel circular containers (70 mm in diameter and 19 mm high). Axial compression was measured using linear variable displacement transducers (LVDTs) having a precision of ±0.002 mm. The loading procedure comprised the following stages: (i) a seating pressure of 12.5 kPa was applied; (ii) stage loading up to 100 kPa with a load increment ratio of one was applied; (iii) unloaded to 25 kPa; and (iv) reloaded up to 800 kPa with a load increment ratio of one. As the depth of most landfills are in the range of 30 to 80 m, 800 kPa is a reasonably high enough stress for the investigation of consolidation properties.

4.2 Hydraulic Conductivity Tests

Direct hydraulic conductivity tests were conducted on bentonite, kaolinite, and a B:K mixture of 50:50 using 0.25M $CaCl_2$, 0.1M HCl, and 0.1M NaOH as permeants, simulating leachate environments with a high content of calcium chloride, acids, and alkalis, respectively (Robinson and Luo 1991). For bentonite, the investigation was confined to $CaCl_2$ because it has the potential to significantly increase bentonite hydraulic conductivity. In the present study, only inorganic chemicals were used to find an equivalent B:K ratio for pure bentonite. The behaviour of the B:K mixture with organic chemicals is beyond the scope of the present paper.

To save time, instead of gradually leaching out the distilled water with the above chemicals, the soils were freshly mixed with the permeants at the corresponding liquid limits (Table 3), and the hydraulic conductivity was measured after each consolidation stage using a falling head permeameter attached to the oedometer cells. Specimen saturation was ensured during the initial cell setup from the remoulded clay stage at the liquid limit. A 150 mm-diameter Rowe consolidation cell was used to establish a reference hydraulic conductivity under a constant head condition using distilled water for the kaolinite, the 50:50 B:K mixture, and the bentonite. All tests were carried out at a constant temperature of 25°C.

It should be noted that the hydraulic conductivity of a clayey soil depends on the effective stress and, hence, the consolidation pressure at each stage has to be realised before initiation of the hydraulic conductivity test.

A consolidation pressure of 35 kPa was used for all cases to facilitate comparison with the studies of Ruhl and Daniel (1997), Gleason et al. (1997), and Lentz et al. (1984), who considered 35 kPa as a suitable value. Swell index tests were conducted to find the effect of chemicals on the swell of the clay mixtures. The determination of hydraulic conductivity was a lengthy process. In the Rowe cell, the hydraulic gradient was maintained at approximately 30 and the inflow and outflow rates within 25% of

Table 3. Variation of the liquid limit, w_L , with different permeants and clay mixtures.

Permeant	Liquid limit, w_L (%)		
	Kaolinite	B:K = 50:50	Bentonite
Distilled water	74.0	243.0	465.0
0.25M calcium chloride ($CaCl_2$)	66.8	90.0	127.0
0.1M hydrogen chloride (HCl)	76.4	150.0	257.0
0.1M sodium hydroxide (NaOH)	51.5	285.0	502.0

each other (Koerner 1998). In the case of the falling head permeameter tests, only inflow was measured at regular intervals. Two pore volumes of flow through the specimen were considered necessary before termination of the test as prescribed by Bowders et al. (1986), who also suggested that the concentration ratio (the effluent concentration to the influent concentration) should approach unity. In the present study, as the soil was mixed with the permeant at the liquid limit and always kept saturated with the same permeant during upward flow through the specimen, the concentration ratio was always near unity.

4.3 Jute Geotextiles and the Jute-Based Clay Liner

A jute geotextile was used as the base for the clay liner. The following jute geotextile index properties were measured: mass per unit area, thickness, wide-width tensile strength, grab tensile strength, and puncture resistance. For the jute-based clay liner, index testing and performance testing were carried out. As part of performance testing, the hydraulic conductivity of the jute-based clay liner was determined using a Rowe cell at a consolidation pressure of 35 kPa with distilled water as the permeant. The specimen was submerged under water for 48 hours to ensure complete saturation and complete swelling.

No biodegradability tests were conducted on the jute; however, its short-term strength is considered adequate for construction purposes where long-term durability is not a requirement, e.g., sealing underground structures.

5 RESULTS AND DISCUSSION

5.1 Compression Index and Swell Index of B:K Ratios With Distilled Water as the Permeant

From the one-dimensional consolidation tests, it was found that the addition of only 10% bentonite doubled the compression index value, C_c , and tripled the swell index value, C_s , with respect to the values for pure kaolinite. The addition of 50% bentonite to kaolinite increased the C_c value by a factor of 10, whereas only 30% bentonite was required in the mixture to increase the C_s value by a factor of 10 (Ahmad et al. 2000). Figure 3 shows the increasing trend of C_c and C_s with increasing bentonite percentages.

5.2 Coefficient of Consolidation and Hydraulic Conductivity of B:K Ratios With Distilled Water as the Permeant

Figure 4 shows the variation of c_v with pressure obtained from oedometers and Rowe consolidation cells for different B:K ratios using distilled water as the permeant. The coefficient of consolidation, c_v , increases with increasing pressure for pure kaolinite and decreases for pure bentonite. For B:K = 20:80, the c_v values remain approximately constant with pressure except at high pressures. For B:K = 30:70, the c_v values display a decreasing trend with pressure similar to the results for pure bentonite. It is clear from Figure 5 that the addition of 10% bentonite reduces the c_v value by more than 10 times

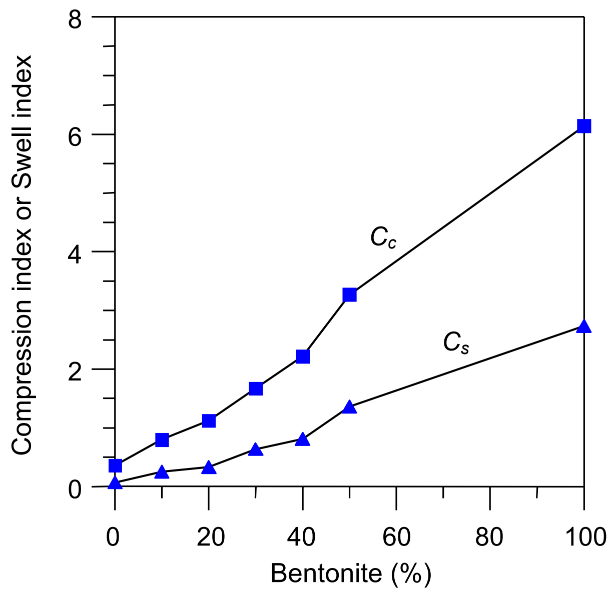

Figure 3. Variation of the compression index, C_c , and swell index, C_s , with percentage of bentonite content.

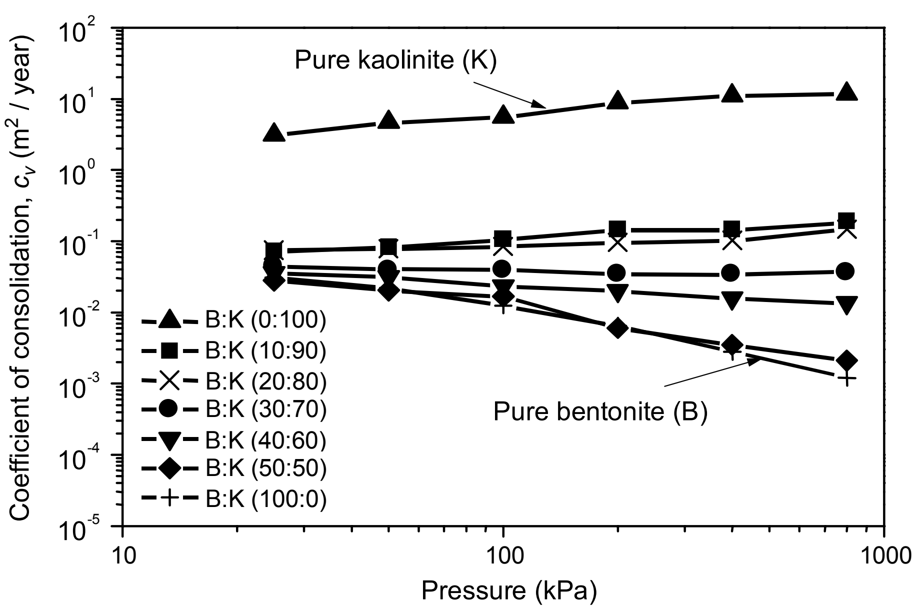

Figure 4. Variation of the coefficient of consolidation, c_v, with pressure for bentonite:kaolinite (B:K) mixtures using distilled water as the permeant.

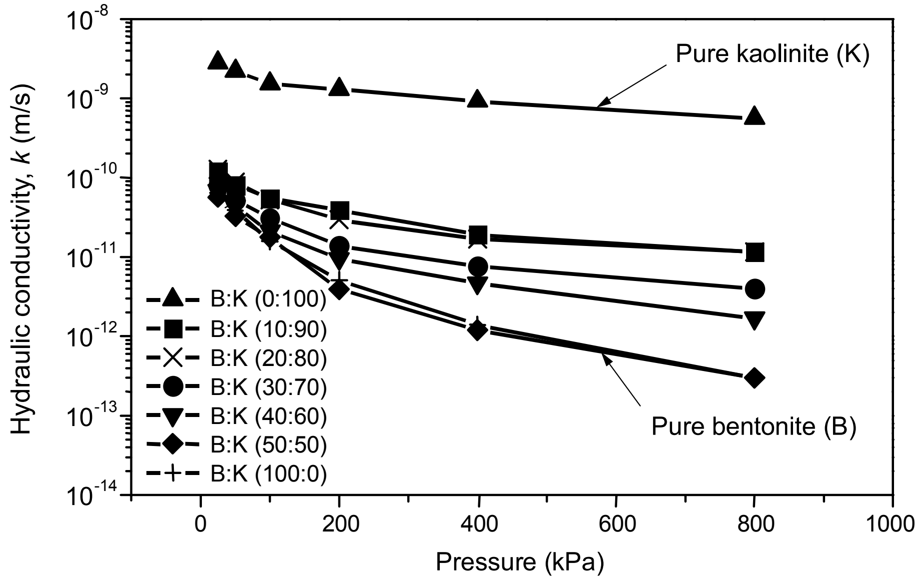

Figure 5. Variation of the measured hydraulic conductivity, *k*, with pressure for different bentonite:kaolinite (B:K) mixtures using distilled water as the permeant.

the c_v value of pure kaolinite. The variation of c_v for B:K = 50:50 was practically identical to that of pure bentonite. Thus, the mixture ratio of B:K = 50:50 is defined as the threshold mixture ratio. The measured hydraulic conductivity, *k*, versus pressure for different B:K ratios is shown in Figure 5. The variation of *k* for B:K = 50:50 is nearly identical to that of pure bentonite.

5.3 Liquid Limit and Swell Index of B:K Ratios With Different Permeants

Swell index tests and liquid limit tests were carried out with different permeants for bentonite, B:K = 50:50, and kaolinite. Figure 6 shows the variation of the liquid limit and Figure 7 shows the variation of the swell index with bentonite percentage. The 0.25M calcium chloride permeant reduces the liquid limit and swell index significantly compared to distilled water. Sodium hydroxide (0.1M) increases these values except for pure kaolinite. For the 0.1M hydrochloric acid permeant, the results are intermediary, but lower than that with distilled water.

5.4 Measuring Hydraulic Conductivity using Consolidation Cells

Direct hydraulic conductivity tests were carried out on pure kaolinite, B:K = 50:50, and pure bentonite in Rowe consolidation cells using distilled water as the permeant. To prevent chemical corrosion of the metallic parts of the cells from $CaCl_2$, HCl, and NaOH permeants, fixed-ring oedometer cells made with thick perspex were employed

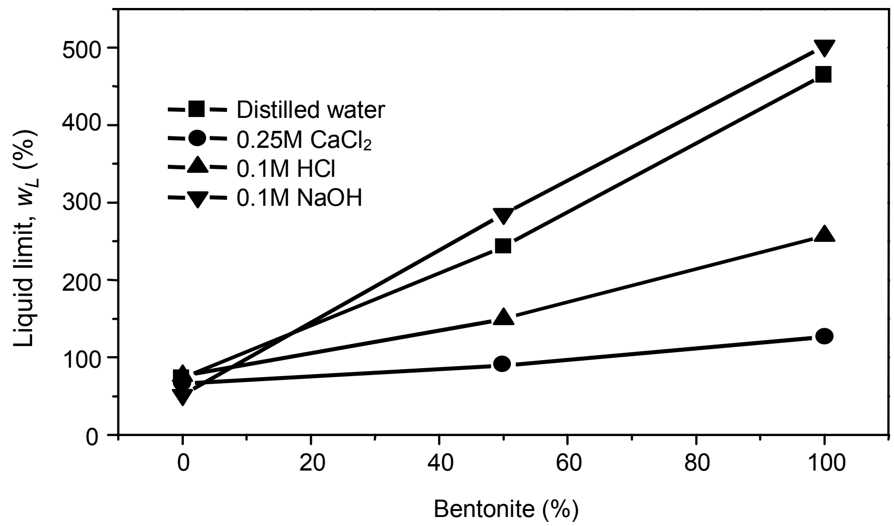

Figure 6. Variation of the liquid limit, w_L, with percentage of bentonite content.

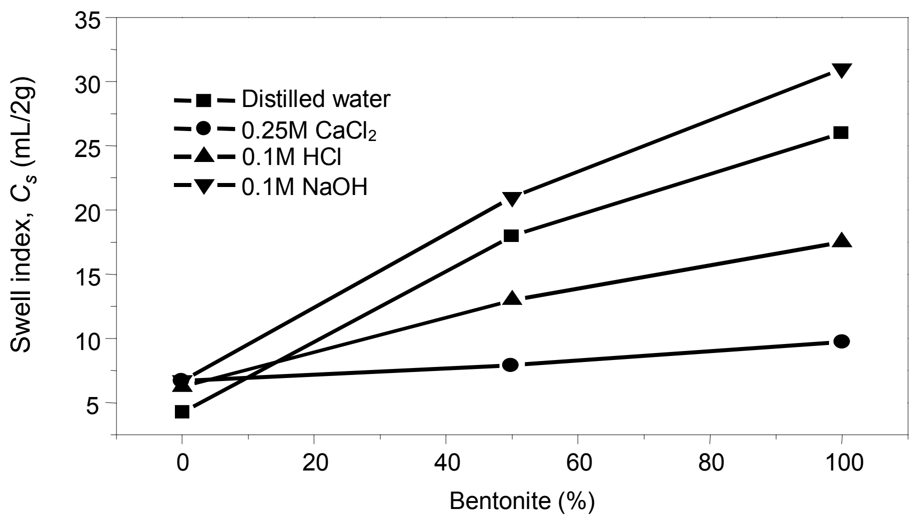

Figure 7. Variation of the swell index with percentage of bentonite content.

with a burette attached to the base of the oedometer cells for the determination of hydraulic conductivity based on the falling head method. Figures 8 and 9 show typical hydraulic conductivity measurements for a Rowe cell using the constant head method and for an oedometer cell using the falling head method, respectively. Figure 10 shows the variation of hydraulic conductivity for kaolinite, B:K = 50:50, and bentonite with

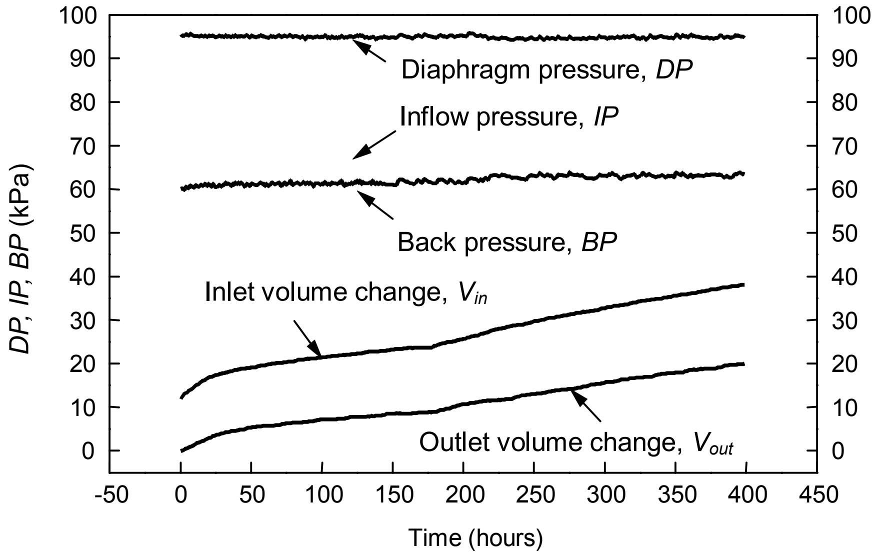

Figure 8. Typical results when evaluating the hydraulic conductivity, *k*, using the constant head method in a Rowe cell (permeant = distilled water, consolidation pressure = 35 kPa, B:K = 50:50).

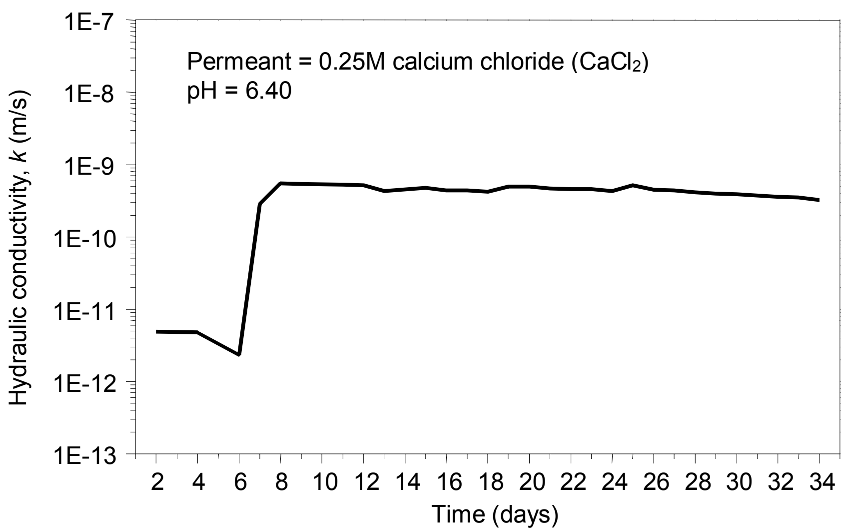

Figure 9. Variation of the hydraulic conductivity, *k*, with time using the falling head method (permeant = 0.25M $CaCl_2$, consolidation pressure = 35 kPa, B:K= 50:50).

distilled water as compared to calcium chloride, hydrochloric acid, and sodium hydroxide permeants. The calcium chloride permeant increased the hydraulic conductivity approximately 4.5 times for pure kaolinite, 16 times for B:K = 50:50, and 34 times for pure bentonite. The hydraulic conductivity values measured using Rowe cells under constant head conditions and oedometers under falling head conditions are approximately equivalent for B:K = 50:50 and using distilled water as the permeant. Hence, for other permeants, which are likely to corrode the metal lining, the falling head method was used at the end of each consolidation pressure increment.

In the following discussion, the hydraulic conductivity measured with the distilled water permeant is the basis for comparing hydraulic conductivity values. In the acidic environment simulated using HCl, it was found that the hydraulic conductivity of kaolinite increased by a factor of 9.25, whereas for B:K = 50:50 it increased by a factor of 2.5. The reduced liquid limit and swell index values, measured using simple geotechnical laboratory tests, may be used as a general indicator that the leachate was changing the properties of the clay, which may eventually lead to increased hydraulic conductivity values.

For the alkaline permeant (0.1M NaOH), the hydraulic conductivity increased by a factor of 1.62 for the kaolinite, but decreased by a factor of 1.26 for B:K = 50:50. The hydraulic conductivity values for kaolinite and B:K = 50:50 in distilled water, an acid, and an alkaline environment are also shown in Figure 10. Slight discrepancies in the liquid limit-hydraulic conductivity relationship may be attributed to experimental errors.

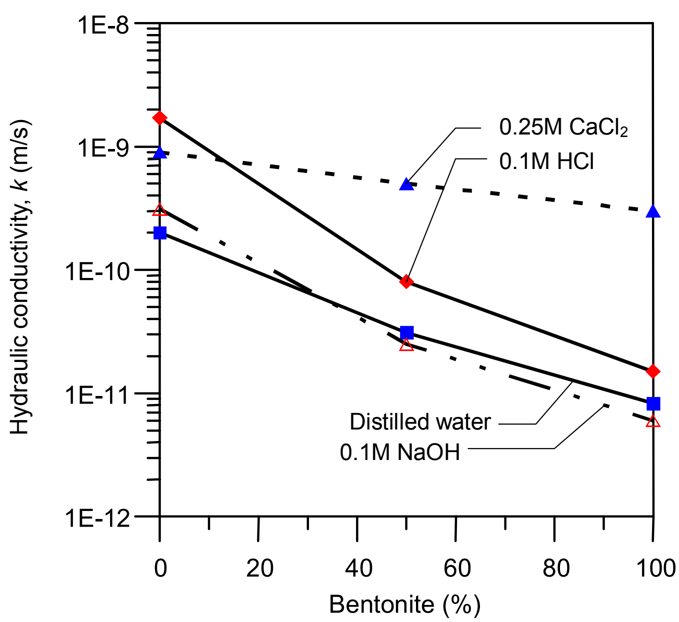

Figure 10. Variation of hydraulic conductivity, *k*, using the falling head method (permeants = distilled water, 0.25M $CaCl_2$, 0.1M HCl, and 0.1M NaOH; consolidation pressure = 35 kPa).

Gleason et al. (1997) found that the hydraulic conductivity of powdered bentonite (w_L = 590 to 603) increased from 6×10^{-12} to 1×10^{-10} m/s using a 0.25M $CaCl_2$ permeant and tap water (from Austin, Texas, USA) having a pH of 10, respectively: an approximate factor of 17 increase. In the current series of tests, the distilled water (pH = 6.8) may not have had sufficient ionic activity as compared to Austin tap water. However, because the ionic activity was not strong, it was considered suitable for comparative studies. The hydraulic conductivity of bentonite (Figure 10) with the $CaCl_2$ permeant is very similar to the results reported by Gleason et al. (1997). Lentz et al. (1984) reported that the hydraulic conductivity of kaolinite with HCl (pH = 1.0) was approximately 1.0×10^{-9} m/s, which is similar to the value in Figure 10 for the HCl permeant (pH = 1.40). Lentz et al. (1984) also reported that the hydraulic conductivity for kaolinite using a NaOH permeant (pH = 13.0) was approximately 4×10^{-10} m/s, which is also very similar to the value obtained for the NaOH permeant (pH = 13.1) shown in Figure 10.

It should be noted that, when using the falling head method to measure hydraulic conductivity, the pressure head at the inlet was approximately 5 kPa, which translates to an approximate hydraulic gradient of 25 to 32, depending on the specimen thickness. Due to this low gradient, each test, except the test using the calcium chloride permeant, required a few months for two pore volumes of the permeant to pass through the mixtures with higher percentages of bentonite. It was observed that the hydraulic conductivity was initially very low, but, with the passage of one pore volume of permeant through the soil, the hydraulic conductivity stabilised: as shown in Figure 9 for B:K = 50:50 using calcium chloride as the permeant. As the inflow increases to replace approximately one pore volume of the specimen, the hydraulic conductivity begins to increase and stabilise within 7 to 30 days depending on the type of permeant. For the 0.25M $CaCl_2$ solution, the time taken for stabilisation is approximately 7 days for a final specimen thickness of approximately 21 mm, while, for the 0.1M HCl and 0.1M NaOH permeants, the time required is approximately 30 days with a final specimen thickness of approximately 16 mm.

6 JUTE GEOTEXTILE AND ITS INDEX PROPERTIES

GCLs in the market today are factory-manufactured, polymer-based geosynthetics. The possible use of natural fabrics, such as jute or coconut coir, as the clay liner base is also investigated in the present paper. Figure 11 is a photograph of the jute geotextile used as the base material for the proposed clay liner in the present study. Table 4 presents the index properties of the jute geotextile. These properties include mass per unit area, thickness, grab tensile strength, wide-width tensile strength, and puncture. It can be seen that the jute geotextiles have sufficient short-term strength for installation stresses. With biodegradability, the strength will decrease within a few years (Ramaswamy 1998): the aspects of which are beyond the scope of the present paper. However, the hydraulic conductivity of the B:K mixture will not be affected by the jute strength.

Figure 11. The jute geotextile used as the base of the bentonite:kaolinte clay liner.

7 FABRICATION OF JUTE-BASED CLAY LINERS

A jute, geotextile-based clay liner was fabricated by compacting a clay layer on top of the jute sheet. A bentonite:kaolinite mixture of B:K = 50:50 with a water content of 70%, which is approximately twice the plastic limit, was used. The resulting clay liner had a mass per unit area of 10 kg/m^2 and an average thickness of 8 mm. Most commercially available GCLs have an overall mass per unit area of 4 to 5 kg/m^2 and a thickness of approximately 5 mm.

8 CONSOLIDATION AND HYDRAULIC CONDUCTIVITY OF THE JUTE-BASED CLAY LINER

Hydraulic conductivity is the most important design parameter for clay liners, as it is the single most influential drainage characteristic controlling the leakage of leachate through the liner. The jute-based clay liner was submerged in distilled water for 48 hours in a Rowe cell before the consolidation test. From the observed dial gauge readings, the liner thickness was estimated to have expanded to approximately 40 mm. Figure 12 shows the variation of the diaphragm pressure, *DP*, back pressure, *BP*, and the pore water pressure, u, during the consolidation process under a 17.5 kPa effective stress. Figure 13 shows the consolidation process under a 35 kPa stress. It should be evident that, when the pore water pressure equalled the back pressure, the consolidation under the prevailing effective stress was complete and direct hydraulic conductivity measurements could begin.

To measure the direct hydraulic conductivity, a low hydraulic gradient was first applied with the initiation of a head difference between the inflow and outflow, so as to avoid the risk of developing a hydraulic fracture in the specimen that could lead to unreliable results. The specimen thickness after the test was 12 mm. Figure 14 is a plot of the changes in pressure and volume over time for this test. After 8 days of permeation, the differential flow rates between the inlet and outlet reach within 25% of the

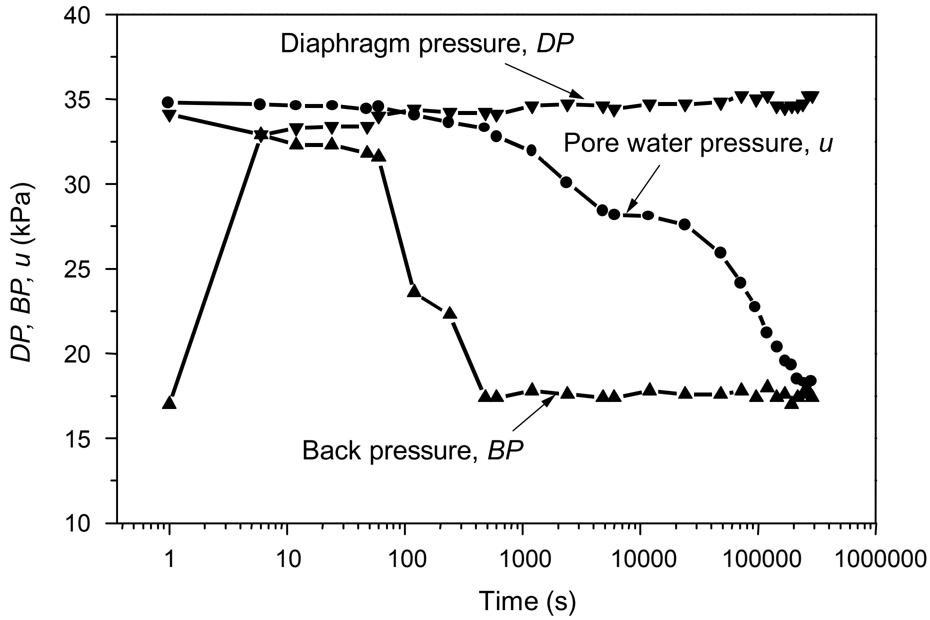

Figure 12. Consolidation of the clay liner with a jute geotextile base under an effective stress of 17.5 kPa.

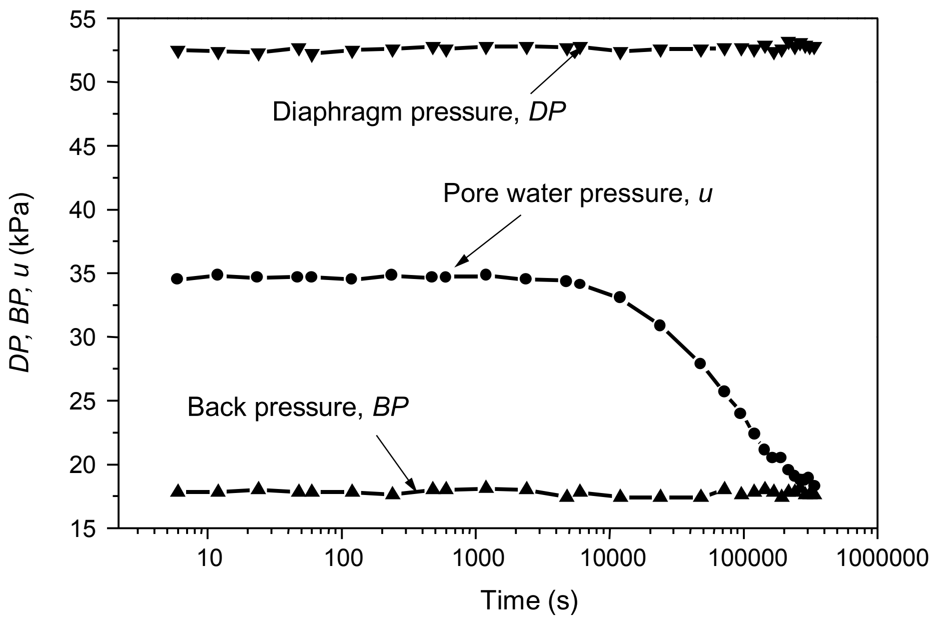

Figure 13. Consolidation of the clay liner with a jute geotextile base under an effective stress of 35 kPa.

inflow rate. The hydraulic conductivity of the 50:50 B:K liner was found to be 3.02 × 10^{-11} and 2.45 × 10^{-11} m/s based on the inflow and outflow rates, respectively.

9 EQUIVALENCY CRITERION FOR THE CLAY LINER

The following equivalency demonstration shows that a GCL-geomembrane composite system is equivalent or superior to a CCL-geomembrane system. Giroud et al. (1997) described an analytical method, which can assess the effectiveness of various composite liners with or without geomembranes. According to this method, the ratio of advective flow rates without a geomembrane is:

$$\frac{q_{CCL}}{q_{GCL}} = \frac{k_{CCL}(1 + h/t_{CCL})}{k_{GCL}(1 + h/t_{GCL})} \tag{1}$$

where: q_{CCL} = unit rate of flow through a CCL; q_{GCL} = unit rate of flow through a GCL; k_{CCL} = hydraulic conductivity of the CCL; k_{GCL} = hydraulic conductivity of the GCL; t_{CCL} = thickness of the CCL; t_{GCL} = thickness of the GCL; and h = head of leachate on the top surface of the liner. The ratio of the advective flow rate in the presence of a geomembrane is:

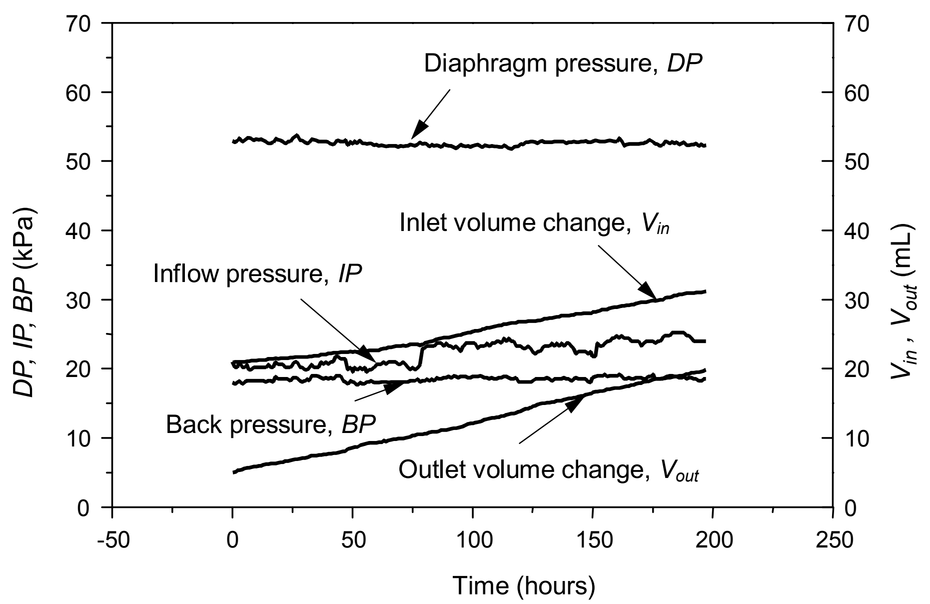

Figure 14. Determination of hydraulic conductivity, *k*, of the jute-based, 50:50 B:K liner in a Rowe consolidation cell (permeant = distilled water, consolidation pressure = 35 kPa).

$$\frac{q_{compCCL}}{q_{compGCL}} = \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \frac{1 + 0.1(h/t_{CCL})^{0.95}}{1 + 0.1(h/t_{GCL})^{0.95}} \tag{2}$$

where: $q_{compCCL}$ = unit rate of flow through a composite liner comprising a CCL; $q_{compGCL}$ = unit rate of flow through a composite liner comprising a GCL; t_{CCL} = thickness of the CCL in the composite liner; and t_{GCL} = thickness of the GCL in the composite liner.

According to USA Federal Regulations, a 0.6 m-thick single composite liner with a maximum hydraulic conductivity of 1×10^{-9} m/s is required for municipal solid waste landfills (Giroud et al. 1997). A CCL thickness of 0.6 m and a hydraulic conductivity of 1×10^{-9} m/s, which is considered as "the standard CCL", are used as the basis for comparison with the proposed jute-based clay liner. The average inflow and outflow hydraulic conductivities of the jute-based clay liner was found to be 2.74×10^{-11} m/s and its average thickness was 12 mm. These values are used in the equivalency demonstration calculations, with distilled water as the permeant.

The typical leachate head in landfills varies between 10 and 100 mm, and 300 mm is the maximum head permitted by regulation (Giroud et al. 1997). To evaluate the consequences of a gross malfunction of the leachate removal system, a 1 m head is considered. Figure 15 shows the ratio q_{GCL}/q_{CCL} (the inverse of the ratio of advective flow rates given in Equation 1) versus leachate head values up to 1 m. It is found that even for a leachate head up to 1 m, the unit rate of flow though the proposed jute-based clay liner is approximately 0.86 times greater than that through the standard CCL.

Using the same CCL and a geomembrane to form a composite liner, the results presented in Figure 16 are obtained. In this case, the flow rate through the proposed liner is 0.46 times the flow rate through the standard CCL for a leachate head of 1 m.

10 CONCLUSIONS

In the present paper, the concept of using a bentonite-kaolinite (B:K) mixture, instead of pure bentonite, with a jute geotextile as the base of a clay liner in a landfill application is discussed. The objective of the present study was to investigate the possible use of kaolinite to replace a percentage of the bentonite used in landfill cover and liner systems. One of the research objectives was to identify which B:K mixture, defined as the B:K threshold mixture ratio, behaves most similarly to pure bentonite. Hence, the changes of various index properties, consolidation properties, and hydraulic conductivity of that mixture under acidic, alkaline, and calcium chloride enriched environments when compared to pure kaolinite and bentonite is reported. A jute-based clay liner was then formed using this threshold B:K mixture and its hydraulic conductivity was measured using distilled water as the permeant. An equivalency demonstration was performed using the method proposed by Giroud et al. (1997).

Consolidation property comparisons of the B:K mixture, with those of pure bentonite and kaolinite, showed that at least 30% bentonite was required in the B:K mixture to obtain the same decreasing trend of c_v values in pure bentonite with increasing pressure. The addition of only 10% bentonite increased the swell index, C_s, of pure kaolinite by approximately 350% and the compression index, C_c, by approximately 225%.

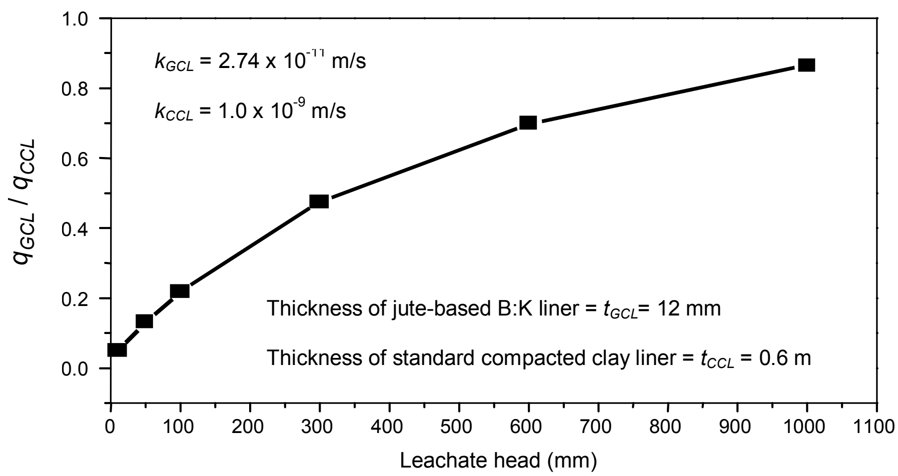

Figure 15. Variation of q_{GCL}/q_{CCL} versus leachate head for a jute-based bentonite:kaolinte liner and a bentonite:kaolinte CCL without a geomembrane.

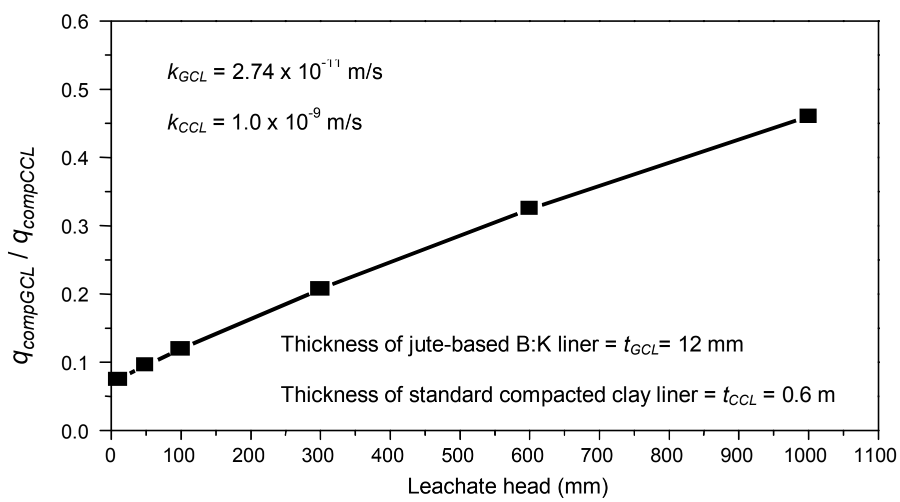

Figure 16. Variation of $q_{compGCL}/q_{compCCL}$ versus leachate head for a jute-based bentonite:kaolinte liner and a bentonite:kaolinte CCL with a geomembrane.

For B:K = 50:50, the swell index, C_s , and compression index, C_c , were approximately 50% of those for pure bentonite. The present study shows that the 50:50 B:K mixture results in coefficient of consolidation, c_v, and hydraulic conductivity, k, values approximately the same as that of pure bentonite. Therefore, B:K = 50:50 is the threshold mixture ratio.

As per US EPA regulations, the typical hydraulic conductivity value for GCLs should be between 10^{-10} and 10^{-12} m/s. From hydraulic conductivity tests using distilled water as the permeant, the average hydraulic conductivity of the 50:50 B:K mixture was found to be 3.14×10^{-11} m/s. When directly permeated with a 0.25M calcium chloride solution, the hydraulic conductivity of the 50:50 B:K mixture was approximately 5.0×10^{-10} m/s, which is approximately 16 times that of the mixture with distilled water as the permeant. This shows the effect of calcium chloride on the hydraulic conductivity of the B:K mixture, which cannot be ignored in the liner design. In the case of 0.1M hydrochloric acid and 0.1M sodium hydroxide permeants, the hydraulic conductivities of the 50:50 B:K mixture were approximately 8.0×10^{-11} and 2.50×10^{-11} m/s, respectively. It is clear from these values that, for the 50:50 B:K mixture all the hydraulic conductivity values were within the range of limits specified by the US EPA, except when calcium chloride was used as a permeant. In general, the variation of the liquid limit value of mixtures of clay soils appears to correlate with the hydraulic conductivity of the mixture.

Following the method proposed by Giroud et al. (1997) for equivalency demonstration, the proposed jute-based, bentonite:kaolinite clay liner was found to be superior to the standard 600 mm-thick CCL with a hydraulic conductivity of 1×10^{-9} m/s. The present study shows that the flow rate through the liner would be less than that for the standard CCL for leachate head values up to 1 m with or without a geomembrane. This demonstrates that a liner packed with a 50:50 bentonite:kaolinite clay mixture could be a cost-effective liner option. Natural geotextiles fabricated with jute or an equivalent, which are biodegradable, can be effectively used where short-term strength is required. Biodegradability of jute is beyond the scope of the present paper and, hence, the long-term stability of jute was not considered.

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NOTATIONS

Basic SI units are given in parentheses.

BP = back pressure (Pa)

C_c = compression index (dimensionless)

C_s = swell index (mL/2g)
c_v = coefficient of consolidation (m^2/s)
DP = diaphragm pressure (Pa)
G_s = specific gravity (dimensionless)
h = head of leachate on top surface of liner (m)
I_P = plasticity index (dimensionless)
IP = inflow pressure (Pa)
k = hydraulic conductivity (m/s)
k_{CCL} = hydraulic conductivity of CCL (m/s)
k_{GCL} = hydraulic conductivity of GCL (m/s)
q_{CCL} = unit rate of flow through CCL (m/s)
$q_{compCCL}$ = unit rate of flow through composite liner comprising a CCL (m/s)
$q_{compGCL}$ = unit rate of flow through composite liner comprising a GCL (m/s)
q_{GCL} = unit rate of flow through GCL (m/s)
t_{CCL} = thickness of CCL in composite liner (m)
t_{GCL} = thickness of GCL in composite liner (m)
u = pore water pressure (Pa)
V_{in} = inlet flow volume change (L)
V_{out} = outlet flow volume change (L)
w_L = liquid limit (%)
w_P = plastic limit (%)