Clayey barrier assessment for impoundment of domestic waste leachate (southern Ontario) including clay–leachate compatibility by hydraulic conductivity testing

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The current use of engineered clayey barriers to control the chemical flux entering the groundwater adjacent to landfill sites is discussed. New analytical methods to predict flux–time relationships controlled by advection and diffusion are presented briefly, followed by an assessment of macropore flow problems inherent in laboratory and especially field-compacted clays.

The clay–leachate compatability of southern Ontario (Sarnia) clays is then assessed with respect to domestic waste leachate using hydraulic conductivity as the assessment tool. The dominant role of channel flow through macropores, even in very carefully controlled laboratory samples, is emphasized, as is the critical role of soil smectite and vermiculite in retardation of species such as K^+ from domestic leachate.

The Sarnia brown and grey clays seem compatible with domestic waste leachate at least with respect to hydraulic conductivity, k. In spite of extensive K^+ retardation, leachate effected a slight decrease in k of the water-compacted brown and grey samples, a feature also observed recently for the contaminated grey clay zone at a field site.

Key words: clay barriers, hydraulic conductivity, compatibility, domestic leachate, channel flow, potassium retardation, migration modelling.

L'utilisation actuelle de barrières argileuses fabriquées pour contrôler le flux de produits chimiques vers l'eau souterraine à proximité des sites d'enfouissement est discutée. Des méthodes analytiques nouvellles pour prédire les relations flux–temps contrôlées par advection et diffusion sont présentées brièvement, suivies d'une évaluation des problèmes d'écoulement dans les macropores qui sont le propre des argiles compactées en laboratoire et particulièrement sur le terrain.

La compatibilité argile–lixiviat des argiles du sud de l'Ontario (Sarnia) est alors évaluée en regard des lixiviats de rebuts domestiques en utilisant la conductivité hydraulique comme crière d'évaluation. Le rôle dominant de l'écoulement à travers les cheminements préférentiels des macropores, même dans les échantillons de laboratoire contrôlés avec beaucoup de soin, est mis en évidence, de même que le rôle critique de la smectite et de la vermiculite du sol dans la retardation d'ions tels que K^+ des lixiviats domestiques.

Les argiles brunes et grises de Sarnia semblent compatibles avec les lixiviats domestiques au moins en regard de la conductivité hydraulique k. En d'epit de l'importante retardation de K^+, le leachate produit une légère diminution de k des échantillons des argiles brunes et grises compactées humidifiées à l'eau, une particularité qui a aussi été observée récemment pour la zone contaminée d'argile grise sur un site.

Mots clés : argile, barrières, conductivité hydraulique, compatibilité, lixiviat domestique, cheminement d'écoulement, retardation de potassium, modélisation de migration.

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Introduction

The use of clay barriers below waste disposal sites to protect underlying groundwater resources has become a contentious issue following experimental and field evidence of failure due to clay–leachate incompatibility and other factors (Anderson *et al.* 1982; Daniel 1984, for example). While some jurisdictions require clay-only barriers, others require synthetic liners often combined with clay liners and drainage systems.

For domestic waste systems, clayey barriers are still generally considered satisfactory. Normally, undisturbed, unfissured natural clay deposits are preferred over compacted clays; however, the latter are required if use is to be made of existing excavations such as abandoned rock quarries and gravel pits.

The purpose of a clay barrier is to reduce the chemical flux exiting from a landfill site to a level sufficiently low that subsequent groundwater dilution renders the water completely safe. To effect this reduction in flux, several requirements may be imposed on the operators: (1) the liner should have a minimum thickness of 1.0–4.0 m depending on whether domestic or industrial waste is being confined, (2) the hydraulic conductivity should be less than 10^{-7} or 10^{-8} cm/s, and (3) the hydraulic conductivity must not increase when permeated with the leachate from the contained waste.

In critical situations, a limit may be placed on the chemical flux exiting from the liner or there may be a requirement of nearly zero contamination beyond the lateral boundaries of the site. Chloride (Cl^-) is often used as the nonreactive (conservative) control solute. In some cases, the hydraulic gradient across the liner may be reduced to nearly zero by drains at the waste–liner interface or by pumping to remove leachate, which is then trucked to a treatment facility. In this case the chemical flux is controlled by diffusion due to the presence of chemical concentration gradients.

In less critical cases, the leachate level is allowed to rise to an equilibrium level *below* the toe of the landfill and advective flow through the barrier (under the higher gradient) is designed to equal rainwater infiltration through the cover. Some states actually require an undersaturated soil section below the base of waste facilities (Research Triangle Institute 1986).

A recent comprehensive review of lining technology was prepared for the United States Environmental Protection Agency (Matrecon Inc. 1983; Research Triangle Institute 1986). Other reviews have been prepared by Folkes (1982), Quigley *et al.* (1984, 1985), and Acar and Seals (1984).

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This paper is one of a sequence of papers dealing with domestic waste leachate migration through deep clay at the Confederation Road site, Sarnia, Ontario. Studies of field diffusion at the site were summarized by Quigley and Rowe (1986), who showed that the chemistry and the modelling had to be closely integrated. An assessment of chemically induced changes in hydraulic conductivity in the contaminated diffusion zone, directly below the waste, was recently reported by Quigley *et al.* (1987*b*). This paper has the twofold objective of reviewing recent flux prediction developments for barrier assessment, then discussing the results of laboratory hydraulic conductivity testing on the Sarnia clays to determine their "long-term" compatibility with respect to domestic waste leachate. This type of testing is frequently required as part of the permit requirements for development of a site.

Numerical modelling—prediction of fluxes

In the past, the calculation of contaminant concentrations and fluxes has most commonly been performed using simple closed-form expressions derived assuming either purely advective transport (plug flow) or pure diffusion. However, as will be shown in the following paragraphs, neither approach is conservative for realistic situations where both advective and diffusive–dispersive transport exist.

In principle, it is possible to calculate concentrations and fluxes for advective–diffusive transport for a wide range of conditions using well-established finite element and finite difference techniques (see Anderson 1979). While these approaches have met with some success in limited applications, they have not been widely used in the design of liners. The reason for this probably lies in the fact that considerable numerical expertise is required to use these techniques combined with the fact that numerical problems can arise when attempting to model predominantly diffusion-controlled contaminant migration through a clay liner and into an aquifer where contaminant transport is predominantly by advection.

Many soil deposits can be idealized as being horizontally layered and in these cases it is not really necessary or efficient to use finite element or finite difference techniques. Rowe and Booker (1985*a*, *b*, 1986*a*, *b*, 1987) have proposed an alternative finite layer procedure that can be used to calculate the concentrations of contaminants at specified locations and times of interest without determining the solution at all points and times. These analyses can be performed on a microcomputer and do not require an extensive knowledge of numerical analysis.

A detailed discussion regarding the merits of the various available techniques is beyond the scope of this paper. However, because applications of finite layer techniques to problems involving contaminant migration are relatively recent, the capabilities of this approach will be briefly described.

The finite layer technique involves splitting the soil deposit into separate layers. For example, separate layers may be used to model surface runoff, the clay cover, the waste, the clay liner, and any underlying aquifers, or other soil layers. The approach is semianalytic. An exact solution can be found for the variation of concentrations within each layer of the deposit; however, the computer is required to perform a number of integrations (specifically, to invert the Laplace transform and, for two- and three-dimensional problems, to invert the Fourier transforms). This approach permits consideration of

(1) a coupled diffusive (dispersive) – advective transport in any of the layers;

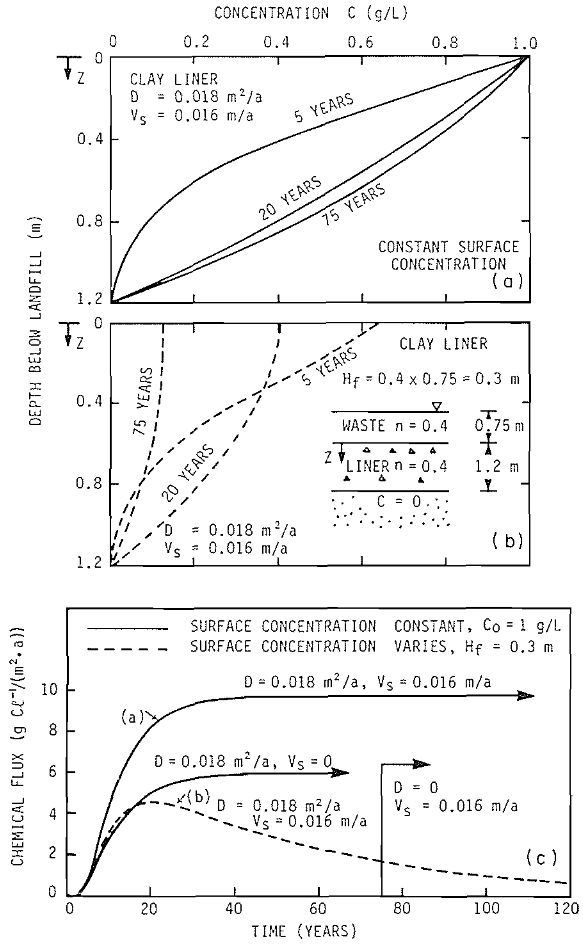

FIG. 1. Time rate of chloride migration, by advection and diffusion, through a 1.2 m thick clay barrier: (*a*) constant waste concentration; (*b*) decreasing waste concentration; (*c*) accompanying chloride flux–time curves (adapted from Rowe 1987).

(2) geochemical reactions between the clay and the contaminant (this may be particularly important for organic contaminants, heavy metal precipitation, potassium fixation, etc.);
(3) depletion of contaminant within the landfill with time due to mass transport into the clay cover and liner;
(4) contamination of both surface runoff and groundwater due to diffusive–advective contaminant transport;
(5) modelling different degrees of washing of the liner because there is different velocity of flow in any one aquifer;
(6) unidimensional, two-dimensional, or three-dimensional contaminant transport.

Space does not permit a detailed discussion of these various features; however, the importance of modelling diffusive–advective transport through clay liners can be illustrated by considering the movement of chloride through a 1.2 m thick clay liner. It is assumed here that the leachate with an initial chloride concentration of 1 g/L extends to a height of 0.75 m above the clay liner, so for a waste with porosity of 0.4, the actual volume of leachate per unit area, H_f, is equal to 0.3 m. For simplicity, it is also assumed here that the liner is totally washed by salt-free groundwater and thus the concentration at the base of the liner is zero. (Less extreme cases are also easily modelled; see Rowe and Booker (1985*a*, *b*).)

In many contaminant migration analyses, it is assumed that the concentration of contaminant remains constant for all time.

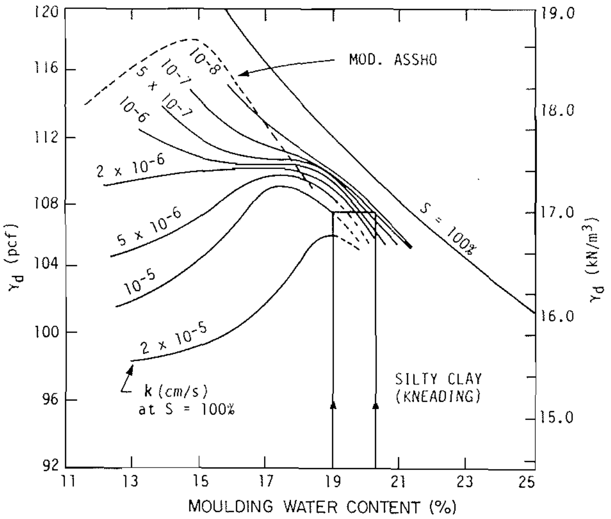

FIG. 2. Fracture-induced variability in laboratory-measured hydraulic conductivity vs. dry unit weight and moulding water content (adapted from Mitchell *et al.* 1965).

A plot of concentration versus depth for this case is shown in Fig. 1*a* for typical values of the effective diffusion coefficient, D, and average linearized seepage velocity, V_s. The corresponding chemical flux into the underlying aquifer is shown in Fig. 1*c*. In this case, chloride begins to arrrive at the base of the 1.2 m thick liner in approximately $2\frac{1}{2}$ years, even though the seepage front (assuming an average linearized seepage velocity) has only advanced 0.04 m in this time. After approximately 14 years the chloride flux has attained a value of 6.4 $g/(m^2 \cdot a)$ and continues to increase to a steady state value of 9.8 $g/(m^2 \cdot a)$. Considering advective transport alone, abrupt arrival of a flux of 6.4 $g/(m^2 \cdot a)$ would be predicted after 75 years. Thus, failure to consider diffusion would result in a gross overestimate of the time required to reach a flux of 6.4 $g/(m^2 \cdot a)$ as well as 35% underestimate of the final steady state flux.

Both diffusion and advection make significant contributions to the contaminant transport. If advective transport was neglected ($V_s = 0$), then the chemical flux would increase to a steady state value of 6 $g/(m^2 \cdot a)$ after approximately 50 years, as shown in Fig. 1*c*.

Although it may sometimes be convenient and conservative to assume that the concentrations of contaminants within the leachate remain constant, in most practical situations it will vary. For example, as contaminant is transported into the soil, the mass of contaminant (and hence generally the concentration) in the leachate will reduce with time. This situation can be readily modelled using the finite layer approach, and the variation in concentration with depth obtained by modelling the decrease in concentration in the leachate is shown in Fig. 1*b*. In this case there is a substantial decrease in contaminant concentration with time in the landfill. For example, after 20 years the concentration in the landfill has reduced to 40% of its original value. The chemical flux into the aquifer given in Fig. 1*c* shows an increase with time until a maximum chloride flux of approximately 4.5 $g/(m^2 \cdot a)$ is reached after 20 years. The flux then decreases for subsequent times. In this case, the assumption of a constant contaminant concentration within the landfill may result in an overestimate of the flux loading of the aquifer by a factor of 2 or more.

The foregoing example illustrates the importance of considering both advection and diffusion when calculating contaminant fluxes through a clay liner. Clearly, the fluxes are dependent on the diffusion coefficients as well as the hydraulic conductivity for the particular contaminants and liner material under examination. The determination of appropriate diffusion coefficients for the case of simple salts has recently been discussed by Rowe *et al.* (1988) and the problem of coefficients for co-diffusion will be addressed in a future paper. The previous discussion has ignored the possible presence of interconnected compaction-induced fractures that may transfer chemicals through the liner at a very rapid rate along certain restricted flow paths. The highly variable arrival time is normally modelled by replacing the diffusion coefficient characteristic of a homogeneous clay barrier with a dispersion coefficient that is normally much larger. In the following section, discussion is focused on the factors affecting the hydraulic conductivity of a clay liner, in particular, the role of macropores and their effect on the rate of clay–leachate interaction. In this paper no attempt is made to model the effects of fractures.

Soil compaction and the macropore problem

To achieve the lowest possible values of hydraulic conductivity, k, compaction of clayey soils is performed using kneading procedures on clayey soil slightly wet of optimum for the compactive effort employed. In the field, such a procedure would involve excessive passes of a club foot or wedge foot roller, and in the laboratory, a spring-loaded kneading rod could be used as in Harvard miniature compaction. A thorough discussion of the interrelationships between k, moulding water content, compaction methods, percent saturation, and aging is presented by Mitchell *et al.* (1965) and summarized by Quigley *et al.* (1985) and Acar and Seals (1984).

Even with the best of compaction procedures, sheared fracture surfaces and macropores between original soil lumps may remain after placement, resulting in k values larger than those for a uniform pore size distribution (Mitchell and Madsen 1987). Field k values 100 – 10 000 times greater than those predicted from lab tests have been discussed by Daniel and coworkers (Daniel 1984; Day and Daniel 1985; Daniel and Trautwein 1986) for example. Accidental drying and (or) ice lensing greatly aggravates the problem.

In the laboratory, up to 1000-fold variations in k can occur for a soil at a given void ratio or density depending on the compaction procedures employed. This is illustrated in Fig. 2, which shows that a silty clay soil compacted by kneading to a density of 17.0 kN/m^3 at moisture contents between 19.0 and 20.3% can exhibit laboratory-measured k values between 10^{-5} and 10^{-8} cm/s.

The general requirement that the hydraulic conductivity of a barrier soil not increase when permeated with the leachate to be contained requires laboratory measurement. Since clayey soils have a low permeability, rather high gradients (100–3000) may be required to obtain a cost-effective testing time, which can still be as long as 3 months. The forced flow generated by these gradients takes place along the previously described fractures and interconnected macropores, making chemical assessment of clay–leachate compatibility very complex.

Soil – domestic leachate compatibility

The inactive soils of southern Ontario whose clay minerals consist of illites and chlorites are relatively insensitive to leachate from domestic waste. In fact, k will normally decrease

TABLE 1. Silty clay composition (Sarnia)

Component	Brown clay (0.3 m)	Grey clay (11.0 m)
Quartz and feldspar	~20%	~17%
Carbonates	~10%	~35%
Illite	~50%	~25%
Chlorite	~ 8%	~22%
Smectite	~15%	~ 1%
Cation exchange capacity	~25 meq/100 g	10 meq/100 g
<2 μm	~60%	~42%

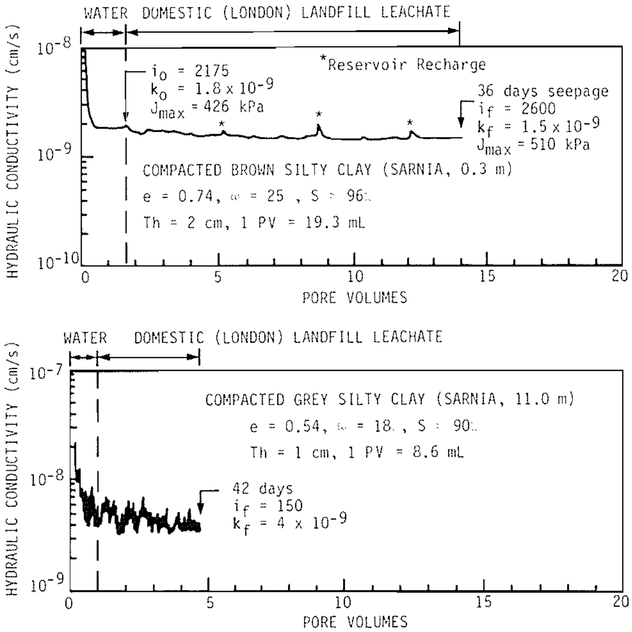

FIG. 3. Hydraulic conductivity of brown and grey Sarnia clays permeated with domestic waste leachate (i_f = final gradient).

(Griffen *et al.* 1976) probably because of Na^+ adsorption, double-layer expansion, and possibly bacterial clogging.

If the soils contain significant amounts of swelling clay (here defined as vermiculite, montmorillonite, or interlayered illite–smectite), *c*-axis contraction or expansion is another complicating factor and can respectively increase or decrease *k*. For example, K^+ fixation by vermiculite effects a 28% decrease in crystal volume plus a contraction of the double-layer thickness because the charge deficiency (and hence the cation exchange capacity) is reduced equivalent to the amount of K^+ fixed. Such phenomena should contract the soil peds, open further the voids or fractures between them, and thus cause increases in the hydraulic conductivity. If a high effective stress is present on the clay liner, chemically induced consolidation should help compensate for any chemically induced increase in the size and frequency of the macropores.

The research results described in the rest of this paper were conducted on soils from Sarnia, Ontario, and represent both weathered, brown, smectite-enriched clays from the desiccated, oxidized crust and unweathered grey clays below the crust (Quigley and Ogunbadejo 1976). The range of soil composition is presented in Table 1.

The smectite in these clays is a high-charge montmorillonite produced by oxidation weathering of iron chlorite present in the unweathered grey clays.

The hydraulic conductivity tests were run for the most conservative case of zero vertical *static* stress on the soil samples. The gradients developed by the constant flow rate test system are dependent on *k*, and for the two tests shown in Fig. 3 were 2600 and 150 for the brown and grey clay respectively. The corresponding values of J_{max}, the maximum seepage stresses at the base of the test specimens, were approximately 510 and 15 kPa, respectively.

Typical hydraulic conductivity curves are presented in Fig. 3 for these two clayey soils and the following observations can be made:

(1) Domestic waste leachate causes a slight reduction in hydraulic conductivity for both the brown and grey clays for the test procedure employed.

(2) The grey clay has a higher *k* than the brown clay (4×10^{-9} compared with 1.5×10^{-9} cm/s), even though it is at a much lower void ratio (0.54 compared with 0.74).

(3) The greater smectite content of the brown clay is in part responsible for its lower *k* value. Also, it will be illustrated later that the denser, grey clay sample contains compaction-induced fractures that allow channel flow.

Curves for the ratio of concentrations in the effluent to those in the influent (C/C_0) are shown in Fig. 4 to illustrate the clay–leachate compatibility of the brown clay compacted to void ratios of 0.54 ("dense") and 0.74 ("loose"). The upper curves (Fig. 4*a*) are nearly "classical" and indicate almost homogeneous flow through equal-sized voids and arrival of the 50% chloride front at close to 1 pore volume (PV). The lower curves demonstrate early arrival and tailing, both indicative of channel flow. The most important aspects of this figure are

(1) Both sets of curves show Na^+ and K^+ retardation due to adsorption onto the clays and resultant displacement of Ca^{++} and Mg^{++} to form a hardness halo effect.

(2) Conservative chloride reaches $C/C_0 = 0.5$ at ~0.8 PV of leachate flow for the "loose" soil (Fig. 4*a*) compared with 0.1 PV for the dense soil (Fig. 4*b*), indicating almost homogeneous flow through the former and channel flow through the latter.

(3) In the absence of macropores, the "dense" soil should retard more K^+ than the "loose" soil, whereas the opposite appears to occur. The higher (early) K^+ values indicate channel flow along compaction-induced fractures.

(4) For sodium, C/C_0 reaches 0.5 at 1.4 PV of leachate flow, indicating the expected retardation (by adsorption) for the "loose" soil (Fig. 4*a*). For the "dense" soil, C/C_0 reaches 0.5 at only 0.8 PV, again indicating early arrival due to channel flow through this sample. This occurs in spite of the much lower gradient on the dense sample compared with the loose sample ($i_f = 150$ compared with 2600).

(5) The abrupt flattening of the sodium curve (Fig. 4*b*) and the long slope towards $C/C_0 = 1$ is called tailing and indicates fracture or macropore flow with gradual diffusion of Na^+ into the pore fluid of the adjacent soil peds and ultimately cation exchange onto the clay.

The extent of K^+ adsorption from domestic leachate by the Sarnia soils increases with increasing amounts of smectite in the specific test specimens. Since the smectite increases from about 1% in the grey clays to about 15% near surface as a result of oxidation weathering of chlorite, much more retardation should occur with passage of leachate through near-surface soils.

This phenomenon is illustrated in Fig. 5, which shows C/C_0 curves for K^+ generated by domestic leachate influent passing through clayey samples from 0.3, 1.7, and 11.0 m depths. The

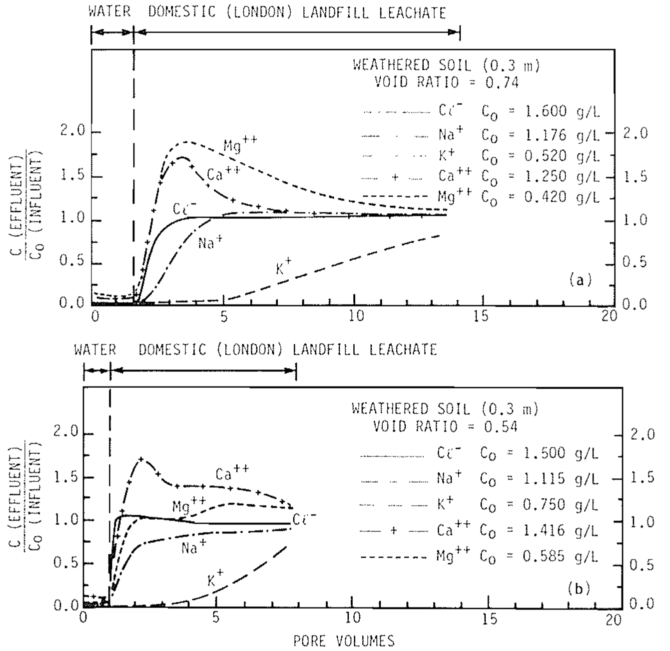

FIG. 4. Effluent chemistry vs. pore volumes of leachate passed through, showing effects of compaction-induced fractures: (*a*) compacted at $e = 0.74$ with few fractures and homogeneous flow; (*b*) compacted at $e = 0.54$ with inferred fractures, channel flow, and early arrival of influent leachate.

samples from 1.7 and 11.0 m were undisturbed Shelby tube samples and the 0.3 m sample was the compacted but unfractured "loose" sample previously shown in Fig. 4*a*. It is believed that the three samples were essentially free of fractures and macropores and that the various degrees of K^+ retardation reflect increasing smectite towards surface.

X-ray diffraction traces obtained on the <2 μm fractions of the surface and deep soils, natural and KCl treated, are shown in Fig. 6. Considering first the grey unweathered clay (bottom traces), it can be seen that the clay minerals are dominated by illite and iron chlorite. KCl treatment and air drying have relatively little effect on the X-ray traces, indicating an absence of smectite–vermiculite.

The weathered brown surface clay in the air-dry state (dashed trace, Fig. 6*b*) shows very significant collapse of smectite due to 0.5 *N* KCl treatment if air dried (solid trace). The 1.4 nm peak is greatly reduced and the 1.0 nm peak greatly strengthened. In the water-wet state (Fig. 6*a*), however, little collapse occurs except in the interlayered illite–smectite phase indicated by the high background between 1.0 and 1.4 nm that develops after KCl treatment.

The results of the X-ray study are summarized in Fig. 7, which is a plot of the 1.5:1.0 nm peak height ratios before and after KCl treatment. If the clays are air dried (ADPO), a very large decrease occurs as a result of K^+ fixation and *c*-axis contraction of the smectite minerals. In the water-wet state, however, much less collapse occurs, indicating that the swelling clay is a relatively low charge variety (i.e., smectite) that will adsorb but not fix as much potassium as a true vermiculite would. Since clay liners will remain wet for the life of a landfill if maintained properly, it is the water-wet or leachate-wet behaviour that is pertinent to performance.

Soil samples treated with leachate containing only 0.75 g/L of K^+ (0.02 *N*) showed very little collapse, even though K^+ was very greatly retarded by preferential adsorption as shown in Figs. 4*a* and 4*b*.

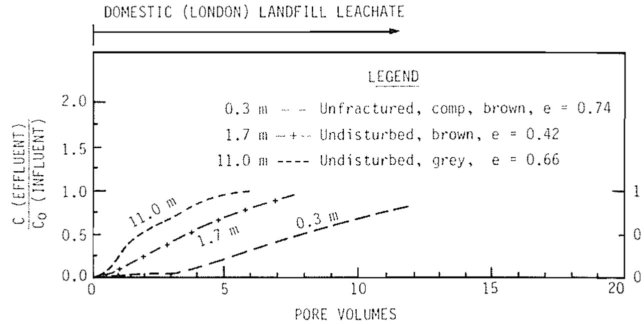

FIG. 5. Potassium retardation illustrated by effluent concentrations for Sarnia clayey soils from three depths (controlled by increasing smectite towards surface).

The concept of retarded arrival of chemicals due to diffusion into the surrounding soil from a flow channel is well described in Freeze and Cherry (1979). A numerical evaluation of the factors controlling retardation in fracture flow situations was presented by Grisak and Pickens (1980) and Grisak *et al.* (1980). A summary plot of the role of velocity, fracture size, dispersivity, matrix diffusion coefficient, and distribution coefficient is presented in Fig. 8 adapted from Quigley *et al.* (1987*a*). Regardless of the combination of system parameters employed, a major requirement of a clay–leachate compatibility test using hydraulic conductivity as the assessment tool is that the soil come into chemical equilibrium with the permeant leachate before the test is terminated.

Figure 9 illustrates the effect of fractures on the retardation of highly soluble potassium (K^+) for both the brown and grey clays. The solid curves represent unfractured or undisturbed specimens, whereas the dashed curves represent fractured specimens compacted at a low void ratio of 0.54 (i.e., fractured by the compaction process). It is quite clear that early arrival of K^+ occurs as a result of fracture flow. For the two unfractured soils, from 0.3 and 11.0 m, passage of ~15 and ~6 PV of leachate was required (Fig. 9) for the effluent and influent liquids to contain equal amounts of K^+. If flow through the soil was homogeneously through equal pore sizes, it could be reasonably assumed that equilibrium had been reached, at least with respect to soluble chemical species. Testing times for these two tests (0.3 and 11.0 m) were 5 and 7 weeks at gradients of 2600 and 2000, respectively.

For the two fractured samples, equilibrium might be difficult to establish because K^+ would have to diffuse from the flow channels into the pore fluid in the adjacent soil peds and then adsorb onto the clay minerals before equilibrium is reached. Arrival of C/C_0 values equal to 1 after a long period of tailing would probably indicate equilibrium. If, however, the fractures opened further owing to soil shrinkage, the hydraulic conductivity would increase and C/C_0 would equal unity after a very short testing time without equilibrium being reached.

Since the hydraulic conductivity of the Sarnia clays did not increase as a result of K^+ retardation, it is concluded that the K^+ did not actually fix in position and collapse the high-charge wet smectite to illite. For other weathered soils containing abundant, higher charge vermiculite, however, such fixation and collapse could occur even in the wet state. It is very important, therefore, to assess the clay mineralogy and the clay–leachate compatibility at other sites, keeping in mind the

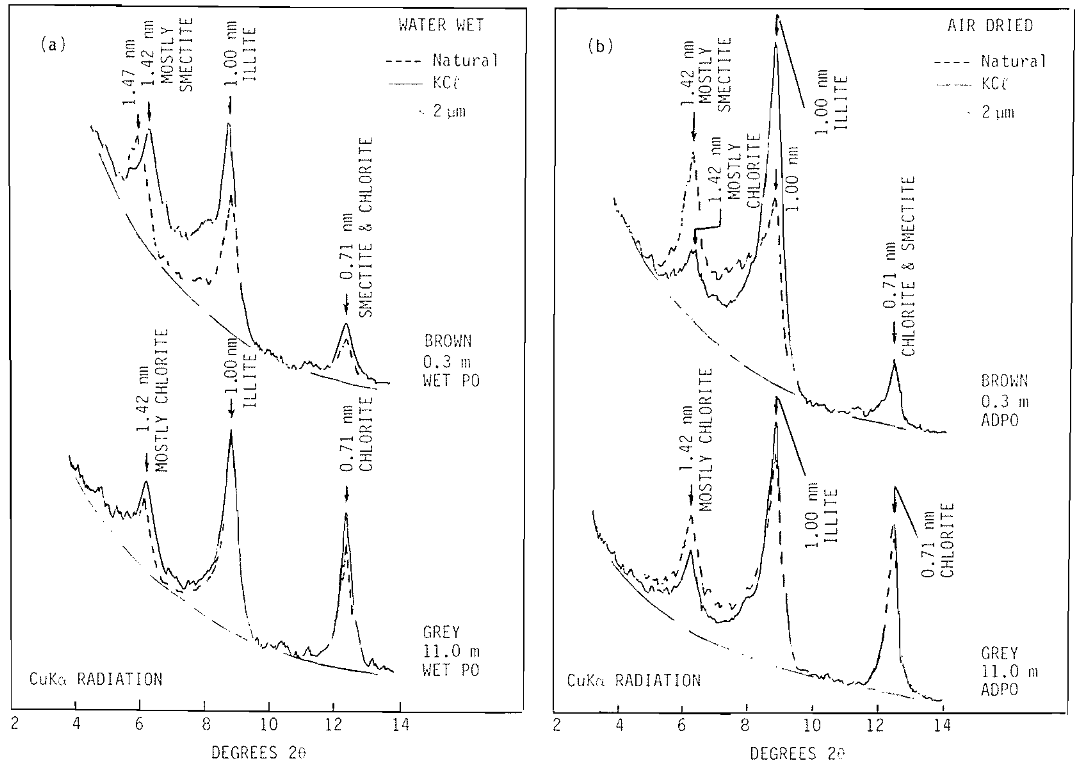

FIG. 6. X-ray diffraction traces of oriented, <2 μm fraction of Sarnia clays from 0.3 and 11.0 m depth, natural and KCl treated: (*a*) water wet; (*b*) air dried.

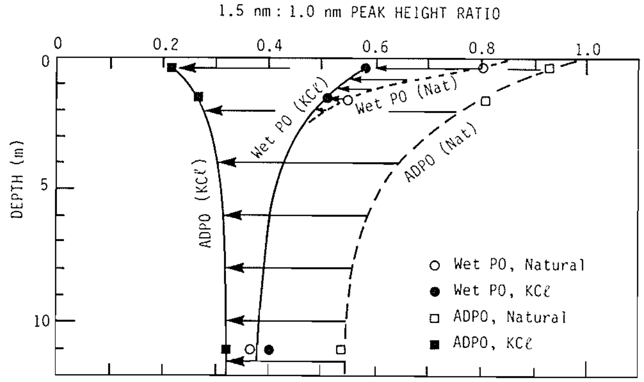

FIG. 7. Ratio of 1.5:1.0 nm peak heights illustrating collapse of smectite by KCl treatment (wet PO = water wet, preferred orientation; ADPO = air dried, preferred orientation).

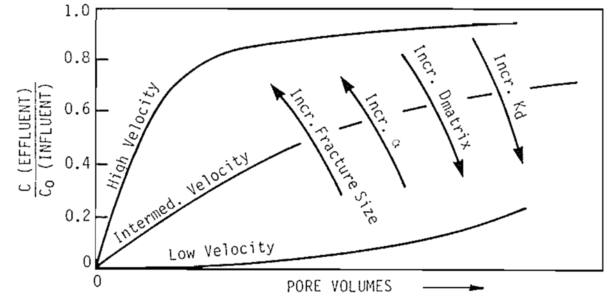

FIG. 8. Factors affecting chemical attenuation during hydraulic conductivity testing through soils containing fractures or connected macropores (α = dispersivity; D = diffusion coefficient; K_d = distribution coefficient). Adapted from Grisak and Pickens (1980) and Quigley *et al.* (1987*a*).

interpretation and control problems created by any fractures or macropores present in the test specimens.

Conclusions

Based on the results presented in this paper, it may be concluded that

(1) Both diffusion and advection (seepage) can make a significant contribution to contaminant transport through clay liners. Failure to consider both factors may result in quite unconservative predictions of the flux loadings beneath the liner as well as the time required to reach a maximum flux loading.

(2) Decreasing contaminant concentration with time within a landfill may have a significant effect on the flux loading of an aquifer beneath a clay liner. The assumption of a constant contaminant concentration with time within the landfill may be excessively conservative.

(3) Owing to the development of interconnected macropores, variations in hydraulic conductivity, *k*, of 1000-fold can occur for a soil at a given density, depending on the compaction procedures employed. In the field, this could give rise to excessive advective transport. In the laboratory, this may make assessment of clay–leachate compatibility difficult because increases in hydraulic conductivity that are attributed to leachate–soil interaction may, in fact, be simply due to channel flow through macropores created during compaction. Any shrinkage due to leachate–soil interaction may further increase channel flow through the macropores.

(4) Retardation of potassium by soils containing smectite–vermiculite may impose testing times of up to 4 months to establish the compatibility of the clay with the domestic leach-

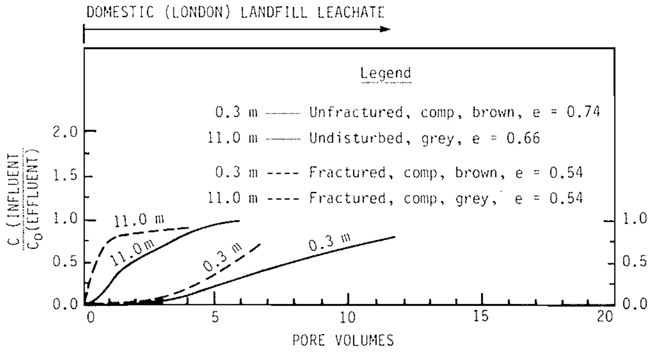

FIG. 9. Influence of compaction-induced fractures and interped macropores on potassium retardation curves (comp = kneading compaction).

ate with which it will make contact. The choice between (1) a very high gradient test with channel flow and a short testing time and (2) a low gradient test with a long, expensive testing time is a very complex technical versus economic decision. The relative importance of diffusion on testing time for the two scenarios has yet to be clarified.

(5) Based on the results presented in this paper, both the grey and brown Sarnia clays are compatible with domestic waste leachate, at least with respect to hydraulic conductivity. Much more testing is required on soils containing more abundant smectite and high-charge vermiculite.

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