MUNICIPAL SOLID WASTE LANDFILLING
ENFOUISSEMENT SANITAIRE

R.M. Quigley

Geotechnical Research Centre
Faculty of Engineering Science
The University of Western Ontario
London, Canada, N6A 5B9

Prepared for the First International Conference on
Environmental Geotechnics, ISSMFE
Edmonton, July 1994

Geotechnical Research Centre Report
GEOT-1-94
January 1994

ISSN 0847-0626

MUNICIPAL SOLID WASTE LANDFILLING
ENFOUISSEMENT SANITAIRE
R.M. Quigley January 1994 GEOT-1-94

MUNICIPAL SOLID WASTE LANDFILLING
ENFOUISSEMENT SANITAIRE

Robert M. Quigley, Geotechnical Research Centre
The University of Western Ontario, London, Canada

SYNOPSIS: The short and long term performance of clayey barriers (the cheapest way to encapsulate waste) is the subject of this paper. Municipal solid waste leachate varies from a moderately saline, slightly organic, slightly acid liquid when fresh to a non-threatening liquid once aged and diluted. Biological activity within the waste is responsible for extensive carbonate and sulphide dumping which tends to clog drainage systems. Concurrent advection and diffusion play major roles in salt and organic transfer through clay barriers. Typical salt fluxes are presented for barriers of differing thickness to illustrate the great importance of diffusion as a transfer process.

Field compaction of natural clays wet of Standard Proctor optimum is advocated as the best way to obtain a "soft" pliable barrier which will self heal under the impact of rapid migration of chemicals before and during increases in stress levels from the waste loading. Provided the barrier mix is designed to self heal, even clay mineral incompatibility problems associated with c-axis contraction (vermiculites and smectites) should not adversely affect long term performance.

A design option available to reduce saline fluxes through barriers is to incorporate thin, very low permeability layers (bentonite or HDPE membranes) into thicker barriers of lower quality soil.

INTRODUCTION

Standard international practice is to encapsulate municipal solid waste (MSW) within a barrier system designed to inhibit migration of polluting chemicals to local groundwater supplies. An integral part of the design is normally a leachate collection system that prevents development of a leachate mound and simultaneously removes large amounts of salt from the landfill thus greatly reducing long term impact on ground water by transferring the salt load to streams after treatment. There are many, many design schemes varying from multilayer composites to hydraulic traps (inward flow against outward diffusion) to very simple rural schemes of direct dumping into clay pits with no drainage system. It is not the purpose of this paper to review design schemes but take a look at some patterns of MSW behaviour. The patterns will include:

1) a brief look at leachate and how it changes with time;

2) the behaviour of good barriers with time, properly compacted wet of Standard Proctor optimum;

3) a look at actual diffusion profiles at two sites; and

4) the size of diffusion fluxes through clay barriers as a function of their thickness.

MSW LEACHATE

Curbside solid waste consists of miscellaneous rubbish (~ 50%), wet plant matter (~ 14%), food wastes (~ 12%) and non-combustibles (~ 24%) (Ham et al, 1978). Recycling apparently will have little net effect on these overall percentages (Ham, personal communication) even though the total waste volume might decrease by up to 50% in some very efficient programs. The resulting elemental composition should remain fairly stable therefore at ~ 21% water, 28% carbon, 4% hydrogen, 22% oxygen, 0.5% nitrogen and 25% non-combustibles.

Leachate is produced during groundwater percolation through waste as it biologically degrades, aerobically at the very top and increasingly anaerobically towards the bottom. The result is production of CO_2 gas at the top, CO_2 and methane at mid-depth and mostly methane at the base of a thick (30 m +) landfill. Simultaneously, the leachate becomes increasingly saline towards the base to levels of about 5 to 10 g/L for a leachate extraction system and the top open for rainfall infiltration. Typical components of leachate include:

Chloride	~ 4 to 6 g/L
Sodium	~ 3 to 5 g/L
Potassium	~ 0.3 to 1 g/L
Magnesium	~ 200+ mg/L
Calcium	~ 300+ mg/L
Ammonium	~ 1 g/L
Heavy metals	~ 0.2 to 0.4 g/L

Whereas most of the salts are extracted by leaching from the waste, NH_4^+ is probably biologically produced. Of the above, K^+ and NH_4^+ represent some danger to any vermiculites and smectites in the clay barrier since both may fix into holes in the clay structure, causing "c" axis contraction and potential decreases in CEC and clay mineral volume (Quigley, 1989, 1993).

When stored in the laboratory, fresh new leachate rapidly changes composition even in an anaerobic state as illustrated on Figure 1.

The pH rapidly rises from slightly acid in most but not all cases as the Eh drops to -250 to -300 mv. Reduction in organic food supply results in a rapid drop in the bacterial count as the leachate becomes dormant. During this period both calcite and amorphous iron sulphide are dumped from solution forming a slimy solid mass as illustrated by Quigley et al (1989) and shown by the decreases in Ca^{++} and Fe^{++} on Figure 1.

These dumping processes apparently occur in the field in a similar manner (King et al, 1993, Brune et al, 1991) often resulting in serious obstructions of drainage layers. Much more needs to be done to understand and rectify these drainage layer clogging problems because they can create serious leachate mounding and high hydraulic heads resulting in much higher advective salt fluxes than originally designed.

The organics present in leachate are originally dominated by short chain carboxylic acids similar to acetic acid. With time, however, other organics appear in the leachate as discussed by Barone et al (1993). These typically may include benzene, ethyl benzene, toluene and xylenes, all of them probably dumped with the waste. A further volatile organic causing some concern is dichloromethane which has shown up at Keele Valley in Toronto at levels of 1-3 ppm (Rowe, 1993, personal communication). This fairly toxic liquid is also fairly volatile and its source remains obscure (biogenic or dumped waste). Since it is a powerful solvent, an industrial source seems more a probability than a biological source within the waste pile.

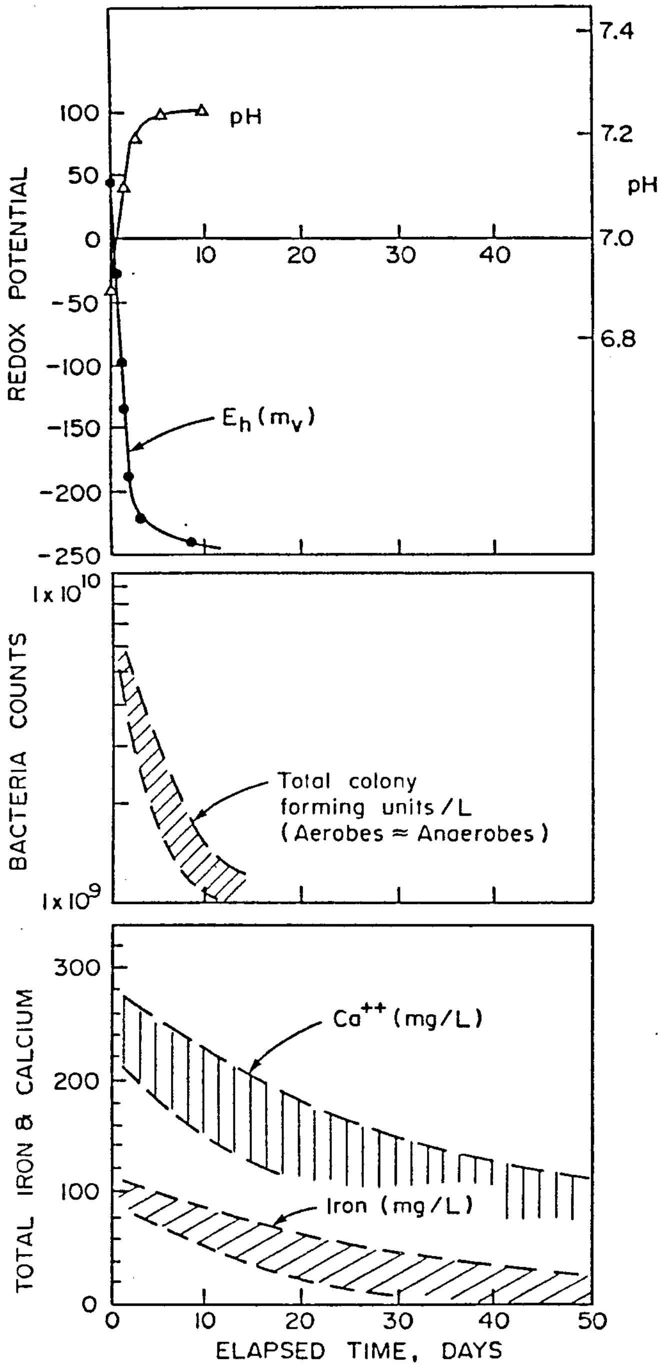


Figure 1. Chemical changes shown by leachate stored anaerobically in the laboratory.

CLAYEY BARRIER PLACEMENT

It is this author's opinion that natural inactive clayey barriers (excluding bentonites) should be placed wet of Standard Proctor optimum by a process of excessive kneading compaction. This corresponds roughly to the plastic limit and produces a clay soft enough to self heal by consolidation as the waste load is applied and as the barrier comes under chemical stress.

Some authors advocate compaction anywhere along but wet of the line of optima, however, a clay compacted wet of Modified Proctor is a very dry, stiff, unyielding material. On the other hand, clays compacted wet of Standard Proctor are somewhat thixotropic (Mitchell et al, 1965) and may show small increases in hydraulic conductivity (**k**-values). Such clays may also display an apparent preconsolidation pressure, σ_p', of 100 to 150 kPa. Deep landfills applying stresses exceeding this σ_p' cause significant consolidation and major reduction in **k**-value. At Keele Valley these reductions amounted to 1.5 orders of magnitude, greatly improving the barrier compared to its as-compacted state. Figure 2 adapted from Leroueil et al (1992) and King, Quigley et al (1993) demonstrates the recommended zone for compaction and the expected improvement in behaviour on addition of effective stress loadings and improvement by exchange of Ca and Mg on most natural clays by Na^+ from typical MSW leachates.

CONTAMINANT MIGRATION

For this presentation, our landfill will be assumed to be clay lined and with a net zero hydraulic head across the barrier. Under this scenario, diffusion is the only process of migration. This is in contrast to a downward flow scenario where both advection and diffusion fluxes would have to be added together, and the upward flow scenario or hydraulic trap, where the advective flow blocks downwards diffusion. Extensive studies at the Confederation Road Landfill on deep clay near Sarnia, Canada and on the Keele Valley Landfill, Toronto, Canada will be used as examples.

Transient migration by diffusion only follows Fick's second law and produces a pattern of migration illustrated on Figure 3 (Quigley et al, 1987).

As discussed at some length by Quigley et al (1987) diffusion is initially a very rapid process (Figure 3b) slowing down dramatically as the gradient dc/dx decreases (i.e. increasing distance from the source). A thin bentonite geosynthetic clay liner would be traversed in a matter of hours, a 30 cm sand/bentonite barrier in a matter of months, and a 1.2 m barrier in a matter of 5 years or so as illustrated on Figure 3a. The corresponding advective breakthrough times might be up to 100 years or more for the 1.2 m barrier at low gradients compared to 5 years for diffusion.

Actual diffusion profiles for common Na^+ and $C\ell^-$ are presented on Figures 4 and 5 for comparison to the theoretical plot on Figure 3. At the Confederation Road Landfill in Sarnia (Figure 4) $C\ell^-$ has migrated ~ 2 m, exactly as predicted for a $D_{C\ell}$ of 6.5 x 10^{-6} cm^2/s over 12 years. Similarly at Keele Valley (Figure 5) $C\ell^-$ has migrated 90 cm in 4.25 years to yield a diffusion coefficient of 6.5 x 10^{-6} cm^2/s.

The distance of migration from the base of the waste at Keele, which is the top of the sand

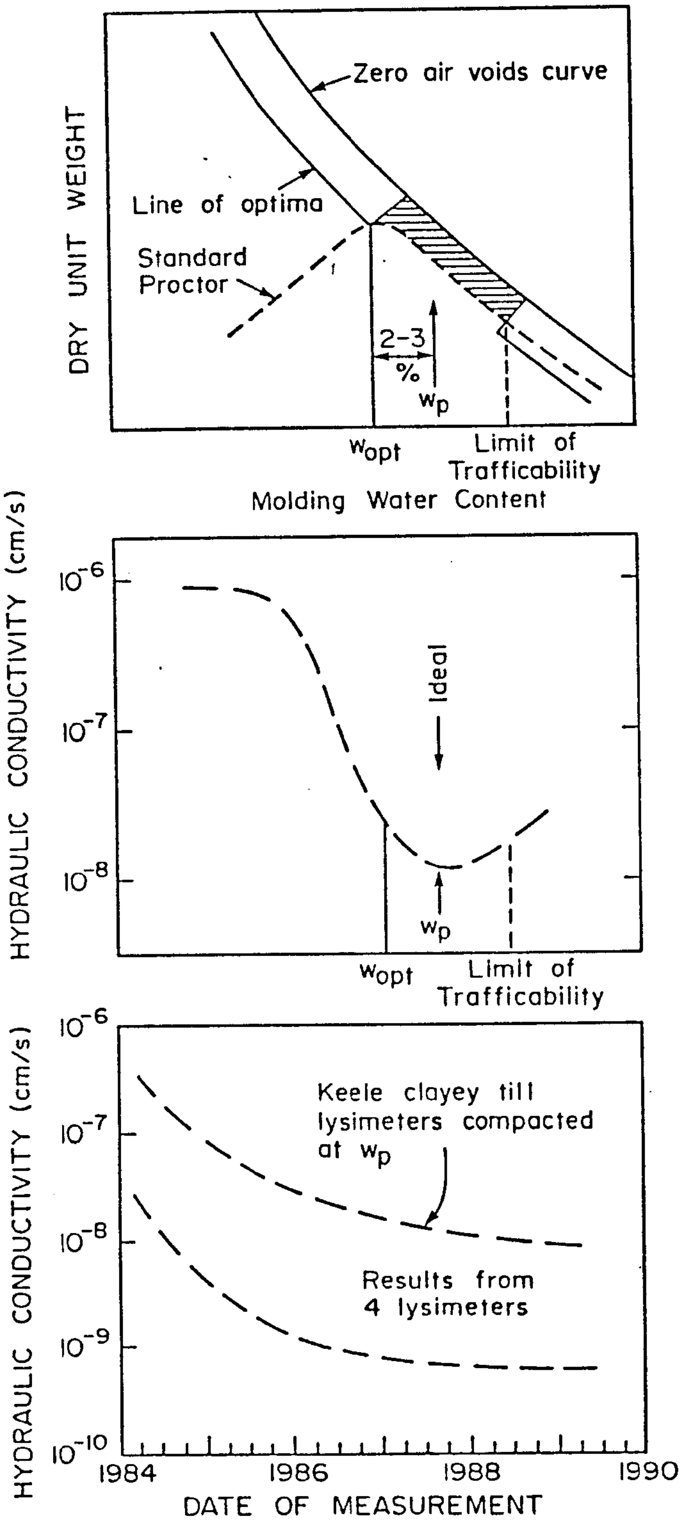


Figure 2. Compaction, permeability and field performance as a function of molding water content (Adapted from Leroueil et al, 1992 and King et al, 1993).

cushion corresponds closely to the theoretical diffusion plots on Figure 5 as well as to apparent conductivity plots in the clay barrier presented by King et al (1993).

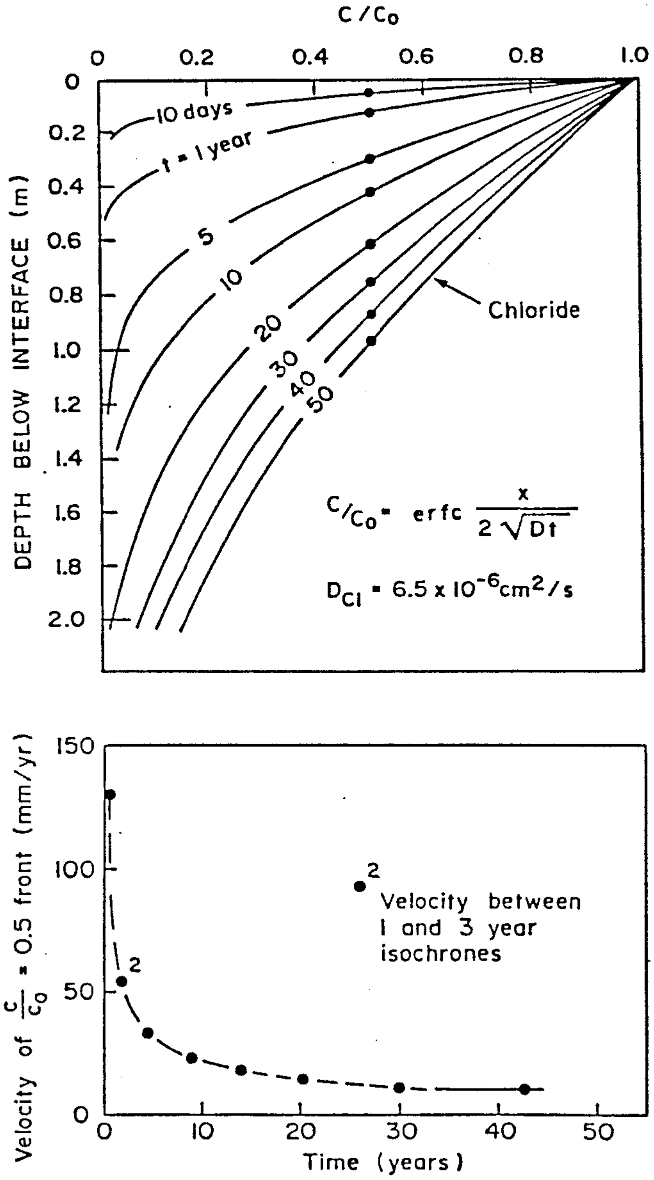


Figure 3. Time rate of migration by diffusion: (a) relative concentration-depth-time plots: (b) velocity of migration of c/c_0 = 0.5 front (After Quigley et al, 1987).

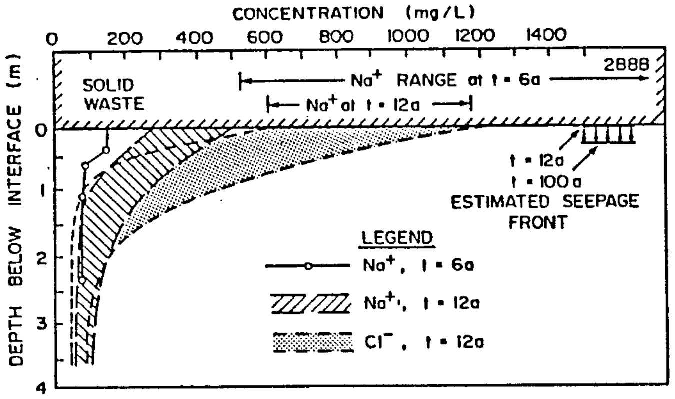


Figure 4. Diffusion profile for Na and Cℓ at t = 6 and 12 years, Confederation Road Landfill. (Adapted from Quigley and Rowe, 1985; Crooks and Quigley, 1984; and Goodall and Quigley, 1977).

In order to provide a complete pattern of diffusion, the cation profiles are presented on Figure 6 as measured on the same samples as chloride in Figure 5. Na^+ has obviously migrated nearly as far as chloride, again starting at the base of the waste at the top of the sand cushion. K^+ is greatly retarded by the vermiculitic clay barrier, migrating only 3 or 4 cm into the clay compared to 35 or 40 cm for Na^+. Finally Ca^{++} shows a desorption halo or concentration hump, so is migrating downward probably paired with $C\ell^-$. These patterns of behaviour are identical to those observed during laboratory compatibility testing and early field results from the Keele lysimeters (King et al, 1993).

A final plot of liquid hydrocarbon diffusion is presented for Keele Valley after Barone et al, 1993. This work, also done at Western, showed clearly that organics migrate by diffusion in exactly the same way as inorganics and within clayey barriers may be subject to little biodegradation. At the time the plots on Figure 7 were prepared (t = 4.25 years) there seemed to be no dichloromethane yet present in the leachate.

In conclusion, an overwhelming body of field data now confirms that diffusion is often the most important mechanism of leachate species migration in well designed sites with very low k-values and little or no advective flow.

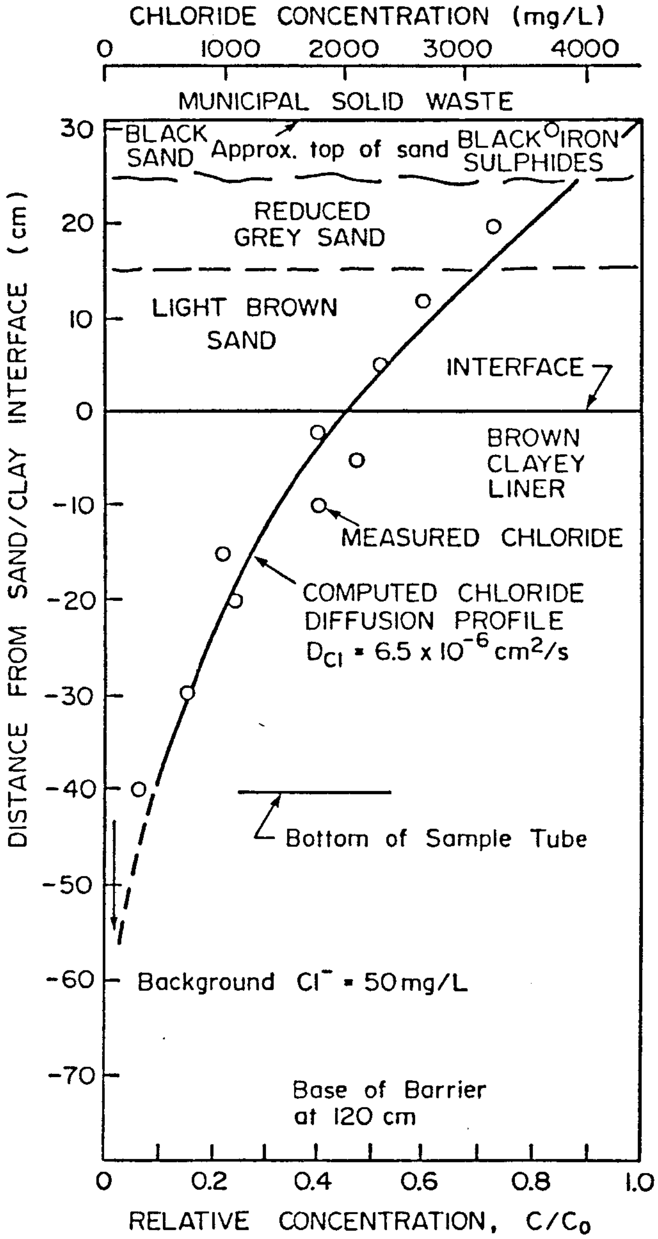


Figure 5. Diffusion profile for chloride and the cations at Keele Valley at 4.25 years (From King, Quigley et al, 1993).

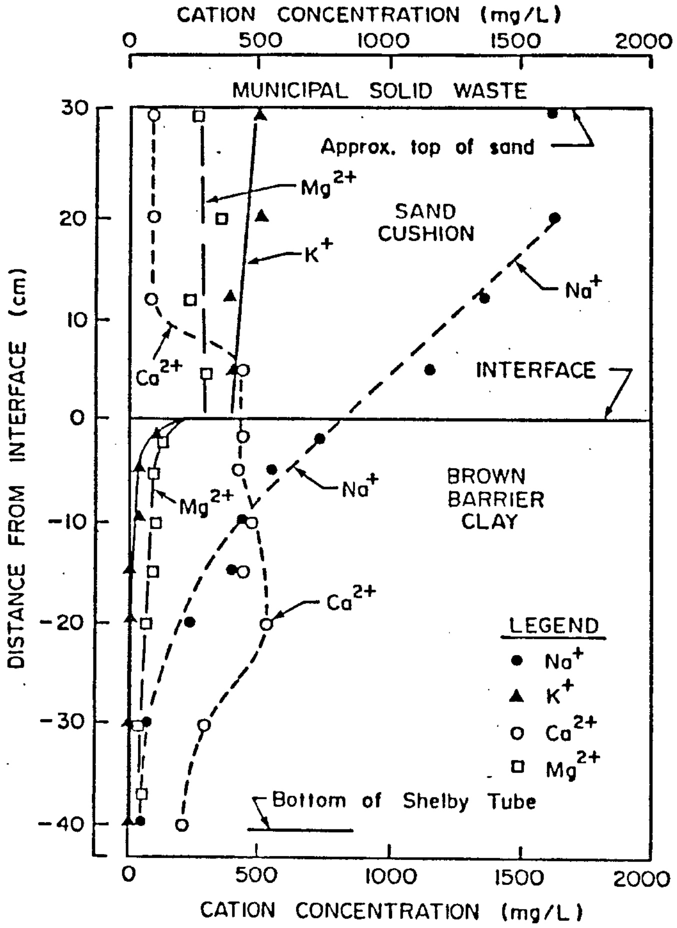


Figure 6. Porewater cation profiles accompanying the chloride profiles on Figure 5 (From Quigley et al, 1990).

SIZE OF CHEMICAL FLUXES THROUGH BARRIERS OF VARIABLE THICKNESS

The magnitude of a diffusion only chemical flux, F, is calculated using Fick's first law, namely, $F = D.n.dc/dx.A$, where D is the relevant diffusion coefficient, n the porosity, dc/dx the chemical gradient across the barrier and A the area of the landfill.

Two figures are presented to illustrate the magnitude of flux as calculated for a 1.2 m thick barrier and a 2 cm thick bentonite geosynthetic clay barrier. Figure 8 for a 1.2 m barrier covered by 30 cm of sand and a linear concentration profile yields a salt diffusion flux of 2 x 10^7 kg/a/100 hectare site for zero advective velocity. This would correspond to some 600 dump trucks of salt. The same barrier would yield a similar advective flux of 600 trucks of salt for a barrier **k** = 10^{-8} cm/s and a gradient near unity. A weakening of the **k** specification to 10^{-7} cm/s increases the advective salt flux by a factor of 10 to 6000 trucks, at which point diffusion can be essentially forgotten as a critical process.

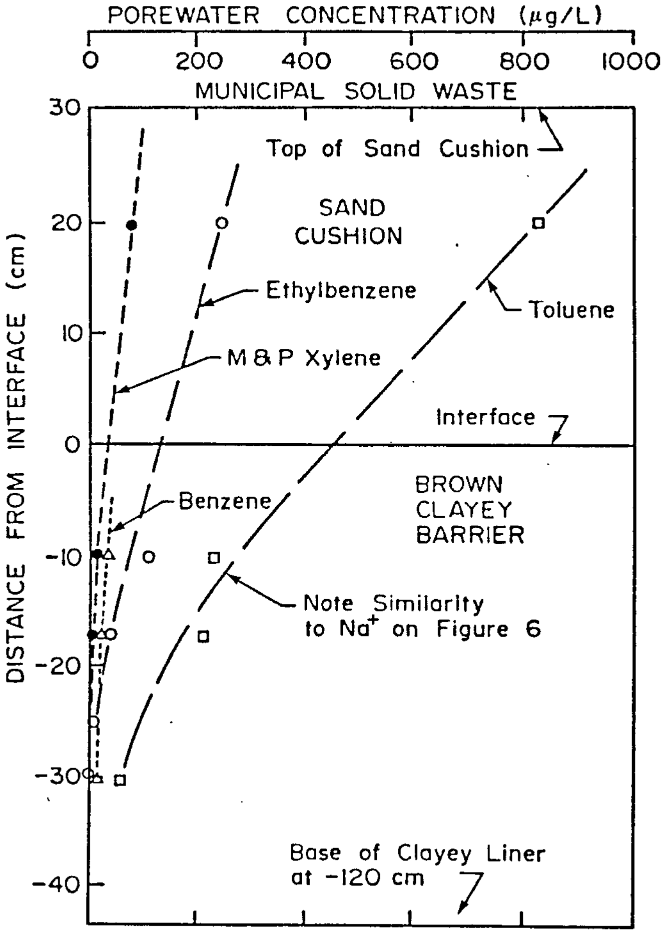
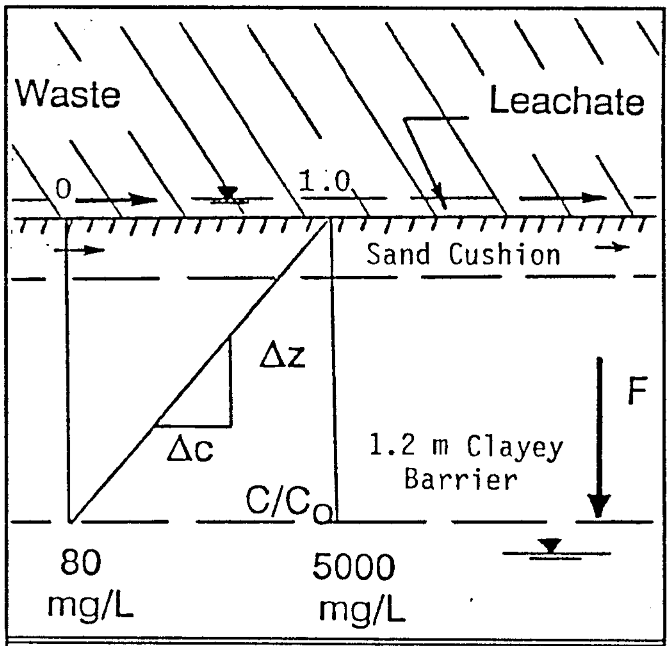


Figure 7. Diffusion profiles for volatile liquid hydrocarbons measured in the barrier soils at Keele (Adapted from Barone et al, 1993).

A similar exercise presented on Figure 9 for a 2 cm thick GCL (bentonite) yields a diffusion only flux of some 60,000 trucks/a from our 100 ha site for a leachate concentration of only 5 g/L. Compare this with a very low advective flux of 100 trucks/a assuming that a low **k**-value of 10^{-10} cm/s can be achieved by the barrier.



$$F_{salt} = D.n.\frac{\Delta c}{\Delta z}.A$$
$$\approx 2 \times 10^7 \; kg/a/100 \; ha \; (v_s = 0)$$
$$\equiv 600 \; trucks/a$$

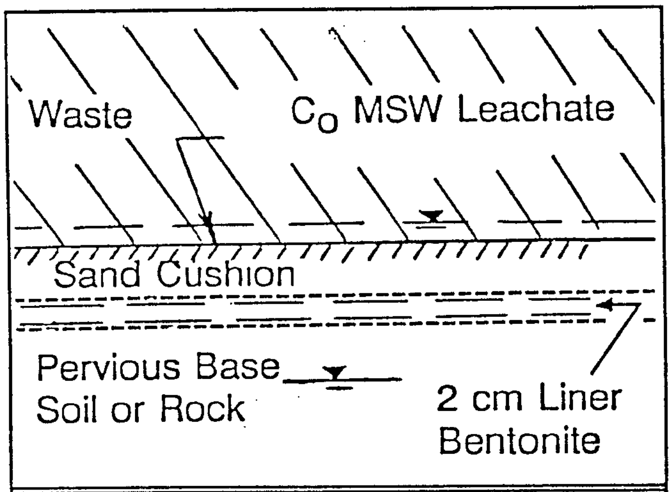
$$F_{salt} = Q_{water} \times C_o$$
$$\approx 1.8 \times 10^7 \; kg/a/100 \; ha$$
$$(k = 10^{-8} \; cm/s)$$
$$\equiv 600 \; trucks/a$$

$$F_{salt} = Q_{water} \times C_o$$
$$\approx 18 \times 10^7 \; kg/a/100 \; ha$$
$$(k = 10^{-7} \; cm/s)$$
$$\equiv 6000 \; trucks/a$$

Figure 8. Comparison of diffusion only flux with advection only fluxes for k-values of 10^{-8} cm/s and 10^{-7} cm/s. Clayey barrier 1.2 m thick, sand cushion 30 cm thick, gradient ≈ 1.

This calculation clearly shows that this barrier should transmit copious quantities of salt to the groundwater environment unless backed up by plastic membranes or liner composites designed to increase the diffusion distance.

A final drawing showing one way to obtain a relatively cheap barrier using mostly inferior soil is presented as Figure 10. A thin layer of impervious material is placed at the base of the barrier. This could be a thin local high quality clay, a geosynthetic clay liner, a HDPE membrane or possibly a combination of two of them would form the hydraulic barrier. Above them a thick inferior clay layer would be used as a diffusion barrier in the same way the sand cushion operated at Keele.



$$F_{salt} = D.n.\frac{\Delta c}{\Delta z}.A$$

$$\approx 200 \times 10^7\ kg/a/100\ ha\ (v_s = 0)$$

$$\equiv 60{,}000\ trucks/a$$

$$F_{salt} = Q_{water} \times C_o$$

$$\approx 0.3 \times 10^7\ kg/a/100\ ha$$

$$(k = 10^{-10}\ cm/s)$$

$$\equiv 100\ trucks/a$$

Figure 9. Comparison of a diffusion only flux with an advection only flux through a geosynthetic clay liner (bentonite) with k = 10^{-10} cm/s and a gradient of ~ 3.

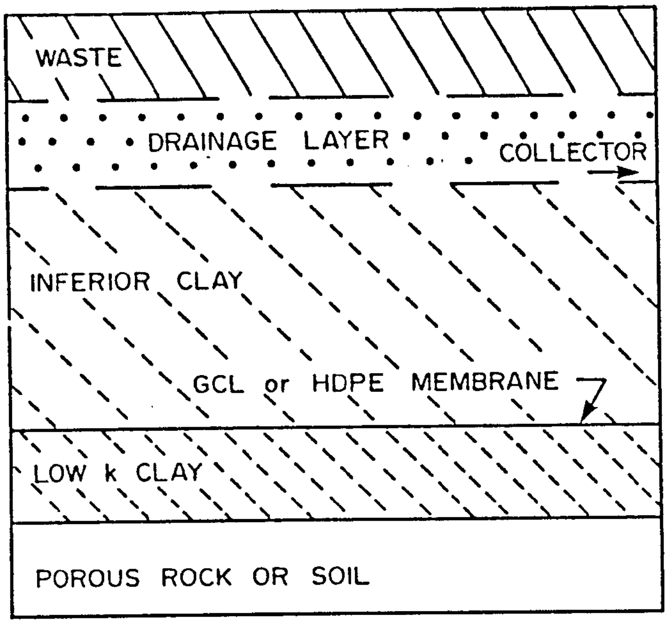


Figure 10. Clayey liner option using high quality clay, GCL or membrane near the base overlain with inferior clayey soil to operate as a diffusion barrier.

CONCLUSIONS

This paper has reviewed the performance of clayey barriers with respect to municipal solid waste disposal. A review of leachate itself followed by barrier performance in contact with leachate at two low advection sites has demonstrated the great importance of diffusion as a migration process. This was further demonstrated by flux calculations for a thin (2 cm) barrier and a thicker (1.2 m) clayey barrier.

At sites where relatively high k-values of 10^{-6} or 10^{-7} cm/s are tolerated, diffusion may be a relatively unimportant migration process since it is swamped by advection. At sites where barrier k-values of 10^{-8} cm/s are mandated or where advection is absent, diffusion is dominant and very important.

REFERENCES

Barone, F.S. Costa, J.M.A., King, K.S., Edelenbos, M. and Quigley, R.M., 1993. Chemical and mineralogical assessment of in situ clay liner - Keele Valley Landfill, Maple, Ontario. Proc. Joint CSCE-ASCE Nat'l. Conf. on Environmental Engineering, Montreal, July 1993, Vol. 2, pp. 1563-1572.

Brune, M., Ramke, H.G., Collins, H.J. and Hanert, H.H., 1991. Incrustation processes in drainage systems of sanitary landfills. Proc. Sardinia 91, Third Int'l. Landfill Symposium.S. Margherita di Pula, Cagliari, Italy, Oct. 1991.

Ham, R.K. in Lockland & Assoc., 1978. Final Report to EPA. Contract #68-03-2536. Recovery, processing and utilization of gas from sanitary landfills, U.S. EPA.

King, K.S., Quigley, R.M., Fernandez, F., Reades, D.W. and Bacopoulos, A., 1993. Hydraulic conductivity and diffusion monitoring of the Keele Valley Landfill liner, Maple, Ontario. Canadian Geotechnical Journal, Vol. 30, No. 1, pp. 124-134.

Leroueil, S., LeBihan, J.P. and Bouchard, R., 1992. Remarks on the design of clay liners used in lagoons as hydraulic barriers. Proc. Canadian Geotechnical Journal, Vol. 29, pp. 512-515.

Mitchell, J.K., Hooper, D.R. and Campanella, R.G., 1965. Permeability of compacted clay. Journal of Geotechnical Engineering Division, ASCE, Vol. 91, SM4, pp. 41-65.

Quigley, R.M., 1993. Clay minerals against contaminant migration. Geotechnical News, Vol. 11, No. 4, pp. 44-46.

Quigley, R.M., 1989. Effects of waste on soil behaviour. Proc. 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, August, Vol. 5, pp. 3135-3138.

Quigley, R.M., Yanful, E.K. and Fernandez, F., 1990. Biological factors influencing laboratory and field diffusion. In: Microbiology in Civil Engineering, (Ed.) P. Howsam, pp. 261-273. (Proc. Fed'n. of European Microbiological Soc. Symp., Cranfield Inst. of Technology, U.K., Sept. 1990.)

Quigley, R.M., Yanful, E.K. and Fernandez, F., 1987. Ion transfer by diffusion through clayey barriers. In: Geotechnical Practice for Waste Disposal '87. ASCE, Geot. Spec. Publ. No. 13, pp. 137-158.