Field observations of clogging in a landfill leachate collection system

I.R. Fleming, R.K. Rowe, and D.R. Cullimore

Abstract: The findings from a rare opportunity to exhume, examine, and sample a granular underdrain leachate collection system at a large municipal landfill site are reported. The “clear stone” drainage blanket was constructed from uniform, coarse gravel (with a nominal 50 mm particle size) obtained by crushing dolomitic limestone. After exposure to municipal landfill leachate for 1–4 years, the drainage stone was found to contain a considerable mass and volume of clog and slime materials. These were composed of mineral precipitates, fine granular particulate, and biofilm, growing under the ambient anaerobic conditions prevalent below the landfilled waste. The spatial distribution, physical and hydraulic properties, and chemical and microbiological composition of this material were examined and compared with similar material recovered from a laboratory mesocosm. The findings suggest a theoretical framework for a model of clogging behaviour of leachate collection drains at municipal solid waste landfill sites.

Key words: municipal waste, leachate, clogging, drainage, biofilm, cementation.

Résumé : Dans cet article, on rapporte les observations faites lors d’un événement rare, à savoir l’exhumation, l’examen et l’échantillonnage d’un système de collecte des lixiviats par drains granulaires sur un grand site de décharge municipale. La couche drainante en “pierre claire” était faite de gravier grossier uniforme (diamètre nominal des particules 50 mm) obtenu par concassage d’un calcaire dolomitique. On a trouvé que la pierre drainante, après 1 à 4 ans d’exposition au lixiviat de décharge, contenait une masse et un volume considérables de matériaux colmatants et visqueux. Ces derniers étaient composés de précipités minéraux, de particules granulaires fines et de biofilm qui s’était développé dans les conditions anaérobies prévalant dans les déchets. La répartition spatiale et les propriétés physiques et hydrauliques ainsi que la composition chimique et micro-biologique de ce matériau ont été examinées et comparées à des matériaux semblables obtenus dans un mésocosme de laboratoire. Ce qu’on a trouvé suggère un cadre théorique pour un modèle de colmatage des drains de collecte des lixiviats dans des décharges d’ordures ménagères.

Mots clés : ordures ménagères, lixiviats, colmatage, drainage, biofilm, cimentation.

[Traduit par la Rédaction]

Introduction

Concern about the uncontrolled release of contaminants from unlined landfill sites or dumps has led to the routine use of natural clay or geosynthetic liners at most new landfill sites. In Ontario, for example, the recent *Regulatory standards for new landfilling sites accepting non-hazardous waste* (Ministry of the Environment Ontario 1998) effectively mandates the use of a base liner for all but the smallest new sites. The provision of a base liner requires, however, that systems be constructed and operated to collect and remove the leachate that is generated.

Such a drainage system may incorporate perimeter collectors, vertical wells or shafts, French drains, or a continuous “drainage blanket” underneath the waste. The most common system for newer landfills in Canada incorporates either a continuous blanket or French drains over the base liner (Fig. 1), separated from the waste by a geotextile filter–separator. Leachate reaching the drains flows by gravity to perforated pipes, then to one or more headers for removal by pumping or gravity. Control of leachate mounding is important to minimize the hydrostatic head on the liner (and thus minimize the advective component of contaminant transport through the liner) and control sideslope leachate breakouts or interference with gas collection systems. Therefore an important unknown in the design of new landfill sites is the long-term performance of the leachate collection system (LCS) (landfill drain) over the service life of the facility.

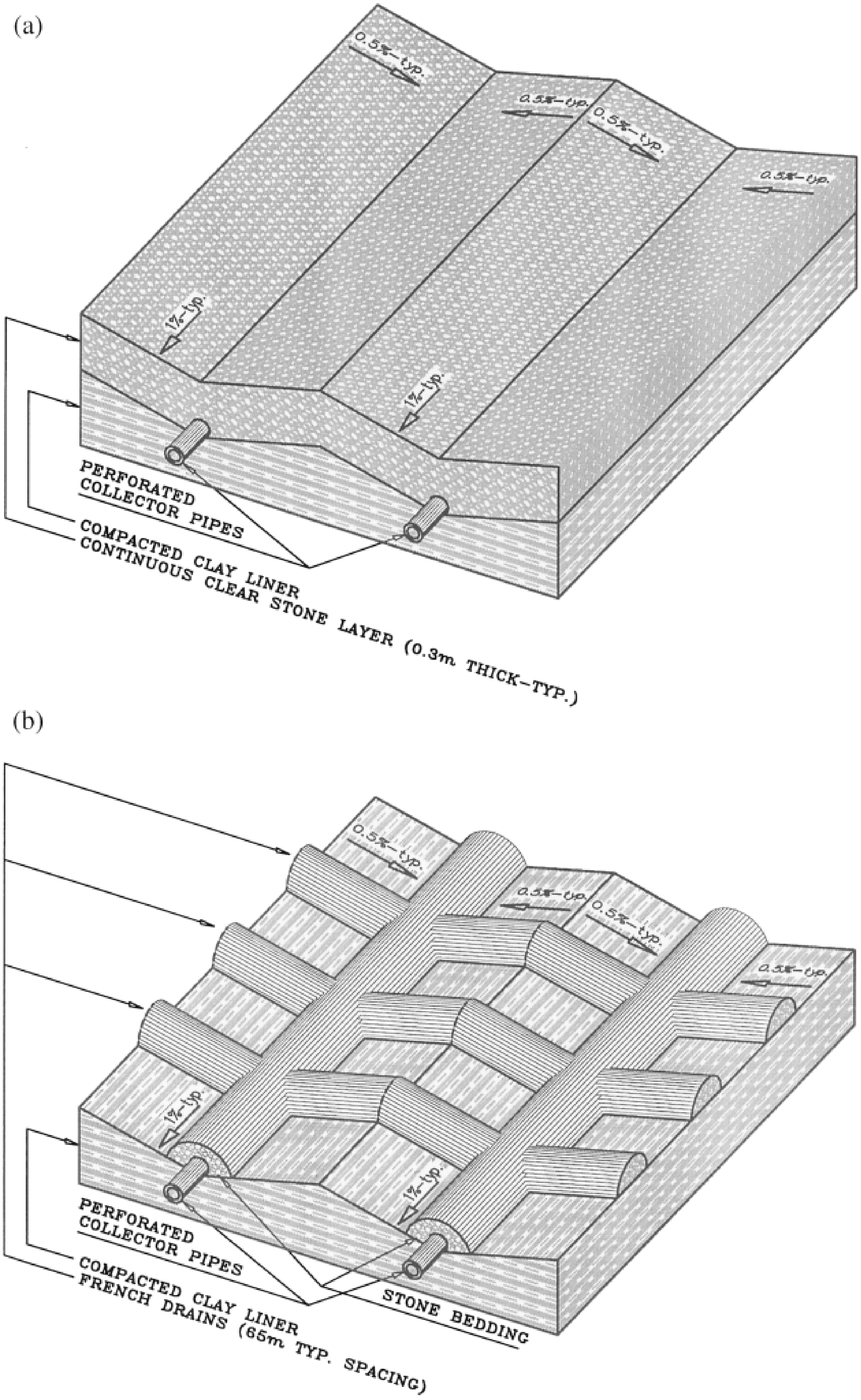
Since the “contaminating lifespan” of a landfill site may be decades or centuries for large deep sites (Rowe 1991; Rowe et al. 1995*b*), it may be necessary to collect and remove leachate for treatment over an extended period of time (“required service life”) during operation and even subsequently after closure.

The heavy nutrient loading associated with the movement of leachate through the drain inevitably causes microbial activity which over time has the potential to affect the drainage function. The microbial activity may include various forms of slime formation associated with biologically induced precipitation of minerals to form concretions or “clog” material.

Received January 12, 1998. Accepted February 23, 1999.

I.R. Fleming. Trow Consulting Engineers Ltd., 1595 Clark Boulevard., Brampton, ON L6T 4V1, Canada.
R.K. Rowe. Department of Civil and Environmental Engineering, University of Western Ontario, London, ON N6A 5B9, Canada.
D.R. Cullimore. Regina Water Research Institute, University of Regina, Regina, SK S4S 5H4, Canada.

Fig. 1. Schematic of drainage to a leachate collection system (LCS). (*a*) Continuous drainage blanket. (*b*) French drains and perforated collector pipes bedded in uniform coarse gravel (clear crushed stone bedding). (Not to scale.)



Biogas generation is also likely to occur, generating a mixture of methane (CH_4) and carbon dioxide (CO_2) with minor hydrogen sulfide (H_2S) and trace amounts of other gases. The accumulation of mineral clog deposits, biodegradation products, and biofilm may result in partial or total occlusion of the void space of the drainage medium, shortening the duration of the period of effective functioning (Brune et al. 1991; McBean et al. 1993; Rowe et al. 1995*a*).

A leachate drainage system performs two key functions: to allow the leachate to be collected; and to minimize through-liner seepage by controlling head. Various solutions are available in the literature for calculating the head above the liner, depending on the geometry of the leachate drains. A simple, commonly used method is adapted from Harr (1962):

$$[1] \qquad h_{\max} = 0.5L\left(\frac{q}{k}\right)^{0.5}$$

where
- $h_{\max}$ is the maximum mound height above the drain (m);
- k is the hydraulic conductivity of the drainage media (or waste) (m/year);
- q is the percolation rate to the bottom of the landfill ($m^3 \cdot year^{-1} \cdot m^{-2}$); and
- L is the spacing between drains (m).

A variety of other methods may be used to estimate the head on the liner, including those presented by McBean et al. (1982), McEnroe (1993), and D'Antonio and Pirozzi (1991). All of these methods are similar to eq. [1] above in that the predicted mound height is increased by increasing drain spacing and percolation rate and by decreasing drain hydraulic conductivity.

Since the required service life of the drainage system may be decades, "clogging" may eventually reduce the hydraulic conductivity of the drainage material, interfering with the smooth operation of the landfill. This paper describes observed changes in the end-of-pipe leachate characteristics and relates these to the findings from field exhumations of clog material from a landfill drain. The microbial, chemical, and mineralogical composition of the clog material and changes in leachate characteristics are then discussed within the context of a conceptual model of the clogging process.

Background and conceptual model

Clogging may be considered to reflect an obstructive process that involves the accumulation of material within the void space of the drainage medium (i.e., increasing the void volume occupancy (VVO) by clog material), thus reducing the hydraulic conductivity of the drainage medium. The clogging process appears to pass through a number of microbially mediated stages which include, but may not necessarily be limited to, formation of surface biofilms, generation of slimes, and the growth of interconnected mineral bioconcretions that gradually become denser and less pervious. Entrapment within these formations of recalcitrant particles (silt and sand particles or fines derived from the waste) may also contribute to accelerated void occupancy (clogging). Structural integrity of the clog may be developed by the precipitation of low-solubility sulphide and carbonate minerals (Brune et al. 1991; Rowe et al. 1995*a*).

Various other researchers have addressed aspects of this problem. The potential clogging of geotextile filters has received particular attention (e.g., Cazzuffi et al. 1991; Koerner and Koerner 1990; Koerner 1993; Rowe 1998). The clogging of porous granular drainage media has not been well understood until recently. Several studies carried out prior to or concurrent with the research program reported herein have helped in forming a conceptual model of the processes. These include, notably, Quigley et al. (1990), Brune et al. (1991), and Paksy et al. (1995).

Brune et al. (1991) found clear field evidence of clogging through field exhumations of landfill drains in Germany and were able to induce significant clogging in laboratory test columns. They also determined that anaerobic microbial activity played a key role in the clogging process and established that in addition to the accumulation of biological "slime," significant amounts of "concreted" solid mineral deposits (composed principally of calcium carbonate and iron sulphide) accumulate in the LCS.

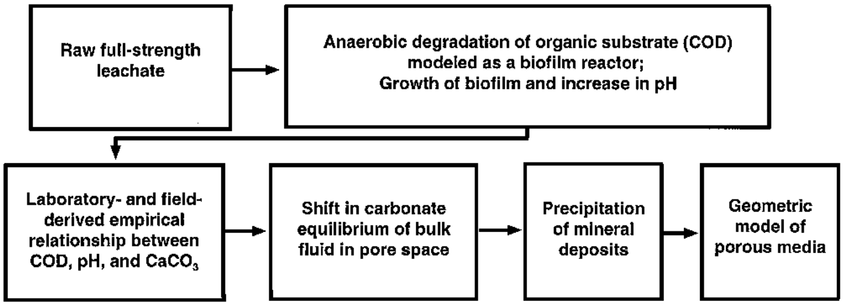
The work of Brune et al. (1991) was descriptive and qualitative. There was no attempt to establish a rationally based quantitative model of the clogging process. Although their field exhumations and laboratory columns both exhibited evidence of significant clogging, the laboratory columns were loaded at rates many times higher than representative field conditions. They concluded that clogging could be significant over the time period of concern at municipal solid waste (MSW) disposal sites and the resulting mineral deposits may be rich in calcite and iron sulphide. Further, their data strongly suggest that clogging is proportional to the loading rate of organic substrate and inorganic salts.

The findings of Brune et al. (1991) regarding the chemical composition of the mineral deposits were consistent with those of Quigley et al. (1990), who found that leachate stored in the laboratory for diffusion tests through clay liners tended to be depleted in calcium as a result of precipitation of calcite and amorphous iron sulphide. Although these findings were reached in the context of a laboratory diffusion study, these researchers did anticipate the significance of their finding with respect to the clogging of LCSs.

More recently, Paksy et al. (1995), Rowe et al. (1995*a*, 1997*a*, 1997*b*), and Cooke et al. (1999) also recognized that a landfill drain may be considered as analogous to an anaerobic fixed-biofilm reactor. The principles developed for fixed-biofilm systems in the wastewater engineering discipline may therefore be applied to the drain clogging problem. The laboratory reactor columns used in the Paksy et al. study were fed with synthetic leachate at a heavy loading rate and experienced a measurable degree of clogging over 4 years.

The work described herein forms part of an overall broad-based interdisciplinary effort aimed at identifying the controls on the clogging process and developing a predictive model of clogging and the evolution of leachate chemistry. This program includes field and laboratory studies, as well as the development of theoretical and computational tools. Reporting on results of a parallel portion of the same overall research effort, Rowe et al. (1997*b*, 1999) described column tests carried out using Keele Valley leachate and synthetic

Fig. 2. Conceptual model of the clogging process.



leachate. These columns had a high flow rate and significant clogging was noted over 1 year at temperatures of 22 and 27°C.

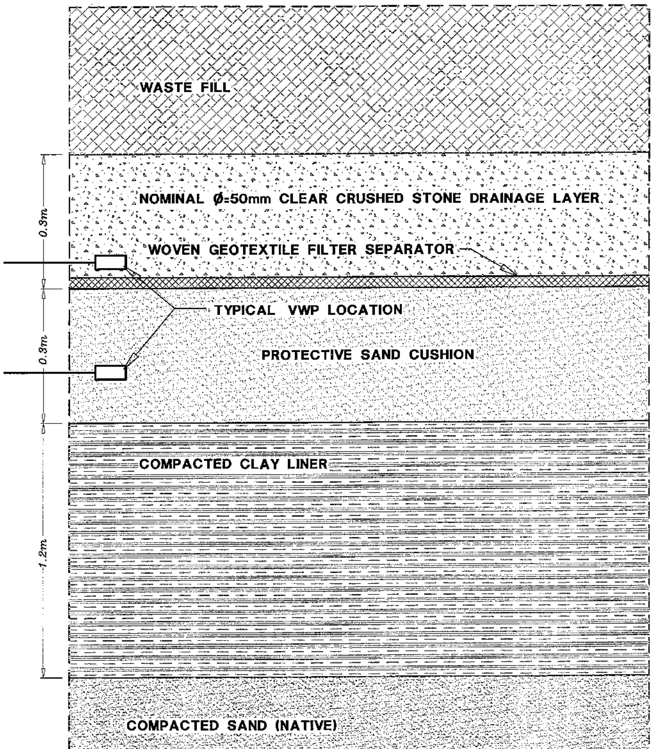
The work described in this paper relates to the observed findings from leachate monitoring, field exhumations of a landfill drainage system, and analysis of clog material. The composition of the clog material is described within the context of a conceptual model of the clogging process. It is hypothesized that the clogging process may be idealized as a series of related processes as shown in Fig. 2. The various steps of the conceptual model are further discussed later in this paper.

The relationship between chemical oxygen demand (COD), pH, and precipitation of $CaCO_3$ is discussed in more detail elsewhere (Rittmann et al. 1996; Rowe et al. 1995*a*, 1997*a*, 1997*b*; Cooke et al. 1999). Essentially, the consumption of the organic substrate, particularly those organic acids readily degradable under anaerobic conditions (which constitute a significant proportion of the total organic load expressed as COD), is accompanied by an increase in the pH of the bulk leachate fluid and the consequent precipitation of calcite. Although other minerals are present in the bulk clog material, the relatively stable calcium fraction in samples from Canada and Germany suggests that for the purpose of predictive modeling, the total mass of clog may be predicted using calcite as a "surrogate" for the complex bulk clog material composed of a mixture of mineral precipitates.

Field study location

The Keele Valley Landfill Site (KVL), located approximately 30 km north of Toronto, Ontario, has received MSW since 1984. The design capacity of the landfill is approximately 33 000 000 m^3. The maximum depth of waste at closure will be 65 m. During construction, a variety of instruments were installed at the site, including systems for the measurement of water levels and temperature over the liner, within the waste, and within the LCS. Other instrumentation within the landfill include area lysimeters installed within and beneath the compacted clay liner for the measurement of through-liner seepage rates and collection of seepage water, and electrical conductivity sensor arrays installed within the liner for the measurement of changes in the pore-water electrical conductivity caused by advective–diffusive transport of leachate through the liner (King et al. 1993; Barone et al. 1997).

Fig. 3. Cross section of base drainage layer at the Keele Valley Landfill (KVL). VWP, vibrating-wire piezometer.



During the early stages of landfill construction (stages 1 and 2, 1983–1988; see Fig. 1*b*) the landfill drainage system consisted of clear stone French drains of approximately 1.2 m^2 cross-sectional area, spaced at 65 m, running at a minimum 0.5% slope to 150 mm diameter collection pipes spaced an average 200 m and sloped at 1% (Conestoga-Rovers Associates 1993).

In the later stages of landfill construction (stages 3 and 4, 1989–1994; see Fig. 1*b*) the landfill drainage system consisted of a 250–300 mm thick continuous drainage blanket of coarse gravel (called clear stone) between 200 mm diameter collection pipes spaced at 200 m and sloped at 1%.

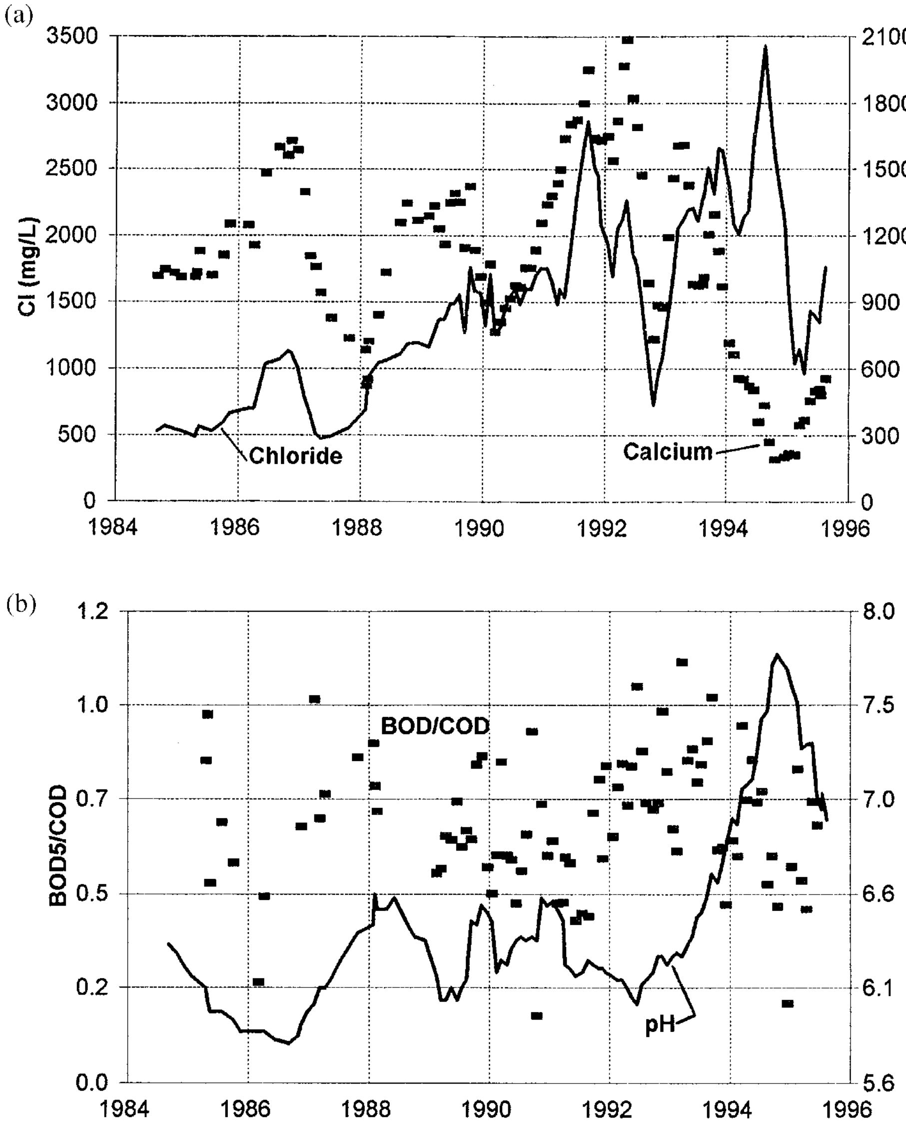
In all landfill stages, the granular material used for drainage was a relatively uniformly graded coarse gravel (referred to herein as clear stone) with a nominal 50 mm particle size. This clear stone was obtained by crushing and screening a locally available dolomitic limestone of the Guelph–Amabel Formation. The collection pipes in stages 1 and 2 are nominal 150 mm diameter, standard dimension ratio (SDR) 11 perforated high density polyethylene (HDPE). In stages 3 and 4, the collection pipes are nominal 200 mm, SDR 11

Table 1. Head (m) and temperature (°C) within the leachate collection system for the period 1984–1995.

Stage	VWP No.	Location	Measurement	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
1	STP 1-92 (lysimeter 1)	Lower waste over lysimeter 1	Head									*2.9*	*3.5*	*4.0*	*5.5*
			Temp.									26.1	27.1	29.9	30.4
1	Lysimeter 2	Over centre of lysimeter	Head	*1.1*	*1.8*	*2.1*	*3.5*	*2.3*	*2.5*	*2.0*	*2.0*	*2.0*	*2.1*	*2.3*	*3.1*
			Temp.	3.8	8.1	6.4	6.3	7.7	9.2	10.0	11.4	12.9	13.3	14.7	17.0
1	STP 2-92 (lysimeter 2)	Lower waste over lysimeter 2	Head									*2.3*	*2.0*	*2.4*	*4.4*
			Temp.									18.5	20.1	24.6	27.3
3	89-A-2	Top of clay liner	Head							*0.4*	*0.4*	*0.5*	*0.5*	*0.5*	*0.5*
			Temp.							3.4	7.4	9.4	10.7	12.4	14.3
3	89-A-1	In clear stone drainage blanket	Head							*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*
			Temp.							3.6	7.5	9.7	11.0	12.9	14.9
3	89-B-2	Top of clay liner	Head							*0.5*	*0.4*	*0.5*	*0.4*	*0.4*	*0.3*
			Temp.							3.3	7.4	8.8	10.2	11.5	12.3
3	89-B-1	In clear stone drainage blanket	Head							*0.4*	*0.4*	*0.4*	*0.3*	*0.3*	*<0.3*
			Temp.							4.4	7.5	9.0	10.5	11.7	12.3
3	91-A-1	Top of clay liner	Head								*0.0*	*0.2*	*0.1*	*0.0*	—
			Temp.								9.7	11.7	11.9	12.8	13.4
3	91-A-2	In clear stone drainage blanket	Head								*0.3*	*0.4*	*<0.3*	*<0.3*	*1.4*
			Temp.								10.5	11.6	11.9	12.9	13.2
4	90-A-1	Top of clay liner	Head								*0.3*	*0.6*	*0.6*	*0.4*	*0.3*
			Temp.								9.2	8.7	11.0	13.5	15.2
4	90-A-2	In clear stone drainage blanket	Head								*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*
			Temp.								8.5	8.8	11.1	13.7	15.5
4	92-A-1	Top of clay liner	Head										*0.3*	*0.3*	*0.4*
			Temp.										13.0	18.6	17.9
4	92-A-2	In clear stone drainage blanket	Head										*<0.3*	*<0.3*	*2.1*
			Temp.										11.7	14.8	12.8
4	93-A-1	Top of clay liner	Head										*0.1*	*0.1.*	*0.0*
			Temp.										11.8	11.9	11.9
4	93-A-2	In clear stone drainage blanket	Head										*<0.3*	*0.3*	*<0.3*
			Temp.										10.0	12.1	11.9

Note: Data from Golder Associates Ltd. (1996). All heads expressed above top of liner.

Fig. 4. (*a*) Variation in raw KVL leachate chloride (Cl) and calcium (Ca) concentration with time for the period 1984–1995. (*b*) Variation in raw KVL leachate BOD5 to COD ratio and pH with time for the period 1984–1995.



HDPE pipe. The perforations of the pipes exhumed during this study were 8 mm (5/16 in.) in diameter distributed as a ring of four holes around the pipe circumference spaced every 150 mm along the pipe. Two holes are located 60° below the spring line and two holes are 30° above the spring line.

Immediately beneath the drainage stone is a 0.3 m thick protective sand "cushion," placed over the compacted clay liner. This fine to medium sand is separated from the drainage stone by a woven polypropylene geotextile separator (Terrafix Terratrack 200W; 180 g/m^2, equivalent opening size (EOS) = 475 μm). King et al. (1993) previously showed that the upper portion of the sand layer was clogged and that it behaves as part of the diffusion barrier (implying there is little lateral flow or mixing within the sand layer and that it does not therefore form a significant part of the drainage layer).

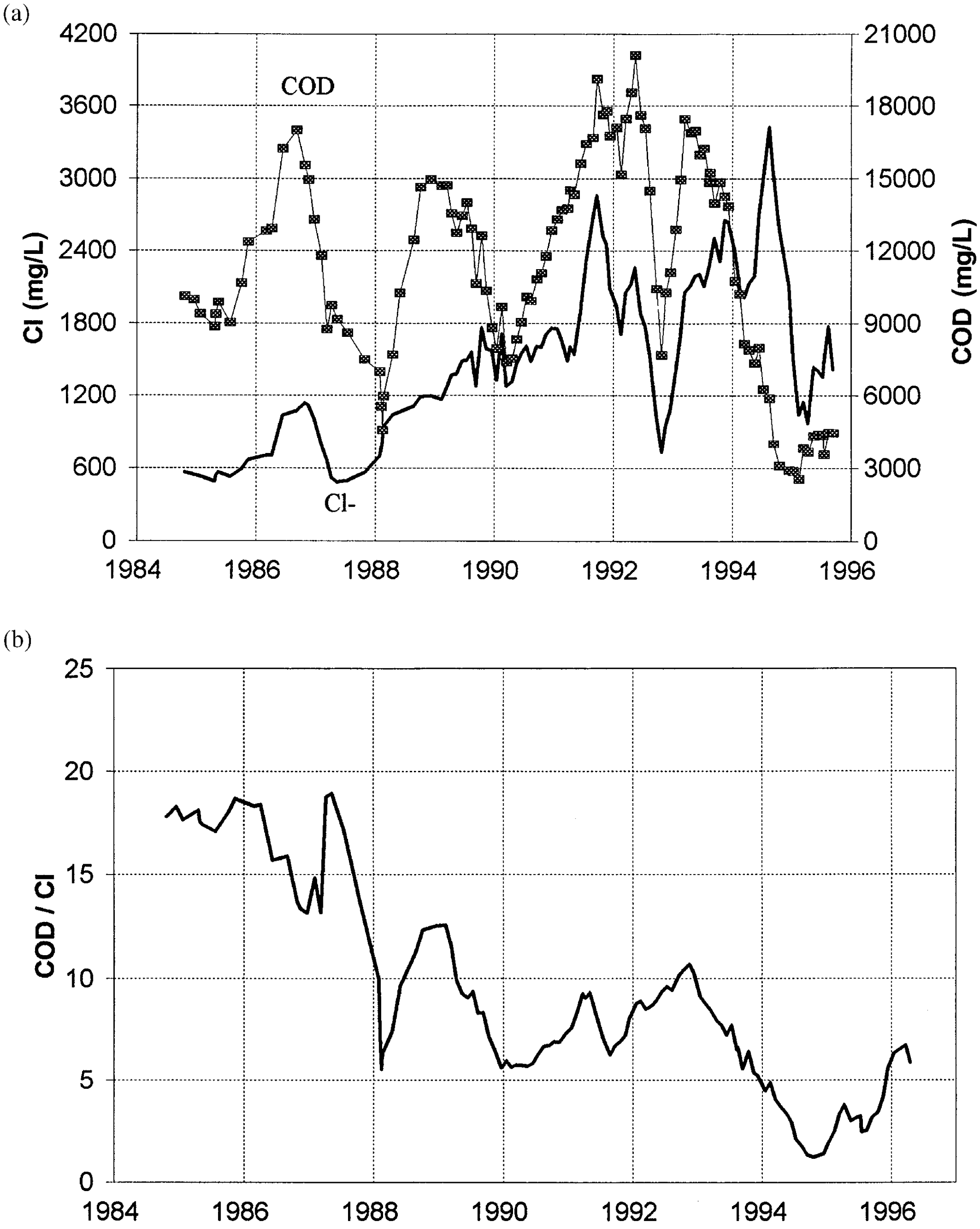
A rigorous quality assurance program of testing and monitoring has been carried out during construction and operation of the landfill. This has been described by Richards and Thompson (1989) and King et al. (1993). Through this work, a substantial data set has been developed for leachate chemistry, leachate flow rates, above-liner leachate head, and leachate temperature.

Since 1992, a laboratory and field investigation at Geotechnical Research Centre, the University of Western Ontario, into the clogging behaviour of LCSs has resulted in the collection of additional leachate data as well as sampling of clog material during exhumations at the KVL. Through this work, the chemical, microbial, and mineral composition of the clog material has been defined.

Monitoring data from the Keele Valley Landfill

The KVL has been extensively monitored during construction and operation. A significant database of leachate chemistry has been collected, along with records of above-liner hydraulic head throughout the landfill and the leachate level at several locations within the LCS. These head measurements have been recorded through monthly readings

Fig. 5. (*a*) Variation in KVL chloride (Cl) and COD concentration with time for the period 1984–1995. (*b*) Variation in KVL leachate COD to chloride ratio with time for the period 1984–1995. COD normalized to chloride.



from temperature-compensated vibrating-wire piezometers (VWPs). The VWP–thermistor installations were installed at strategic locations throughout the landfill site, over the liner within the protective "sand cushion," and in the overlying clear stone drainage layer.

Figure 3 illustrates the base-liner–leachate drainage system at the KVL, with typical installation locations for the VWP–thermistor installations (Golder Associates Ltd. 1996). Instrumentation is typically installed in the sand cushion to monitor the leachate liner head on the compacted clay liner. At some locations, however, instruments were installed in the clear stone drainage layer to monitor potential mounding over the stone–geotextile–sand interface. These instruments enable the measurement of head and temperature within the leachate drains as shown in Table 1 for the period 1983–1995. These data were summarized by Barone et al. (1997), who discussed these results in the context of the implications for advective–diffusive transport of leachate contaminants through the compacted clay liner.

It is evident that the temperature and leachate mound height tend to increase in parallel. This most likely reflects the anaerobic microbial activity responsible for both the increasing temperature and the clogging processes which cause progressive decrease in the free void space and the hydraulic conductivity of the drainage stone. As a result, a leachate "hydraulic mound" progressively grows. There may be a period of lower temperatures immediately after the waste is placed, during which the moisture content and the

Fig. 6. (*a*) Correlation between Ca and COD concentrations for KVL leachate (1984–1995). (*b*) Correlation between Cl and COD concentrations for KVL leachate (1984–1995). (*c*) Correlation between calcium and COD concentrations for raw leachate and laboratory effluents.

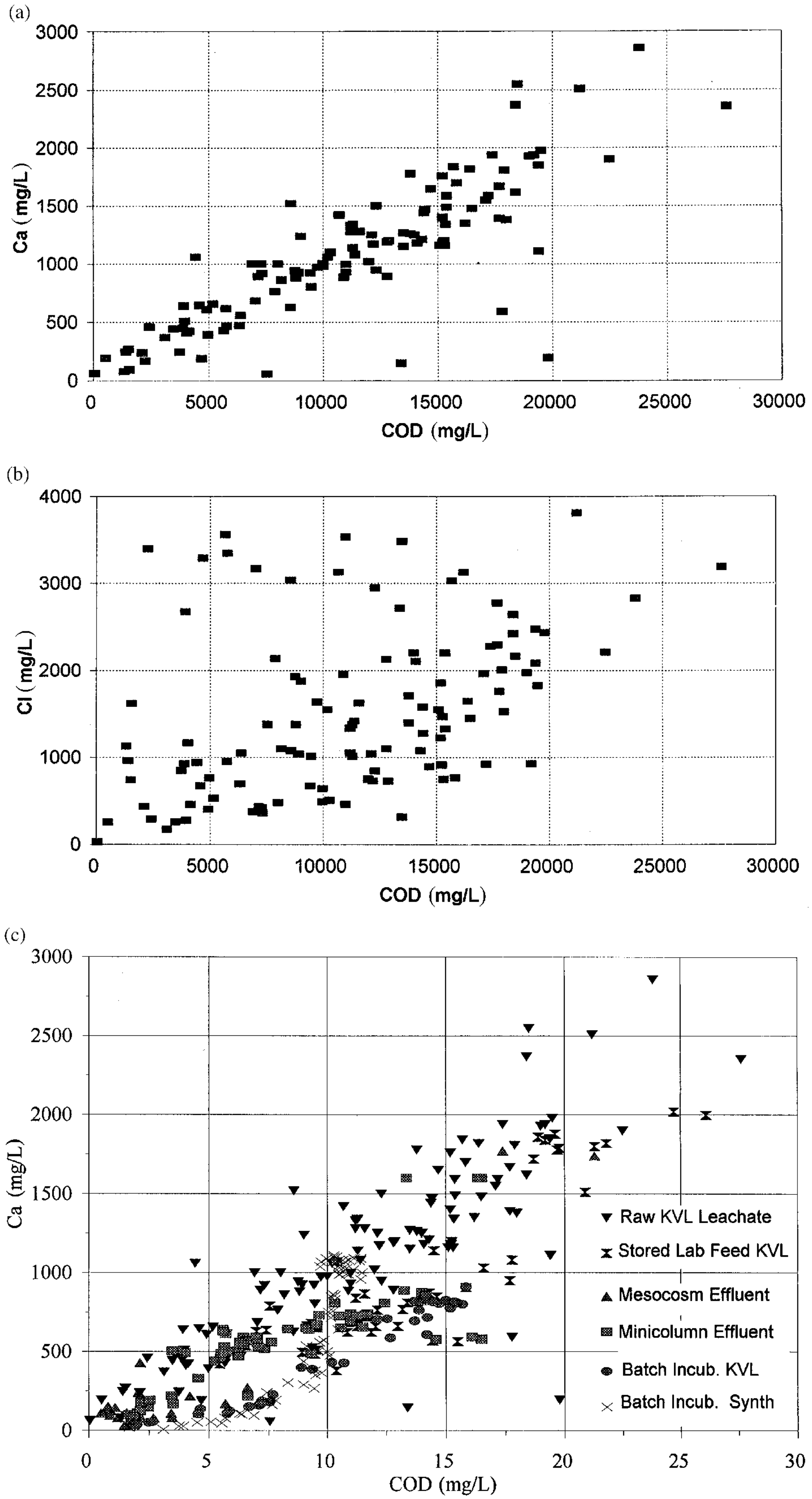
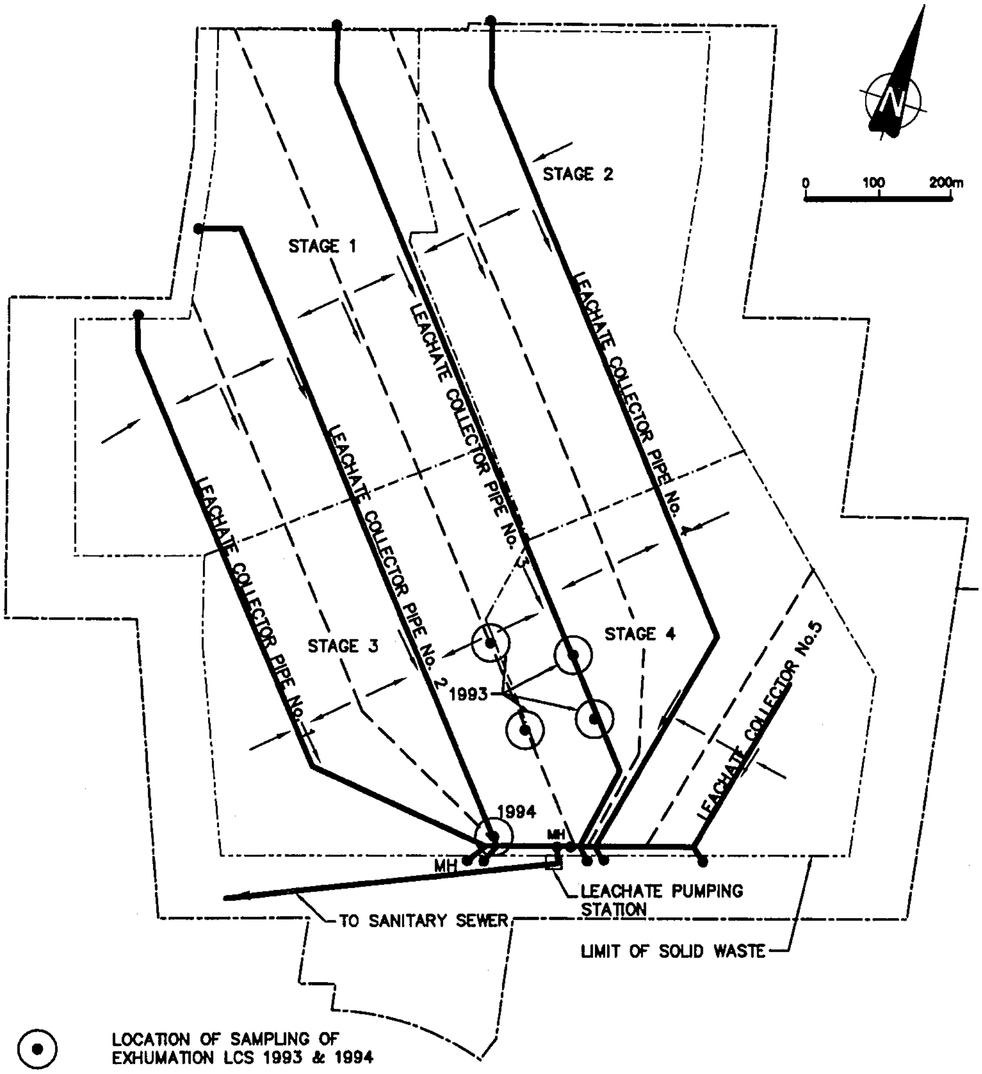


Fig. 7. Sampling locations at the KVL (base plan modified from Conestoga-Rovers Associates 1993). MH, manhole.



rate of anaerobic microbial metabolic activity increase.

The temperature in stage 1 is 27–30°C. The increases in temperature and leachate mound may be coupled and likely reflect the effect of increased heat-generating anaerobic activity after sufficient free water becomes available. This, in turn, tends to increase the amount of clogging, thus restricting drainage and leading to increased mounding of leachate and more increased anaerobic activity. Since the solubility of calcite, one of the major clog minerals, decreases with increasing temperature, the system can be seen to have several interdependent mechanisms that reinforce each other, tending to accelerate both clogging and mound growth.

During the present study (1993 to present), the temperature of the leachate has been directly measured during regular collection from a manhole adjacent to the temporary leachate pumping station. The measured temperatures ranged from 8 to 14°C. During the exhumation of the LCS at the landfill on 14 December 1993, a temporary extension of a leachate collection pipe was removed to connect the next section of permanent perforated pipe. For over 2 h, leachate flowed at over 7 L/s (100 Imperial gallons per minute), and the temperature of the flowing leachate was consistent at 10.5°C. This field observation supports the monitoring data.

Figures 4A and 4B illustrate the history of key leachate parameters in “raw” leachate over time during the operation of the landfill (based on analysis of samples taken from the end of the LCS). The concentration of calcium in the raw leachate has decreased since peaking in 1992, while the chloride concentration has either remained stable or has risen. The pH, biochemical oxygen demand (BOD5), and COD were reasonably stable over time until about 1993. Since then, there has been a marked increase in pH accompanied by a general decrease in COD (Fig. 5A). This suggests that the soluble or “stable” inorganic load (represented by chloride) in the leachate at the end of the collection system has remained relatively constant while the relatively insoluble or “unstable” fraction of the inorganic loading (calcium) has decreased in parallel with a decrease in the organic loading and an increase in pH. Monitoring data from Keele Valley show a similar trend for other lower solubility species such as iron.

Figure 5A also shows that COD and chloride exhibited similar temporal variations, including a significant decrease in leachate strength in 1993. This most likely reflects dilution at the location of the sampling point caused as a result

Fig. 8. Clear stone drainage layer at Keele Valley.

of then-ongoing construction activities at the site. More significantly, Fig. 5A shows that, relative to COD, the dissolved chloride has increased during the past 12 years.

During the same period, Fig. 5B shows a consistently decreasing trend in raw leachate organic load represented as COD, normalized with respect to the inorganic "strength" of the leachate represented by the chloride ion. Dissolved calcium follows the same trend as COD. It is evident that a significant evolutionary change is occurring, resulting in a decrease in the organic and unstable inorganic load relative to that of the stable inorganic leachate strength.

The historical leachate strength monitoring data are shown in a different format in Fig. 6A. COD and calcium are compared for samples of raw and partially stabilized samples of Keele Valley leachate stored for use as laboratory feedstock. Also shown are samples of laboratory reactor effluents at various degrees of stabilization. A strong linear correlation is evident. Figure 6A shows a similar plot for the same samples of COD versus chloride; a much weaker cor-relation is associated with dilution associated with the natural seasonal variation in the leachate. If the trend of Fig. 6A was purely due to dilution, both plots would show the same degree of scatter.

These historical monitoring data clearly suggest that there has been a qualitative shift in the relative organic–inorganic load or strength of the leachate, especially since 1993. There has been an apparent depletion of dissolved minerals in the leachate removed from the landfill at the pumping station. The presence and distribution of these minerals within the landfill drainage system could be associated with ongoing clogging processes. In an effort to locate and characterize the clog materials, samples were collected during exhumations of the landfill drain.

Collection of samples from field exhumations

During 1993 and 1994, construction and development at the KVL resulted in several locations where the LCS was temporarily uncovered. Figure 7 shows these locations on a plan view of the landfill. Development of the landfill has progressed from north to south, with each year's construction of landfill base (compacted clay liner, sand cushion, and clear stone drainage blanket LCS) covered with refuse 3–5 m thick immediately after construction. Temporary berms located at the end of each year's construction were removed to connect the liner and LCS to the preceding area of landfill. The final section of base liner was constructed at the southwest corner of stage 4 during 1994. This last area of liner construction is located at the lowest point of the base grading, where the leachate collection header pipe collects flow from each of the main collection lines. The header pipe is connected to a pipe which penetrates the sidewall liner to feed by gravity to the leachate pumping station, located in the middle of the south margin of landfill.

During autumn 1993, several temporary berms were removed, providing an opportunity to inspect the condition of the clear stone drainage blanket after 1–4 years exposure to leachate. Four areas were exhumed as shown in Fig. 7. In autumn 1994, after construction of the last section of landfill base, the temporary header pipe was removed and a permanent header installed. The exposed section of drainage blanket, perforated collection pipe, and temporary header pipe had been exposed to leachate for up to 5 years.

The stone drainage blanket was found to contain significant quantities of soft black slime, coating the individual 50 mm diameter clear stone, and often occupying most of the void space. Figure 8 shows a section of drainage blanket during installation (immediately to the east of the area of temporary header which was exhumed in 1994, shown in the extreme top right of the photograph). The permanent toe header is connected to the collection pipes, and cleanout risers are provided.

Such a black slime or “biofilm” is typical of microbial consortia in an anaerobic system with a heavy organic load. These bioslimes are typically greater than 90% water. However, the observed moisture content of the slimes from the KVL was generally lower (Table 2) than 90%. This is consistent with the large observed fraction of mineral precipitate present in the slime (Table 3). Other significant physicochemical properties of bioslimes result from the presence of extracellular polymeric substances (EPS), which may entrap water and form distinct charged regions.

Figure 9 shows the clear stone adjacent to the temporary toe header after exposure to leachate for 4 years. Soft slime had accumulated to fill much of the pore space. The distribution of slime within the drainage blanket was relatively uniform laterally along the pipe. The degree of clogging or void volume occupancy (VVO or reduction in free pore space between the stones) was visually estimated to be 50–100% in the lower saturated zone of the drainage layer and was 30–60% in the upper unsaturated portion of the drainage layer. The clog material in the lower portion of the drainage layer (where it was saturated) was, not surprisingly, more liquid and less viscous than the material coating the clear stone above the zone of saturation (Figs. 9, 10). The pH of the slime was variable and difficult to measure, however field estimates ranged from 7.5 to 8.8. The oxidation–reduction potential (ORP) of the slime itself was not measured, since a bulk value would be meaningless given that large redox gradients are often maintained across very small biofilm thickness. Leachate samples have been collected for which ORP values as low as –200 mV measured, with a typical range of –50 to –150 mV.

The hydraulic conductivity of the clear stone and slimy clog material was estimated from a laboratory permeameter test carried out on a sample taken from near the location of the photograph in Fig. 9. The test configuration is shown in Fig. 11. The sample was taken carefully (although the structure was disturbed), sealed, refrigerated, and tested anaerobically with leachate permeant under a low (upward) hydraulic gradient which ranged from 0.18 to 0.37 for successive trials. The resulting hydraulic conductivity value of 10^{-4} m/s may therefore overestimate the true value in situ, especially since the structure of the stone–slime matrix had been disturbed. Nevertheless, this value is two to three orders of magnitude lower than laboratory-measured values for similar stone (never exposed to leachate and with no accumulation of clog material) which ranged from 0.03 to 0.3 m/s. This apparent decrease in the hydraulic conductivity of the clear stone occurred during 4 years of exposure to leachate.

At the location of one VWP installation at the base of the waste, sand fill and geotextile had been placed during construction between the waste and the drainage stone. It is significant that at this location the drainage stone was relatively clean (especially the upper 10 cm thickness with an estimated VVO of 0–20%). Thus it appears that the geotextile and sand fill provided effective separation of the waste and

Table 2. Measurements on bioslime samples.

	Field Samples from KVL					Autopsy Samples from Lab Reactor			
	93-1	93-2	93-3	93-4	93-5	LS-03	LS-04	LS-05	LS-06
Age (years)	1	1	3	4	4				
Description	Stn. 4 berm	Stn. 4 berm	Temp 3 line	Stn. 3 berm	Stn. 3 berm				
Depth (cm)						3–4	9–15	15–23	23–30
Slime moisture content (%)[a]	78.0	40.2	37.5	25.2	20.8	50.1	61.7	63.6	50.2
Stone moisture content (%)[b]	1.4	2.7	1.8	1.9	1.4	0.9	1.0	0.9	1.1
Stone density (g/mL)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Avg. stone diameter (sphere; mm)	46.8	44.3	45.5	42.3	42.7	36.2	36.2	36.0	36.5
Avg. mass of slime–stone (g)	4.7	2.2	68.8	44.4	47.5	4.4	3.1	4.1	24.3
Slime density (g/mL)[c]	1.3	1.3	1.5	1.8	2.1	1.5	1.5	1.5	1.5
Avg. slime layer thickness (mm)	0.5	0.3	5.6	3.7	3.4	0.7	0.5	0.7	3.3
Calculated void volume occupancy (%)	10	5	>100[d]	86	78	17	12	16	92

[a] Calculated as Mw/Mtot.

[b] Caculated as Mw/Ms.

[c] Estimated for samples 93-1 and 93-2, and measured for samples 93-3, 93-4, 93-5, and LS-03.

[d] This sample was taken from an area where visual observations indicated little or no open pore space, and thus tends to substantiate the field observations.

Table 3. Total elemental analysis of slime and solid samples from exhumation of KVL drainage system.

	Sample 94-1 (whole): black slime over pipe	Sample 94-3 (whole): white “calcite” over pipe	Sample 94-5: black “fish eggs” clog material near pipe 2					Sample 94-6 (whole): solid in pipe 2
			Whole	23.5%* <0.2 mm	68.2%* 0.2–2.5 mm	6.5%* 2.5–5 mm	1.8%* 5–10 mm	
Mositure content (wt.%)	42.4	15.6	30.4	<1	<1	<1	<1	28
TOC as C (wt.%)	5.6	11.4	8.92	na	na	na	na	11.5
Organic matter (wt.%)	1.8	<1	3.3	4.2	3.5	3.4	5	8.5
Carbonate CO_3 (wt.%)	24.9	41	34.7	21.5	37.9	44.5	45.6	40.9
Ca (wt.%)	13.4	20.5	20.2	13.8	24.7	26.9	26.4	24.4
Si (wt.%)	19.4	3.8	9.62	16.3	6.57	2.21	1.98	1.88
Mg (wt.%)	2.21	12.1	0.898	1.19	0.779	1.01	0.664	0.574
Fe (wt.%)	2.27	0.701	6.27	4.2	7.13	9.31	8.89	10.1
Al (wt.%)	1.02	0.161	0.329	0.64	0.143	0.128	0.099	0.093
S (wt.%)	0.33	0.165	0.737	1.7	1.67	na	na	2.93
Total P (mg/kg)	796	219	853	997	712	863	901	946
TKN N (mg/kg)	1600	220	3200	3600	2400	3000	2600	6300
Mn (mg/kg)	500	567	2270	860	2870	3670	3500	2990
Ti (mg/kg)	349	70	122	245	59	52	45	43
Zn (mg/kg)	180	58	108	276	60	62	63	147
Sr (mg/kg)	197	79	419	246	468	497	563	524
Ba (mg/kg)	55	12	111	75	120	137	141	109
Cu (mg/kg)	26	8	11	2020	40	24	12	7
Pb (mg/kg)	16	5	9	14	5	5	4	6
Cr (mg/kg)	23	7	16	22	14	19	18	15
Co (mg/kg)	8	3	12	13	13	17	16	22
B (mg/kg)	40	25	28	38	21	21	22	30

Note: TOC, total organic carbon,; TKN, total Kjeldahl nitrogen; na, not available; nd, not detected.
*Proportion of the total (whole) sample on the basis of dry weight.

clear stone drainage blanket over this small area and had substantially reduced the amount of clogging that had occurred. The prevention of the migration of (solid mineral) fines into the clear stone drainage layer may also provide some benefit in avoiding the decrease in average pore size and increase in specific surface which would result. This is discussed further later in this paper.

Slime buildup was observed to be most pronounced near the perforated collection pipes (see photograph, Fig. 12) where the leachate flow within the drainage blanket is highest. Within the perforated pipes, significant accumulation of solid material had occurred (Fig. 13), and most of the 8 mm diameter perforations in the pipe were blocked by clog material (Fig. 14), especially the lower rows of holes, through which leachate could not drain (Fig. 15).

As described in more detail below, the clog included a significant fraction of fine gravel, sand, and other material not generally present in the clear stone. This material was likely washed into the LCS from the overlying waste in the absence of a filter between the top of the clear stone drainage blanket and the overlying waste. These particles appeared to have been cemented by a calcite-rich mixture of minerals derived from the leachate. It is hypothesized that the fines washed into the LCS were trapped by the biofilm coating the clear stone (slime which includes a significant fraction of extracellular polymeric materials). Within the biofilm, the microbial digestion of the COD and consequent rise in pH would then cause the precipitation of the mineral solids. Solid chunks of clog material over 100 mm wide and 75 mm thick were removed from the 200 mm diameter pipe in pieces up to 0.3 m long (Figs. 15, 16). These clog materials consisted of cemented particles in a loose “conglomerate” structure (Fig. 17).

A significant fraction of the particles loosely cemented together in the large solid clog samples removed from the pipes were actually larger than the opening size of the perforated piping. It is therefore evident that many of these particles must have grown inside the pipe by precipitation of leachate minerals, likely around a nucleus of silt, sand, or other particle washed into the drainage system. Since the leachate flow is focused to a large degree within the leachate collection pipes, the rate of clogging appears to be strongly influenced by the leachate flow rate.

As noted earlier, the VVO was estimated during the field exhumation. Subsequently, in the laboratory, the slime was washed off selected representative samples and the mass and volume of slime were measured. Table 2 shows these results and the calculated VVO for five samples ranging in age from 1 to 4 years. Significantly, as the VVO increased, the measured specific gravity of the slime increased. This may reflect the continuing precipitation of mineral solids into the biofilm as the clog “matures” from soft slime toward a cemented structure.

Composition of samples from field exhumations

Samples of exhumed drainage stone and clog material

Sample 94-8: black slime and stone at junction of header and tile 3						Sample 94-9: grey “mud” at junction (little stone)				
	22.0%*	31.2%*	20.3%*	18.8%*	7.7%*		50.7%*	19.1%*	16.4%*	13.8%*
Whole	<0.2 mm	0.2–2.5 mm	2.5–5 mm	5–10 mm	>10 mm	Whole	<0.2 mm	0.2–2.5 mm	2.5–5 mm	5–10 mm
13.7	<1	<1	<1	<1	<1	46.2	<1	<1	<1	<1
11.7	na	na	na	na	na	7.21	na	na	na	na
<1	<1	<1	<1	<1	<1	1.2	1.2	<1	<1	<1
42.7	41.6	60.5	60.7	60.8	60.2	32.9	25.8	54.8	58.3	59.1
20.6	18.3	21.5	208	20.8	21.5	15.5	14.5	20	20.9	20.6
2.19	8.11	0.522	0.34	0.564	0.476	12.3	15.6	3.14	0.76	1.1
12.3	7.75	13.8	13.8	13.9	14.2	4.85	3.08	11.4	13.9	13.3
0.706	1.43	0.371	0.367	0.409	0.317	1.9	2.04	0.697	1.16	0.365
0.166	0.517	0.0247	0.0234	0.0215	0.0333	0.837	0.893	0.058	0.030	0.039
0.198	na	0.199	0.143	0.232	0.156	0.25	0.269	0.228	na	na
215	496	114	111	118	120	653	766	173	128	129
270	720	22	nd	14	nd	1200	960	180	38	22
553	668	521	512	524	498	584	584	539	529	528
68	190	8	8	7	8	303	302	22	12	13
52	203	22	16	12	14	107	166	34	20	534
74	123	60	59	60	61	160	177	79	60	65
10	28	3	2	2	2	49	56	11	4	3
8	903	21	10	9	4	23	125	14	14	9
6	13	nd	2	3	4	8	21	4	16	2
6	13	3	2	nd	nd	17	18	4	2	4
4	6	4	2	3	2	8	8	2	3	3
25	29	18	21	22	23	32	30	19	19	25

were analyzed for a suite of organic and inorganic parameters. All analyses represent total elemental analysis subsequent to digestion of the sample. Table 3 summarizes key parameters for several samples of slime and slimy stone from the drainage blanket at the KVL.

Stone particles with diameters ranging from 1.5 to 12 mm were found in some soft slime samples. Clear stone samples were also tested to provide a reference, since in certain locations the clear stone that makes up the drainage layer may have been delivered to the site with a significant fine stone fraction. This would potentially cause partial filling or “bridging” of large open pores, increasing the specific surface available for biofilm growth and ultimately increasing the rate and degree of pore occlusion by slime and mineral clog material.

The geochemical composition of the drainage blanket (dolomitic limestone from the Guelph–Amabel Formation of the Niagara Escarpment) is distinct from that of the calcareous solid mineral deposit formed in the landfill drain. The presence of stone fines was determined by separating the samples into various size fractions and testing each fraction separately.

Table 3 shows that significant “contamination” of certain samples may be attributed to fines in the clear stone. In samples 94-8 and 94-9, which were observed to contain significant stone fragments up to 15 mm in size, a well-defined “signature” for the clear stone emerges. The specific attributes of this signature include 14% by weight Mg, 21% by weight Ca, and total Kjeldahl nitrogen (TKN) < 25 ppm.

The varying composition of the other samples suggests that the processes and the leachate are not uniform, and further reflects the potential contamination by other soil fines presumably washed in from the waste, including silicate- and carbonate-rich soil particles. It is evident, however, that calcium represents 20–30% of the clog material mass, for both the soft slime and solid clog samples. Table 4 compares the average composition of the clog material from this study with that obtained from German landfills as reported by Brune et al. (1991). They are remarkably similar. There are insufficient data at present to conclude whether this similarity represents a general case or reflects some overall similarities in the geologic setting (i.e., generally carbonate rich geologic materials). The potential for dissolution of the drainage stone itself has been discussed by Bennett et al. (1999).

The amount of sand- and gravel-size material in the clog material is related to the particular base design used at the KVL, where no filter was placed between the top of the clear stone drainage blanket and the overlying waste. Based on the chemical analysis of the particles found in the soft slime and the original collection stone (as discussed above), it is known that at least some of the mineral material found within the drainage system must have been carried into the stone by the leachate. As evidenced by the observations reported below for one small area where a geotextile was placed between the stone and the waste, this particular contribution to the clog could be either substantially reduced or eliminated at landfill sites where a filter was placed between the drainage layer and the overlying waste.

Also, as discussed above, it is evident that some of the fines present in the “clear” stone when it was placed were carried by the leachate from the stone layer through the

Fig. 9. Clear stone after 3 years contact with leachate.

Fig. 10. Exhumation of temporary toe header at KVL.

perforations in the pipe. Therefore, not all of the mineral material recovered during the exhumations represents “true” mineral clog deposits (i.e., mineral deposit precipitated in place within the biofilm coating the solid surfaces). This is demonstrated by the larger particles of the conglomerate structures shown in Figs. 13–17.

Figures 18 and 19 show photomicrographs of the solid mineral clog material recovered from inside the temporary header pipe which are typical of microbial clogging structures. These photographs were taken of the dried, washed mineral deposits. Figure 18 shows the inner surface of the clog structure which had been in contact with leachate and coated with a slime layer at the time of sampling. Figure 19 shows the “bottom” of the clog structure, at the interface with the piping. The decreased void space apparent in Fig. 19 relative to Fig. 18 suggests that the mature clog (i.e., at the base of the biofilm) has achieved a greater (mineral) density relative to the growing surface of the biofilm–clog. The coral-like structure of the material suggests the microbial contribution to the clogging mechanisms. Figures 20 and 21 show photomicrographs of a similar sample of clog material removed from the feedstock manifold in the laboratory. The structure of the laboratory clog material is very similar to that of the clog removed from the landfill drain.

Microbial assays of slime material indicated the presence of a complex consortium of anaerobic and facultatively anaerobic bacteria. Microbial examination of the various forms of slimes and bioconcretions using the Biological Activity Reaction Test BART™ (Droycon Bioconcepts Inc., Regina, Sask.) revealed a complex clustering of microbial consortia within the samples both in the field and in the laboratory, as described later in this paper. BART™ is a novel biodetection system in which a selective nutrient gradient is counter-positioned vertically and upwards against an oxidation–reduction gradient (downwards to reductive). The water sample occupies a 15 mL volume and allows the appropriate growth of the selected bacterial groups. The aggressivity of these bacteria is reflected by the lag time until the observation of the first visible positive reaction, indicating that the bacteria are present (Cullimore 1993). The form of reaction indicates the consortial composition. The tests are thus descriptive and semiquantitative.

Landfill drainage layer as an anaerobic fixed-biofilm reactor

The historical monitoring data for leachate chemistry at Keele Valley suggest that there has been a qualitative shift in the relative organic–inorganic load or strength of the leachate, especially since 1993. The raw leachate that has been sampled may not actually represent true full-strength raw leachate, if there is such a thing.

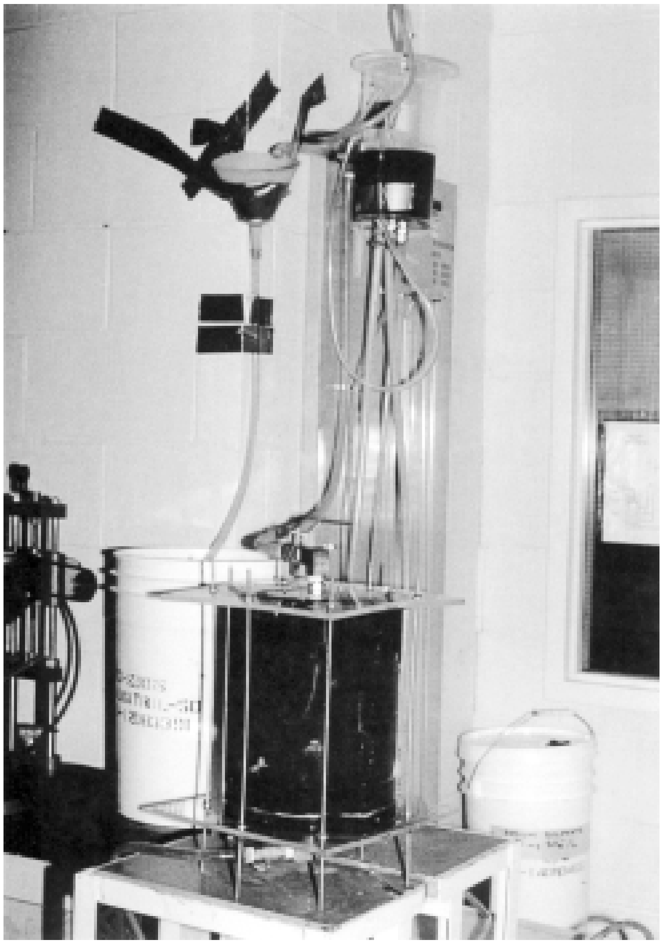
If the granular drainage blanket underdrain system is considered to represent an anaerobic biofilm reactor and if the hydraulic residence time is calculated, it becomes evident that, because of the size of the system, even a very inefficient anaerobic biofilm reactor could have a significant effect over time. To illustrate this, the mean hydraulic residence time is calculated below for the KVL.

A simple drain geometry is present in stages 3 and 4 (the southern half) of the KVL where a continuous drainage blanket underlies the waste. In the older half of the landfill to the north (stages 1 and 2), the drainage stone is not continuous, rather it is present as discrete French drains with 30 m spacing.

The spacing of the perforated collector pipes at the Keele Valley site is 200 m, the drainage blanket in stages 3 and 4 is 30 cm thick, and the total porosity of the clear stone is approximately 0.48. The total pore volume across a 1 m wide strip is 14.4 m^3 (= 100 m × 1 m × 0.3 m × 0.48).

To estimate the hydraulic retention time, the 30 cm thick clear stone blanket at the Keele Valley site is assumed saturated to about half its thickness. This is consistent with the monitoring data given in Table 1 for the total head on the liner. Many of the VWPs placed within the stone do not indicate any head; however, this is not unexpected, since these head measurement (approx. 0.15 m) represent the extreme low end of the operating range of the instruments. The “field capacity” of the stone (drained volumetric moisture content) is estimated at 3% v/v, similar to that measured in laboratory studies at the University of Western Ontario (Rowe et al. 1995*a*) and that reported by Badv and Rowe (1996). The moisture fraction of the total pore volume is thus 51.5% of the total pore volume or 7.4 m^3.

Fig. 11. Laboratory constant-head permeameter test configuration.

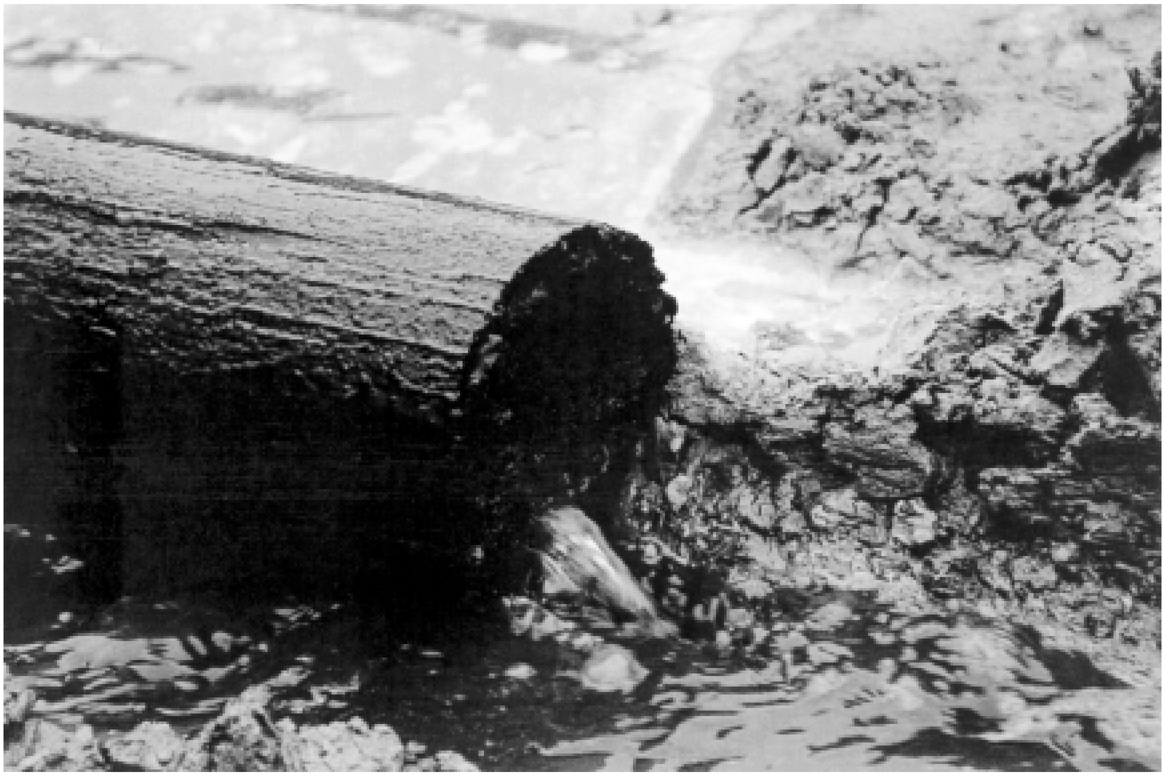


The annual hydraulic loading is not known exactly. The leachate discharge to the sanitary sewer averaged 170 m^3/d between 1989 and 1993 (Conestoga-Rovers Associates 1993). This corresponds to less than 0.1 $m^3 \cdot year^{-1} \cdot m^{-2}$ of percolation to the drainage layer and likely does not represent the entire infiltrating volume of water. Infiltration is often assumed to be about 0.25–0.4 $m^3 \cdot year^{-1} \cdot m^{-2}$ for landfills in Southern Ontario before cover is placed. Such an infiltration rate would produce significantly more leachate than has been collected up to this point in time. Much of the infiltrating water is therefore considered to be stored in the newly deposited waste as the waste progressively reaches its field capacity, estimated by Conestoga-Rovers Associates (1993) to be 400 kg/t of waste. Assuming an average waste thickness of 40 m, initial waste moisture content of 25% dry weight, and infiltration between 0.25 and 0.4 $m^3 \cdot year^{-1} \cdot m^{-2}$,

Fig. 12. Exhumation of temporary collector pipe (1993).

Fig. 13. Clog material inside temporary toe header (1994).

Fig. 14. Blockage of perforations in toe header (1994).



an estimate of the time for the waste to reach field capacity may be made as follows using assumed values close to those measured at the landfill:

1000 kg of waste over scales	750 kg dry solids and 250 kg moisture
Waste “apparent density” in place	800 kg/m^3 = 1000 kg waste over scales per 1.25 m^3 600 kg waste solids per m^3 in place 200 kg initial moisture per m^3
Moisture to achieve field capacity	400 kg/t of waste passing scales = 320 kg moisture per m^3
Daily cover	0.2 m^3 soil = 350 kg soil cover per m^3
Bulk density when placed	800 + 320 + 350 = 1470 kg/m^3
Dry density in place	600 + 350 = 950 kg/m^3
Average thickness of waste	40 m
Moisture to achieve field capacity	320 kg moisture per m^3 × 40 m = 12 800 kg moisture per m^2 = 12.8 m^3 moisture per m^2
Time to achieve field capacity	12.8 m^3 moisture per m^2 at 0.4–0.25 $m^3 \cdot year^{-1} \cdot m^{-2}$ = 32–51 years

The calculation above suggests that much of the current infiltration is retained in storage within the waste mass and hence the average hydraulic retention time during the period before the waste reaches field capacity is very large and varies with time. Once the leachate reaches the drainage blanket, the average hydraulic retention time (HRT) is calculated using the values above to be in the range of 70–100 days. These values do not include the residence time in the perforated pipes and header before the leachate reaches the pumping station where all of the raw leachate samples were collected. This retention time is significant, since substantial “treatment” of the leachate (i.e., microbial digestion of the available organic substrate) can be expected over such a period, even in a very inefficient “reactor.” This suggests that the raw leachate samples collected from the leachate pumping station at the downstream end of the LCS actually represent partially treated effluent from a large, dynamic, in situ treatment system.

For the leachate in the stage 1–2 area where there is no continuous underdrain, the volume of drain is lower, although the calculated HRT in the clear stone drains based on the same assumptions and again ignoring residence time in the waste or in the collection pipes still remains in the range of 10–15 days, sufficient time for significant microbial degradation of the organic in the leachate. None of the investigations described in this report were carried out in that area of the site, although significant leachate mounding is known to have developed in this portion of the site (Barone et al. 1997).

The decrease in the ratio of COD to Cl^- over time is consistent with this hypothesis, and is not entirely explainable by widely used engineering models for the evolution of leachate chemistry and organic load (McKinley and Met 1984; Demetracopoulos et al. 1986; Farquar 1989; Lu and Bai 1991). The data of Figs. 4 and 5 suggest that the leachate organic load was significantly decreasing by 1993, only 9 years after the site commenced receiving waste and at a point in time when less than 30% of the site had reached its final design elevation and over 10% of the footprint remained to be constructed. Based on earlier work by Farquar

Fig. 15. Solid clog material buildup inside temporary toe header.

Fig. 16. Solid clog material removed from drainage pipe (this specimen has dimensions of about 100 mm wide × 75 mm thick × 300 mm long).

Fig. 17. Calcareous cemented structure of pipe clog material.

(1989), McKinley and Met (1984), and others, the leachate organic strength during the period of continued landfilling of fresh waste would have been expected to increase in parallel with the inorganic load, or at least stabilize. The data indicate that the reverse has occurred.

This observation has important implications for the practical and cost-effective pretreatment of landfill leachate, since it suggests that it may be possible to design a system to naturally or passively treat the leachate (i.e., reduce the organic loading) within or beneath the landfill itself. This could potentially reduce or even eliminate the requirement for leachate pretreatment prior to discharge to a sanitary sewer for cotreatment with municipal sewage.

However, the same processes that reduce the organic load of the leachate at the point of collection and discharge also cause or are associated with the accumulation of mineral and biological solids within the LCS. Significant accumulation of clog material near the collection pipes can result in almost total VVO and may eventually hamper the ability to control the hydraulic head within the landfill, thus increasing through-liner seepage and potentially causing operational difficulties.

Comparison with laboratory studies of clogging

The leachate data collected from the KVL show that a change in leachate quality has occurred over time within the drainage system. For practical reasons, it not usually possible to directly examine this change in leachate characteristics to confirm that this change is occurring between the points at which the leachate enters the system and the point of collection (i.e., along the leachate flow path within the drainage layer).

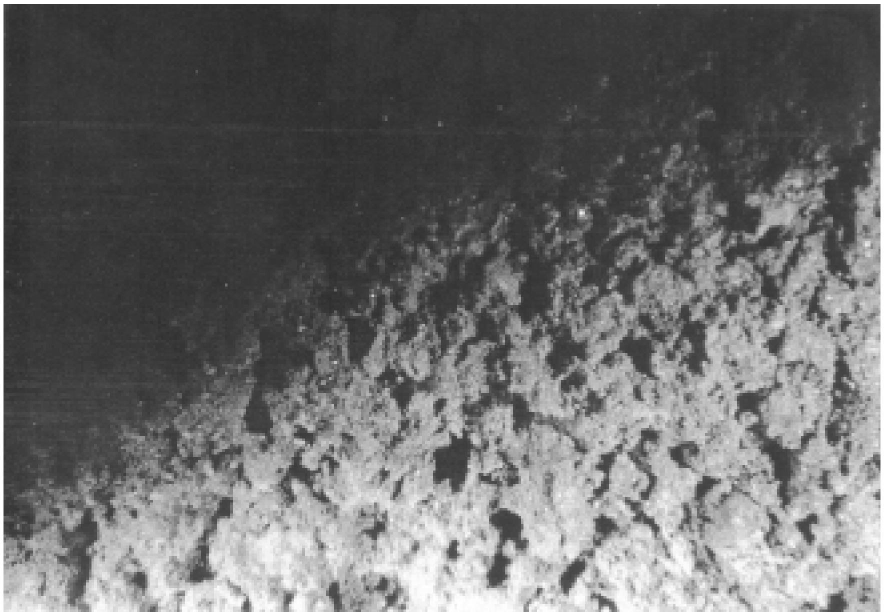
Table 4. Comparison of chemical composition of clog material.

	Keele Valley Landfill (this study)	Germany (Brune et al. 1991)
Calcium	20	21
Carbonate	30	34
Silicon	21	16
Magnesium	5	1
Iron	2	8

It is possible to test this hypothesis in the laboratory. To do this, the collection system was simulated in the laboratory by 18 mesocosms (reactors) which were packed with clear stone similar to that used for the drainage blanket at Keele Valley. These mesocosms were constructed of welded PVC, 0.25 m wide, 0.6 m high, and 0.7 m long. The raw leachate from the KVL was used as a feedstock source for the mesocosms that were fed leachate at one end at a controlled rate intended to represent the leachate loading conditions of the drainage blanket immediately adjacent to the collection pipes. Leachate was also added to the surface of the waste at a very low rate to simulate the infiltration of moisture from the waste mass. These tests are ongoing.

Anaerobically aged municipal solid waste (5–10 years old) overlies the clear stone in the mesocosms. The waste samples were taken from auger cuttings that were depth averaged over 10 m to ensure representative and consistent

Fig. 18. Photomicrograph of top of clog, sample 94-12. Magnification 6×.



samples. This waste is separated from the stone by various alternative geotextile and granular filter materials. Anaerobic conditions have been maintained since 1993; the mesocosms are sealed and maintained at a slightly elevated pressure (± 100 mm H_2O) by the ongoing generation of gas within the mesocosms and by the addition of synthetic landfill gas (60% methane and 40% CO_2) as required to maintain system pressure. The organic and inorganic constituents of the leachate feedstock and mesocosm effluents have been regularly analyzed to measure changes in leachate characteristics across the mesocosms.

Rowe et al. (1995*a*) documented the findings from the early stages of this ongoing investigation. They observed a decrease in COD and calcium in concentrations in the leachate between the influent and effluent in the mesocosms. They also noted a linear relationship between the total COD and dissolved calcium in both the raw leachate feedstock and partially treated leachate effluent from the laboratory reactors. Rittmann et al. (1996) described the chemistry of these reactors and the implications for combined clogging–pretreatment of the leachate. Based in part on laboratory data similar to those presented in Fig. 6A, they described the calcium carbonate chemistry of the leachate and the observed shift in pH associated with the microbial digestion of the organic substrate (as COD) and concluded that (1) "COD removal allowed or accelerated the precipitation of $CaCO_3$, which is the major inorganic component of the "clog slimes" in leachate-drainage systems"; and (2) "the solution phase (leachate) was significantly out of equilibrium with $CaCO_3$ and gas-phase CO_2. The disequilibria suggest that the rate of $CaCO_3$ precipitation may have been controlled by the dissolution of gas-phase CO_2."

The linear relationship between COD and dissolved calcium shown in Fig. 6A suggests a constant value for the "yield coefficient" of mineral deposits in the clogging material, defined as the mass of calcium removed from solution per unit mass of COD removal. Rowe et al. (1997*a*) describe how this relationship is used in a numerical model of leachate evolution–clogging within a landfill drain. The concept of *mineral yield* in this system enables a fixed-biofilm model for COD removal, as developed for wastewater applications by Rittmann and McCarty 1980) and Rittmann and Brunner (1984), to be linked to a geometrical packed-spheres model to link the change in porosity (i.e., increasing VVO) to a corresponding decrease in hydraulic conductivity. The mass of mineral is distributed geometrically within the void space of the packed-sphere system and clogging occurs progressively.

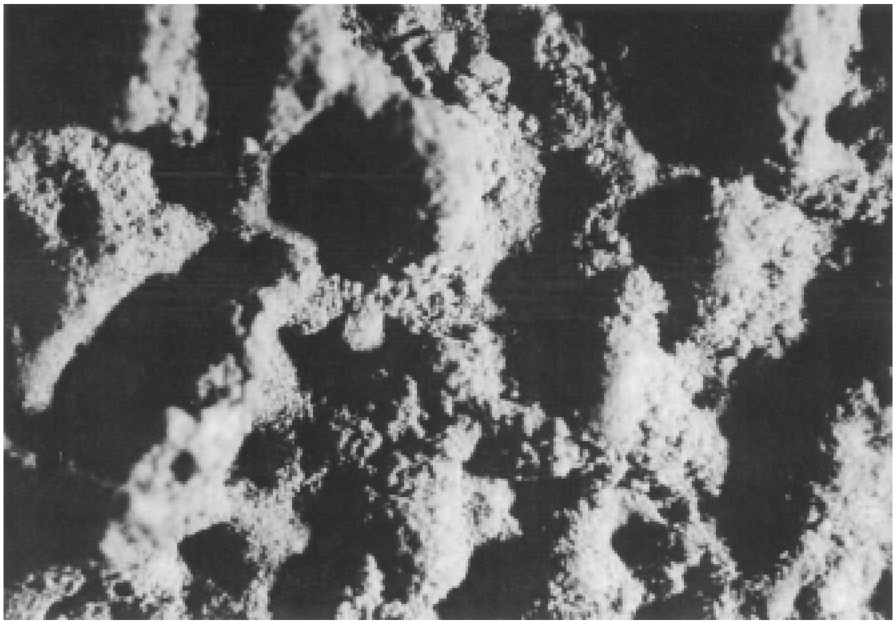
In Fig. 6C raw leachate sample analyses from Metro Toronto's routine monitoring program are plotted along with data for stored leachate from KVL (used as feedstock for laboratory testing) and with the mesocosm effluent results of Rowe et al. (1995*a*). Also shown are data from various other laboratory reactors ("batch incubation" tests and smaller one-dimensional column tests). It appears that as the anaerobic digestion of the COD proceeds, the dissolved calcium in the leachate precipitates. The laboratory samples exhibit a slightly lower calcium concentration relative to the COD. This most likely reflects the calcium that precipitated during storage and distribution in the laboratory, even with the stored leachate chilled to 10°C and used within approximately 7 days.

The termination of one of these mesocosms permitted microbial examination of the various slimes and bioconcretions that revealed a complex clustering of microbial consortia as already noted for the landfill exhumation. These consortia were focused at different locations, with different bacterial groups dominating in the different locations. These included coliform and enteric bacteria, sulphate reducers, slime-forming pseudomonads including *Pseudomonas aeruginosa*, iron bacteria, denitrifyers, and methanogens.

The major clustered consortia that were recovered were dominated by sulphate-reducing bacteria (SRB), denitrifying bacteria (DN), methanogenic bacteria (MTB), iron-related

Fig. 19. Photomicrograph of bottom of clog, sample 94-12. Magnification 6×.

Fig. 20. Photomicrograph of top of clog, sample A-3. Magnification 12×.



bacteria (IRB), or slime-forming bacteria (SLYM). In this sense, slime-forming bacteria consist of those consortia which generate sufficient extracellular polymeric material to give the biofilm a mucoid appearance. Genera include *Pseudomona*, *Klebsiella*, *Enterobacter*, *Micrococcus*, and *Baccilus*.

Within the mesocosm, there was a concentric pattern, with the MTB dominating the core of the mesocosm, surrounded by focused sites of high-SRB and (or) high-DN communities. IRB tended to be observed around the discharge ports of the mesocosm, whereas the SLYM bacteria appeared more dispersed. Enteric bacteria appeared to be dominant in the DN group. No attempt was made to enumerate the methane-oxidizing bacteria (Section 4, Family IV, *Methylococcaceae*), since, being strict aerobes, these would not be expected to be present in the reductive conditions under which the mesocosms were maintained. In a landfill environment, however, these might be expected to dominate consortia at the redox fronts.

Conclusions

A thick black slime layer quickly built up on a 50 mm diameter clear stone drainage blanket underlying the KVL after 1–4 years exposure to leachate. The slime appeared more viscous in the upper part of the drain, whereas below the

Fig. 21. Photomicrograph of bottom of clog, sample A-3. Magnification 6×.

pipe, in the zone of permanent saturation, the slime was more liquid. Void volume occupancy increased from the top to the bottom of the drainage layer.

A marked increase in solids content within the growing and aging clog structure is indicated by a measurable increase in slime specific gravity between 1 and 4 years and an observable increase in the density of the mineral structure as evidenced by photomicrographs.

The amount of clogging within the clear stone drainage blanket was visibly higher near the perforated drainage pipes where there is higher flow of leachate (Fig. 12). Within the pipes, significant precipitation of mineral deposits resulted in the accumulation of large solid mineral clog structures. Both of these observations suggest a loading-rate control on the accumulation of clog. This is consistent with the conceptual model presented herein and with the findings published by Brune et al. (1991).

The observations made in the field are compatible with or even expected given the overall framework of the geochemistry of the leachate as described by Rittmann et al. (1996) and the proposed conceptual model. Specifically, there is an observed increase in leachate pH and decrease in calcium content concurrent with decreasing load of organic substrate (expressed above as COD). This reflects the precipitation of inorganic minerals as the leachate is exposed to and the organic load consumed by the anaerobic biofilm as observed in the field exhumation described herein. Thus it appears that the clear stone drainage blanket LCS represents an anaerobic fixed-film reactor for leachate pretreatment. This is supported by the more controlled observations from the laboratory mesocosms.

If the relationship between calcium and COD in the leachate (Fig. 6) can be established for a particular landfill site, a biofilm model of COD removal in a fixed-bed reactor could be linked with a geometric model of the drainage stone to predict the distribution and rate of clogging of the drainage blanket as described by Rowe et al. (1997*a*, 1997*b*). The data also allows the development of a simple predictive model (Rowe and Fleming 1998).

Acknowledgments

The authors would like to thank the Municipality of Metropolitan Toronto and its staff, particularly Martin Edelenbos, Lou Ciardullo, and Eugene Benda, for their support and assistance with this project. Without their cooperation and the opportunity to collect leachate and drainage stone samples from Keele Valley Landfill, this research program would not have been possible. Mark Armstrong, the late Professor Bob Quigley of the University of Western Ontario, and Professor Bruce Rittmann of Northwestern University have provided invaluable assistance and guidance. Frank Barone of Golder Associates Ltd. and Chris Thompson and Richard Zmuda of Trow Engineering Consultants Ltd. also provided valuable assistance. The authors gratefully acknowledge Peter Bennett for the preparation of the photomicrographs. Funding for this work came initially through a research contract with the former Interim Waste Authority and subsequently from Collaborative Research Grant No. CPG0163097 provided by the Natural Sciences and Engineering Research Council of Canada.

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