Laboratory studies of clogging of landfill leachate collection and drainage systems

I.R. Fleming and R.K. Rowe

Abstract: The findings of a series of studies investigating the clogging of leachate collection and drainage systems for municipal landfill sites are described. Batch tests, column studies, and field-scale "mesocosm" test cells were used to study the development of a thick microbial biofilm covering the surfaces and filling the pore space of the granular drainage media. Within this biofilm, anaerobic microbial consortia effect the stabilization of the organic load (expressed as chemical oxygen demand), with the concurrent precipitation within the granular drainage system of various minerals dominated by calcite.

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

Résumé : Les résultats sont presentés d'une investigation de colmatage et encrassement de la couche drainant utilisé pour la collection des lixiviats aux sites de décharge municipaux. Dans le média de drainage, un biofilm a s'établi, le dedans des procédés microbiologique anaérobies causent la diminution de la démande d'oxygène. Concurremment, les minérales soluble ont précipités d'une formation minérale, enrichi de calcite.

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

Introduction

Concern about uncontrolled release of contaminants from unlined dumps has led to the routine use of natural clay or engineered liners at most new landfill sites. The provision of a base liner, however, requires that systems be constructed and operated to collect and remove the leachate that is generated. Since the "contaminating lifespan" may be decades or centuries for large deep landfills (Rowe 1991), 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 (Ontario Ministry of the Environment and Energy 1993). 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 its required service life.

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 formations associated with biologically induced precipitation of minerals to form concretions or "clog" material. 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; Fleming et al. 1999).

Clogging involves the accumulation of material within the void space of the drainage medium (i.e., increasing the void volume occupancy (VVO) of clog material), which decreases the effective porosity or interconnectedness of the pores in the granular drainage medium. This reduces the hydraulic conductivity of the drainage medium and will eventually impair effective drainage.

The clogging process appears to pass through a number of microbially mediated stages that 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 precipitation of low-solubility sulphide and carbonate minerals (Brune et al. 1991; Rowe et al. 1995; Fleming et al. 1999).

Brune et al. (1991) 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 related to the loading rate of organic substrate and dissolved inorganic salts. This conclusion has been confirmed by Rowe et al. (2000*a*), who demonstrated the control of mass loading on the clogging rate in column tests packed with glass beads.

Brune et al. (1991) reached the following conclusion: "Once a landfill has reached the stable methane phase with

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I.R. Fleming.[1] Department of Civil and Geological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada.
R.K. Rowe. GeoEngineering Centre at Queen's–RMC, Department of Civil Engineering, Queen's University, Kingston, ON N6A 5B9, Canada.

[1] Corresponding author (Ian_Fleming@engr.usask.ca).

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its lightly loaded leachate, incrustation hardly occurs." Although this statement might be true, they did not present data that would clearly demonstrate that it is indeed true. In fact, it would be difficult to reliably conclude, as they did, that this "stable methane phase" has occurred generally within the LCS and the landfill as a whole, based on the monitoring of the composition of the leachate after it has passed through the "biofilm reactor" (represented by the LCS). Thus the issue remains open as to whether or not clogging will continue to occur for landfills in the stable methane phase.

The purpose of this paper is to describe a laboratory testing program used to investigate the fundamental processes governing clogging. From these laboratory investigations and related field studies (described by Fleming et al. 1999), an overall understanding of the process of clogging has been developed. Based on results of laboratory and related studies, recommendations for filter and drainage system design are proposed.

The work described herein formed part of an overall broad-based interdisciplinary effort aimed at identifying the mechanisms controlling the clogging process and developing a predictive model of clogging and the evolution of leachate chemistry (Cooke et al. 1999, 2001). This program includes field and laboratory studies and the development of theoretical and computational tools. The processes governing the precipitation of mineral deposits within a granular drainage layer will be described in a separate paper.[2]

Laboratory experiments

The laboratory testing program described in this paper consisted of three components: batch, column, and "mesocosm" tests. A series of batch incubation tests were undertaken to investigate the mechanisms controlling clogging. The ambient temperature and pressure were varied to evaluate the effect on the rates of depletion of the organic load of the leachate (expressed as chemical oxygen demand or COD) and dissolved minerals (source of mineral clog material). Batch tests were run both with and without porous drainage media to assess the difference between attached and suspended growth.

Ten 1 day flow columns (short- to medium-term tests) were packed with uniform spheres (4, 6, or 15 mm diameter) and subjected to high loadings of Keele Valley Landfill leachate. Nineteen continuously fed mesocosm test cells (medium- to long-term tests) were packed with coarse (19 and 38 mm nominal size) gravel (crushed dolomitic limestone) and permeated with Keele Valley Landfill leachate at flows approximating field conditions.

Leachate samples were taken on a weekly basis from the Metropolitan Toronto Keele Valley Landfill site in Maple, Ontario, for chemical characterization and monitoring and for use in the laboratory mesocosm and batch testing program.

Batch tests

Bottle-incubation tests

Fresh raw leachate from the Keele Valley Landfill site was incubated at various temperatures in sealed 125 mL polyethylene sample bottles. The containers were initially filled with 100 mL of leachate, leaving a head space that was periodically vented to relieve the buildup of biogas pressure. The chemical composition of the leachate is presented in Table 1. The test containers were not filled with gravel or glass beads; these tests therefore represented primarily "suspended growth" (microbial cells suspended within bulk fluid) rather than "attached growth" of a fixed biofilm on the surfaces of the packing material, as the only surface available for attached growth was the inside surface of the 125 mL polyethylene bottle.

Although there are obvious differences between these two conditions, it is significant that the microbial stabilization of the leachate's organic load can be modeled using almost identical input parameters for the Monod equation to predict changes over time in the organic substrate concentration. Calcite precipitation was observed in all tests, as was an increase in the leachate pH, reflecting the microbial consumption of organic acids. These concurrent processes were observed in both batch (suspended and attached growth) and continuous-flow column and mesocosm tests. In all cases, there was a consistent relationship between the mass of calcium (Ca) removed from solution and the mass of organic load (expressed as COD) that was stabilized (Fleming 1999). These findings support the use of simple batch tests to investigate the clogging processes. The detailed geochemical interpretation of the laboratory data will be described in a separate paper.[2]

The bottle-incubation tests were conducted concurrently with a similar series of tests using a synthetic leachate mixture, intended to simulate the raw leachate from the Keele Valley Landfill. The composition of the synthetic leachate used in these tests is summarized in Table 1.

The leachate in the batch tests was periodically sampled for COD and calcium. Figure 1 shows the results for COD in the static bottle-incubation tests of fresh Keele Valley leachate at various temperatures. The measured COD rapidly decreased from approximately 16 000 to 2000 mg/L. Below about 6000 mg/L, the test results indicated a slower rate of decrease in the measured COD values, which may reflect the depletion of the acetate in the leachate and the relatively slower kinetics of fermentation of less readily degradable organics. After 69 days (at 28 °C) and 95 days (at 22 °C) the measured COD did not decrease any further, reflecting the refractory COD of about 2000 mg/L or 12% of the initial concentration. Although retention times this long (70–100 days) may be longer than expected in a freely draining LCS, the purpose of these batch incubation tests was to demonstrate the biological stabilization processes rather than to simulate the rate of such processes. It is likely that in a field situation, a faster rate of organic degradation would result from the significant microbial bioslime that develops in the drainage layer (Fleming 1999).

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[2] Fleming, I.R., Rittmann, B.E., and Rowe, R.K. 2003. Geochemistry of clogging in landfill leachate collection and drainage systems. In preparation.

Table 1. Composition of synthetic leachate used in batch tests and range of concentrations of raw Keele Valley leachate (1993–1998).

(A) Synthetic leachate	Concentration
Acetic acid (mL/L)	7
Propionic acid (mL/L)	5
Butyric acid (mL/L)	1
K_2HPO_4 (mg/L)	30
$KHCO_3$ (mg/L)	312
K_2CO_3 (mg/L)	324
NaCl (mg/L)	1440
$NaNO_3$ (mg/L)	50
$NaHCO_3$ (mg/L)	3012
$CaCl_2$ (mg/L)	2882
$MgCl_2 \cdot 6H_2O$ (mg/L)	3114
$MgSO_4$ (mg/L)	156
NH_4HCO_3 (mg/L)	2439
$CO(NH_2)_2$ (mg/L)	695
Distilled water	To make 1 L
NaOH	To pH 5.8–6
$Na_2S \cdot 9H_2O$	To Eh = –120 mV
Trace metal solution	
$FeSO_4$ (mg/L)	2000
$HsBO_3$ (mg/L)	50
$ZnSO_4 \cdot 7H_2O$ (mg/L)	50
$CuSO_4 \cdot 5H_2O$ (mg/L)	40
$MnSO_4 \cdot H_2O$ (mg/L)	500
$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ (mg/L)	50
$Al_2(SO_4)_3 \cdot 16H_2O$ (mg/L)	30
$CoSO_4 \cdot 7H_2O$ (mg/L)	150
$NiSO_4 \cdot 6H_2O$ (mg/L)	500
96%H_2SO_4 (mL/L)	1
Distilled water	To make 1 L

(B) Keele Valley leachate	Concentration
Chemical oxygen demand (mg/L as O)	6100 – 25 000
Biochemical oxygen demand (mg/L as O)	3400 – 16 400
pH	5.9–6.8
Total organic carbon (mg/L as C)	1440–7060
Electrical conductivity (mS/cm)	10–23
Total suspended solids (mg/L)	40–370
Volatile suspended solids (%)	29–65
Total Kjeldahl nitrogen (mg/L as N)	370–1340
Ammonia (mg/L)	220–770
Nitrate (mg/L)	0.02–16.00
Sulphate (mg/L)	34–290
Sulphide (mg/L)	0.2–10.0
Chloride (mg/L)	1400–3800
Alkalinity (mg/L $CaCO_3$)	3200–8100
Calcium (mg/L)	660–2880
Iron (mg/L)	46–357
Magnesium (mg/L)	306–695
Manganese (mg/L)	1.7–20.0
Phosphorous (mg/L)	2.5–8.7
Potassium (mg/L)	420–1040
Sodium (mg/L)	824–2220
Total phenolics (4AAP) (mg/L)	0.2–4.5
Volatile organic acids (mg/L)	2260–7420
Microbial ATP (ng/L)	Avg. 20
Total heterotrophs (no./mL)	$2 - 40 \times 10^8$

For the synthetic leachate, Fig. 2 shows that the measured total COD did not significantly change over a period of 30 days after charging the sample bottles with 100 mL. At this time, the samples were inoculated with 5 mL fresh or "live" Keele Valley leachate, which contains approximately 10^7 bacterial cells per millilitre (Table 1). Subsequent to inoculation, the total COD decreased steadily over time from an initial value of approximately 11 000 mg/L (for all tests) to as low as 1670 mg/L for a test incubated at 28 °C. The synthetic leachate was mixed from laboratory reagents and distilled, deionized "megapure" laboratory water (selected for its low microbial content relative to the alternatives, tap water or distilled water). Test results suggest that, initially, the synthetic leachate did indeed contain only a very small microbial population, since the COD in the tests only began to decrease after the samples were inoculated with biologically active fresh leachate from Keele Valley. This strongly supports the conclusion that the mechanism of COD removal is biological.

The effect of temperature on the COD consumption rate was also evaluated. By the end of the 138 day incubation period for Keele Valley leachate, the COD reduction was 88% at 28 and 22 °C, and 32%–36% at 10 °C. For the synthetic leachate, the COD reduction was 64%–84% at 28 °C, 52%–62% at 22 °C, and 10%–11% at 10 °C.

Figure 3 shows the results for calcium with time for Keele Valley leachate and shows that the total calcium in the Keele Valley leachate decreased in parallel with the measured decrease in COD during the batch incubation tests.

Figure 4 shows the results for calcium with time for the synthetic Keele leachate and shows that the total calcium in the synthetic leachate decreased rapidly after the inoculation of these samples with 5 mL of fresh Keele Valley leachate. For the synthetic leachate batch tests incubated at 22 or 10 °C, there was no measurable decrease in dissolved calcium (or COD) during the period prior to inoculation of the tests with fresh Keele Valley leachate, within the accuracy of the test procedures employed.

There appeared to be some apparent loss of dissolved calcium from the synthetic leachate at 28 °C prior to inoculation. This was not observed in the samples incubated at 22 or 10 °C and most likely reflects the decreasing solubility of $CaCO_3$ with increasing temperature.

Figures 5 and 6 show the results of the batch incubation tests with dissolved calcium plotted against total COD for each of the synthetic leachate tests (at all temperatures) and the fresh Keele Valley leachate (at all temperatures). The results are striking. For the Keele Valley leachate, a strong and close to linear trend is evident, with an apparent slope of about 7.5 mg/L Ca per 100 mg/L COD. This value is similar to the values obtained using different test procedures, as described later in the paper. Looking closely at Fig. 5, it is possible that below about 5000 mg/L COD, the data suggest a flatter slope, suggesting that the COD becomes increasingly dominated by more recalcitrant organics as the readily degradable forms (acetate, propionate) are consumed.

For the synthetic leachate, Fig. 6 suggests a nonlinear relationship. The shape of this curve is similar to that found for the later series of "packed flask" batch tests (discussed later in the paper) and that of a partially empirical, partially theoretical quantitative model presented by Fleming (1999).

Fig. 1. COD stabilization in batch incubation tests, Keele Valley leachate (lines show general trends only).

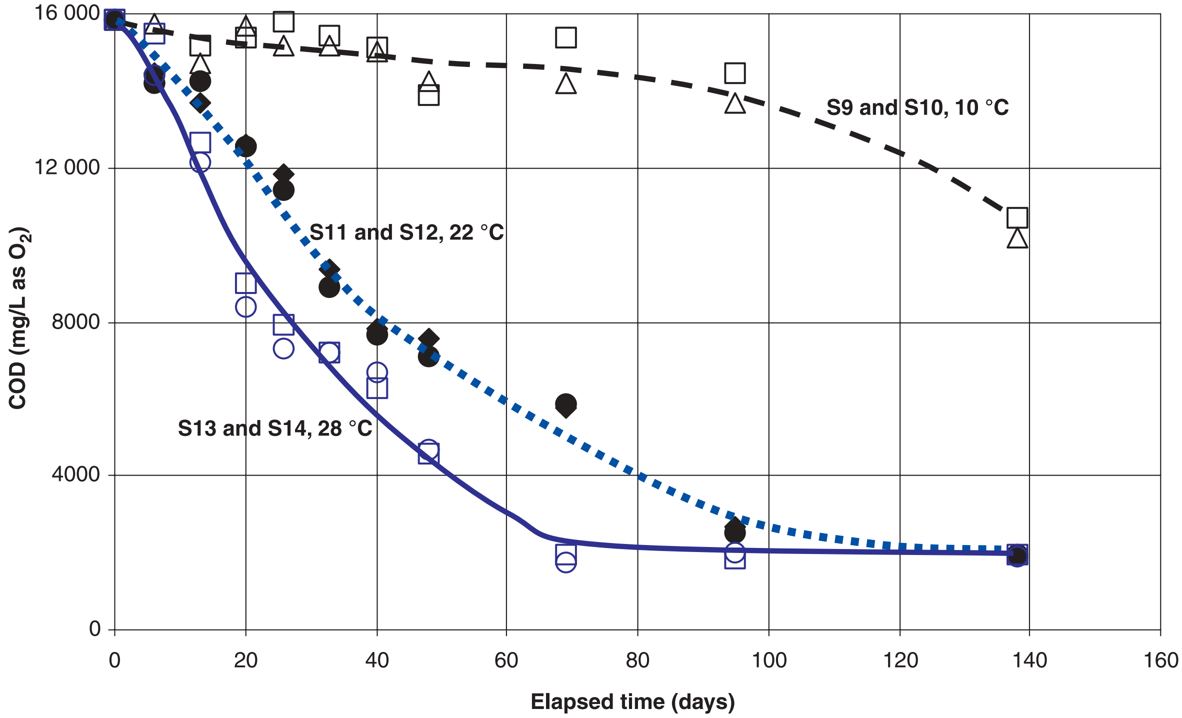
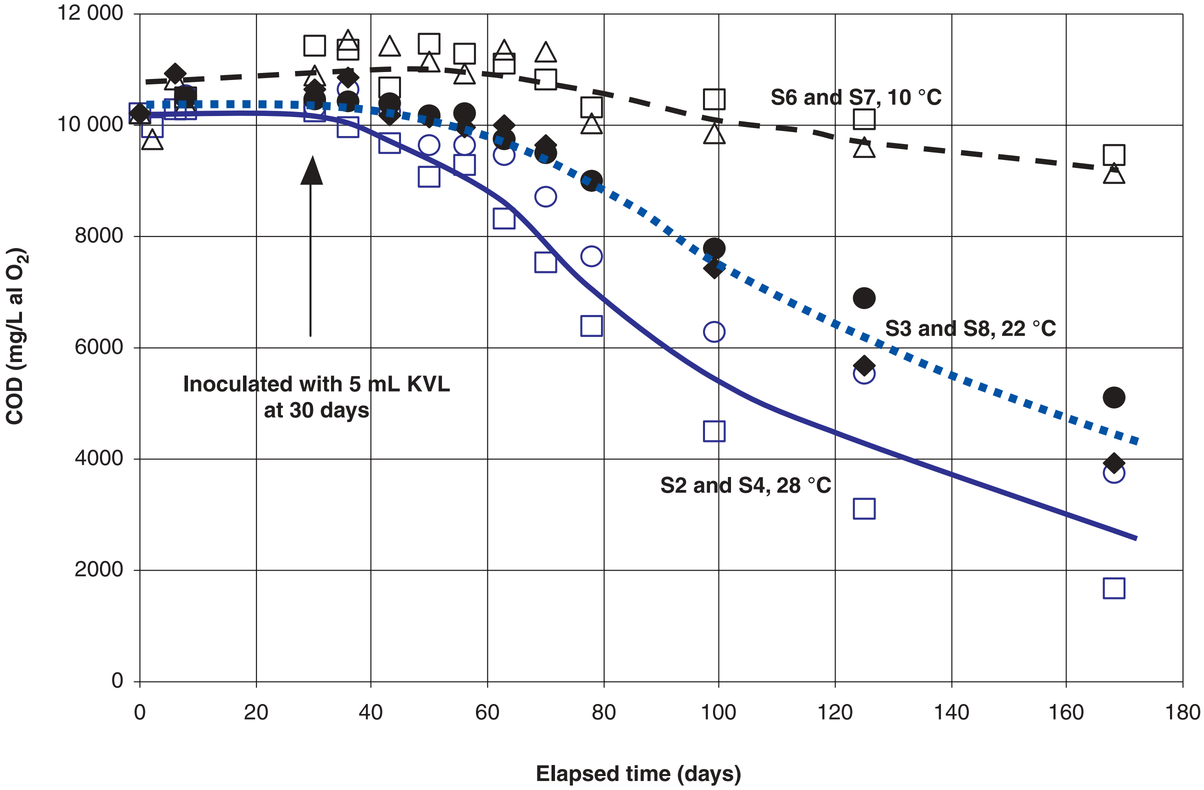


Fig. 2. COD stabilization in batch incubation tests, synthetic leachate (lines show general trends only). KVL, Keele Valley leachate.



Within the 10–28 °C range of temperatures studied, there is at most only a slight effect of temperature on the relationship between the dissolved calcium and total COD. The rate at which the tests moved from the top left to the bottom right of Figs. 5 and 6 was strongly influenced by temperature. Importantly, however, the path followed during the anaerobic stabilization process seems to be independent of temperature within the range of 10–28 °C. This observation is important in the development of a proposed practical design and analysis tool for the evaluation of the clogging

Fig. 3. Decrease in calcium during batch incubation tests, Keele Valley leachate (lines show general trends only).

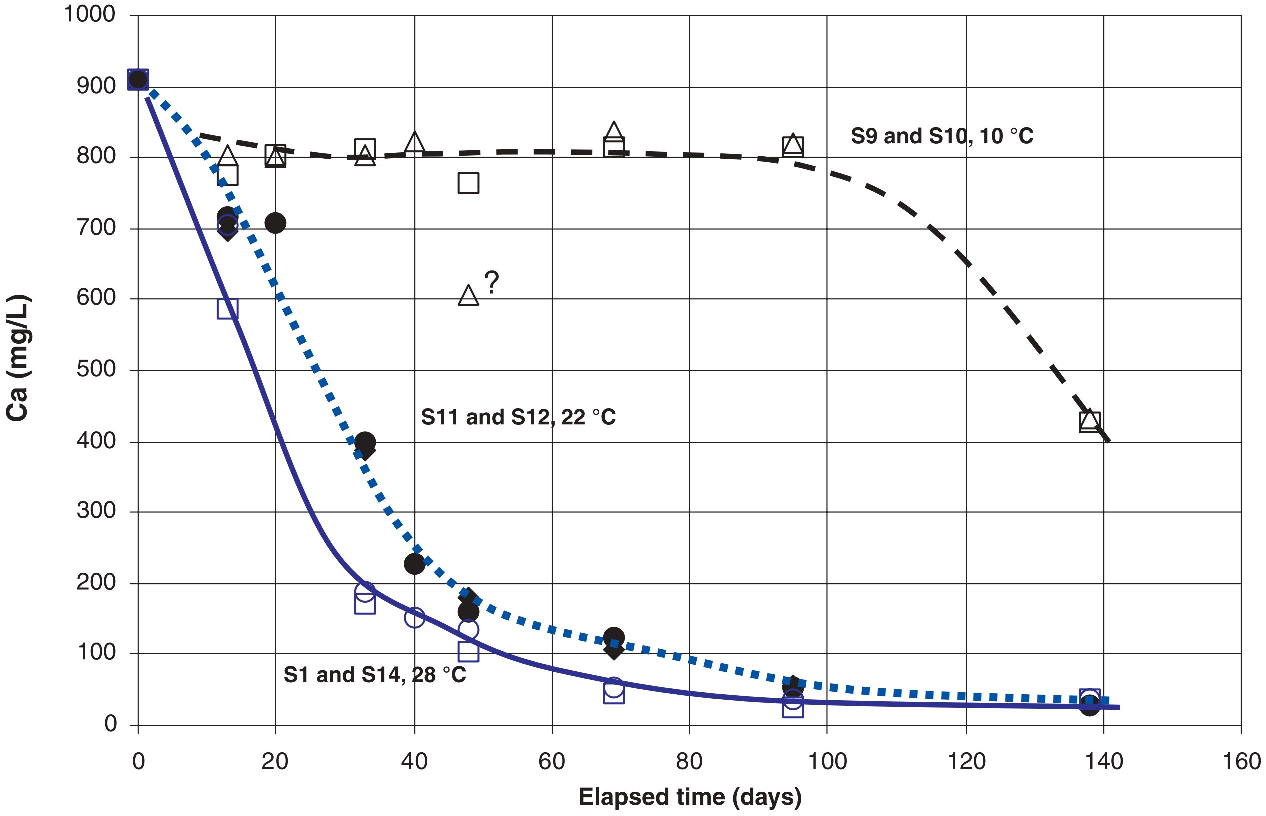


Fig. 4. Decrease in calcium during batch incubation tests, synthetic leachate (lines show general trends only).

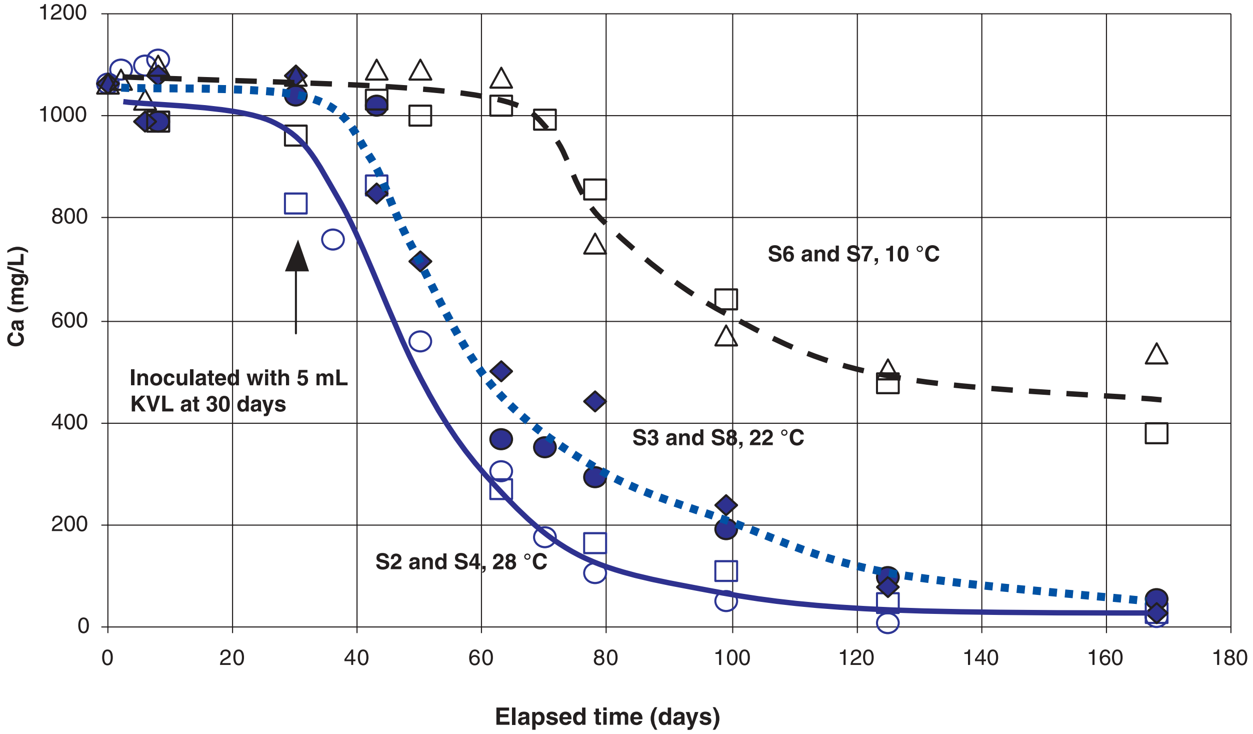


Fig. 5. COD and calcium depletion during batch incubation tests, Keele Valley leachate.

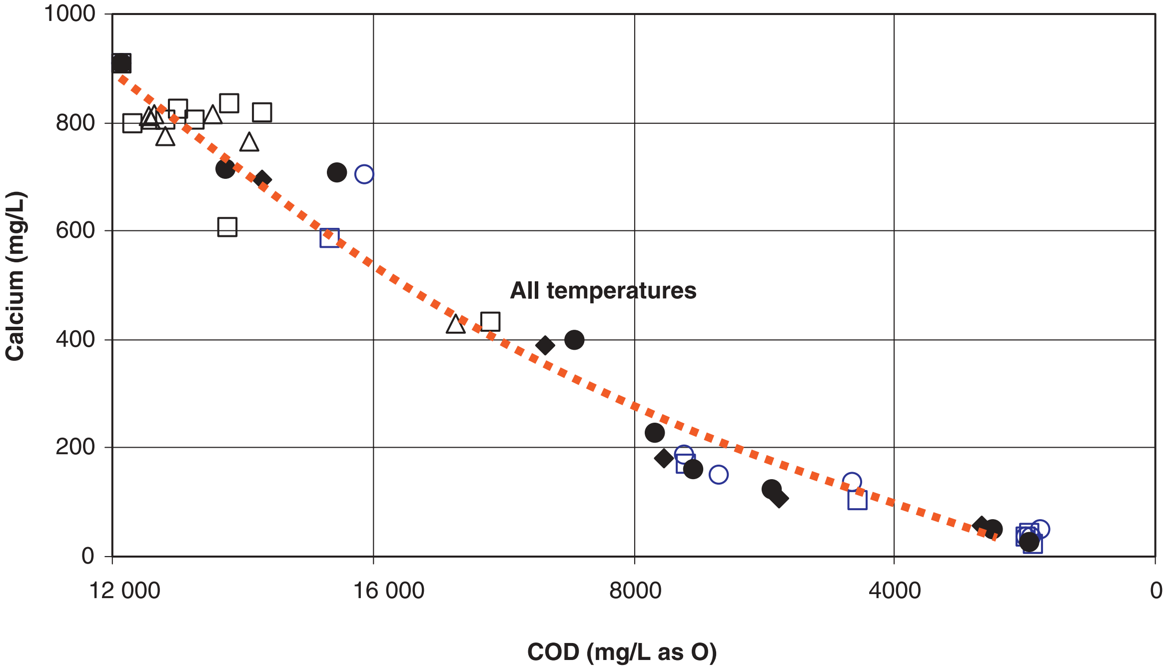
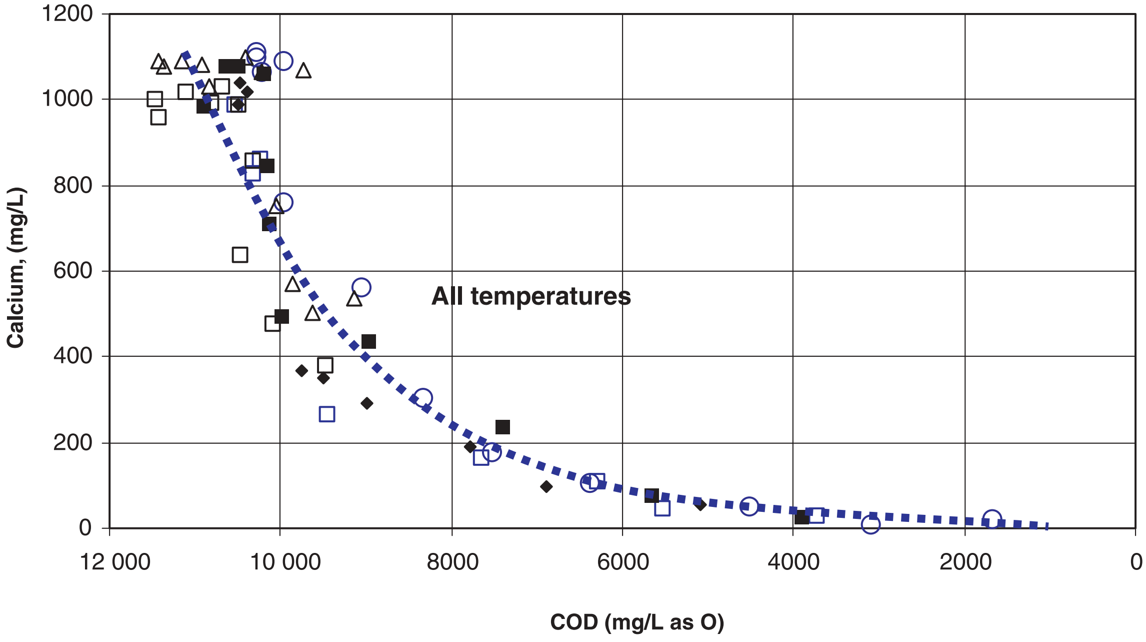


Fig. 6. COD and calcium depletion during batch incubation tests, synthetic leachate.



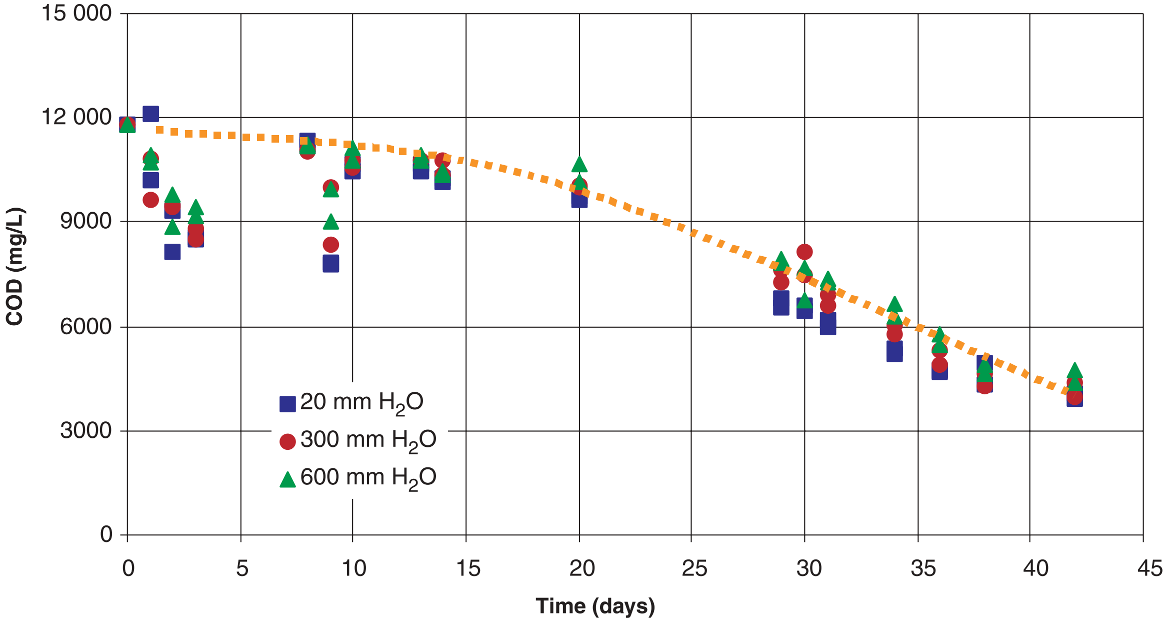
problem in landfill drains, in that the temperature and its control over the rate of the process may be ignored for the simple design tool, and the degree of clogging considered independently (Rowe and Fleming 1998; Fleming 1999).

Another inference, which can be made on the basis of these batch tests, is that suspended microbial growth (with no packing) adequately represents the field (attached growth) condition. This inference is examined in the following section in which the behaviour of attached-growth batch tests is compared with the results of the suspended-growth batch tests described in this section. This suggests that a strategy for relating COD stabilization to changes in the bulk chemistry of the leachate may be to consider the fluid chemistry independent of the specifics of the microbiology (species, morphology of microbial consortia, metabolic pathways, etc).

Packed-flask batch incubation tests

A second round of tests was conducted to evaluate an hypothesis discussed by Rittmann et al. (1996) and reported here in the following broad terms. From the interpretation of the dissolution–precipitation equilibrium for calcite in influ-

Fig. 7. COD stabilization with time in the packed-flask batch tests at 28 °C with various ambient pressures of synthetic landfill gas, Keele Valley leachate.



ent and effluent samples from mesocosm studies, it was inferred that the disequilibrium of the system with respect to carbonate could represent a rate-limiting factor with regard to the precipitation of $CaCO_3$ as calcite. The reason for this phenomenon is hypothesized to be associated with limited mass transfer of carbonate to calcite nucleation sites (i.e., the tendency for off-gassing from the system) as discussed by Rittmann et al. (2003). As a result, batch incubation tests were repeated with some important differences as described in this section.

All tests were carried out at 28 °C in 2000 mL plastic flasks attached to fermentation locks that allowed pressure to be maintained in the test container while allowing degassing to prevent overpressuring. These pressures were selected to be in the range representative of the conditions at the mid-point elevation of a functioning drainage system (from 20 to 600 mm H_2O). For duplicate tests R-1 and R-2, standard polystyrene fermentation locks were used to allow biogas to vent while maintaining a pressure equivalent to about 20 mm of water. For tests R-3–R-4 and R-5–R-6, larger fermentation locks were fabricated to control the internal pressure at approximately 300 and 600 mm, respectively. All test flasks were filled with glass beads (marbles of diameter 15–18 mm) to provide a large surface area for attached biofilm growth.

The leachate in the batch tests was periodically sampled without allowing any introduction of air. COD, calcium, volatile organic acids, pH, and oxidation–reduction potential (ORP) were measured (detailed methodology is given by Fleming 1999). Within the range of pressures tested, there was no significant effect of varying the partial pressure of CO_2 (and CH_4) and the COD and Ca results for the three different partial pressures plotted within the typical scatter of data. The depletion of COD over time in these flask incubation tests, presented in Fig. 7, followed a trend generally similar to that presented in Fig. 1 for the earlier series (at 28 °C) of suspended-growth, bottle-incubation tests. Although a detailed examination of the data suggests differences at various times, in both cases the COD of fresh Keele Valley leachate at 28 °C decreased over approximately 50 days from an initial COD of 12 000 – 16 000 mg/L to about 4000 mg/L. Similarly, calcium depletion over time (Fig. 6) decreased over about 40 days at 28 °C following a trend generally similar to that observed in the earlier tests (Fig. 3). Although it may be argued that a retention time as long as 50 days is unrepresentative of a freely draining functioning LCS, there is field evidence from the Keele Valley Landfill to suggest that this depletion of COD and Ca does occur in a functioning LCS (Fleming et al. 1999).

The measured pH increased in all cases during the tests. This finding suggests that the mechanism for the precipitation of $CaCO_3$ is related to an increase in pH (and consequent tendency for $CaCO_3$ precipitation) as a result of the biological consumption of the organic acids in the leachate and the release of $CO_{2(g)}$ into the gas phase. Fleming (1999) further discusses this in the context of the overall geochemical framework.

Figure 9 presents the results of the bead-filled flask experiments in the same way as Figs. 5 and 6 for the bottle-incubation tests; with calcium plotted against COD. Again the results are generally similar to those obtained from the bottle-incubation tests. In the bead-filled flasks, there was a more rapid, immediate decrease in dissolved calcium, and the trend appears nonlinear, similar to that exhibited by the synthetic leachate in the suspended-growth, bottle-incubation tests. Below a COD value of approximately 10 000 mg/L, the relationship between COD and calcium, although not linear, could be approximated by a slope of about 10 mg/L Ca per 100 mg/L COD. This value is quite close to the value of 7.5 mg/L Ca per 100 mg/L COD suggested by Fig. 6 for the bottle-incubation tests. This provides additional support for the conclusion that suspended-growth

Fig. 8. Calcium depletion with time in the packed-flask batch tests at 28 °C with various ambient pressures of synthetic landfill gas, Keele Valley leachate.

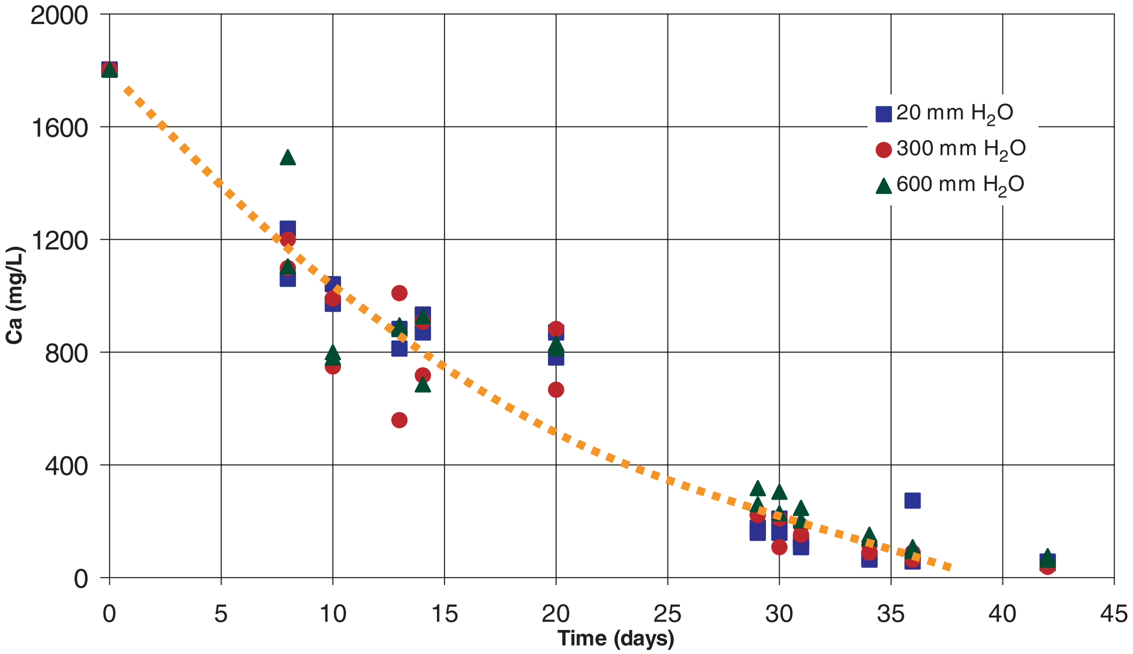
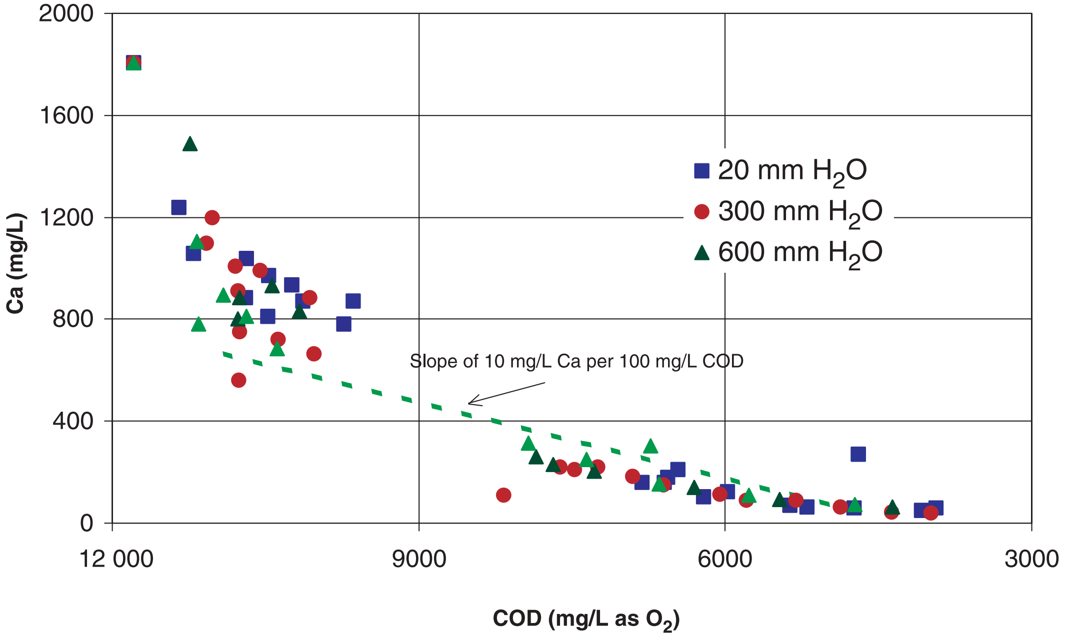


Fig. 9. COD and calcium depletion during packed-flask batch tests at 28 °C with various ambient pressures of synthetic landfill gas, Keele Valley leachate.



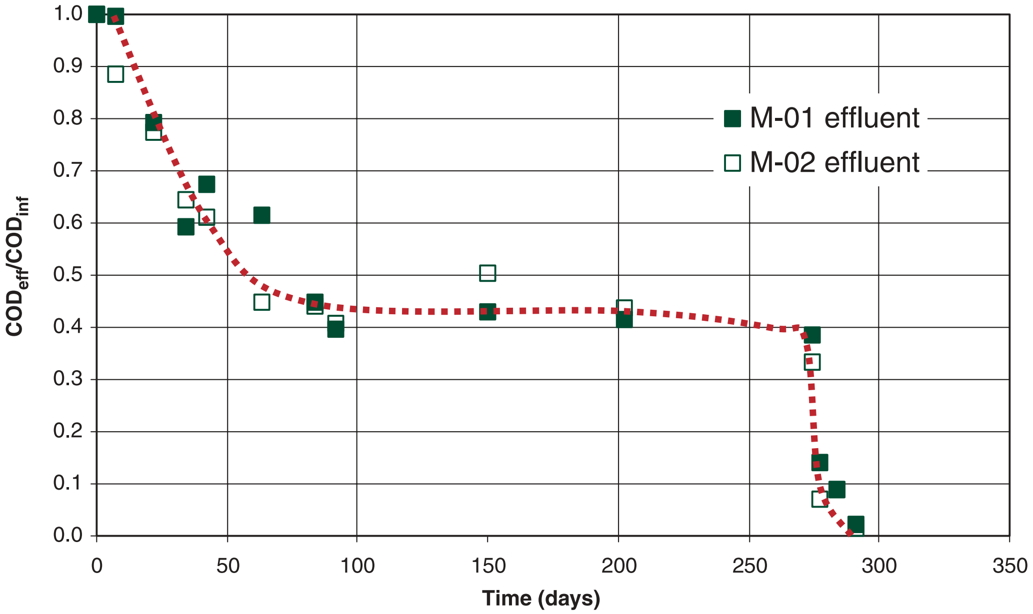
tests may be used in the laboratory to investigate the behaviour of the predominantly attached-growth system.

Column tests

Laboratory column tests were carried out to evaluate clogging under controlled conditions. The test conditions for the column reactors are described in detail by Rowe et al. (2000*a*, 2000*b*).

One of the purposes of the column tests was to evaluate a geometric packed-spheres model of the drainage medium (Cooke and Rowe 1999). The columns were therefore packed with uniform spherical glass beads to maintain a high degree of control over pore size and shape and to evaluate the relationship between the porosity and specific surface during the growth of the clog "film" on the surfaces of the media. The relationship between the measured porosity and hydraulic conductivity values under clogging conditions was also examined. Relatively small particle size "drainage media" were used to reduce the time frame required for "significant" clogging (until a measurable drop in material per-

Fig. 10. COD stabilization in continuous-flow column tests at 28 °C using 4 mm glass beads. COD_{eff}, effluent concentration of COD; COD_{inf}, influent concentration of COD.



meability). For these columns, the drainage media were composed of 4 and 6 mm diameter glass beads and glass marbles of approximate diameter 16 mm.

This work has been described by Fleming (1999), Armstrong (1998), and Rowe et al. (2000*a*, 2000*b*). These columns (and other columns that were subsequently constructed) were used to study the effect of (*i*) temperature, (*ii*) particle size, and (*iii*) loading rate on the rate and degree of clogging. Leachate was introduced from the bottom of the columns, the piezometric head was measured at several points along the upward vertical flow path, and provision was made for collection of samples and measurement of flow volumes. The entire system was kept sealed and oxygen ingress prevented to maintain anaerobic conditions.

Figure 10 shows a typical normalized COD versus time plot for a typical pair of duplicate column reactors, packed with 4 mm glass beads and tested at 28 °C. The effluent concentration was normalized with respect to influent concentration because there was a significant variation during the course of the testing program in the strength of the raw leachate collected from the Keele Valley Landfill. The short-term fluctuations in leachate strength reflected ongoing construction and stormwater drainage operations at the Keele Valley site. There was, however, a real and sustained longer term change in leachate chemistry at Keele Valley during the course of the study, as described by Fleming et al. (1999). The COD test results for the effluents from the two duplicate reactors were very similar. After approximately 80 days, the removal of COD appeared to remain constant at about 60% for over 200 days. Subsequent to that, the apparent COD removal was greater; this is a consequence of the significant decrease in the amount of flow that could be delivered through the column during the later stages of the test due to the significant degree of clogging that had occurred. Under this low-flow condition, the retention time in the reactor was greater, disrupting the conditions that had for almost 200 days maintained near-steady-state COD removal in the reactor. A similar trend was observed for calcium with time in all experiments.

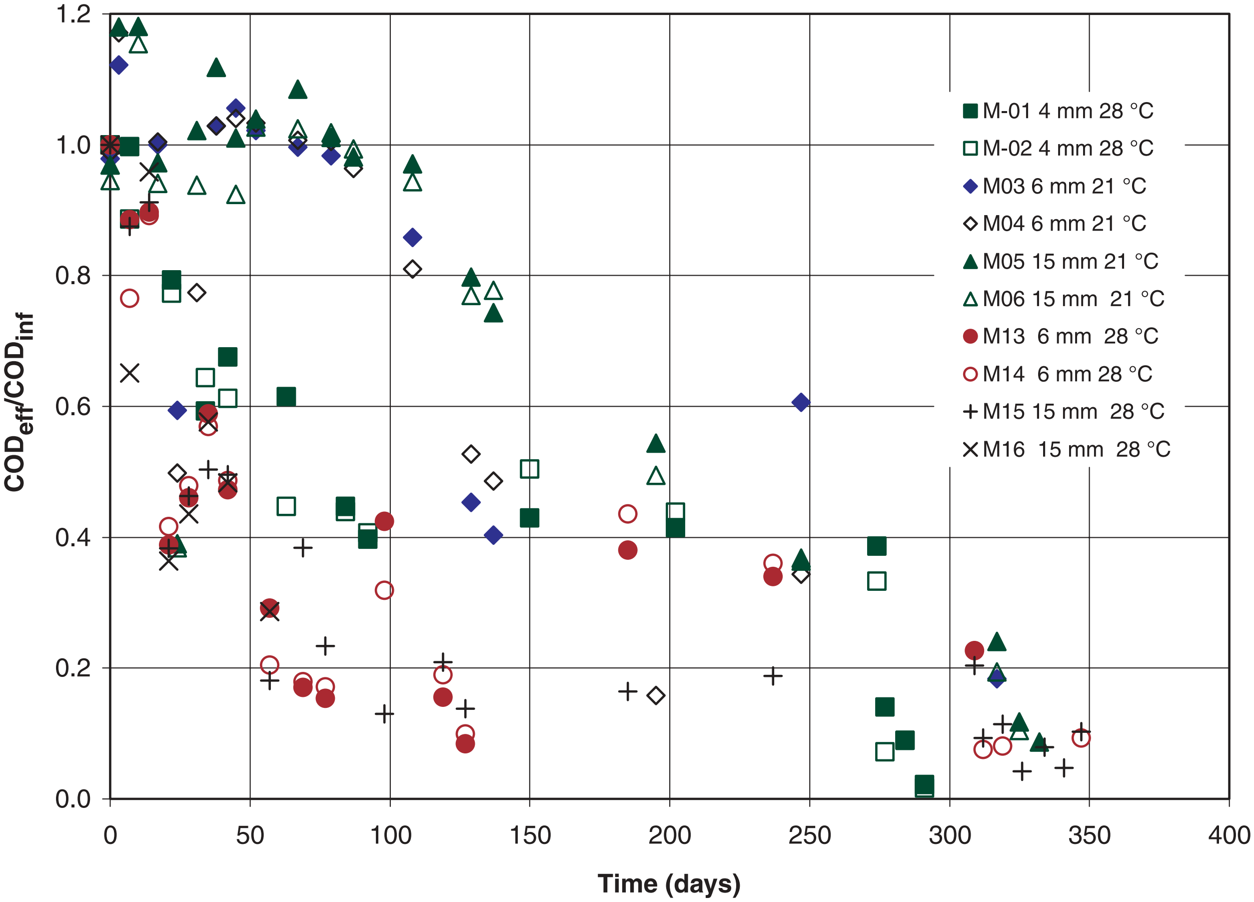
Figure 11 presents the COD data from all 10 column reactors plotted together. The significant observation that can be drawn from this figure is that the data tended to converge after sufficient time. It is evident that through the period between 50 and 150 days, the reactors tested at 28 °C consistently "outperformed" (i.e., removed more COD than) those tested at 21 °C (>40% COD removal at 28 °C compared with <20% COD removal at 21 °C). This reflects the longer lag period at the lower temperature. Significantly, however, after about 200 days this temperature difference is not clearly evident in the data, and by the end of the test there is little difference in terms of percent COD removal between columns M-05–M-06 at 21 °C and M-14–M-15 at 28 °C.

Figure 12 presents the calcium removal with time for 10 column reactors plotted together. Again, the significance is that the temperature appears to control the time required to reach stable removal conditions; after sufficient time, however, the difference in temperature has little effect. The implication of this finding with respect to the development of a practical design tool has already been noted.

Figure 13 presents these same data from all of the column reactors at 21 and at 28 °C presented with calcium plotted against COD. It is evident that differences exist between the various tests, however, a strong linear trend is evident with a slope of approximately 15 mg/L Ca (as $CaCO_3$) per 100 mg/L COD, or 6 mg/L Ca per 100 mg/L COD. When the data are plotted in this way, the apparent effect of temperature is minimized, as was the case for the batch tests.

The relationship between calcium and COD suggested by Fig. 13 is similar to that obtained from Fig. 5 for the bottle-incubation batch tests using Keele Valley leachate (7.5 mg/L Ca per 100 mg/L COD) and from Fig. 9 for the bead-filled flask batch tests (approximately 10 mg/L Ca per 100 mg/L COD). The important conclusion is that the conditions in

Fig. 11. COD stabilization with time in continuous-flow column tests.



and results from batch tests may be used to approximate those of a continuous-flow system. Fleming et al. (1999) presented these data and field data from the Keele Valley Landfill and concluded that the yield of mineral precipitate in the various laboratory tests was consistent with that found in the field. This further supports applying the findings of the batch tests to the full-scale continuous-flow system represented by the drainage layer under operating conditions in a landfill site.

Mesocosm studies

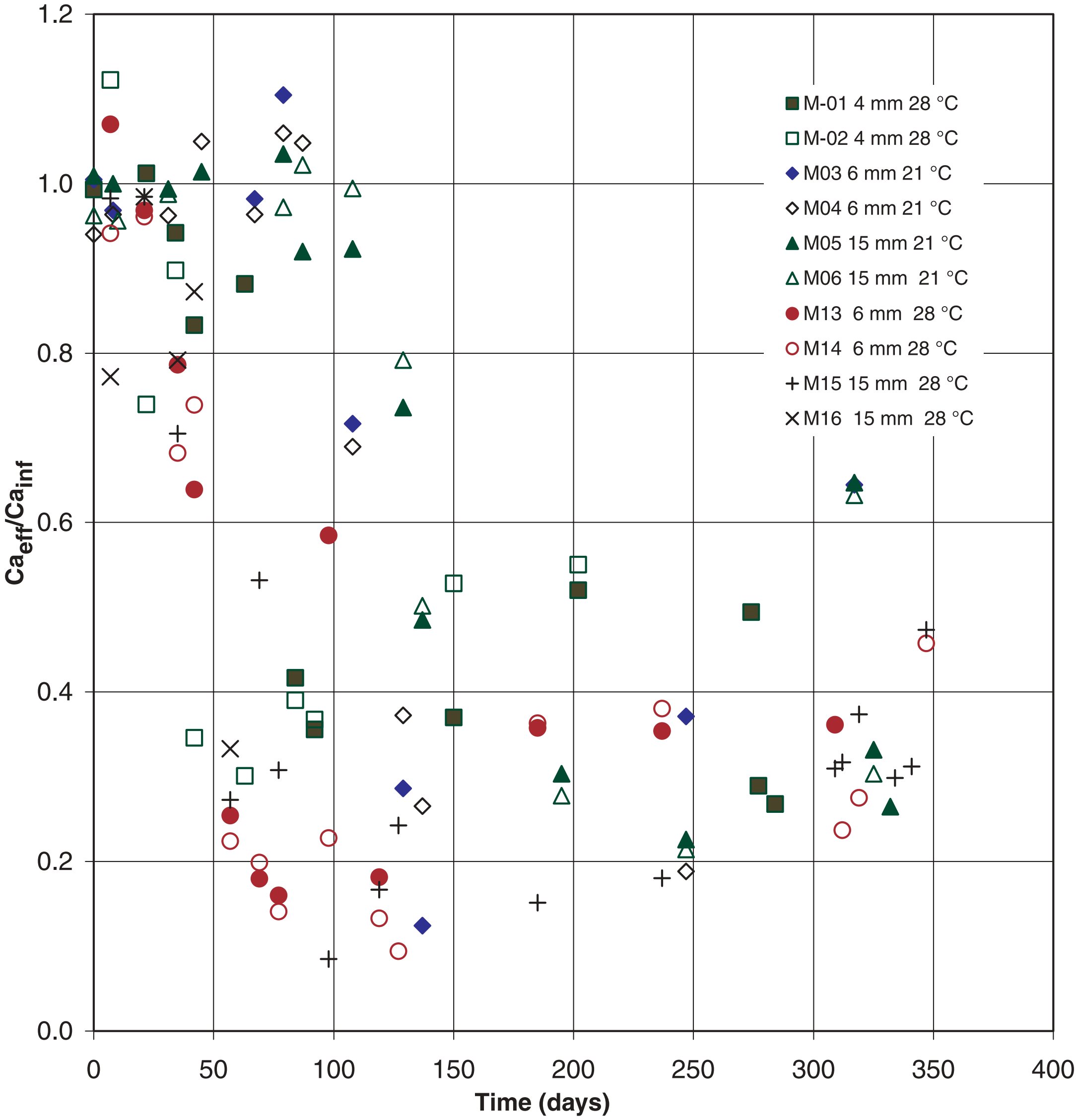
Nineteen field-scale laboratory reactors, or mesocosms, were designed to represent different materials and combinations of materials used in practice to construct landfill underdrains or leachate collection and removal systems (LCRS). In contrast to the heavily loaded column tests described previously, the LCRS mesocosms were fed full-strength, fresh Keele Valley leachate feedstock at a controlled rate representative of field conditions. The mesocosms simulated two-dimensional leachate flow, involving a small component of vertical percolation within a predominantly horizontal flow system. For the purpose of establishing the "field-scale" horizontal flow rate required for the laboratory reactors, the anticipated leachate flow was calculated for that section of a continuous granular underdrain "blanket" closest to leachate collection pipes spaced at 50 m (i.e., $q = 0.5Lq_{\text{inf}}$, where q is the flow per unit width of drain, L is the spacing between collection pipes, and q_{inf} is the annual infiltration rate or leachate production per unit area of landfill). For the laboratory mesocosms of width 0.25 m, the lateral flow rate required to simulate the average horizontal flow in the drainage layer near the collection pipe is Q = 3.4 L/d (2.4 mL/min), which was delivered to each mesocosm test cell on a continuous-flow basis using peristaltic pumps.

The development of the clog was monitored by periodically measuring the drainable porosity of the granular material (i.e., partially draining the mesocosm and measuring the volume of leachate and the change in liquid level). The influent and effluent chemistry were also monitored.

The mesocosms were constructed and testing commenced in June 1993; some tests are still ongoing. Figure 14 shows the general configuration of the mesocosm test cells (described in this section). Tables 2 and 3 present specific data with regard to the design variables (i.e., filter type) for the various test cell configurations. These were described in detail by Fleming (1999). Most test mesocosms were constructed and operated in duplicate.

The mesocosm dimensions, 0.25 m (W) × 0.6 m (L) × 0.7 m (H), were governed by the size of granular material used, the maximum cumulative height of the layers to be placed, the leachate feedstock requirements (assuming weekly supply of fresh leachate), and the overall weight of the filled cell when in operation. The test cells were custom fabricated of welded 9 mm PVC sheet. Leachate feedstock

Fig. 12. Calcium removal with time in continuous-flow column tests. Ca_{eff}, effluent concentration of calcium; Ca_{inf}, influent concentration of calcium.



and effluent ports, water level measurement piezometers, and gas supply and venting fittings were installed on each cell as required. Sand and geotextile were placed on the base (graded at 1% toward the outlet), simulating typical landfill construction.

The leachate feedstock delivery system design was governed by the requirement to reliably deliver relatively low flow rates to the cells on a continuous basis. The required downward vertical percolation component of the two-dimensional flow system for the surface area of 0.15 m^2 was approximately 0.03 m^3/year or 80 mL/day. To deliver this small flow, a continuous feed was not feasible and an intermittent timer-controlled dosing system was adopted which delivered 20 mL to each mesocosm every 6 h to approximate as closely as possible a continuous-flow system.

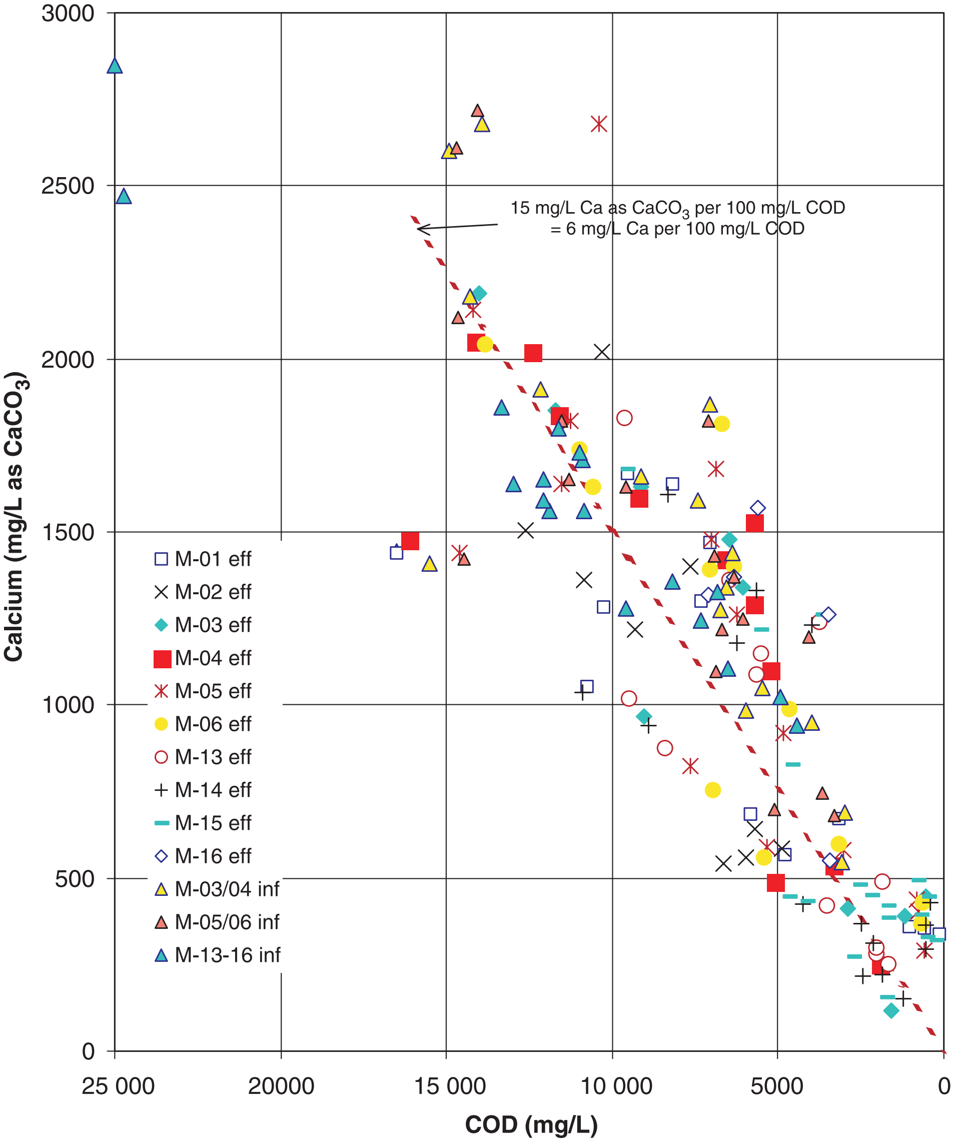
The interior atmosphere of each test cell, and of the tanks in the leachate storage system, was maintained anaerobic and at a pressure 150–200 mm of water above atmospheric pressure. The laboratory temperature was maintained at 28 ± 1 °C to simulate conditions anticipated in an active LCS.

Refuse compost (5–10 years in age and taken from the City of London W12A landfill site) was placed above the gravel drainage layer to reproduce field conditions as closely as possible. This refuse was intended to represent a source of particulate that could intrude or be carried into the drainage layer and of microbiological components of the waste mass that might be absent from the leachate as collected. Additionally, this waste layer was subjected to infiltration of leachate from above and therefore reached and was maintained at its “field capacity” moisture content estimated at 70%–90% dry weight (Conestoga-Rovers and Associates Limited 1993). The combination of moisture, nutrients, and finer grained materials may represent an environment conducive to early microbial growth, and it was therefore reproduced as far as possible.

Design variables

Several design variables were examined by varying the conditions between different cells or groups of cells. Four groups of basic mesocosm designs were used (denoted D-1

Fig. 13. Calcium versus COD for all column tests.



to D-4) to reflect primary variations in design relating to the presence and composition of a filter–separator layer between the gravel drainage layer and the overlying waste compost layer and the presence of an extra “sacrificial” gravel layer between the waste and upper geotextile filter.

Within each of the groups representing an essentially similar design, additional mesocosms were built to test the effect of minor changes in materials or operating conditions. These test cells were added primarily to assess the significance of suspected key factors affecting clogging and to assist in the interpretation of laboratory testing results. Table 2 summarizes the various test configurations that were used.

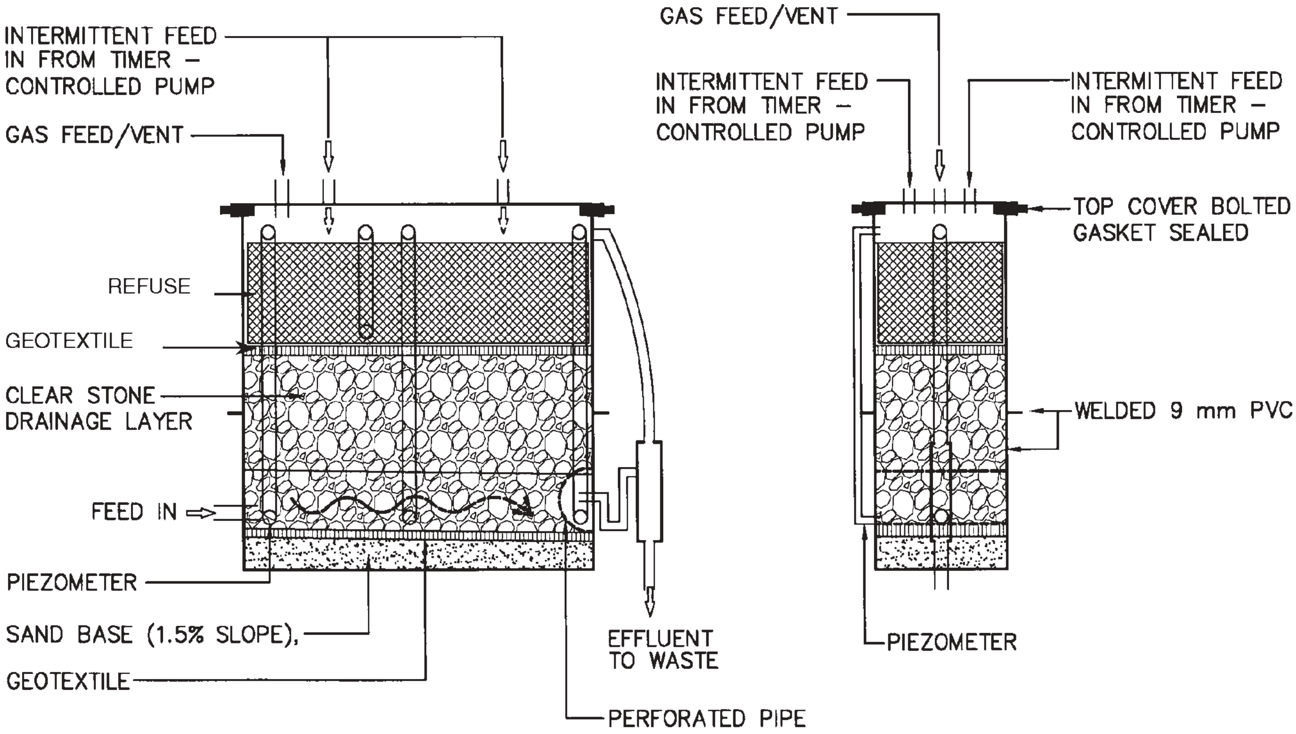
(1) The D-1 group of mesocosms incorporated a geotextile filter between the gravel and the overlying waste. In one duplicate pair, a nonwoven, needle-punched, polypropylene geotextile was used (Polyfelt TS650). The TS650 product is lighter than the TS900 material placed under the liner. For brevity, these two nonwoven geotextiles will be denoted “lightweight” and “heavyweight,” respectively. Another duplicate pair incorporates a woven slit-film geotextile (Terratrack 24-15) with physical and strength properties similar to those of the lightweight nonwoven geotextile but of significantly lower specific surface and larger filtration opening size. Table 3 summarizes the material properties of the geotextiles used.

(2) One duplicate pair of D-3 mesocosms differs from the D-1 group in that an additional sacrificial gravel drainage layer was placed between the upper lightweight nonwoven geotextile and the waste.

(3) One pair of D-4 mesocosms utilized a graded granular filter consisting of 4 cm of pea gravel (6 mm nominal size) and 4 cm of graded concrete sand (D_{50} = 0.6 mm, D_{10} = 0.2 mm).

(4) The remaining 10 mesocosms make up the D-2 group, characterized by the absence of any filter overlying the gravel drainage layer. This design essentially emulates that of the southern half of the Keele Valley Landfill site. For most mesocosms, the cells were filled with a 30 cm thick layer of nominal 38 mm gravel. To investigate the effect of changes in the particle size used for

Fig. 14. Mesocosm reactors (mesocosms at 28 °C fed with Keele Valley leachate at continuous flow of 2.4 mL/min with intermittent dosing of leachate from top).



the drainage layer, two duplicate mesocosms were filled with 19 mm gravel. Both size drainage materials were crushed and washed clean dolomitic limestone from Steetley Quarries Ltd., Dundas, Ont.

For most cells, the average water level was maintained near the bottom of the gravel layer. For one duplicate pair the gravel drainage layer was maintained saturated throughout.

The remaining D-2 group cells were constructed identically. Four mesocosms were placed in series with identical cells to evaluate the decreasing level of clogging with flow distance or retention time within the system. In this way, some provision may be made to account for the fact that the feedstock leachate that is collected represents the "effluent" from the LCRS in the field at the Keele Valley Landfill.

Mesocosm test results

Removal of COD and dissolved solids from the leachate

Initially, the fresh leachate exhibited a high organic strength (biochemical oxygen demand BOD_5 = 10 000 – 16 000 mg/L, COD = 14 000 – 24 000 mg/L) and dissolved solids (total dissolved solids TDS = 10–20 g/L, Cl^- up to 3200 mg/L). Shortly after commencing operation of the mesocosm tests, significant removal of COD and dissolved solids was noted. The data from these tests are summarized in Figs. 15 and 16. As discussed earlier, the "raw" leachate collected at Keele Valley underwent significant variation in strength at the point of sampling during the period of testing (see solid line in Fig. 15). Figure 16 shows the mesocosm effluent data for COD, calcium, and iron normalized to raw leachate influent (average Ca 1420 mg/L, average Fe 195 mg/L) during the first 11 months of the testing program. The influent concentration (C_0) was taken to be the laboratory analysis of the fresh or stored feedstock sample taken closest in time to that of each effluent sample. Effluent samples were taken from selected individual mesocosms. The similarity to the column results is not surprising, since both represent continuously fed, anaerobic, fixed-film reactors. It is evident from Fig. 16 that the iron, in particular, is almost totally depleted in the mesocosm effluent.

Autopsy and sampling of mesocosms

After 20–60 months in operation, a number of the mesocosms were disassembled and examined. Samples of stone and slime were weighed, dried, washed, dried, and reweighed to measure the physical properties of the slime. Subsamples were also taken for total elemental analysis (Table 4). The material was very similar in appearance and physical, chemical, and microbiological composition to the field samples from Keele Valley Landfill (Fleming et al. 1999). Total carbon represented 5%–9%, calcium 9%–14%, magnesium 1.7%–3.1%, and iron 1.2%–2.5%. Lower concentrations of various metals were observed in the clog material, including lead, copper, nickel, zinc, and chromium. Figure 17 shows the clog material part way through a typical autopsy.

The VVO generally increased downward; at the bottom of the mesocosm the pore space was completely filled with slime. At the waste–gravel interface there was considerable intrusion of fines into the drainage layer, and the VVO in the upper 3 cm was estimated to range from 50% to 90% of the

Table 2. Design variables for the mesocosm tests.

Duplicate cells	Design group	Filter between stone and waste	Drainage layer Thickness (cm)	Stone size (mm)	Leachate level above base of stone (cm)	Leachate feed and effluent
C-01, C-02	D-1	Geotextile, nonwoven, needle-punched	30	38	6	Fresh feedstock, one pass discharge to waste
C-03	D-2	None	30	38	6	Fresh feedstock, discharge to C-23
C-04	D-2	None	30	38	6	Fresh feedstock, discharge to C-26
C-05, C-06	D-3	Nonwoven geotextile between two stone layers (sacrificial upper stone layer)	20 + 20[a]	38	6	Fresh feedstock, one pass discharge to waste
C-07	D-4	Granular filter, 4 cm each of pea gravel and sand	30	38	6	Fresh feedstock, one pass discharge to waste
C-08	D-4	Granular filter, 4 cm each of pea gravel and sand	30	38	6	Fresh feedstock, one pass discharge to waste
C-19	D-2	None	30	19	6	Fresh feedstock, one pass discharge to waste
C-20	D-2	None	30	19	6	Fresh feedstock, one pass discharge to waste
C-21	D-1	Geotextile, low surface area, woven	30	38	6	Fresh feedstock, one pass discharge to waste
C-22	D-1	Geotextile, low surface area, woven	30	38	6	Fresh feedstock, one pass discharge to waste
C-23	D-2	None	30	38	6	Two in series; feed C-03 effluent, discharge to C-24
C-26	D-2	None	30	38	6	Two in series; feed C-04 effluent, discharge to waste
C-24	D-2	None	30	38	6	Three in series; feed C-23 effluent, discharge to C-25
C-25	D-2	None	30	38	6	Four in series; feed C-24 effluent, discharge to waste
C-27, C-28	D-2	None	30	38	—[b]	Fresh feedstock, one pass discharge to waste

[a] Two layers.
[b] Entire stone layer saturated.

total pore space. The observations made during the autopsy tended to support the conclusions inferred from the field studies (Fleming et al. 1999).

Porosity measurements in the mesocosm test cells

During the course of the tests, measurements of the "drained porosity" in the gravel drainage layer of the mesocosm test cells were made by temporarily shutting off the flow to the cell, measuring the static water level (relative to the overflow level), and draining the cell into a graduated cylinder and measuring the change in water level. The rate of drainage of the cells was kept low (typically less than 100 mL/min) to minimize large flow velocities that might induce fluid shear or otherwise cause disruption to the growing biofilm.

Figures 18 and 19 show the changes over time of the measured drainable porosity for selected mesocosm tests. From these data, the following conclusions were drawn.

After approximately 46 months, most laboratory mesocosms exhibited significant loss of drainable porosity to as low as 0.18, from an initial average value of 0.42 for the 19 mm stone and 0.48 for the 38 mm stone. Some of the mesocosms, however, experienced less change in drainable porosity during that time. For example, a greater decrease in porosity occurred in the upstream (group D-2) cells of those operated in series relative to those located downstream. Mesocosms C-23–C-26 placed inline downstream of replicate mesocosms generally exhibited less clogging (except for a surprisingly low porosity value of 0.27 from C-25 after 1400 days). This is expected, given the importance of loading rate on clogging (Rowe et al. 2000*a*).

Similarly, mesocosms C-19 and C-20 cells were constructed using 19 mm rather than the 38 mm gravel used for all other tests and exhibited a greater degree of clogging throughout the tests; this is consistent with the findings of Rowe et al. (2000*b*) regarding the effect of particle size and likely reflects the greater surface area available for the growth of biofilm.

A pair of mesocosms that were tested with the leachate level completely saturating the drainage layer also exhibited a greater degree of clogging; this is attributed to increased mass removal or "treatment" of the leachate associated with a hydraulic retention time about three times that of the other test cells (i.e., 7.3 days rather than 2.4 days at the beginning

Table 3. Summary of geotextile properties. EOS, equivalent opening size; FOS, filtration opening size; *K*, coefficient of permeability.

	Application			
	Lightweight nonwoven geotextile (LGT)	Heavyweight nonwoven geotextile (HGT)	Woven geotextile (WGT)	Woven geotextile
Laboratory mesocosms	Between waste and LCS stone in D-1 mesocosms and between two LCS stone layers in D-3 mesocosms	Below LCS stone over sand base	Between waste and LCS stone; D-1 mesocosms	
Field	Above LCS, Halton test liner	Below LCS Halton Landfill (test liner)		Below LCS stone over sand cushion at Keele Valley Landfill
Manufacturer	Polyfelt	Polyfelt	Terrafix	Terrafix
Product	TS650	TS900	Terratrack 24-15	Terratrack 200W
Composition	Needle-punched, nonwoven polypropylene	Needle-punched, nonwoven polypropylene	Woven polypropylene	Woven polypropylene
Mass (g/m^2)	235	475	140	180
Thickness (at 2 kPa) (mm)	2.3	3.8	0.5	0.6
FOS (μm)	110	80	700	475 (EOS)
Grab tensile strength (N)	755	1375	750	965
Mullen burst strength (kPa)	1795	2895	2200	2500
Permittivity (s^{-1})	1.60	0.70	0.04 ($K = 1.9 \times 10^{-2}$ cm/s)	0.04 ($K = 3.3 \times 10^{-2}$ cm/s)

Fig. 15. Removal of COD in mesocosms.

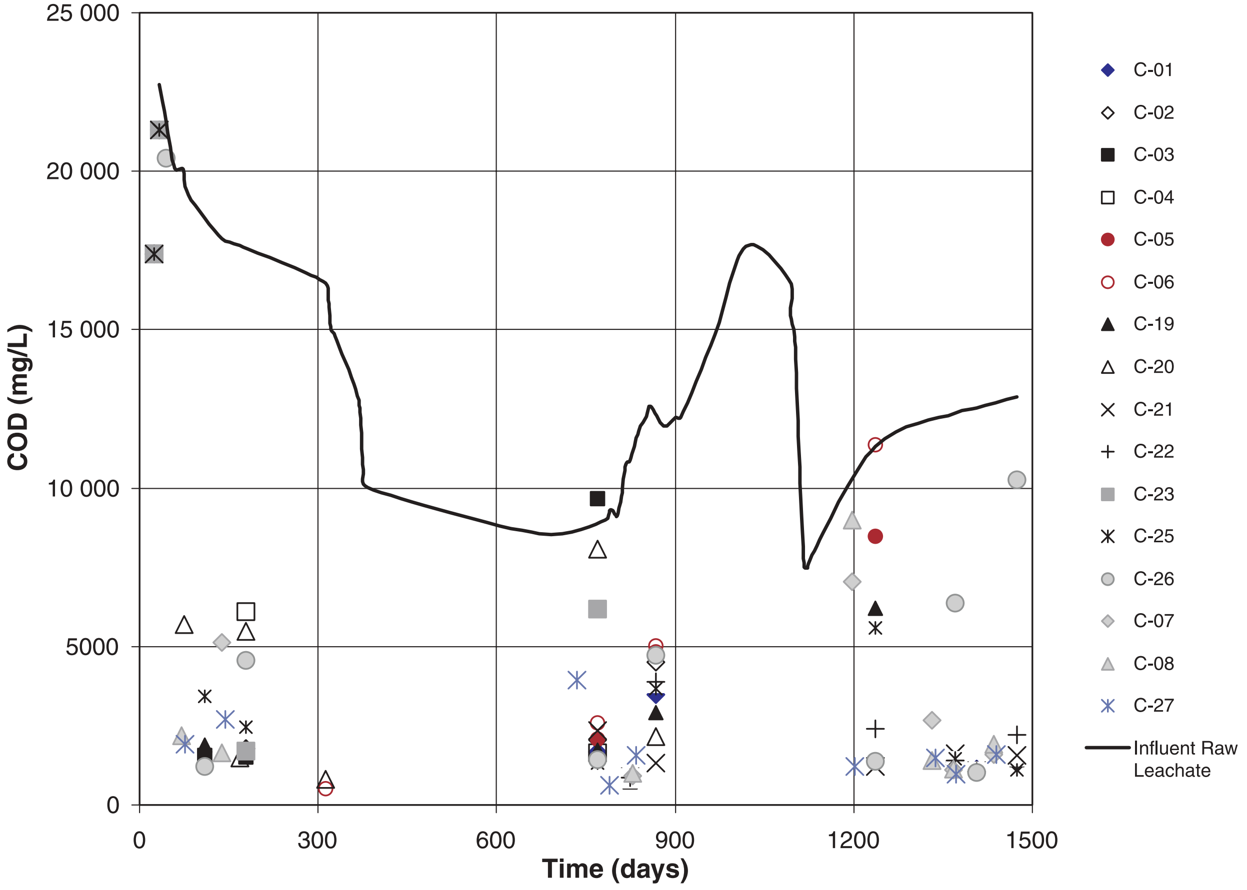


Fig. 16. Removal of COD, calcium, and iron in mesocosms at 28 °C during first year of operation.

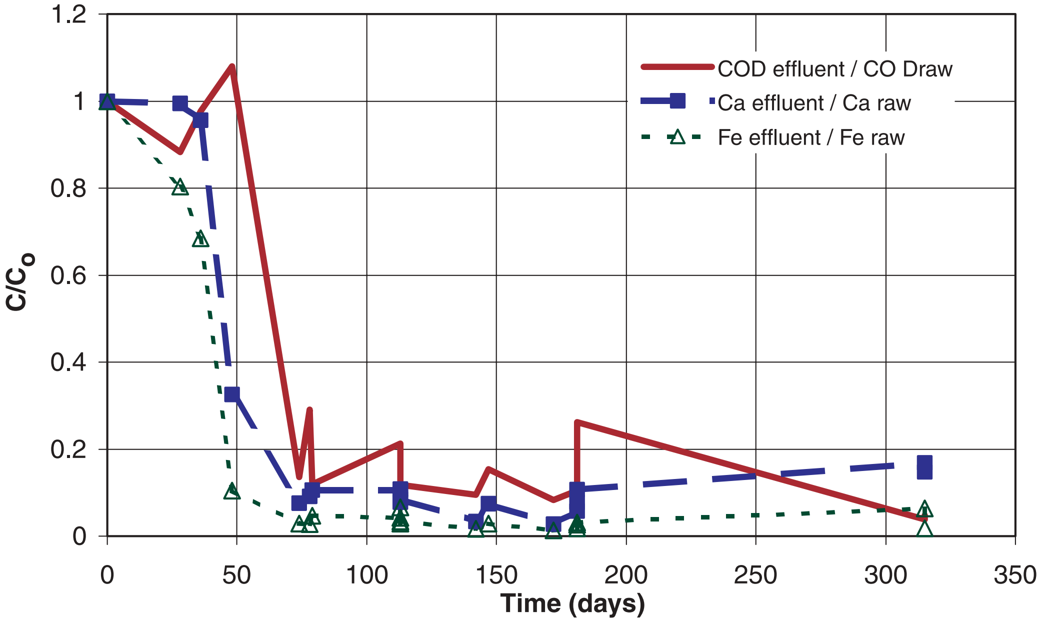


Fig. 17. Drainage stone in mesocosm after 20 months exposure to leachate.

of the test when the drainable porosity of the 38 mm gravel was about 0.47).

Overall, a measurable decrease in the porosity of the gravel drainage layer occurred in most mesocosm tests. During the course of this work, however, the porosity of the gravel was not impaired sufficiently to induce a measurable hydraulic gradient under the flow rates tested.

No measurable perching of leachate was observed above the waste–gravel interface. This enables a lower bound to be placed on the geotextile permeability for the D-1 cells. The minimum measurable height of perch is approximately 6 mm. For geotextile thickness of 2 mm and vertical infiltration rate of 0.2 m/year through the geotextile, the geotextile permeability is greater than 2×10^{-9} m/s. Given the high initial hydraulic conductivity of the geotextile and relatively low flow rate in the cross-plane direction, it is likely that additional time is required before measurable perching is observed due to clogging of the geotextile filter.

The nonwoven geotextile filter used in the laboratory investigation between the top of the drainage blanket and the overlying refuse initially reduced the apparent rate of clogging of the underlying drainage layer compared with similar tests conducted without a geotextile filter, although after 1400 days there was little, if any, difference.

Table 4. Composition of slime samples S1–S9 from laboratory microcosm C-28.

							Sand below stone and geotextile	
Parameter	S1	S2	S3	S5	S6	S7	Grey (reduced), S8	Brown (unaltered), S9
Moisture content (wt.%)	39.80	28.60	29.20	51.00	57.10	45.40	14.30	13.50
Carbon (total)	na	5.48	4.84	4.52	8.68	6.58	0.04	0.08
Organic matter	8.0	7.5	9.5	10.5	10.0	9.0	<0.1	<0.1
Carbonate as CO_3	16.7	31.9	23.8	14.1	24.5	22.9	13.1	<0.1
Ca	13.60	9.38	12.10	10.40	11.80	10.80	0.03	0.03
Si	15.60	19.60	18.60	19.60	17.90	19.00	42.10	42.10
Mg	1.69	1.97	1.78	1.80	3.06	1.75	0.03	0.03
Fe	2.46	1.48	1.21	1.55	1.76	1.89	0.08	0.08
Al	0.85	0.68	0.52	0.74	0.58	0.90	0.03	0.03
S	nd	nd	0.16	nd	0.26	0.10	nd	0.21
Total (wt.%)	58.9	78.0	72.5	63.2	78.5	72.9	55.4	42.6
P (μg/g)	853	742	655	718	667	1040	22	22
TKN	530	670	820	1100	820	860	39	19
Mn	875	406	381	498	604	504	7	8
Ti	230	185	127	171	156	202	9	10
Zn	226	427	239	360	293	361	9	6
Sr	224	111	141	155	190	162	nd	nd
Ba	65	55	38	62	59	59	nd	nd
Ni	20	15	11	17	19	17	nd	nd
Cu	52	124	99	116	96	120	4	2
V	18	13	11	14	12	16	nd	nd
Pb	44	68	42	91	52	113	1	nd
Cr	23	13	12	17	18	25	nd	2
Co	8	5	5	6	4	6	nd	nd
B	23	16	13	18	20	19	nd	nd
Zr	nd	nd	nd	nd	nd	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd	nd	nd
Be	nd	nd	nd	nd	nd	nd	nd	nd
Cd	nd	nd	nd	nd	nd	nd	nd	nd
Mo	nd	nd	nd	nd	nd	nd	nd	nd
Total (wt.%)	59.2	78.3	72.8	63.5	78.8	73.3	55.4	42.6

Note: Total elemental analyses by MDS Environmental Ltd. using inductively coupled plasma (ICP) scan and wet chemistry. Organic matter determined by dichromate digestion and may be similar to loss on ignition (LOI). na, not available; nd, not detectable; TKD, total Kjeldahl nitrogen.

A granular filter reduced the porosity decrease relative to tests carried out without a filter. During much of the testing period, there appeared to be a decreased degree of clogging in mesocosms constructed using a graded granular filter (4 cm each of 6 mm pea gravel and concrete sand with D_{10} = 0.2 mm); at 1400 days, however, these cells had on average experienced substantial clogging.

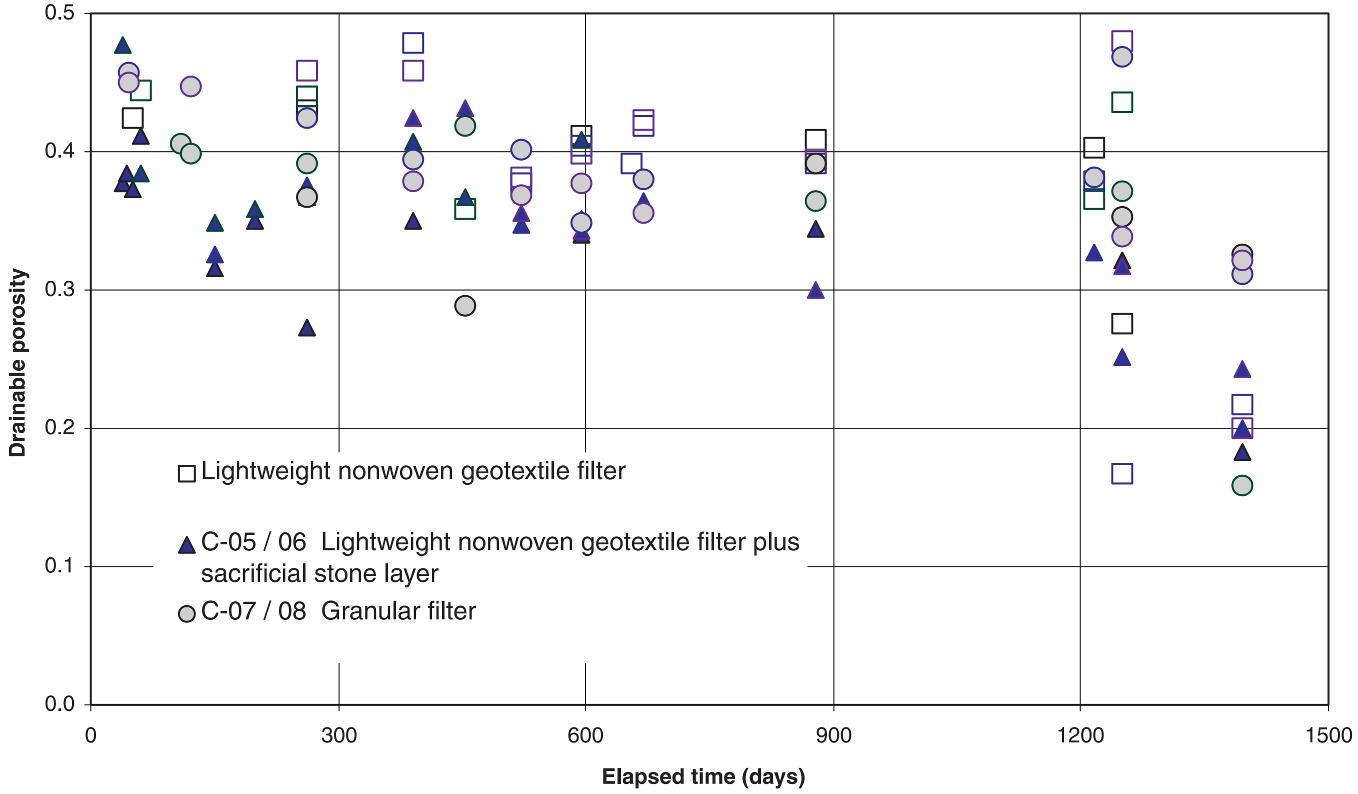
The woven geotextile filter–separator was less effective at reducing the clogging of the underlying gravel than was the nonwoven geotextile or the granular filter, although the data exhibit scatter.

A sacrificial layer of drainage media overlying the geotextile filter did not measurably improve the protection against clogging of the underlying drainage media. This finding is surprising and may have been an artifact of the test design and methodology as discussed by Fleming (1999). Essentially, the test design did not completely account for the presence of such a sacrificial layer over the entire drainage blanket. In the mesocosm, most of the "raw leachate" flow was directed laterally right into the drainage blanket underneath the sacrificial layer and only the small component of vertical flow was directed through the sacrificial layer.

The dolomitic limestone used in the laboratory testing and at the Keele Valley Landfill showed no signs of attack by the leachate. This may be because the early acid-stage leachate will likely be at or near calcium carbonate saturation, especially if carbonate-rich soils are used for daily–interim cover. This issue was addressed by Fleming (1999) and Bennett et al. (2000).

The drainage layers were observed to clog from the bottom up, and increased hydraulic retention time appears to increase the amount of clog precipitated per unit volume of leachate. Therefore a sufficient slope should be provided between and perpendicular to the collection pipes and along

Fig. 18. Laboratory porosity measurements for selected mesocosms.



the pipes. This will decrease the saturated fraction of the drain and shorten the drainage path and the hydraulic retention time, thus providing some protection against clogging failure.

Designs should incorporate a reasonably large thickness of drainage blanket, to provide ongoing drainage after the initiation of clogging within the lower portion of the drain. If, after some initial clogging, the leachate is not allowed to drain freely, the increased hydraulic retention time may result in an increased efficiency of COD consumption and calcium removal with a consequently greater amount of clog deposition per unit volume of leachate. For a constant rate of infiltration and leachate generation, this would result in a shorter effective service life.

Conclusions

The results of batch tests showed that anaerobic microbial activity in landfill leachate is associated with the decrease, over time, of the organic load in the leachate (measured as chemical oxygen demand). This has been demonstrated under both conditions of attached and suspended microbial growth. In particular, the “mineral yield” or mass of mineral precipitate formed per mass of COD stabilized (using Ca as a surrogate for the entire mineral mass, which is dominated by calcite) was found to be similar for suspended- and attached-growth systems.

This effect has been shown to be biological in origin; synthetic leachate mixed from laboratory reagents exhibited no decrease in COD until inoculated with fresh Keele Valley leachate.

The effect of temperature on the rate of COD and calcium depletion was examined in the laboratory. For batch tests conducted at room temperature (21–22 °C) and at the elevated laboratory temperature (27–28 °C) there was a moderate difference in the rate of COD consumption. Significantly, the end points of the tests tended to converge. At 10 °C, the rate of depletion of both COD and calcium was considerably slowed.

The batch test data obtained at different temperatures exhibit close to the same relationship between calcium and COD when plotted as Ca versus COD, independent of time. These values ranged from 6 to 10 mg/L Ca per 100 mg/L COD in all batch and continuous-flow tests.

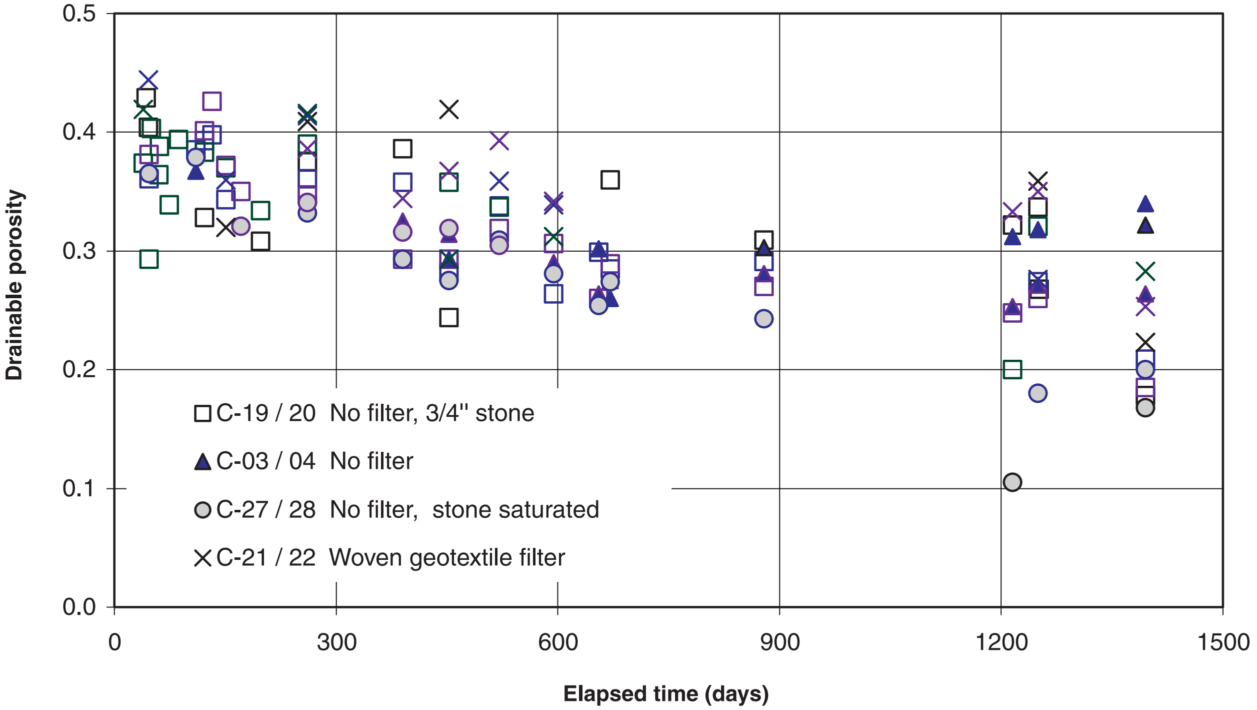
This suggests that the tests at different temperatures followed the same path, simply at different rates. For the unmixed, suspended-growth, bottle-incubation tests carried out at 22 °C, the end point of these tests after about 90 days was essentially the same as that achieved in 70 days at 28 °C for similar unmixed, suspended-growth, batch incubation tests.

The mesocosm effluent from most test cells exhibited a significant level of COD removal after a short initial period of apparent microbial colonization (development of the biofilm). Thereafter, a generally stable degree of COD removal occurred during the period that the mesocosms experienced a decrease in drainable porosity. COD removal is strongly correlated with precipitation of calcite and depletion of dissolved calcium in the leachate.

Laboratory mineral precipitate deposits constitute approximately 30%–40% calcite by weight. This value is similar to that obtained from field-derived clog deposits in Canada and Germany.

The data from the field-scale mesocosm tests tend to support the conclusions of Rowe et al. (2000*a*, 2000*b*) regarding

Fig. 19. Laboratory porosity measurements for selected mesocosms.



the importance of loading rate and particle size which were made on the basis of heavily loaded laboratory columns.

The mesocosm results enable practical conclusions and recommendations to be made regarding specific design details of the drainage layer and filters. These may be summarized as follows:

(1) The presence of an appropriate filter–separator between the top surface of the drainage layer and the overlying waste improves the performance of the drainage layer against clogging.
(2) A graded granular filter or nonwoven geotextile filter–separator performed better than a woven geotextile with physical properties and strength similar to those of the nonwoven geotextile.
(3) A sacrificial stone layer overlying the filter–separator did not improve the protection of the underlying stone.
(4) Less clogging was associated with a larger particle size of “clear” (washed or screened) crushed dolomitic limestone.
(5) There was no evidence of dissolution of the dolomitic limestone in contact with the leachate.
(6) Given the observed increase of clogging associated with the saturated stone layer and longer hydraulic retention time, it is likely prudent to minimize this effect by incorporating a sufficient slope to the LCS. Until additional data are developed in this regard, the authors consider that the slope should be approximately 1%. Although this recommendation does not flow precisely from the various laboratory and field studies, it reflects the understanding gained in the course of the studies regarding the fundamental mechanisms involved in the clogging of landfill LCSs.

Related recommendations regarding pipe and perforation size and spacing are given by Fleming (1999) and Fleming et al. (1999) based on data collected during the field studies.

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