Mass loading and the rate of clogging due to municipal solid waste leachate

R. Kerry Rowe, Mark D. Armstrong, and D. Roy Cullimore

Abstract: The results of laboratory column tests conducted to assess the effect of the mass loading on the clogging of porous media are presented. The tests were conducted using actual leachate from the Keele Valley Landfill under saturated, anaerobic conditions. It is shown that clogging is greatest where there is the greatest mass loading (near the inlet in this case, but likely near the collection pipes in a field situation). An empirical relationship between the hydraulic conductivity and drainable porosity is presented. Even though it is shown that higher flow rates give rise to less efficient bioreactors, the columns with high flow still experience greater rates of clogging than those with low flow. The columns were found to be severely clogged when the drainable porosity had decreased to about 10% of the initial value. The bulk (wet) density of the clog material is found to range between 1.6 and 2 Mg/m^3 and, on a dry mass basis, 27% of the clog is calcium and 47% is carbonate. The columns were colonized by a diverse consortium of bacteria including methanogens, sulfate-reducing, and denitrifying bacteria, with methanogens being dominant in the portion of the column where clogging was most severe.

Key words: leachate collection, clogging, porous media, mass loading, flow rate, anaerobic, microbial.

Résumé : On présente les résultats d'essais de colonnes en laboratoire réalisés pour évaluer l'effet de la charge massique sur le colmatage de milieux poreux. Les essais ont été conduits avec le vrai lixiviant du remblai sanitaire de Keele Valley dans des conditions saturées anaérobiques. On montre que le colmatage est le plus important là où le chargement est le plus massique (près de l'entrée dans le présent cas, mais probablement près des tuyaux de captage dans une situation de terrain). On présente une relation empirique entre la conductivité hydraulique et la porosité de drainage. Bien qu'il soit démontré que des vitesses d'écoulement plus élevées donnent naissance à des bioréacteurs moins efficients, les colonnes avec des flux rapides montrent néanmoins de plus hauts taux de colmatage que celles avec des flux lents. On a trouvé que les colonnes étaient sévèrement colmatées lorsque la porosité de drainage avait diminué d'environ 10% de la valeur initiale. On trouve que la masse volumique totale (mouillée) du matériau de colmatage se situe entre 1.6 Mg/m^3 et 2 Mg/m^3 et, sur la base d'une masse sèche, 27% du matériau colmatant est du calcium et 47% est du carbonate. Les colonnes sont colonisées par un consortium diversifié de bactéries incluant des méthanogènes, des bactéries réductrices de sulfates et dénitrifiantes avec des méthanogènes dominantes dans la portion de la colonne où le colmatage était le plus sévère.

Mots clés : captage de lixiviant, colmatage, milieu poreux, charge massique, flux, anaérobique, microbien.

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Introduction

Leachate collection systems (LCS) are an essential engineered component of most modern municipal solid waste landfills. The LCS is designed to allow collection and removal of leachate while controlling the height of leachate mounding above the liner systems, thereby reducing contaminant transport through the liner system. Due to the chemical and biological nature of the leachate collected by a LCS, there is potential for biological- and chemical-induced clogging of the LCS. The work by Brune et al. (1994) and Rittmann et al. (1996) outlines a process for the accumulation of clog material in the drainage layer. In particular, Rittmann et al. identified the potential link between the consumption of chemical oxygen demand (COD) and carbonate deposition in porous media permeated by leachate. The importance of these processes with respect to North American landfills has been highlighted by observations at the Keele Valley Landfill as discussed by Fleming et al. (1999). It was found that the accumulation of clog material (which included both organic and inorganic material) was greatest near the leachate collection pipe and least well away from the pipes. Fleming et al. postulated that the rate of clogging was directly related to the fact that the leachate flow (and hence, presumably, the mass loading) was greatest in the immediate vicinity of the leachate collection pipe. They also demonstrated that more than 50% of the clog material was calcium carbonate ($CaCO_3$), a finding consistent with similar field observations in Germany (Brune et al. 1994).

One can hypothesize that an increase in mass loading due to different design characteristics may increase clogging around leachate collection pipes (Rowe and Fleming 1998).

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It would be highly desirable to have experimental evidence to substantiate the effect of mass loading on the rate of clogging of porous media. A number of investigators have performed column experiments (e.g., Brune et al. 1994; Paksy et al. 1998; Peeling et al. 1999), but none have systematically examined the effect of changing mass loading on rates of clogging using actual landfill leachate. Thus, the primary objective of the experimental study reported herein is to examine the effect of mass loading on the rate of clogging in well-controlled laboratory column experiments conducted using leachate collected from a functioning leachate collection system (at the Keele Valley Landfill site in Toronto) for flows that bracket those expected near the leachate collection pipe in Ontario landfills for pipe spacing of between 50 and 200 m. A second objective is to provide experimental parameters, obtained under controlled conditions, that can be used for estimating the rate of clogging of leachate collection systems with equations proposed by Rowe and Fleming (1998). A third and final objective is to provide experimental data that can be subsequently used to verify more sophisticated theoretical models of the clogging of granular media which are presently being developed (Rowe et al. 1997; Cooke et al. 1999). The present study provides both data relating reduction in drainable porosity to changes in COD and calcium (Ca) concentrations for different rates of mass loading, and experimental data relating the change in hydraulic conductivity to the change in drainable porosity.

The conceptual problem

Design considerations for a leachate collection system include the rate of leachate generation, drainage pipe spacing, collection system slope, and hydraulic conductivity of the drainage layer (McBean et al. 1995; Rowe et al. 1995). Assuming a uniformly distributed rate of leachate percolation, q_o, from the waste, and subsequent lateral flow to the pipe due to the accumulation of leachate, the annual flow (per unit width), Q_L, as it approaches the pipe is equal to

$$[1] \qquad Q_L = Lq_o$$

where L is the horizontal length of the drainage path to the pipe.

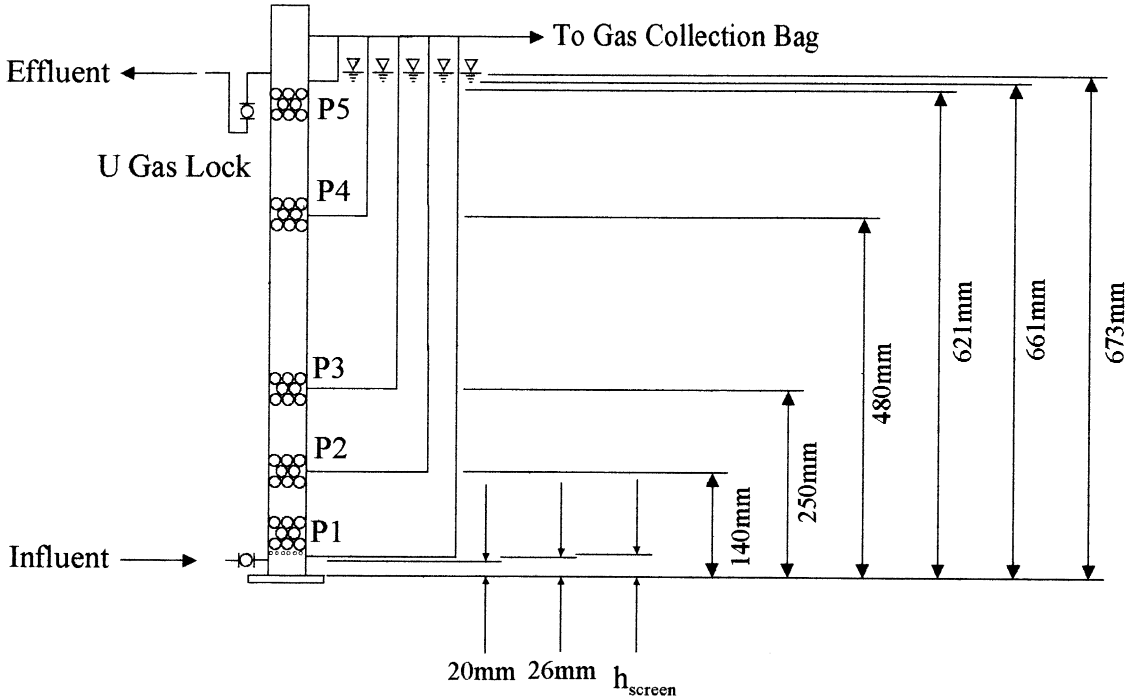
When dealing with an underdrain system involving a drainage blanket one can anticipate that the leachate entering the system at some distance x from the leachate collection pipe will experience some biological treatment (e.g., reduction in COD) and related reduction in inorganic load (e.g., due to precipitation of $CaCO_3$). One can hypothesize that the amount of treatment is related to the residency time and hence will be greatest for leachate entering the system at the drainage divide ($x = L$) and least for leachate entering the system adjacent to the collection pipe. Leachate entering at $x = L$ will mix with leachate entering at $x < L$, and the leachate reaching the collection pipe will be a mixture of leachate that has entered the system at different times and experienced different degrees of "treatment." However, since the flow is greatest adjacent to the pipe, it can be hypothesized that the overall mass loading will also be greatest in the vicinity of the pipe and accordingly the potential for clogging would be greatest near the pipe. This hypothesis is consistent with the field observation that clogging tends to focus near the leachate collection pipes (Rowe 1998; Fleming et al. 1999). Thus, the column experiments discussed in this paper were designed to simulate the lower, saturated portion of the last segment of the LCS before the leachate enters the leachate collection pipe. These columns are considered to be reasonably representative of this location provided that the flow through this segment of the LCS is saturated and essentially one-dimensional. This is likely to be approximately true, since the flow due to percolation in the vertical direction is much smaller than the flow in the horizontal direction. For example, if one considers a 0.5 m segment adjacent to the leachate collection pipe and a value of $L = 50$ m, then the vertical flow in this segment would be only 1% of the horizontal flow in the lower, saturated portion of the granular layer near the collection pipe and can be considered essentially one-dimensional.

Methodology

Leachate was passed through six columns containing a porous media consisting of glass beads (nominal diameter of 6 mm) at nominal flow rates of 1, 2, and 4 L/d. The flow rates examined correspond to the range of flows that might be expected for $q_o = 0.1$–0.2 m/a, $L = 50$–100 m, and a saturated thickness of about 0.025–0.05 m.

The columns were constructed from 50 mm i.d. PVC monitoring well pipe as shown schematically in Fig. 1. In the waste water treatment literature, the columns would be referred to as anaerobic, fixed-film reactors; however, it should be noted that the flow rates and particle sizes are substantially different from those normally used in fixed-film reactors. The mean initial drainable porosity of the beads was 0.376, with a standard deviation of 0.004. The municipal solid waste (MSW) leachate was collected from the Keele Valley Landfill located in Maple, Ontario, and transported to the laboratory in sealed HDPE tanks to maintain anaerobic conditions. By the time it was collected, this leachate had already travelled through granular material in the leachate collection system. It has likely experienced a reduction in strength (e.g., COD, calcium concentration) due to anaerobic processes in the drainage layer as well as precipitation of $CaCO_3$ and other precipitates due to a change in pH. Thus the leachate may not be representative of that entering the system from the waste at a location well away from the leachate collection pipe. However, it is considered to be reasonably representative of the leachate in the granular material close to the collection pipe (where the greatest clogging was observed by Fleming et al. 1999). Hence the columns are considered most representative of the saturated zone within 0.5 m of the leachate collection pipe. At the laboratory, the leachate was pumped to a system of continuously circulated, pH-controlled tanks and kept at a temperature of 10°C until used. Typically, the storage tanks were replenished with fresh leachate every 7 d. The leachate in the tanks normally showed a decrease in COD concentration of no more than 10% between refilling events. Leachate was fed into each pair of columns with peristaltic pumps. The initial hydraulic retention times in the columns varied between 13.4 and 3.4 h for 1 and 4 L/d design flow rates, respectively. Anaerobic conditions within the columns were maintained at

Fig. 1. Schematic diagram showing the location of piezometers (P1–P5) in column tests MK1–MK6.



all times, and excess gas was collected in Tedlar gas collection bags.

During the course of the study, water-quality tests were performed to assess the column performance. On a weekly basis the influent and effluent were tested for COD, calcium hardness as $CaCO_3$, pH, redox potential E_h, and fluid temperature. These tests were performed using Hach method 8204 for calcium hardness, and the results are expressed as milligrams per litre of $CaCO_3$. Biological activity was monitored by performing Biological Activity Reaction Tests (BART™).

Five piezometers were installed along the columns as indicated schematically in Fig. 1. Since the flow rate was specified and known (monitored), the hydraulic conductivity between any two piezometers could be deduced from a difference in head between the piezometers. However, because of the small flows and the challenge of measuring small head differences in a biologically active system that had to be maintained in anaerobic conditions, it was not practical to reliably detect a change in hydraulic conductivity (from the initial value of $k_{init} \cong 0.327$ m/s with a standard deviation of 0.026 m/s based on American Society for Testing and Materials (ASTM) Standard D2434) until it had decreased by between four and five orders of magnitude.

The drainable porosity was obtained a number of times by stopping the flow and allowing the column to drain (while maintaining anaerobic conditions). By measuring the amount of leachate drained out between two given locations, the drainable porosity was deduced between these locations. Since some fluid is retained in the particles in the column, this drainable porosity is less than the total porosity but is generally representative of the free-draining pores in a gravitational field. It was generally not possible to measure drainable porosities less than 3–5%, and hence no data were obtained in these regions other than knowing that no leachate could be drained from these regions within a 15 min period and hence the pore size is small and the drainable porosity very low.

The final drained porosity and hydraulic conductivity were measured at the conclusion of the testing for each column. The columns were then placed in a glovebox with a nitrogen atmosphere (to maintain anoxic conditions) and cut open to allow access to the beads. Beads were taken from six sampling points (25–100, 100–200, 200–300, 300–400, 400–500, and 500–600 mm above the column base). The biofilm properties were measured by weighing the samples and drying them at 105°C to establish the biofilm water content per bead. The beads were then weighed again, heated to 550°C, and reweighed to obtain the mass of organic material per bead. Finally, the glass beads were cleaned to obtain the mass of inorganic material per bead. The biofilm was measured for the wet (bulk) and dry density and ash (solids recovered after the sample was heated to 550°C) density. Samples of dry clog material were sent for elemental analysis.

Water quality results

Leachate quality during the operation phase of the test programme is summarized in Table 1. This represents the chemistry of the influent for the six columns. The variations in the leachate COD and $CaCO_3$ concentrations implied by the range are reflective of the variable nature of leachate. The fluid temperature for each column is between 1 and 2°C below the environmental temperature of 27 ± 1°C, since the columns are fed from a distribution manifold connected to cold-room storage tanks, which are kept at approximately 10°C. The average leachate flows were very close to the design flow rate during the steady state flow period before the severe clogging within the columns caused a reduction in

Table 1. Summary of influent leachate quality.

	COD (mg O_2/L)		Hardness as $CaCO_3$ (mg/L)		Fluid temperature (°C)		pH		E_h (mV)	
Column	gm	Range	gm	Range	am	sd	am	sd	am	sd
MK-1	11 190	9 266 – 13 464	1324	913 – 1886	25.7	1.7	7.00	0.18	–169	37
MK-2	11 280	9 310 – 13 615	1322	913 – 1879	25.7	1.7	7.00	0.18	–169	36
MK-3	10 984	9 232 – 13 029	1339	983 – 1802	25.7	1.5	6.99	0.19	–170	39
MK-4	10 915	9 168 – 12 956	1291	892 – 1833	25.9	1.7	6.99	0.19	–170	38
MK-5	10 175	8 641 – 11 950	1466	1176 – 1816	25.1	1.2	6.92	0.19	–164	37
MK-6	9 993	8 628 – 11 550	1463	1166 – 1823	25.0	1.2	6.93	0.20	–164	37

Note: Ranges are calculated by taking the geometric mean (gm) and the standard deviation (sd) of the natural logarithm of the data: range = exp(gm – sd) to exp(gm + sd). am = arithmetic mean.

Fig. 2. Variation in influent and effluent (*a*) COD and (*b*) $CaCO_3$ versus elapsed time.

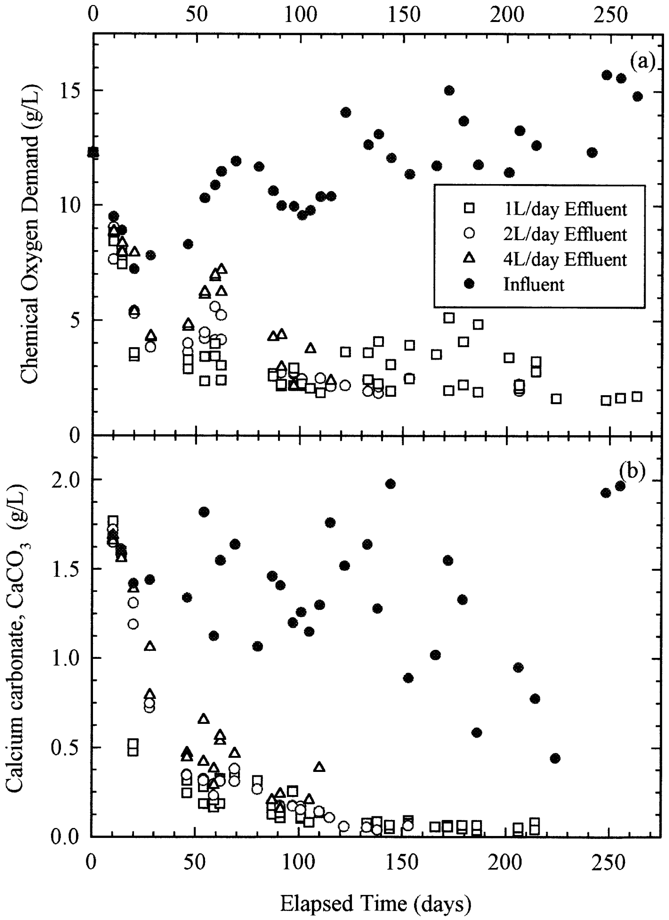
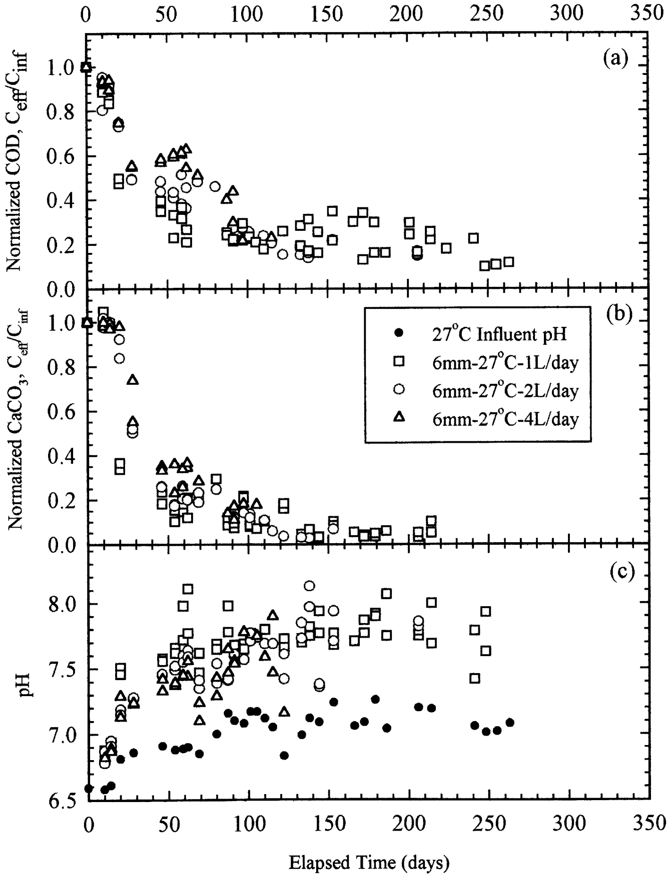


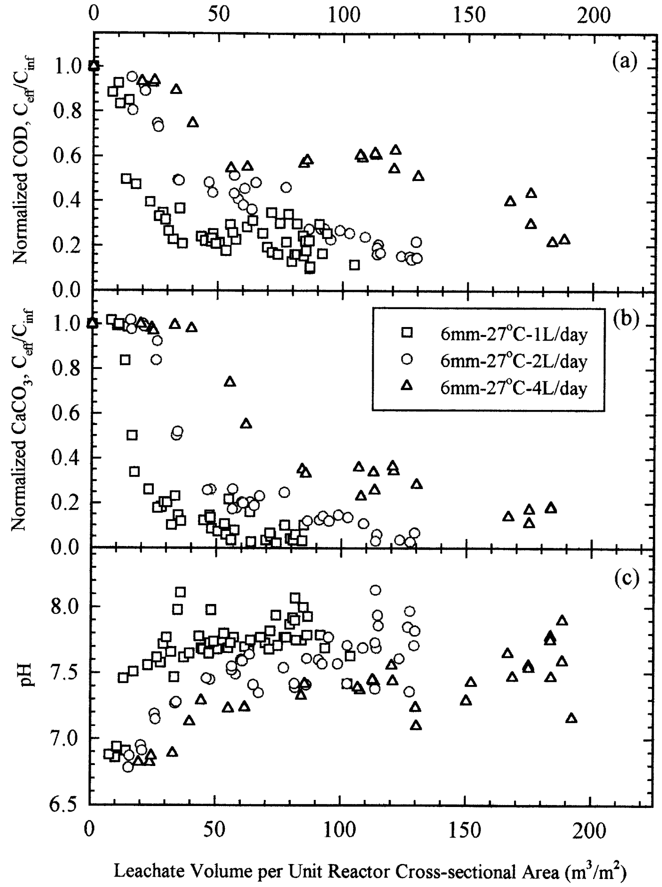
Fig. 3. Variation in (*a*) normalized COD, (*b*) normalized $CaCO_3$, and (*c*) pH with elapsed time.



flow rate that could not be compensated without creating excessive heads at the inlet of the column.

The Keele Valley leachate varied with time, with a trend of increasing COD over the testing period (see Fig. 2). To minimize the effect of influent variability, the effluent COD and $CaCO_3$ were normalized by dividing by the corresponding influent concentration as shown in Figs. 3*a* and 3*b*. The normalized COD plot (Fig. 3*a*) shows a decrease in COD with time until a relatively constant normalized "steady state" effluent COD of approximately 0.2 was reached. The plot of normalized $CaCO_3$ shows a time lag between test initiation and $CaCO_3$ removal of about 20 d for all columns. This lag is considered to be due to the time required for the establishment of a biofilm on the beads that will "treat" the leachate. During the first 20 d there was only a minor reduction in normalized COD, a modest shift in pH (from about pH 6.6 to 6.9), and no significant change in the normalized $CaCO_3$ concentration. During the lag period the flow per unit area throughout the column was 13, 27, and 41 m^3/m^2 for the 1, 2, and 4 L/d columns, respectively (the flow rates for the 1 and 2 L/d columns were actually 1.3 and 2.65 L/d for the first 20 d), and in assessing the mass loading required to cause clogging it may be appropriate to subtract these initial flows that occurred in establishing the

Fig. 4. Variation in (*a*) normalized COD, (*b*) normalized $CaCO_3$, and (*c*) pH versus flow, where flow is expressed in terms of leachate passing through the column per unit area of column.



biofilm, since this stage appeared to be essentially independent of flow rate.

For the 1 and 2 L/d columns, between 20 and 140 d, the normalized COD dropped to about 0.2, the pH of the effluent moved to about pH 7.8 to 7.9, and the normalized $CaCO_3$ concentration dropped to less than 0.05. The 4 L/d columns followed a similar trend with time but had to be terminated (because they were clogged) shortly after reaching steady state effluent values. The data suggest that the general trend in terms of COD consumption and deposition of $CaCO_3$ is independent of the flow rate over the range of flow rates examined.

The amount of COD and $CaCO_3$ removed by the columns appears to follow similar trends for three different average flow rates, giving the appearance that flow rate has no impact on clogging rate. The effect of flow rate becomes apparent if the volume of leachate passed through the columns is taken into account, as shown in Fig. 4. When plotted in this way, the change in flow rates can be seen to cause a shift in the curves. This is partly because the time to establish a biofilm seems to be independent of flow rate (see Fig. 3*b*), and hence much more leachate had passed through the column for the 4 L/d columns (41 m^3/m^2) than for the 2 L/d (27 m^3/m^2) and 1 L/d (13 m^3/m^2) columns prior to the onset of $CaCO_3$ removal (see Fig. 4*b*).

For a given volume of flow through the system, the lower flow rate results in more efficient leachate treatment (lower COD and $CaCO_3$ concentrations for a given volume of fluid passing through the column) than that for the higher flow rates (see Figs. 4*a* and 4*b*). Thus, due to the shorter residency period in the columns with the higher flow rates, the columns at higher flow rate are less efficient biological reactors than those at lower flow rates. Even though the shorter hydraulic residency time associated with higher flow rates results in a less efficient biological process and “leachate treatment” (i.e., a smaller reduction in COD and $CaCO_3$ concentration for a given volume of leachate through the column), the larger flow rate also corresponds to larger mass loading. This results in more deposition of $CaCO_3$ (and other inorganics) in a given period of time. Consequently, a column with a flow rate of 4 L/d experiences a significant reduction in drainable porosity and hydraulic conductivity much earlier than the 2 L/d columns, which in turn clogged faster than the 1 L/d columns.

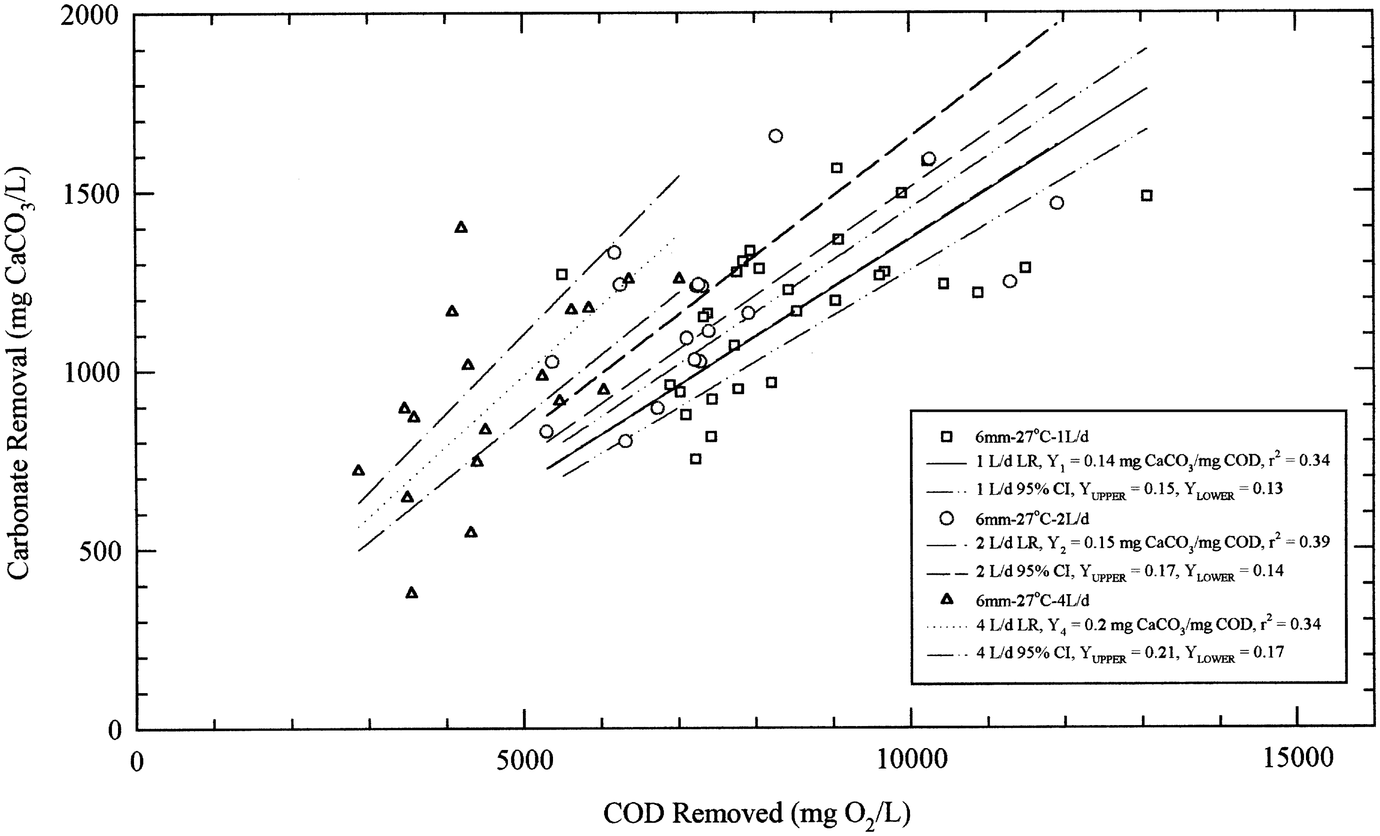
Eventually, the hydraulic conductivity in each column dropped sufficiently that it was no longer practical to maintain the design flow rate. The average elapsed time at which each pair of tests was terminated was 261, 230, and 121 days for the 1, 2, and 4 L/d columns, respectively (i.e., 85.9, 102, and 157 m^3/m^2, respectively, after the flow during the lag period is subtracted). The total volume of leachate (per unit cross-sectional area of the column) through the columns at the time of termination (due to excessive clogging) averaged 98.9, 129, and 198 m^3/m^2 for the flow rates of 1, 2, and 4 L/d, respectively.

Calcium carbonate yield

From the data collected for influent and effluent COD and calcium hardness as $CaCO_3$, the yield Y_C of $CaCO_3$ was calculated, with units of milligrams of $CaCO_3$ removed per milligram of COD removed. The yield coefficients were obtained by plotting the COD removed versus the $CaCO_3$ removed, and fitting the data by linear regression. The results are shown in Fig. 5 together with the 95% confidence intervals for the regression lines. The slopes of the three lines are 0.14, 0.15, and 0.2 mg $CaCO_3$ per milligram COD for the 1, 2, and 4 L/d columns, respectively. Interestingly, it can be seen that in terms of yield coefficient, the higher the flow rate, the greater the yield of $CaCO_3$ (i.e., the greater the deposition per unit of COD removed). A possible explanation is that the rate of biofilm shear increases as the flow rate increases. Detached bacteria could be reflected in the effluent COD, thereby increasing the COD effluent values for the 4 L/d columns relative to the 1 or 2 L/d columns.

The difference in yield seems to be greater for the 4 L/d columns relative to the 2 and 1 L/d columns. The yield coefficients for the 2 and 1 L/d columns are very similar. An ordinary one-way ANOVA test performed on the three linear regression slopes indicated that the difference between the 1 and 2 L/d columns was not statistically significant, whereas the difference between the 4 L/d and either the 2 L/d or 1 L/d columns was statistically significant. Due to scatter in the data, the coefficient of correlation (r^2) values for all of the linear regression lines are below 0.5. This scatter is characteristic of the variable chemical composition of MSW

Fig. 5. Measured $CaCO_3$ removed versus COD removed and $CaCO_3$ yield coefficient Y_C deduced by linear regression for each of the three different flow rates (1, 2, and 4 L/d).



leachate. However, the data indicate a trend with the amount of $CaCO_3$ removed increasing with an increase in the amount of COD removed. When all the data are considered together, the slope of this overall trend as shown in Fig. 6 gives a yield of 0.15 mg $CaCO_3$ per milligram COD and has a r^2 value of 0.44. This yield coefficient is an important parameter needed to model the rate of clogging of leachate collection systems in some models (Rittmann et al. 1996; Rowe et al. 1997; Cooke et al. 1999) and, despite the scatter in the data, provides an indication of the order of magnitude of yield that may be expected for the Keele Valley Landfill leachate.

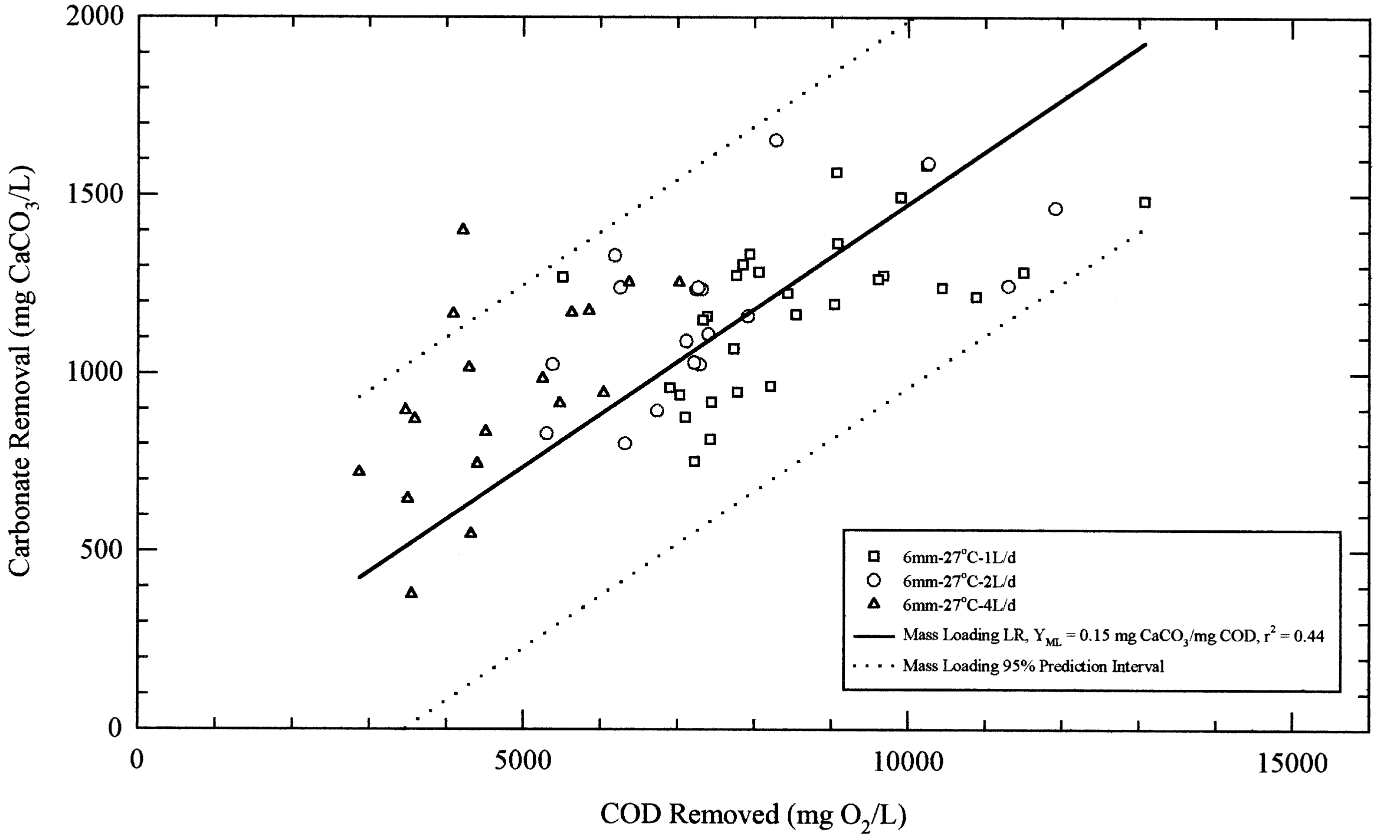
The yield coefficient can also be useful for assessing the amount of carbon held in the calcium carbonate versus carbon released by the decrease in COD. Since carbon accounts for 0.12 mg per milligram of $CaCO_3$ and the yield coefficient is approximately 0.15 mg $CaCO_3$ milligram of COD, this gives 0.018 mg C in $CaCO_3$ per milligram of COD consumed. The leachate COD is primarily comprised of acetic, propionic, and butyric acids, with 43, 35, and 22%, respectively (J. Van Gulck, personal communication), assuming that the recalcitrant portion of the COD is evenly distributed between the three primary components and this gives 0.46 mg of carbon per milligram of COD. This simple calculation shows that the carbon attributable to the carbonate deposited within the columns would account for approximately 4% of the total carbon removed from the leachate, in terms of COD removed. The remainder of the carbon is primarily released as by-products of microbiological processes in the form of carbon dioxide and methane. Thus the amount of carbon in $CaCO_3$ is only a small proportion of the available carbon, and hence the availability of calcium rather than carbon (or oxygen) is likely to be the factor limiting $CaCO_3$ deposition. This finding is important for the development of clogging models.

Biological activity

BART™ tests were used to define the level of aggressivity (which is related to the size of the bacterial population) and microbial community structure in the influent and effluent samples during column operation and in the clog material along each column at disassembly. The biodetectors used were capable of identifying the presence or absence and relative aggressivity of heterotrophic aerobic bacteria (HAB); iron-oxidizing and iron-reducing bacteria (IRB), including sheathed iron bacteria such as *Gallionella*, pseudomonads, and enterics; sulphate-reducing bacteria (SRB); slime-forming bacteria (SLYM); denitrifying bacteria capable of reducing nitrate to nitrogen gas (DN); total coliforms (T.COLI); and methanogenic bacteria (BIOGAS).

The following provides a summary of the data from tests performed on influent and effluent samples during column operation (full details are given by Armstrong 1998). Both the influent and effluent samples consistently contained a very aggressive microbial community (a population estimated to exceed 75 million colony-forming units per millilitre (cfu/mL)) dominated by facultative anaerobes. Over the

Fig. 6. Measured $CaCO_3$ removed versus COD removed and $CaCO_3$ yield coefficient Y_{ML} deduced by linear regression of data at all three flow rates.



course of the testing there was a decrease in the population of iron-related bacteria in both the leachate influent and effluent. The influent was a mixture of aerobes, anaerobes, and enterics (microorganisms, whose normal habitat is the human gastrointestinal tract, such as coliforms) and the effluent was a mixture of anaerobes and enterics. This suggests that the column environment was not a suitable environment for aerobic bacteria. This observation is supported by the results from the SLYM which show a shift from a mixture of slime formers and aerobic bacteria, in the influent, to dense slime formers in the effluent. At column initiation, the influent and effluent leachate contained a diverse community of SRBs with an estimated population of around 15 million cfu/mL. However, the aggressivity of the influent leachate SRBs decreased with time, whereas aggressivity of the effluent increased. This is attributed to growth and detachment of sulphate-reducing bacteria in the columns which increased until the end of the test. The effluent leachate testing indicates that a mixed community of facultative anaerobes, iron-related bacteria, sulphate-reducing bacteria, slime formers, and enterics is present within all of the columns. Generally, the effluent population was similar to the influent population except for the increase in sulphate-reducing bacteria in the effluent as noted above.

The community structure within the columns was examined after column disassembly, and the results for the samples of clog material taken during the column disassembly procedure are summarized below (see also Armstrong 1998 for tabulated reaction patterns and delay times).

The “Biogas” BART™ indicated that methane-producing bacteria are present at all levels within the columns. This is not surprising, but what was notable was the clearly defined division between the very high activity in the lower 200–300 mm above the base (where the leachate entered the column and there were only 2–3 “days of delay” in the BART™ test before the first reaction was observed) and the low activity in the upper portion of each column (where there were typically 8–11 d of delay before the first reaction was observed in BART™ tests). This suggests that there is a significant change in the methanogen population in the biofilm as leachate moves along the column.

All columns had a very aggressive population dominated by facultative anaerobes at all levels. In addition, enterics (such as coliforms) and denitrifying bacteria were generally present at all levels. Finally, there was a fairly consistent distribution of dense slime formers throughout each column.

It is evident from the results taken from influent, effluent, and column autopsy samples that there is a large microbial consortia, consisting of methanogens, coliforms, sulphate-reducing bacteria, denitrifying bacteria, and facultative anaerobes, active in the leachate and the column. The presence of these groups of bacteria in landfill waste and leachate has been documented by numerous researchers (Jones et al. 1983; Brune et al. 1994; Palmisano and Barlaz 1996). It is hypothesized that bacteria growing within the decomposing waste detach from the developing biofilms, flow with the leachate into the leachate collection system, and colonize the surfaces of the granular drainage material. This is consistent

Fig. 7. Drainable porosity profiles for MK-1 and MK-3 (*a*) during steady state operations, and (*b*) after failure. Initial porosity n_{initial} = 0.377 and 0.373 for MK-1 and MK-3, respectively.

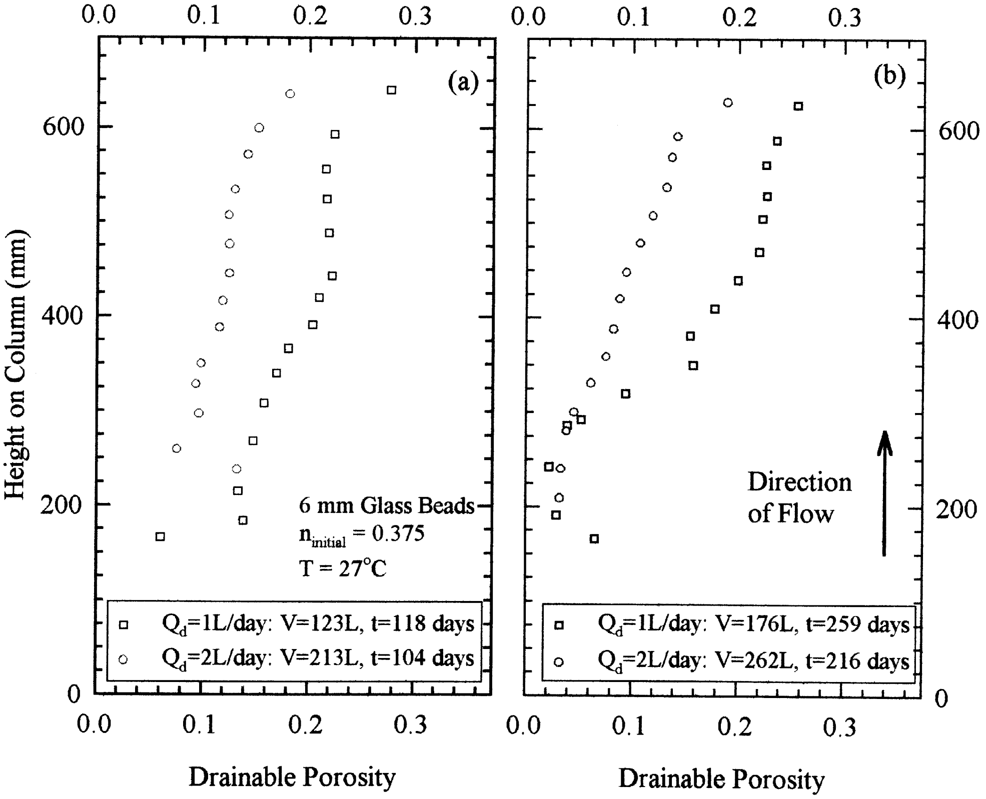


Table 2. Drainable porosity when column reached steady state.

Column	Design flow (L/d)	Elapsed time (d)	Leachate volume passed (m^3/m^2)[a]	Weighted average drainable porosity	Average decrease in drainable porosity (%)	Cumulative $CaCO_3$ mass loading (g)	Cumulative $CaCO_3$ mass removal (g)
MK-1	1	118	63	0.17	54	175	91
MK-2	1	118	56	0.17	55	155	88
MK-3	2	104	108	0.10	72	304	143
MK-4	2	104	99	0.16	57	284	148

[a] To obtain the volume passes after the initial lag period, subtract 13 m^3/m^2 for MK-1 and MK-2 and 27 m^3/m^2 for MK-3 and MK-4.

with the observation that, with the exception of aerobes, the bacterial groups found in the influent leachate were found in the biofilm of the columns at disassembly. The presence of these groups of bacteria signifies that the columns are being colonized by bacteria that would be found in a “typical” landfill. Thus, the columns are likely simulating the conditions found in a LCS. The presence of a large population of methanogens that thrive in anaerobic environments (Palmisano and Barlaz 1996), in the lower portion of each column, suggests that the bacteria not only colonized the columns, but also developed niches that allowed specialized bacteria to grow and thrive.

Drainable porosity

Figure 7*a* shows the drainable porosity profiles during steady state operation when the rate of removal of COD and $CaCO_3$ is relatively stable (see Fig. 3). Results for the column with a flow rate Q_d = 1 L/d are shown after 118 days and 63 m^3/m^2 (123 L) of leachate passed through (see Figs. 3 and 4), which corresponds to an average flow of Q_d = 1.04 L/d. The Q_d = 2 L/d column is shown after 104 d and 108 m^3/m^2 (213 L) of leachate passed through (see Figs. 3 and 4), which corresponds to an average flow Q_d = 2.05 L/d. It can been seen that the increase in mass loading, due to the higher flow, has lead to a greater reduction in drainable porosity after relatively similar periods of time. Figure 7 also shows that the reduction in drainable porosity is greatest at the influent end of the column (where the mass loading is greatest) and smallest at the outlet end of the column.

The weighted average drainable porosity represents the overall available pore space in the column. The average values and the cumulative $CaCO_3$ loading and mass removal in the column are given in Table 2 for the cases shown in Fig. 7*a*. These represent an upper bound to the drainable porosity, since near the inlet the drainable porosity was too low to measure, so the lowest measured value was taken as the

Table 3. Drainable porosity when columns had clogged.

Column	Design flow (L/d)	Elapsed time (d)	Leachate volume passed (m^3/m^2)[a]	Weighted average drainable porosity	Average decrease in drainable porosity (%)	Cumulative $CaCO_3$ mass loading (g)	Cumulative $CaCO_3$ mass removal (g)
MK-1	1	259	90	0.15	61	237	145
MK-2	1	265	108	0.17	56	250	170
MK-3	2	216	133	0.09	76	378	203
MK-4	2	244	124	0.14	62	347	195

[a] To obtain the volume passes after the initial lag period, subtract 13 m^3/m^2 for MK-1 and MK-2 and 27 m^3/m^2 for MK-3 and MK-4.

porosity in these regions. The greater mass loading at 2 L/d flow compared with 1 L/d leads to a greater loss of drainable porosity per unit time, 0.62%/d compared with 0.46%/d, respectively. The lower mass loading rate leads to a slightly larger mass of clog developing per litre of leachate passed through the column, with an average of 0.73 g $CaCO_3$ removed per litre at 1 L/d compared with 0.68 g $CaCO_3$ removed per litre at 2 L/d. This is consistent with the normalized COD and $CaCO_3$ plots, which show that removal efficiency increases as flow rate decreases due to the higher hydraulic retention time.

When the clogging became significant at the influent end of the column it became impractical to maintain the design flow rate. The column was defined as having "clogged" when it was not possible to transmit more than 10% of the daily design flow rate under a head of 2.4 m, relative to the base of the column. The tests were then terminated. Drainable porosity profiles for the 1 and 2 L/d columns are shown in Fig. 7*b*, just prior to termination of the tests. Both columns had similar drainable porosities of about 3% in the lower 250 mm of column (above the column base). The weighted average drainable porosities and the cumulative $CaCO_3$ loading and removal are summarized in Table 3 for the profiles shown in Fig. 7*b*.

The 2 L/d column had a greater absolute and percent decrease in drainable porosity in a shorter period of time. There was a significant decrease in flow rate (relative to the design flow rate) at 122 d (after 127 m^3/m^2 of leachate passed through the column at an average flow rate of 2.05 L/d). The column operation was discontinued after 216 d of operation. For the 1 L/d column, the decrease in flow rate below the design flow rate began at 140 d (after 74.8 m^3/m^2 of leachate passed through the column at an average flow rate of 1.05 L/d), and the column was discontinued after 259 d.

Hydraulic conductivity

Based on the constant-head method (ASTM Standard D2434), the initial hydraulic conductivity, k_{init}, of 0.327 m/s (standard deviation = 0.026 m/s) was used as a reference against which the hydraulic-conductivity reduction, defined as k/k_{init}, could be calculated for the six columns tested. The hydraulic-conductivity reduction between piezometers P1 and P2 (at the inlet end of the column, see Fig. 1) versus volumetric flow and elapsed time are shown in Fig. 8. Figure 8*a* shows the hydraulic-conductivity reduction versus volumetric flow per unit cross-sectional area, and Fig. 8*b* shows hydraulic-conductivity reductions versus elapsed time. Due to the limitations of evaluating hydraulic conductivity (e.g., low flow rate and gas bubbles in the piezometer tubing adding to the difficulty reading small (less than 5 mm) differences in piezometer heads at early times), there were no data collected before the hydraulic conductivity had dropped between four and five orders of magnitude. Figure 8*a* shows that for equal volumes of leachate passed, the 1 L/d columns experience the greatest loss of hydraulic conductivity. This is due to the high COD and $CaCO_3$ removal efficiency of the 1 L/d columns relative to the other columns (i.e., greater mass removal from the leachate per unit flow). It appears that for equal periods of time, the 4 L/d columns may have a greater loss in hydraulic conductivity, since they remove a greater mass of $CaCO_3$ per unit time. By the time the columns were judged to have clogged, the flow had dropped to about 10% of the design value and the hydraulic conductivity, *k*, had decreased by seven orders of magnitude. At the time of test termination, the hydraulic conductivity had dropped by between 8 and 10 orders of magnitude (see Fig. 8).

Based on porosity and hydraulic conductivity measurements conducted between piezometers (see Fig. 1) at different times, it was possible to establish the following empirical relationship between hydraulic conductivity and drainable porosity for the 6 mm glass beads (see Fig. 9):

$$[2] \qquad k = A\, e^{bn} \qquad (n \geq 0.03)$$

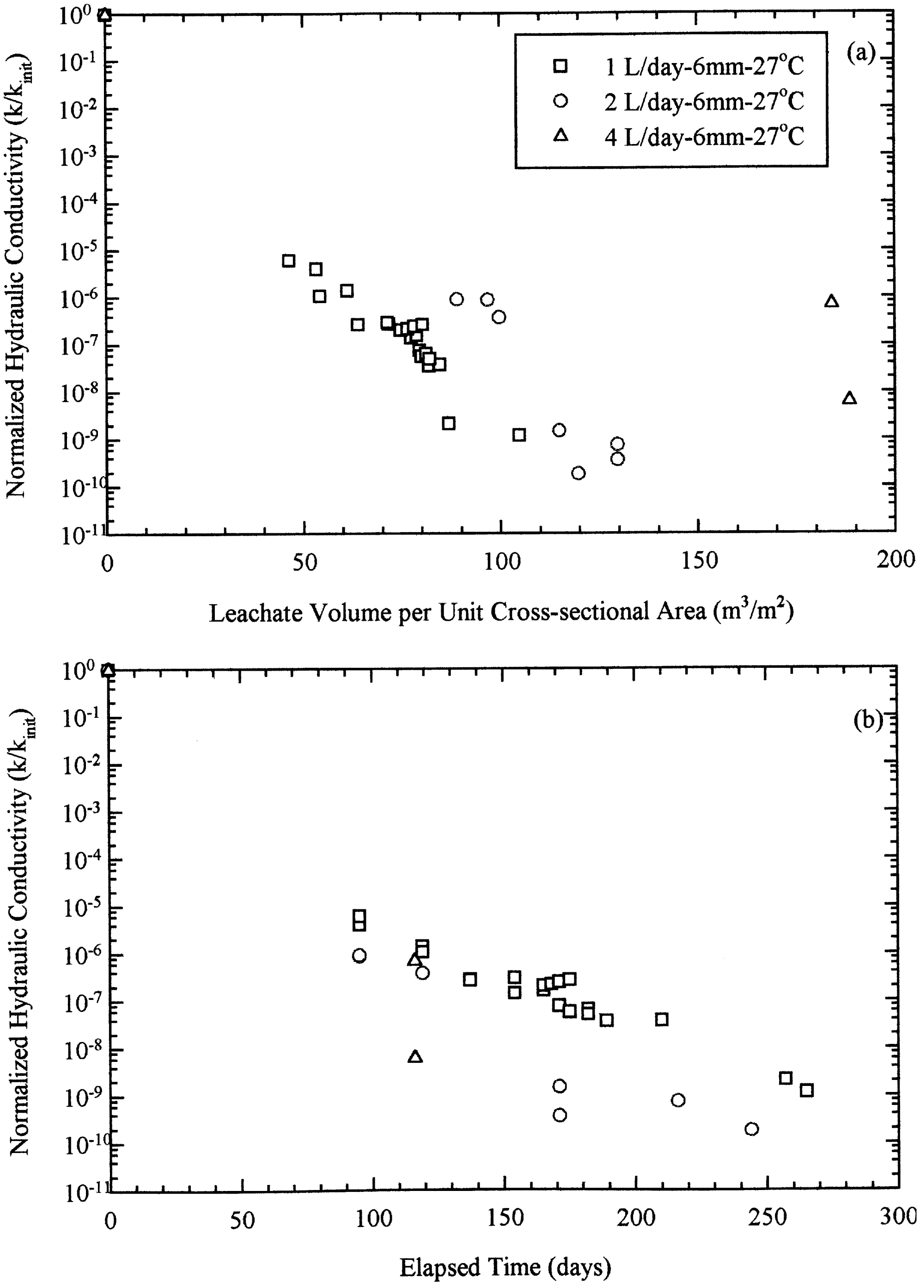
where $A = 1.11 \times 10^{-9}$ m/s, $b = 50.47$, and $r^2 = 0.88$. As mentioned previously, it was not possible to measure *k* reliably until it dropped by about four to five orders of magnitude. For this reason, there are no data to support this correlation between the $k = k_{\text{init}}$ and $k = 10^{-4}k_{\text{init}}$.

It can be seen that the hydraulic conductivity drops with decreasing drainable porosity in a similar manner at all flow rates and that there is a seven to eight order of magnitude drop in hydraulic conductivity by the time the drainable porosity drops to about 10% of the initial value.

Column disassembly

After termination of the test, the columns were disassembled and the distribution and composition of the clog material were examined. The biofilm is composed of an active component that contains the bulk of the living microbes and an inactive component that is composed of dead microbes and mineral precipitates. Figure 10 shows the distribution, along the column, of total wet solids (TWS), total dry solids (TDS), and total volatile solids (TVS) as mass deposited per bead. For these parameters, the three flow rates show the same trend of decreasing mass per bead with increased distance from the column base, where the leachate inlet was

Fig. 8. Normalized hydraulic conductivity versus (*a*) leachate volume per unit cross-sectional area, and (*b*) elapsed time.



located. This is consistent with the distribution of drainable porosity that is lowest near the column inlet and increases as one moves up the column (see Fig. 7*b*). However, it was also evident that there is generally more clog material per bead for the higher flow rates (4 L/d) than for the lower flow rates (2 and 1 L/d) over the entire length of the column. However, although the percentage of volatile solids increases as one moves up the column, there is no evident trend due to the flow rate in terms of the proportion of volatile solids. The high flow rates seem to have provided more nutrients along the entire length of the column (giving higher total dry solids at all elevations) by the time the tests were terminated. This appears to have resulted in more active biofilm (represented by TVS) and inactive mineral clog represented by TDS–TVS. The ratio of active biofilm to mineral clog (which is related to the percentage of volatile solids) did not seem to change significantly with flow rate. There did appear to be a consistent trend of lower biofilm water content as the flow rate increased. Thus it appears that at the lower flow rate more water was "trapped" in the clog material.

The bulk (wet) biofilm density, biofilm thickness, and void volume occupancy calculated for the position 100 mm above the column base are summarized in Table 4. The variation in the clog bulk density may be due to the nature of the test, which was an adaptation of ASTM Method D854. In this instance, the volume of biofilm is calculated from the volume of the beads and biofilm, less the volume of the clean beads. The clog thickness calculated from the average total clog wet mass and the clog bulk density indicates that

Fig. 9. Relationship between drainable porosity and hydraulic conductivity for 6 mm glass beads at 27°C.

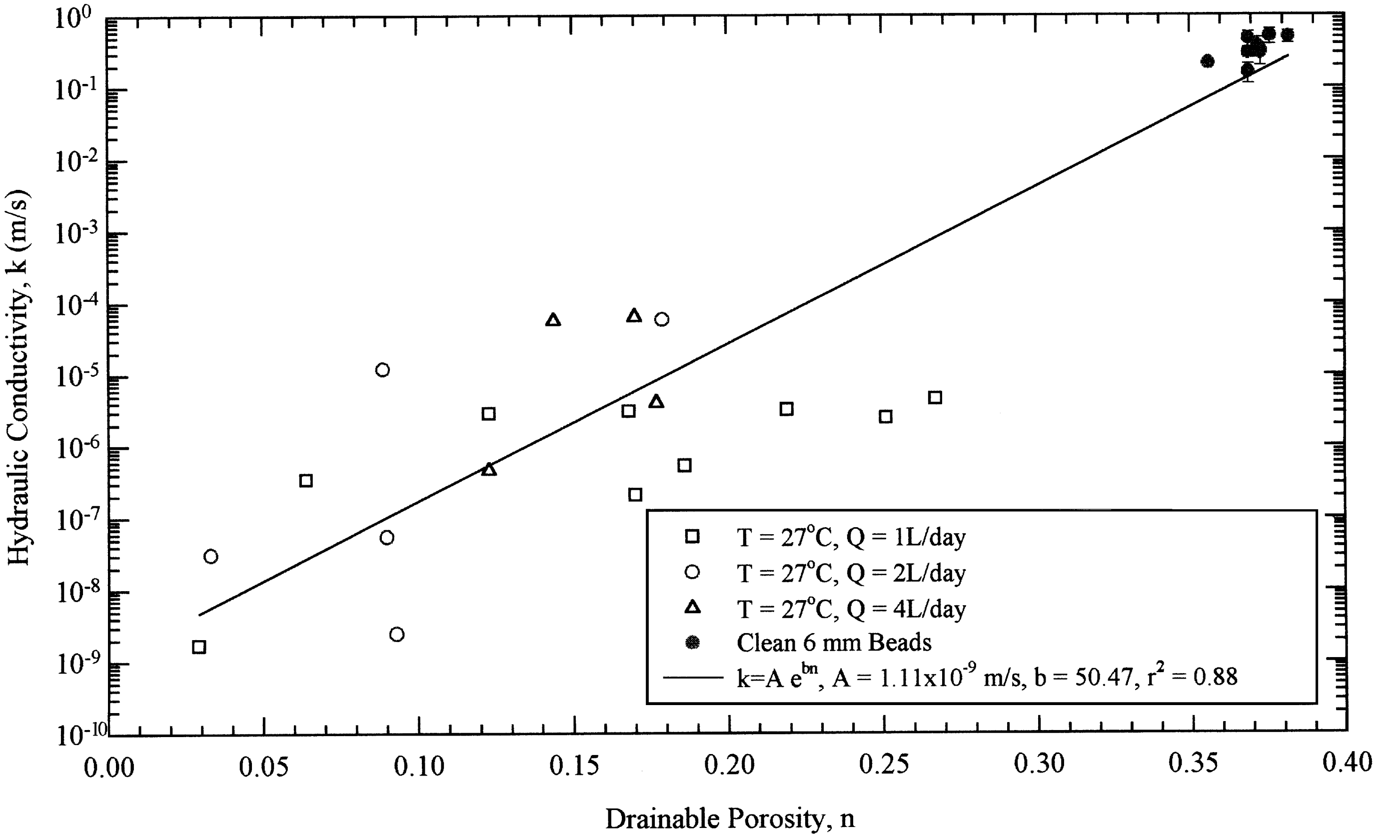


Table 4. Summary of clog thickness.

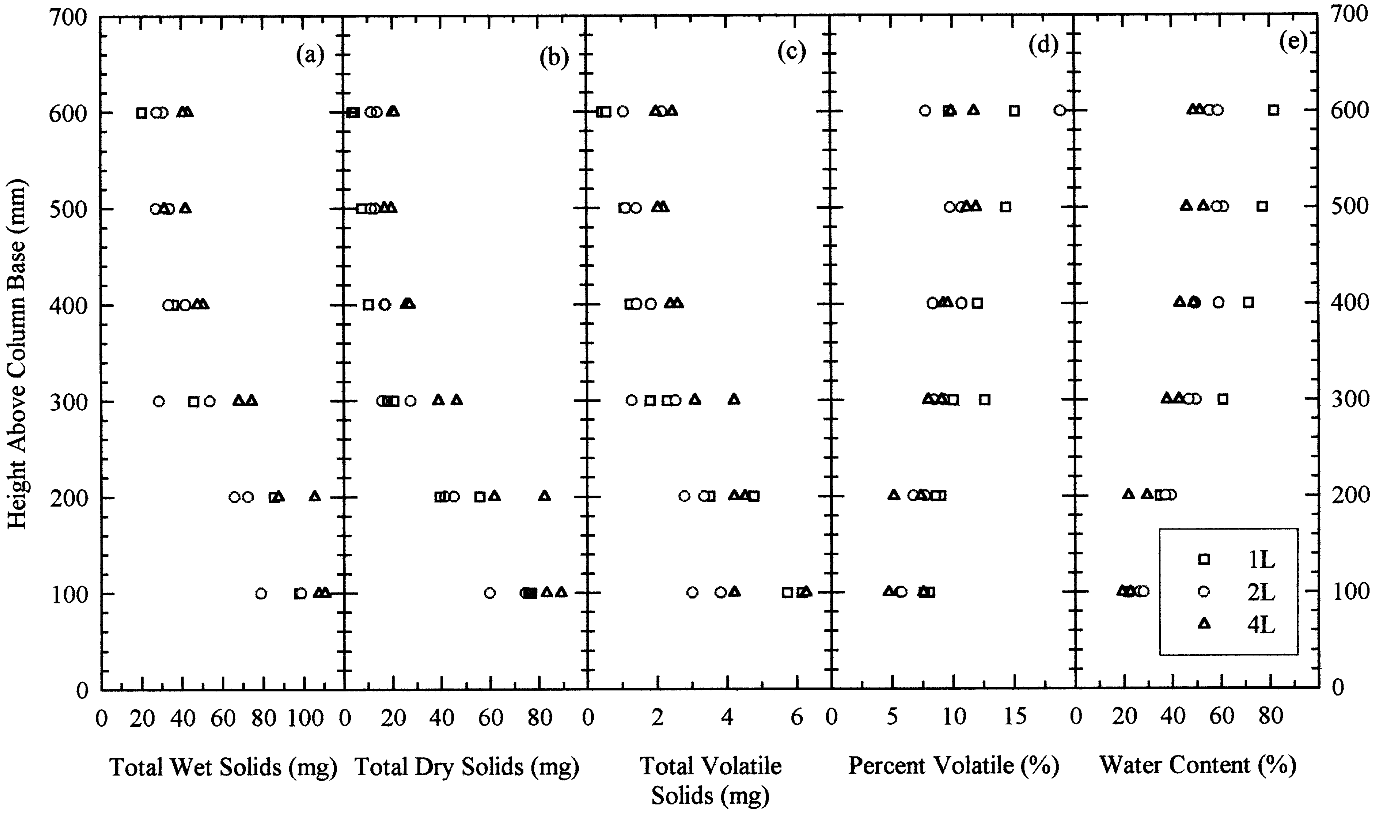
Column:	MK-1	MK-2	MK-3	MK-4	MK-5	MK-6
Sample position (mm above column base):	100	100	100	100	100	100
Design flow rate (L/d):	1	1	2	2	4	4
Slime moisture content (%)		21.86	26.39	28.04	22.59	19.33
Bead density (g/cm^3)	2.49	2.49	2.49	2.49	2.49	2.49
Average bead diameter (mm)	6	6	6	6	6	6
Average total clog wet mass per bead (mg)		97.8	98.8	118.2	107.3	110.4
Wet (bulk) density (mg/cm^3)	1638	1779	1990	1912	1622	1604
Average clog layer thickness (mm)		0.49	0.44	0.55	0.58	0.61
Void volume occupancy (calculated) (%)	68.5	68.5	72.5	79.1	81.0	89.1
Remaining porosity (total) (calculated)	0.12	0.12	0.10	0.08	0.07	0.04

the clog thickness increases with increasing flow. The void volume occupancy (VVO) (i.e., percentage of initial void now filled with biofilm or mineral clog) and remaining total porosity were calculated from these results. The calculated remaining porosity is larger than the drainable porosity at the same elevation for the columns in question (see Fig. 7*b*), since the calculated value includes pores that contain water but are blocked.

Samples from column MK-6 (Q_d = 4 L/d) were taken from six positions along the length the column for total elemental analysis. Samples were also taken from the 25 to 75 mm position for columns MK-1, MK-3, and MK-5 to compare clog composition with respect to flow rate. The analysis program included inductively coupled plasma spectrophotometry (U.S. EPA Method 6010) for trace metals, alkaline metals, and sulphur using a Thermo Jarrell Ash ICAP 61E Plasma Spectrophotometer. Silicon was analyzed by inductively coupled plasma – atomic emission spectrometry (ICPAES) and conversion to silica (Standard Methods (1985) 425A (modification)). Total Kjeldahl nitrogen (TKN) was analyzed by continuous liquid flow (ASTM Method D3590, 84A and 84D). Volatile solids were obtained by ignition to constant weight at 600°C (U.S. EPA Method 160.4).

Table 5 summarizes the results of the elemental analysis for column MK-6. The water content is least near the bottom (in the most clogged zone) and increases with distance from the influent entry point. Part of this water is likely from the biofilm. The percentage of both total organic carbon (TOC) and organic matter (as TVS) are essentially uniform along

Fig. 10. Analysis of clog material after termination of columns: (*a*) total wet solids mass per bead, (*b*) total dry solids mass deposited per bead, (*c*) total volatile solids mass per bead, (*d*) percent volatile solids, and (*e*) water content of clog material (105°C).



the column (there is no obvious trend), suggesting that the amount of biofilm is likely relatively constant along the column. Hence, the water incorporated in the biofilm would also be expected to be relatively constant. Thus, increased water content as one moves up the column likely represents water attached to the outside biofilm and possibly water in the porous structure of the developing clog. The percentages of Ca^{2+} and CO_3^{2-} were relatively consistent along the column and did not show any distinct trend. Recognizing that the ratio of Ca to CO_3 is 0.666 in $CaCO_3$, it can be seen that some of the carbonate must be in a form other than $CaCO_3$, since the average ratio is about 0.56. Given the amount of Mg and Fe, it is hypothesized that some of the carbonate is a magnesium and iron carbonate, however this was not verified. Calcium represented between 25.5 and 31% of the dried (at 105°C) clog material, with an average fractional value of 26.8% (f_{Ca} = 0.268). The proportion of Ti and Ba seemed relatively uniform along the column. There was scatter but no clear trend of variation with position for Fe, S, P, TKN-N, Zn, Ni, V, and Cr. However, some elements do show a distinct trend. Most notably, Cu and, to some extent, B increased to much higher proportions towards the top of the column compared with the bottom and Mg, Na, Al, K, and Sr showed a less significant but still clear trend of increasing as one moves up the column. In contrast, Mn and, to a lesser extent, Co decrease as one moves up the column.

The results from the elemental analysis on samples taken near the inlet (25–75 mm) to columns MK-1, MK-3, MK-5, and MK-6 are summarized in Table 6. There is some scatter in the data but no obvious effect of flow rate on calcium or carbonate content. The average calcium content of 26.4% for the 25–75 mm zone in these columns is very similar to that obtained along column MK-6 (26.8%). The proportion of carbonate in MK-3 between 25 and 75 mm seems high compared with other values obtained; however, the results for MK-1 and MK-5 between 25 and 75 mm are very similar to those obtained along column MK-6 (Table 5). The silicon may have been contaminated from the cutting process, where clog material and glass beads were cut to remove samples. Magnesium, sodium, potassium, sulphur, TKN, and zinc concentrations may decrease with increasing flow rate but, with the possible exception of potassium, the correlation is, at best, weak. There appears to be a better correlation between the variation in these parameters and the TVS (i.e., increasing concentration with increasing TVS), since Mg, Na, K, S, and Zn play roles in microbial nutrition and TKN represents the nitrogen found in organic materials (e.g., amino acids, proteins, and polypeptides) (Grady and Lim 1980). The increase in TVS content of MK-6 (relative to MK-5) correlates well with the observed increase in Mg, Na, Fe, S, TKN, and Zn and is consistent with this explanation.

Table 7 summarizes the average Keele Valley leachate parameters and the average results from the elemental analysis of the solid clog material in the columns. Considering the ratio of concentration in the solid clog material to that in the leachate, it can be seen that all parameters (except for Na and K, which show no significant accumulation) tend to accumulate in the solid clog to some degree. The high accumulation ratio for calcium results from the significant precipitation of $CaCO_3$ as the leachate passed through the

Table 5. Total elemental analysis of clog material from MK-6 autopsy.

	Position above the column base (mm)						
Parameter	025–075	150–175	250–275	325–375	425–475	525–575	Average
WC (%/wet)	19.3	22.1	37.7	43.1	46.0	48.8	36.2
TOC (%/dry)	13.4	12.2	14.1	12.7	13.1	13.2	13.1
TVS (%/dry)	10.6	7.7	10.7	9.3	10.7	10.7	10.0
CO_3 (%/dry)	ns	47.6	44.2	46.5	49.7	49.3	47.5
Ca (%/dry)	26.9	25.9	25.7	31.0	25.5	25.7	26.8
Si (mg/kg)	nd	nd	nd	nd	83	198	141
Mg	10 400	9 430	12 700	15 700	14 400	14 700	12 888
Na	2 070	1 860	3 010	3 540	3 980	4 440	3 150
Fe	48 900	43 600	40 600	53 800	37 200	39 400	43 917
Al	109	104	98	150	143	163	128
K	558	642	1 060	1 070	1 590	1 800	1 120
S	6 070	2 730	4 160	5 010	3 940	4 530	4 407
Total P	1 040	849	798	814	736	807	841
TKN-N	8 000	5 000	6 100	6 900	6 800	10 000	7 133
Mn	2 920	2 810	2 030	2 230	1 770	1 760	2 253
Ti	11	11	11	13	12	12	12
Zn	838	587	757	781	803	972	790
Sr	696	689	785	959	869	895	816
Ba	113	109	109	129	108	108	113
Ni	77	60	71	66	65	77	69
Cu	8	4	5	45	37	33	22
V	3	2	2	1	2	2	2
Pb	nd	nd	nd	nd	nd	nd	nd
Cr	17	14	15	20	17	19	17
Co	10	8	9	5	6	6	7
B	9	8	12	14	14	20	13
Ca/CO_3	—	0.544	0.581	0.666	0.514	0.522	0.564

Note: All values presented as mg/kg are per kilogram of dry clog material. CO_3 = carbonate; nd, not detected; ns, not measured; TOC, total organic carbon; TVS, total volatile solids (organic matter); WC, water content.

columns. Since magnesium carbonate has a greater solubility than calcium carbonate, magnesium does not accumulate as rapidly as calcium despite the similar concentrations in the leachate. The accumulation ratios of TOC and TKN are close and small relative to most other parameters examined. TKN represents the nitrogen in organic matter and so it is considered likely that the accumulation of TKN and at least part of that of TOC and P are related to biofilm growth and not precipitation. The high accumulation ratio for phosphorous (about three orders of magnitude greater than that of other parameters) likely arises because phosphorus, like carbon and nitrogen, is required for cellular growth but is found in the leachate at a concentration between three and four orders of magnitude smaller than these other parameters. In the clog material, the ratio of TOC:N:P is 44:4:1. It has been noted that C:N ratios for heterotrophic bacteria are difficult to quantify because carbon is used for catabolism (cell growth) and synthesis (e.g., extra polymer substances, EPS) (Cullimore 1993). The N:P ratio (typically 4:1 to 8:1) is considered to be a better measure, since these elements are largely retained within the cellular structure. The N:P ratio for the clog material of 4.2:1 implies that the accumulation of TOC, N, and P is related to the biofilm growth. The accumulation ratio for sulphur is higher than that for the other listed parameters, probably because it also accumulates as FeS, as noted by Brune et al. (1994).

Other parameters in order of decreasing accumulation ratio are Cu, V, Mn, Ba, Co, Fe, Ti, Zn, Al, Ni, and Cr. Solubility tables for metal carbonates and metal hydroxides, as well as metal sorption on calcite, indicate that a complex relationship exists between pH, pCO_2, and metal cation concentrations (Sawyer et al. 1994; Zachara et al. 1993). Sequential extraction would be necessary to evaluate the partitioning of these metals into the exchangeable, carbonate-bound, iron and manganese oxides, organic matter, and residual fractions (Gupta and Chen 1975; Tessier et al. 1979); however, this was beyond the scope of the present study.

Brune et al. (1994) suggested that the primary components of mineral clog material (incrustation) were calcium, magnesium, iron, and carbonate. Table 8 compares the composition of the clog material formed along column MK-6 with the clog material examined by Brune et al. (1994) and Fleming et al. (1999) and shows that the results are similar, with $CaCO_3$ representing more than half of the solid clog material in all cases. The major difference is with respect to silicon. This likely arises from the fact that, in the field, sand and silt particles can be washed into the collection system and attach to the soft sticky biofilm. However, in the laboratory

Table 6. Total elemental analysis of clog material (25–75 mm position) from selected columns.

Parameter	MK-1	MK-3	MK-5	MK-6	Average
Water content (%/wet)	41.2	22.6	29.0	19.3	28.0
TOC as C (%/dry)	6.7	6.0	6.6	13.4	8.2
Organic matter (TVS; %/dry)	11.2	8.8	8.5	10.6	9.8
Carbonate as CO_3 (%/dry)	49.8	58.0	48.7	ns	52.2
Ca (%/dry)	24.2	27.1	27.2	26.9	26.4
Si (mg/kg)	33 900	27 100	30 200	nd	30 400
Mg	12 700	10 300	8 360	10 400	10 440
Na	3 060	2 080	1 980	2 070	2 298
Fe	37 000	35 300	35 000	48 900	39 050
Al	163	132	164	109	142
K	1 800	1 110	782	558	1 063
S	10 100	6 090	5 780	6 070	7 010
Total P	2 140	2 360	1 960	1 040	1 875
TKN-N	10 000	6 900	6 500	8 000	7 850
Mn	1 720	2 430	2 350	2 920	2 355
Ti	27	23	21	11	21
Zn	1 500	787	570	838	924
Sr	751	705	653	696	701
Ba	88	102	96	113	100
Ni	108	68	57	77	77
Cu	16	14	184	8	56
V	17	15	15	3	13
Pb	<1	<1	<1	nd	nd
Cr	14	14	12	17	14
Co	12	10	10	10	10
B	15	14	21	9	15
Ca/CO_3	0.49	0.47	0.56	—	0.50
Mg/TVS	0.11	0.12	0.098	0.098	0.11
Na/TVS	0.027	0.024	0.023	0.020	0.024
Fe/TVS	0.33	0.40	0.41	0.46	0.40
K/TVS	0.02	0.01	0.01	0.01	0.01
S/TVS	0.090	0.069	0.068	0.057	0.072
TKN/TVS	0.089	0.078	0.076	0.075	0.080
Zn/TVS	0.013	0.009	0.007	0.008	0.009

Note: All values presented as mg/kg are per kilogram of dry clog material; nd, not detected.

this material will have settled out before the leachate is passed through the columns. The small amount of silicon found in the laboratory samples is likely from the cutting procedure used to collect samples and not from the leachate itself. If the proportions of all three clog compositions are adjusted to exclude Si, then the proportion of Ca is consistent in all three studies (25–27% of the solid clog excluding Si). The proportion of carbonate measured in the columns is a little higher than that observed by the aforementioned authors, and the amount of Mg is lower than that encountered in the Keele Valley exhumation but similar to that obtained by Brune et al. (1994).

Conclusions

The results from this study have shown that mass loading has a significant impact on the rate and extent of clogging in a granular medium. This is primarily due to the increased mass of inorganic material available for precipitation on the granular medium. The blockage of pores by accumulation of organic and inorganic clog material reduces the hydraulic conductivity of the porous media, and in a field case would reduce the effectiveness of the drainage layer. It was shown that clogging is greatest where there is greatest mass loading (near the inlet in this case, but likely near the collection pipes in a field situation). An empirical relationship between hydraulic conductivity and drainable porosity for the 6 mm glass beads as clog material accumulated was obtained.

It was found that although higher flow rates gave rise to less efficient bioreactors (i.e., a smaller reduction in organic and inorganic loading per unit volume of leachate in a given time), this was more than compensated for by the increase in mass loading associated with the higher flow rates. For these tests, “clogging” corresponded to a decrease in drainable porosity to about 10% of the nominal value and a drop in the hydraulic conductivity by about seven orders of magnitude.

The yield coefficient, Y_C, of $CaCO_3$ appears to have increased somewhat with increased flow rate, which may be due to shearing effects at higher flow rates. This shearing can increase the effluent COD (i.e., reduce the amount of

Table 7. Comparison of Keele Valley leachate composition (mg/L) with the clog material from columns MK-1, MK-3, MK-5, and MK-6 (mg/kg).

	Keele Valley leachate geometric mean[a]	Mass loading columns average	Ratio
DOC/TOC	4 184	82 000	20
Ca	536	263 500	492
Si	ns	30 400	—
Mg	401	10 440	26
Na	1 864	2 298	1
Fe	205	39 050	190
Al	0.94	142	151
K	856	1 063	1
S	46[b]	7 010	152
Total P	0.72	1 875	2 604
TKN-N	1 065	7 850	7
Mn	6.3	2 355	374
Ti	0.12	21	179
Zn	5.7	924	163
Ba	0.29	100	349
Ni	0.65	77	119
Cu	0.01	56	4 483
V	0.03	13	492
Cr	0.15	14	92
Co	0.03	10	348

Note: KVL data are the geometric means of the Keele Valley leachate data published in annual reports for the period over which this study was conducted.

[a] Overall geometric mean of Keele Valley leachate during the course of this study.

[b] SO_4 in leachate converted to S.

Table 8. Comparison of relative chemical composition of clog material (dried at 105°C).

				Excluding Si		
	Keele Valley (Fleming et al. 1998)	Germany (Brune et al. 1994)	MK-6 (this study)	Keele Valley (Fleming et al. 1998)	Germany (Brune et al. 1994)	MK-6 (this study)
Calcium (% dry wt.)	20	21	27	25	25	27
Carbonate (% dry wt.)	30	34	47	38	40	47
Silicon (% dry wt.)	21	16	—	—	—	—
Magnesium (% dry wt.)	5	1	1	6	1	1
Iron (% dry wt.)	2	8	4	3	9	4
Ca/CO_3	0.67	0.62	0.57	0.66	0.63	0.57

COD removed, other things being equal) and hence increase the ratio of $CaCO_3$ removed to COD removed. The apparent scatter in the data is indicative of the variable nature of MSW leachate, but a trend between increasing COD and $CaCO_3$ exists. The average yield coefficient from all tests was 0.15 mg $CaCO_3$ per milligram of COD removed. This is an important parameter needed to model the rate of clogging of leachate collection systems (Rittmann et al. 1996; Rowe et al. 1997; Cooke et al. 1999).

The columns were found to be colonized by a diverse consortia of bacteria, including methanogens, sulphate-reducing bacteria, and denitrifying bacteria, which have been found in typical landfill waste and leachate. The very high aggressivity (hence large population) of methanogens in the lower half of the column indicates that the bacteria are not only colonizing the columns, but also developing niches to allow specialized bacteria to grow and thrive.

The results of this study lead to several conclusions of practical significance relating to the design and operation of a LCS. First, since the rate of clogging has been shown to be related to mass loading, reducing the distance between the leachate collection pipes would decrease the total volume of leachate collected for one individual pipe and hence reduce the mass loading and rate of clogging around the pipe. Second, this study has found bulk (wet) densities of clog material, ρ_c, between 1.6 and 2.0 Mg/m^3. This, combined with the observed total calcium fraction of 27% of total clog material ($f_{Ca} \approx 0.26$), can be used in simple engineering calculations such as those proposed by Rowe and Fleming (1998) to estimate the rate of clogging of different collection system designs.

Finally, this study has provided experimental data that can be used by researchers developing more sophisticated clogging models (e.g., Cooke et al. 1999) to test model accuracy under relatively controlled conditions.

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