Biodegradation (2006) 17: 415–422
DOI 10.1007/s10532-005-9012-z

An investigation into the microbial clogging potential of selected filter media as a result of biodegradation of a high-strength sulphate-rich alkaline leachate

Zhengjian Wang & Charles Banks*
School of Civil Engineering and Environment, University of Southampton, SO17 1BJ, Southampton, UK
*(*author for correspondence: e-mail: cjb@soton.ac.uk)*

Accepted 8 August 2005

Key words: anaerobic biodegradation, cement kiln dust, clogging, filter pack, landfill, leachate

Abstract

The research examines the potential for bio-clogging in filter packs containing fine sand of the type typically used in extraction wells for pumping leachates containing fine particulate matter, such as cement kiln dust (CKD). Three filter media with different particle sizes were used: 1.7–4.75, 0.35–1.0, and 0.235–0.45 mm. Each sand filter was tested using a leachate recirculating column reactor with a free drainage layer, on top of which was placed the filtration medium which was kept saturated and at a positive hydrostatic head by a 2-l reservoir of leachate. The leachate was collected from a landfill site that had been used for the co-disposal of municipal solid waste (MSW) and CKD. The leachate used was filtered by passing through a Whatman GFA filter paper before being added to the reactors in order to eliminate as far as possible the non-biological clogging which might have resulted from the introduction of particulate matter in the form of CKD. The filters and a control experiment were run under anaerobic conditions at 35 °C. The bio-clogging potential was observed by taking differential manometer readings from manometers located in the drainage and reservoir sections of the reactor. No clogging was detected using the coarser of the filter media, but there was some clogging when a finer filter medium was used. Head space gas analysis indicated that methanogenic activity was inhibited and analysis of the liquid phase indicated that the microbial process responsible for removal of chemical oxygen demand (COD) was principally one of sulphate reduction.

Introduction

Most modern landfills include pre-installed leachate collection systems to control the leachate level in order to comply with environmental regulations. The leachate collection systems are usually located at the base of the landfill and typically consist of perforated HDPE collection pipes embedded within a granular drainage blanket which is positioned below the waste and above any low-permeability liners (VanGulck & Rowe 2004). Clogging of leachate collection systems, however, is a common problem due to the build-up of fine particles on the drainage materials. Based on their numerous field studies, Brune et al. (1991) concluded that clogging on drainage materials is caused by the combined effect of physical, chemical and biological processes. To overcome clogging problems leachate extraction wells are often used. These have a design similar to wells used for extraction of ground water and consist of two parts: a screen casing and a non-screen casing. The well screen allows leachate to flow freely into the well, and prevents waste from entering with leachate. Surrounding the well screen a filter material, such as gravel, is packed to prevent solid matter flowing into the wells. Sediment ingression is still a potential problem, however, especially when the waste body contains very fine particle materials.

The current laboratory-based study was set up to simulate the conditions likely to be encountered in a leachate extraction system serving a co-disposal landfill site filled with a mixture of municipal solid waste (MSW) and cement kiln dust (CKD). The on-site leachate extraction system has historically experienced a serious blockage problem thought to be caused by the build-up of deposits in pumps and pipelines. A field-based investigation concluded that failure of the leachate extraction system was initiated by ingression of fine particles of CKD into the wells, rather than by chemically-induced precipitation. CKD is a lime-based material of a very fine particle size, with more than 80% of the individual particles having a diameter less than 50 μm (USEPA 1999). These fine CKD particles can move through conventional filter pack media in the well screens and consequently are pumped into the leachate collection system causing serious blockages. To overcome this problem consideration has been given to the use of finer filter materials in the well packing to alleviate CKD ingression in wells. There is, however, a greater potential for microbial clogging when using fine materials in filter packs, especially when the leachate has a high organic strength and elevated temperatures as were typically encountered on the site. The rate of microbial clogging depends on a number of factors: the pore space in the filter pack, the depth of the filter layer, the face velocity, the nutrient status of the leachate, its temperature and redox potential. To maintain the filter free of clogging the rate of microbial film detachment from the particle surfaces must be equal to, or greater, than the rate of biofilm formation. The parameters under design control are the velocity of flow (controlled by pump flow rates) and the particle size of the filter pack. To test the feasibility of using different filter pack arrangement a laboratory system was designed to allow simulation of the performance of different configurations when exposed to leachate from the co-disposal landfill site.

The purpose of the experiments was to investigate the secondary effects of bio-clogging within the filter medium as distinct from determining its filtering capacity for cement kiln dust (CKD). The experiments were therefore designed to use a leachate from which the CKD particles had been eliminated by prior filtration through a 0.45 μm pore size glass fibre filter leaving only soluble and colloidal material within the leachate feed. With the elimination of CKD particles prior to the leachate being passed through the filter medium it is reasonably safe to assume that accumulated material on the filter was formed either by microbial growth processes, or by precipitation of soluble material or agglomeration of colloidal material. Precipitation is unlikely to have occurred as the anions present in this type of leachate are primarily chloride and sulphate, both of which have a high solubility in combination with the cations found. Agglomeration of colloids, however, cannot be discounted in contributing towards clogging but the limitations of the experimental design using site specific leachate rather than a synthetic product did not allow this to be fully investigated.

Materials and methods

Experiment design

The experimental apparatus (Figure 1) comprised a reactor of 150 mm diameter and 300 mm height. At the bottom of this reactor was a perforated drainage bar surrounded by a 20 mm layer of coarse texture reticulated polyurethane foam (2.4 pores cm^{-1}) which acted a physical support for the filter pack medium. The filter material itself was layered on top of the support to a depth of 100 mm, leaving a freeboard of 180 mm as a leachate reservoir in the reactor. This provided a small head of leachate above the medium and ensured saturation conditions at all times. The leachate collection tube was connected to a peristaltic pump that recirculated the leachate from the bottom of the filter to the leachate reservoir, via a cartridge filter containing fibre glass wool. The peristaltic pump was operated at a fixed speed to simulate a pre-determined velocity at the face of the filtration medium. Temperature was controlled at 35 °C by means of an external water jacket surrounding each of the reservoirs. The head loss through the filter medium was monitored using a pair of manometers, one located in the drainage layer of the filter and the other in the leachate reservoir just above the surface of the filtration medium. Where no filter medium is present the

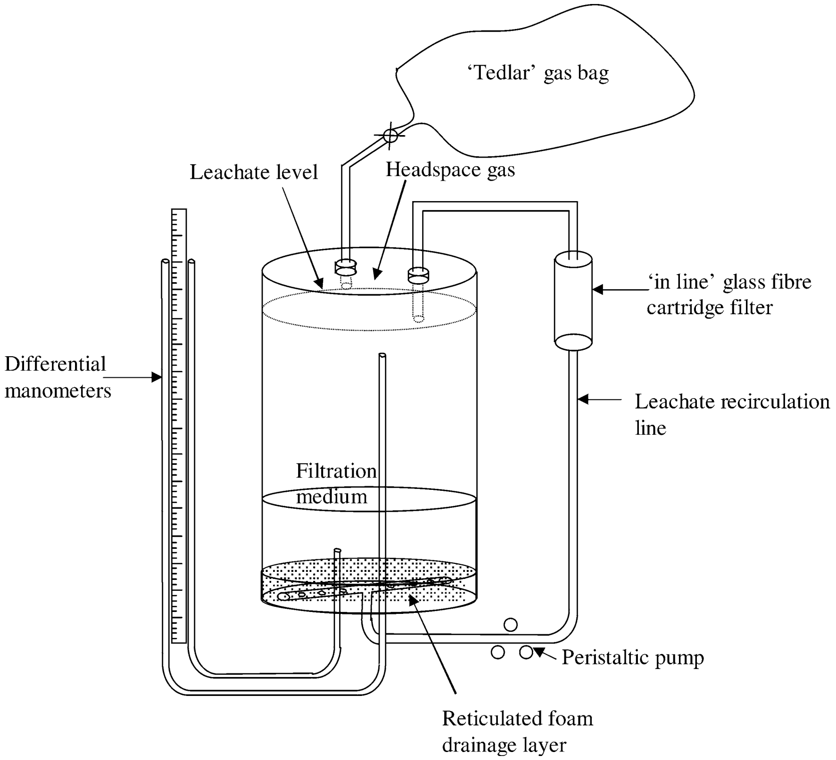

Figure 1. Experimental apparatus.

readings of the two manometers should show no measurable differential effect. Any restriction to the free flow of the leachate between the reservoir and the drainage layer will result in a differential reading expressed as Delta P (ΔP).

In total four reactors were set-up, one of which acted as a control without any filtration medium. The other three were layered with sand filter medium, each with a different particle size. These were: MGS (trade name used by Marton Geotechnical Sevices, UK) with a particle size between 1.7 and 4.75 mm; FCP (Cardigan Sand & Gravel Co. Ltd., UK) with a particle size between 0.35 and 1.0 mm; and FMP (Cardigan Sand & Gravel Co. Ltd., UK) with a particle size between 0.235 and 0.45 mm.

As the experiments were designed to assess the influence of biological film formation the leachate used was filtered by passing through a Whatman GFA filter of pore size 0.45 μm before being charged into the reactors. Each reservoir was filled with 2 l of filtered leachate which was circulated through the reactors with a controlled flow rate of 50 ml min^{-1} to simulate an actual filter face velocity of about 4.07 m day^{-1}. The manometers were read every day, and 5 ml samples of leachate were taken from each filter twice per week for analysis. Meanwhile 5 ml of fresh leachate was fed into the filters as a replacement. The leachate samples were analysed for pH, COD, VFAs and sulphate concentrations.

The experimental filters were operated over a period of 220 days divided into four cycles. The first cycle covered day 1 to 62, the second from day 63 to 112, the third from day 113 to 188, the fourth from day 189 to 220. At the end of each cycle the reacted leachate was drained from each filter and replaced by 2 l of fresh leachate. Leachate recirculation was recommenced immediately following leachate replacement.

Analytical methods

Leachate pH and COD were determined according to standard methods (APHA 1995). Volatile fatty acids (VFAs) were analysed using a Varian STAR 3400 CX gas chromatograph. The samples were first pre-treated by acidifying to 10% with formic acid and then centrifuged at 17,000 rpm before the supernatant liquor was analysed. Samples were compared with standard solutions (500 mg l^{-1}) of acetic, propionic, isobutyric, butyric, isovaleric, valeric, caproic and heptanoic acids. Sample concentrations were determined by integration of peak areas against those of standards at the recognised elution times. Sulphate, chloride, nitrate and nitrite concentrations were analysed using a Dionex DX500 ion chromatograph. Ammonia was measured by using a Bran Luebbe Auto-Analyzer. Methane composition was determined by using a Varian CP−3800 gas chromatography. All the metal elements (K, Na, Ca and Mg) were analysed by using a Varian spectra AA-200 atomic absorption spectrometer. Dissolved sulphide concentration was determined by a Visocolor PF-11 Filter Photometer. The 'in-line' cartridge filter was constructed of a 22 mm diameter 100 mm long PVC tube with detachable inflow and outflow tubes at either end. The filter was packed with a known weight of previously dried commercially available glass fibre used as a rolled insulation material (Rockwool, UK). At the end of an experimental cycle the glass fibre and any trapped solids were carefully removed into a preweighed and dried ceramic crucible together with wash water from the filter. The crucible and its contents were then dried to constant weight in a fan assisted oven at 105 °C and the solids accumulation was taken to be the difference in weight between the 'clean' and 'dirty' glass fibre packing material. The results are expressed as a dry weight and no differentiation was made as to the nature of the solids that were trapped; these were assumed to be solids that had formed within the filter medium and subsequently been washed off as a result of the hydraulic shear forces exerted on the filter by leachate recirculation.

Leachate chemistry

The leachate used in this experiment was collected from a MSW and CKD co-disposal landfill. It was alkaline in nature and contained very high concentrations of COD, sulphate and other ions (Table 1). Four different batches of leachate were collected over the experimental period and these varied in their composition, with the leachate strength being stronger during the third and fourth cycle than for the first two cycles.

Table 1. Leachate chemistry

Parameter	Values
pH	8.65–8.76
Chemical oxygen demand (COD) (mg l^{-1})	12,800–22,900
Ammonia nitrogen (NH–N) (mg l^{-1})	550–720
Nitrate and nitrite nitrogen (NO_x–N) (mg l^{-1})	0.14–0.28
Phosphorous (PO_4–P) (mg 1^{-1})	5.7–12.4
Volatile fatty acids (VFA) (mg l^{-1})	3058–4878
Sulphate (SO_4^{-2}) (mg l^{-1})	3921–8700
Chloride (Cl^-) (mg l^{-1})	10,785–14,564
Potassium (K) (mg l^{-1})	13,000–19,000
Sodium (Na) (mg l^{-1})	2100–4800
Calcium (Ca) (mg l^{-1})	25.8–76.7
Magnesium (Mg) (mg l^{-1})	96.1–290.4

Results and discussion

The ΔP results for the four reactors are shown in Figure 2. As expected these showed no difference in the control where there was no filtration medium. There was also no difference for the reactor packed with the coarsest filter media (MGS: particle sizes between 1.7 and 4.75 mm). For the two reactors packed with finer sand an initial reading of 0.6 cm was recorded for the reactor with FCP filtration medium (particle sizes between 0.35 and 1.0 mm) and 1.5 cm for FMP (particle sizes between 0.235 and 0.45 mm). The ΔP readings for the FCP medium oscillated over the experimental period and are indicative that there were accumulations of clog material, with the material being washed off the filter medium on a periodic basis. In the reactor packed with FMP the ΔP value showed a much more constant increase from around day 60 and reached a peak of 3.9 cm around day 140, indicating a gradual accumulation of clogging material. There was then a decline in ΔP reaching a stable level by day 200. This might be attributed to an initial build-up of microbial film, which after a period of time became friable allowing it to be detached from the filter medium by the relatively high face velocity. In all cases, however, there was no evidence of significant microbial clogging occurring on any of the filtration media at the pumping rates used.

The concurrent reduction in sulphate and the removal of soluble COD is indicative that one of the main degradation processes is *via* microbially mediated sulphate reduction. This was further supported by visual inspection of the filter medium

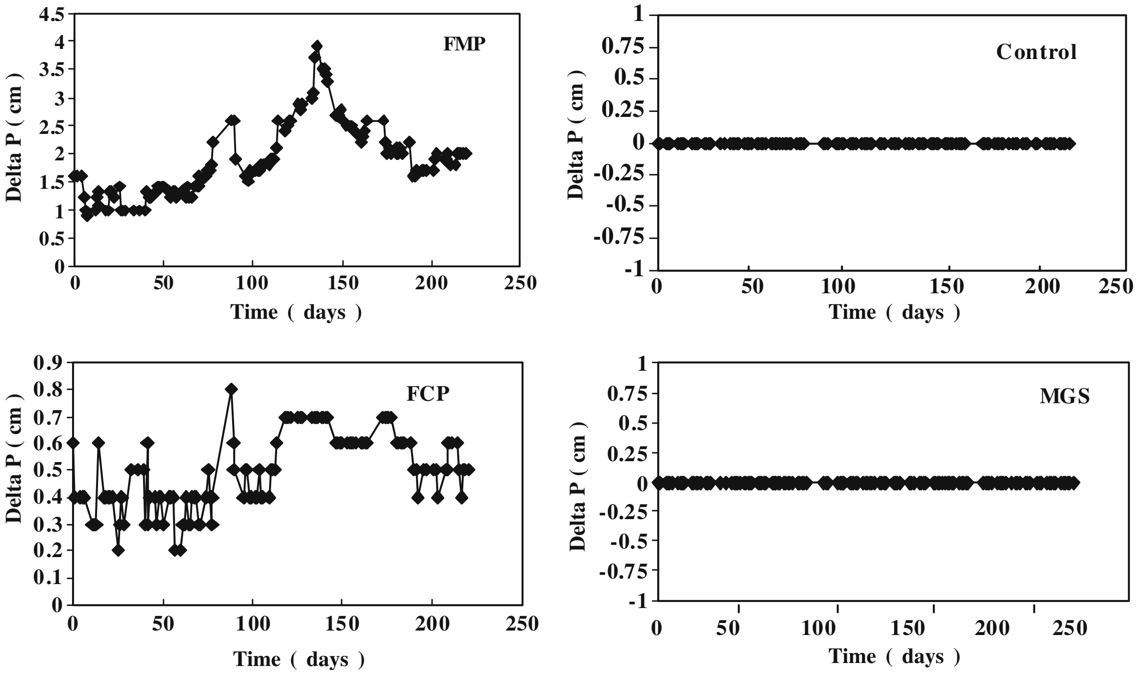

Figure 2. Reactor manometer readings.

and the reactor itself in which the surfaces were blackened and typical of a reduced sulphide environment. It is also likely some fermentation reactions leading to the production of acid products could take place under the conditions found, but the leachate itself was already rich in fermentation products, which would be further oxidised in the sulphate reduction process. The process of methanogenesis was thought to play only a very small role in the further breakdown of fermentation intermediates as only very small amounts of methane were detected in the head spaces of each of the filters. The sulphate-reducing bacteria have a thermodynamic advantage over methanogenic bacteria (Equations 1–4) by virtue of having a higher maximum specific growth rate (μ_m) and a lower half saturation value (K_s), which gives them a kinetic advantage (Archer & Kirsop 1991). Once sulphate reduction becomes established then the toxicity of soluble sulphides further depresses methanogenic activity. This usually starts to occur when there is an initial sulphate concentration of greater than 1.0 g l^{-1} and tends to produce total inhibition when sulphate concentration exceeds 4.5 g l^{-1} (Wheatley 1991). It is generally accepted that inhibition will occur when the dissolved hydrogen sulphide (H_2S) concentration exceeds 200 mg l^{-1} (Lawrence & McCarty 1961).

$$CO_2 + H_2 \rightarrow CH_4 \quad \Delta G = -135.1\text{J} \tag{1}$$

$$SO_4^{2-} + H_2 \rightarrow S^{2-} \quad \Delta G = -154.0\text{J} \tag{2}$$

$$CH_3COO^- \rightarrow CO_2 + CH_4 \quad \Delta G = -28.5\text{J} \tag{3}$$

$$SO_4^{2-} + CH_3COO^- + H_2 \rightarrow H_2S + 2HCO_3^- \quad \Delta G = -47.3\text{J} \tag{4}$$

Table 2. Leachate dissolved sulphide concentrations

Status	Soluble sulphide concentration (mg l^{-1})			
	Control	MGS	FCP	FMP
Cycle 1	150	370	390	440
Cycle 2	145	365	405	430
Cycle 3	140	385	410	445
Cycle 4	144	405	410	455

The dissolved sulphide (HS^-) concentrations in the leachate of each reactor at the end of each cycle are given in Table 2. These high soluble concentrations are enabled by the alkaline pH values (between 8 and 9) observed in the reactors (Figure 3) which promote the solubility of H_2S.

Figure 3 shows reactor pH and volatile fatty acid concentrations. The pH in all the reactors was around 8 despite the relatively high initial acid concentration of around 4000 mg l^{-1} for cycles 1, 3 and 4 and 3000 mg l^{-1} for cycle 2; this was indicative of the high inherent buffering capacity of the leachate. In the reactors containing the filter medium there was a gradual decrease in volatile fatty acids over each of the cycles, but the corresponding reduction in VFA in the control reactor was lower indicating an overall lower level of microbial activity. This would suggest that the microbial consortium responsible for VFA reduction was more abundant when a support particle suitable for bio-film attachment was present.

It can be seen from Figure 4 that COD and sulphate removals for the filters with packed

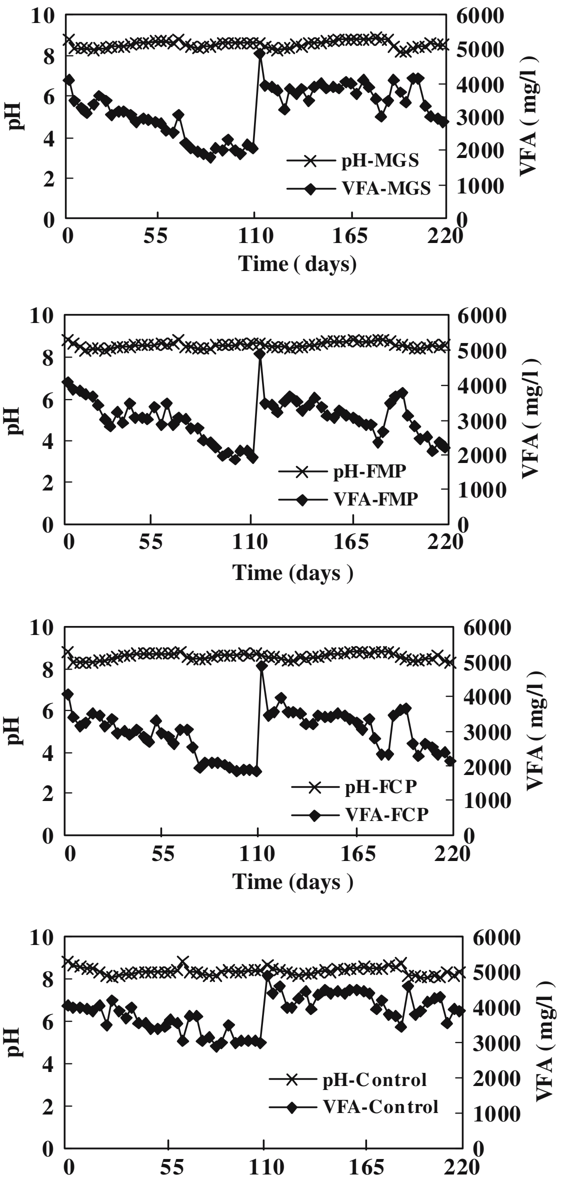

Figure 3. Reactor pH and VFA concentrations.

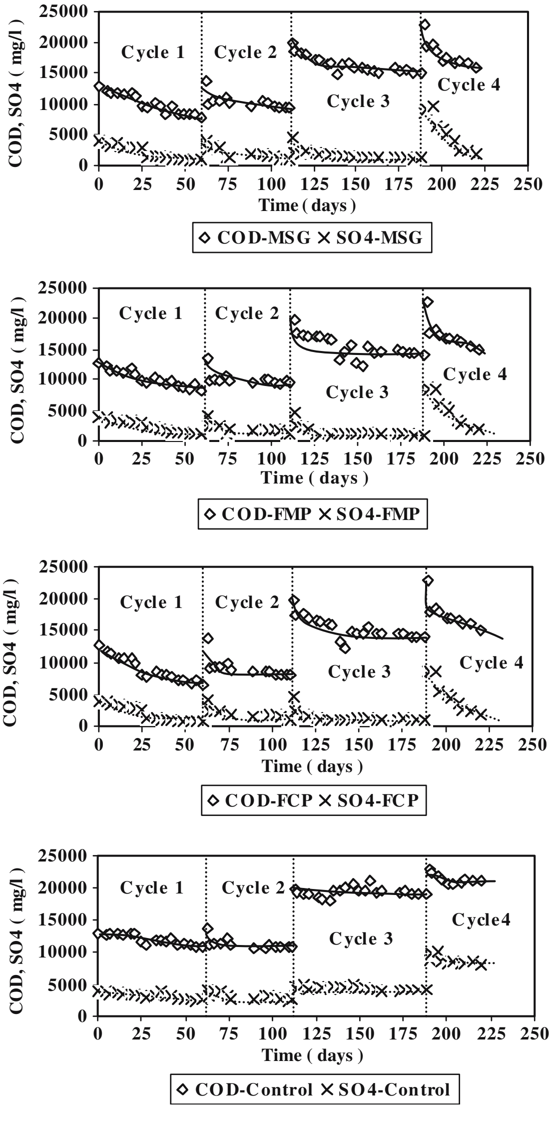

Figure 4. Reactor COD and SO_4^{2-} concentrations.

Table 3. Solids accumulation measured from the 'in-line' glass fibre filter and COD removal for each cycle

Statue	COD removed (g)				Solids accumulation (g)			
	MGS	FMP	FCP	Control	MGS	FMP	FCP	Control
Cycle 1	10.2	9.4	12.7	4.0	0.16	0.08	0.12	0.08
Cycle 2	8.8	8.6	11.2	5.6	0.15	0.07	0.11	0.11
Cycle 3	9.8	11.4	11.8	1.6	0.16	0.09	0.11	0.03
Cycle 4	14.0	15.6	15.4	3.6	0.23	0.12	0.13	0.08

materials (MGS, FCP and FMP) were much greater than those in the control reactor. The differences in COD and sulphate removal between the filter materials with the different particle sizes, is only small and cannot be regarded as being significant. This result is not as definitive as the findings of Lyew & Sheppard (1997), who found a positive correlation between surface area, sulphate reducing activity and the amount of sulphate removed.

Each reactor was fitted with an external 'in-line' cartridge filter filled with glass fibre wool which was designed to capture any particulate suspended solids flushed through the drainage layer of the reactors. In a normal leachate extraction system the solids entering the pump well from the filter pack would be removed with the leachate *via* the pump. The 'in-line' filter was used to simulate this removal without having to replenish the leachate itself. This type of filter will, however, have limitations and would not be expected to remove particles the size of individual bacteria or small colloids, but the filter was effective in trapping flocculent polymeric type materials. Because the CKD particles with a size greater than 0.45 μm were removed by filtration before the leachate was added to the reactors, then the solids caught by the glass fibre wool filters were solids generated within the reactors, and the assumption was made that these would be primarily due to the growth of biomass. The results relating to solids capture by the 'in-line' filters are shown in Table 3 along with the calculated total COD removed.

It can be seen that only a very limited amount of biomass was generated in the control experiment and this corresponds to the relatively low COD removal. Where the reactors contained a filter pack, the coarser the sand particle the more the solids accumulated on the glass fibre cartridge filter. Assuming all the solids captured by the cartridge filters were biomass generated by the bio-degradation of organics in the leachate, the biomass yield, for example from the MGS filter, was on average 0.016 g biomass $gCOD^{-1}$. This is much lower than a typical reported figure of 0.05 g biomass $gCOD^{-1}$ removed when fatty acids are bio-degraded under anaerobic conditions (Borja et al. 1995). It is therefore likely that the majority of the biomass produced from the biodegradation of COD remains trapped on the sand filter, especially when finer sand media was used. These trapped bio-solids, however, were not sufficient to cause a significant microbial clogging problem on the filter.

Conclusions

The following conclusions may be drawn:

1. The use of MGS as a filter pack in the leachate extraction wells would not result in microbial clogging to an extent that would impair performance at the face velocity used. The use of finer sands such as FCP or FMP leads to a slight potential for blockage, which was more pronounced with the finer material: it was however, not significant.
2. Sulphate reduction was thought to be the predominant microbial reaction and the methanogenic process was entirely inhibited by the sulphate-rich alkaline leachate.
3. The finer the particle size of the filter the more potential there was for the growth of a microbial consortium leading to removal of COD and soluble sulphide production.

Acknowledgements

The authors wish to thank Viridor Waste Management for the support of the research through their Landfill Trust.

References

APHA (1995) Standard Methods for the Examination of Water and Wastewater. 19th edn., American Public Health Association, Washington DC, USA

Archer DB & Kirsop BH (1991) The microbiology and control of anaerobic digestion. In: Wheatley A (Ed) Anaerobic Digestion: A Waste Treatment Technology, (pp 43–91). SCI Elsevier Applied Science, London

Borja R, Banks CJ & Wang Z (1995) Kinetic evaluation of an anaerobic fluidized-bed reactor treating slaughterhouse wastewater. Bioresource Technol. 52(2): 163–167

Brune M, Ramke HG, Collins H & Hanert HH (1991) Incrustations process in drainage systems of sanitary landfills. In: Proceedings of the Third International Landfill Symposium, Cagliari, Italy, pp. 999–1035

Lawrence AW & McCarty PL (1961) The effects of sulfides on anaerobic treatment. Proceedings 19th Industrial Wastes Conference, Purdue University

Lyew D & Sheppard JD (1997) Effects of physical parameters of gravel bed on the activity of sulphate-reducing bacteria in the presence of acid mine drainage. J. Chem. Technol. Biotechnol. 70: 223–230

USEPA (1999) Environmental Fact Sheet: Management Standards Proposed for Cement Kiln Dust Waste. United States Environmental Protection Agency Office of Solid Waste. Report No. EPA530-F-99–023, Washington DC

VanGulck JF & Rowe RK (2004) Influence of landfill leachate suspended solids on clog (biorock) formation. Waste Manage. 24(7): 723–738

Wheatley AD (1991) Anaerobic digestion: industrial waste treatment. In: Wheatley A (Ed) Anaerobic Digestion: A Waste Treatment Technology, (pp 43–91). SCI Elsevier Applied Science, London