ABSTRACT Recent research findings related to biologically induced clogging of leachate collection systems in municipal solid waste landfills are summarized. Three major clogging mechanisms are identified based on both field and laboratory studies which examine the factors that affect the clogging rate. Based on these studies, a sophisticated numerical model has been successfully developed to predict the clogging of drainage media and service life of leachate collection systems. Some findings based on this model are reported. A practical method for estimating the service life of leachate collection systems with different design configurations is discussed together with measures for extending the service life of these systems.

INTRODUCTION
Modern municipal solid waste (MSW) landfills commonly require a leachate collection system (LCS) over a low permeability composite liner to control the escape of contaminants from the landfill. The purpose of LCSs is to collect and remove the leachate from the bottom of landfill and therefore minimize the leachate head which provides the driving force for the leakage of contaminants to the surrounding environment through defects in the geomembrane component of a composite liner or due to advective transport through a simple clay liner (Rowe et al. 2004, Rowe 2005). Since the contaminating lifespan of a landfill may be decades or even centuries (Rowe et al. 2004), the performance of the LCS is critical for a well designed modern landfill and there is a need to be able to predict the service life of a given system.

There have been several “generations” of leachate collection systems (Rowe 1999). Prior to modern landfill engineering, if there was any leachate collection at all, it consisted only of perimeter drains around the edge of the landfill (Fig. 1). This simply served to collect leachate seeping through the landfill cover and did little to control subsurface contaminant migration. The first generation of leachate collection from the base of the landfill involved toe drains around the outside edge of the landfill base (Fig. 1). This was an improvement in that it reduced the potential for lateral migration though the sidewalls of the landfill but was unable to significantly reduce the leachate mound in the landfill and hence the vertical advective migration (leakage) though the base of the landfill (Rowe 1999).

The second generation of LCS involved installing what are commonly called “French drains” or “finger drains” which involved gravel drains, often with perforated drainage pipes (with or without a geotextile wrapping; Fig. 2). These drains were placed at a spacing that typically ranged from 50m to 200 m on the base of the landfill. The drains provided some control of the leachate head on the base of the landfill but their effectiveness decreased rapidly with time due to “clogging”. The high mass loading of leachate constituents (volatile fatty acids, suspended solids, and dissolved inorganic constituents like calcium) to the geotextile and granular material in the drains gave rise to substantial biofilm growth, deposition of particulate material such as silts and fine sands, and
biologically induced chemical precipitation (primarily calcium carbonate for drains within the landfill) that substantially reduced the hydraulic conductivity of drains (Rowe 1992, Koerner et al. 1993, Rowe 1998a,b). The reduced hydraulic conductivity of drains led to leachate mounding in the waste between the drains and substantial leakage of contaminants through the base of the landfill (Rowe 1998a). The third generation of LCSs design involved a continuous drainage blanket of granular material with perforated drainage pipes at a regular spacing and, often, a geotextile between the waste and granular porous media (Fig. 3; Rowe 1992).

While the evolution in LCS design has been very positive in terms of improving the performance of the LCS, field observations (e.g. Bass 1986, Brune et al. 1991, Koerner et al. 1993, 1994, McBean et al. 1993, Koerner and Koerner 1995, Rowe 1998a, Fleming et al. 1999, Craven et al. 1999, Maliva et al. 2000, Bouchez et al. 2003) have shown that for all designs, a clog mass develops in the LCSs which is controlled by a combination of physical, biological, and chemical mechanisms (the deposition of suspended solids, the growth of biomass, and the precipitation of minerals). In all cases, the clogging of LCSs reduces the hydraulic conductivity of the porous media and, if the design is not adequate, can eventually induce leachate mounding on the bottom liner in the landfill. However, as will be discussed in this paper, the rate of clogging and the time it takes before there is significant buildup of leachate head on the base of the landfill (the service life of the LCS) is highly dependent on details of the design of the LCS.

Fig. 1 Schematic Showing Perimeter and Toe Drains at a Landfill (not to scale, modified from Rowe 1999, Rowe and VanGulck 2004). (For colour figure, refer to CD)
Fig. 2  Schematic Showing Examples of Finger Drain/French Drain Leachate Collection System Designs (a) No Geotextile Filter; (b) Geotextile Filter Wrapped around Collection Pipe, and (c) Geotextile Filter Positioned between the Waste and Gravel (modified from Rowe 1992, Rowe and VanGulck 2004). (For colour figure, refer to CD)
For modern MSW landfills, the leachate head in LCSs is normally required to less than 0.3 m, (Rowe et al. 2004). Thus the service life of the LCS could be defined as the time it takes before the design head is exceeded. The estimation of the service life of LCSs with different design configurations requires an understanding of the clogging mechanisms and the effects of the different factors on the clogging.

This paper follows 20 years of research into the clogging of LCS and many papers on this topic. In particular, it builds on a number of overview papers including most recently Rowe and VanGulck (2004) and Rowe (2005, 2009). Thus the objective of this paper is to (i) summarize key findings relating to the factors that affect the clogging rate of LCSs and subsequent mounding of leachate in the LCSs, and (ii) highlight recent research directed at predicting the service life of different LCS designs. Insights from a sophisticated numerical model will be discussed together with an approximate simplified approach for predicating service life. Finally comments will be made regarding the implications for designing LCS to have a long service life.

FIELD STUDIES
The previous section referenced many field observations relevant to the clogging of LCSs. This section highlights a few cases with findings particularly relevant to the discussions in this paper. The field studies of LCSs in Germany (Brune et al. 1991) demonstrated that clogging of leachate collection systems was accelerated when the leachate entering the LCS had a high concentration of both organic acids and inorganic substances (as reflected by high COD, BOD and Ca concentrations). They also indicated that the mode of landfill operation (in particular the rate of landfilling) could have a significant effect on the leachate characteristics and hence the rate of induced clogging.

Rowe et al. (1995, 2004) reported a case where a 0.3m thick sand layer on top of a compacted clay liner experienced significant clogging within less than 4 years. This sand layer had become effectively part of the diffusion barrier and was not facilitating any significant lateral flow of leachate.

Fleming et al. (1999) reported on the exhumation, in the mid 1990s, of a coarse (50mm) gravel drainage layer after 4-5 years of operation. They reported significant clogging in the lower portion of the gravel where the hydraulic conductivity had decreased by about three orders of magnitude to about 10^{-4} m/s. However, because of the high initial hydraulic conductivity of this gravel, the layer was still effectively controlling the leachate.
head to below the maximum design value as it still is 15 years later at the time of writing (2010). They quantified clogging in terms of the proportion of the void space filled with clog material, called the void volume occupancy or VVO. It was also reported that the presence of a filter-separator layer between the waste and drainage layer substantially reduced the clogging (VVO) of drainage media relative to locations where there was no filter separator present between the waste and gravel layer.

Fleming et al. (2010) reported the failure, within 3 years of construction, of a perimeter drain system installed in 2004 at the edge of an old MSW landfill. The drainage system consisted of a 300 mm diameter double-walled HDPE pipe with smooth inside walls and corrugated outside walls, wrapped with a lightweight heat-bonded nonwoven geotextile and installed 3-5 m below ground surface within a sand ($D_{90}=1$ mm, $D_{50}=0.2-0.4$ mm, $D_{10}=0.1-0.2$ mm) backfill placed in a trench excavated to below the water table. Clogging was reported to be primarily due to oxidation of iron rich leachate contaminated groundwater arising from the landfill. The channels between the ribs of the corrugated pipe were filled with clog material consisting of microbial biofilm and precipitation of iron oxides and hydroxides. Most of the perforations in the pipe were at least partially occluded and those near the invert were completely blocked. The hydraulic conductivity of the geotextile wrapping the pipe decreased from $8 \times 10^{-4}$ m/s to $3 \times 10^{-4}$ m/s while that of the sand decreased from an initial $3 \times 10^{-4}$ m/s to $4 \times 10^{-5}$ m/s. Due to nature of the design combined with this reduction in hydraulic conductivity, by 2007 leachate-contaminated groundwater was bypassing the drain and was reported to be discharging to a nearby creek. The three primary problems with this design were suggested to be: (i) the geotextile filter should have been placed farther from the perforated collection pipe, to move it as far as possible from the aerated zone surrounding the pipe and to reduce the mass loading of leachate per unit area of geotextile; and (ii) large diameter granular drainage material should have been used around the collection pipe since this would provide a large void space and minimize the effects of clogging as well as allowing the use of larger perforations in the pipe. The use of a corrugated pipe is also questionable. Since the groundwater flowing inside the pipe will cause mineral precipitation in the oxygen rich environment in the pipe, the pipe should be regularly inspected and cleaned by flushing.

Koerner and Koerner (1995) reported the findings of field exhumations of LCSs at a number of locations, two of which are summarized here. At a MSW landfill, the perforated collection pipe was wrapped with a geotextile (heat bonded nonwoven with an apparent opening size, AOS, of 0.15 mm and permittivity, $\psi$, of 1.1 s$^{-1}$) and in a layer of gravel (6 to 30 mm particle size). The exhumation was initiated because of a significant reduction in flow after 1 year and the consequent development of a high leachate mound. Upon exhumation it was found, inter alia, that there was clogging of the void space of the gravel which reduced the hydraulic conductivity of the gravel from $2.5 \times 10^{-4}$ m/s to $2 \times 10^{-5}$ m/s. Clogging of the geotextile also was observed with the hydraulic conductivity, $k$, decreasing from an initial $4 \times 10^{-4}$ m/s to $3 \times 10^{-5}$ m/s.

An industrial landfill with solids and sludge (slurry fines had particles with 70% finer than 150 µm) had a blanket underdrain that no longer collected fluid after only 6 months and, as a consequence, a high leachate mound had developed. The underdrain was comprised of a protection sand layer (0.075 to 4 mm) over a geotextile (AOS=0.19 mm) over pea gravel (1 to 20 mm) drainage layer with 100 mm diameter geotextile (needle punched nonwoven, AOS=0.19 mm, $\psi$=1.8 s$^{-1}$) wrapped HDPE perforated pipe. The continuous geotextile between the sand and gravel was still performing well and the hydraulic conductivity had only dropped from about $5 \times 10^{-3}$ m/s to $9 \times 10^{-5}$ m/s. The pea gravel was also relatively clean. However the geotextile wrapping around perforated pipe had excessively clogged and the hydraulic conductivity had dropped from $5 \times 10^{-4}$ m/s to $4 \times 10^{-6}$ m/s.

Junqueira et al. (2006) reported the performance of four leachate collection systems (sand, gravel, a
combination of geotextile and tires, and a geocomposite drainage layer) in experimental domestic waste cells over a period of 5 years. Among four different drainage systems, the leachate from the cell with a sand drainage layer had lowest COD values and highest pH values suggesting that the greatest leachate treatment (and hence clogging) occurred for the sand layer as the leachate passed through the drainage layer. Compared to the leachate from the cell with a geotextile and whole tires, the leachate from the cell with gravel had greater amounts of total suspended solids which showed that the geotextile can reduce the amount of total suspended particles in the leachate.

These cases empirically imply that:

i. clogging is particularly problematic when pipes are wrapped with geotextile,
ii. both sand and gravel drainage layers are prone to clogging but coarse gravel takes much longer to clog than finer gravel which in turn takes longer to clog than sand,
iii. geotextiles used as a continuous separator layer experience some clogging but provide protection to the underlying gravel underdrain and perform substantially better than geotextiles used to wrap pipes, and
iv. pipe perforations should be as large as possible and the pipe should be regularly inspected and cleaned by flushing as needed.

Although this paper is primarily focussed on clogging of LCS for MSW landfills under anaerobic conditions, it is noted that there is also field evidence of clogging in industrial waste landfills and ash monofills. Also clogging can occur under both aerobic and anaerobic conditions.

LABORATORY STUDIES

While field cases are highly instructive, invariably there is no opportunity to control the conditions such that one can assess the effects of different variables on the clogging process. Controlled laboratory experiments provide a means of addressing this limitation of field studies using both the real and synthetic leachate.

Clogging of Geotextiles

Many studies of clogging of geotextiles were conducted in the 1990s and have been summarized by Rowe et al. (2004) and Rowe (2005). Some of the more recent studies are summarized below. In many cases they are relevant to geotextiles at the aerobic-anaerobic/anoxic interface (e.g. perimeter drains).

Mendonca et al. (2003) reported results from laboratory flask tests examining ochre formation on the geotextile filters. Three different types of geotextile were used in their tests (nonwoven polyester, nonwoven polypropylene, and woven polypropylene geotextiles) where the effects of the iron concentration, available dissolved oxygen, and pH on the biofilm formation were considered. They indicated that iron bacteria play an important role in the ochre formation at an aerobic-anaerobic/anoxic interface. This can be particularly critical in perimeter drains (see Fleming et al. 2010). Higher concentration of dissolved iron, and larger amounts of available dissolved oxygen (but less than a certain maximum value) induced the most biofilm formation. Low pH (3.3) resulted in low bacterial activity and low ochre formation but the inhibition due to low pH values disappeared at a pH of about 5 and considerable ochre formation occurred for pH above 5.

Mendonca & Ehrlich (2006) conducted column tests to study the ochre formation on different types of geotextile where the bottom face of the geotextile filters was open to the air to simulate an aerobic-anaerobic/anoxic interface for the filters. They found that there was significant formation of clog mass resulting in a 7 to 45 fold decreases in the hydraulic conductivity of the geotextile filters compared to the virgin material.

Palmeira et al. (2008) examined the biological clogging of three types of needle-punched nonwoven geotextile permeated with leachate. The geotextile specimens were placed at the permeameter mid-height and subjected to an upward flow of real leachate under what are inferred to be anaerobic conditions. A reduction in the geotextile hydraulic conductivity by between
three and four orders of magnitude due to clogging was reported.

Clogging of Granular Material
In the following subsections, the results of findings from laboratory column tests where a leachate is permeated through a granular material filling the columns from one end of the column to the other are reported. The studies involving saturated columns (Brune et al. 1991, Armstrong, 1998, Rowe et al. 2000a, b, Rowe & McIsaac 2005, McIsaac & Rowe 2005) examined the effect of particle size and grain size distribution, leachate characteristics and flow rate (mass loading), temperature, and alternative drainage media (tire shreds). McIsaac & Rowe (2008) also examined the clogging of 50 mm gravel under unsaturated conditions over a period of 8 years.

To mimic the flow conditions adjacent to a collection pipe in real landfill LCS, two-dimensional laboratory mesocosm studies were conducted in real time and real scale where the leachate from the top infiltration percolated vertically down through the waste and into the drainage layer, and the drainage layer conveyed leachate from both lateral input flow and top infiltration to collection pipes (Fleming et al. 1999, Fleming & Rowe 2004, McIsaac & Rowe 2006, 2007). Operated under anaerobic conditions, all mesocosm tests were permeated with real leachate collected from the Keele Valley Landfill at flow rates representative of field conditions. One mesocosm was terminated after 20 months operation and the clogging of the gravel after this short exposure is shown in Fig. 4 (Fleming & Rowe 2004). Most of mesocosms were terminated after 6 years operation but one was operated for more than 12 years. McIsaac & Rowe (2006) reported results for 300-mm thick coarse gravel (nominal diameter 38 mm) with and without the filter-separator layer between the waste and gravel layer or within the gravel layer. The saturated thickness of the gravel was 100 mm and three different filter-separator layers were used (woven geotextile, nonwoven geotextile, and graded granular filter). McIsaac & Rowe (2007) presented mesocosm results for two different saturated thicknesses (100 mm and 300 mm), and results for different particle sizes (19 mm and 38 mm). The results from mesocosms run in series were also reported for the case where the leachate at the effluent port from one mesocosm became the influent for the next mesocosm in the series.

The key findings from these studies are reported in the following subsections.

Effect of Grain Size
Brune et al. (1991) reported the results from the column tests on granular material with different grain size distributions (2-4 mm, 2-8 mm, 1-32 mm, 8-16 mm, 16-32 mm). They showed that the rate of clogging was least for 16-32 mm and increased as the particle size became smaller or the material became much more graded. Fine gravel clogged faster than the coarser gravel but slower than finer drainage material (2-4 mm) and well graded drainage material (1-32 mm) which experienced almost a complete loss of permeability during the period of testing.

Rowe et al. (2000a) reported similar findings for columns filled with uniformly graded glass beads of different sizes (4 mm, 6 mm, and 15 mm). Clogging of the finer (4 mm) beads was faster and focused near the influent end of the column. As the particle size increased, the rate of clogging was slower and more uniformly distributed throughout the column.

The mesocosm tests reported by McIsaac & Rowe (2007) demonstrated that 38 mm gravel in the saturated zone performed much better (i.e. less clogging) over 12.6 years than the 19 mm gravel did over a 6 year period under otherwise similar conditions.

These findings indicate that the service life of the LCS can be extended by using granular material with as large a particle size and as uniform a grain size distribution as practicable.

Effect of Mass Loading
Brune et al. (1991) reported that there was little clogging when the “lightly-loaded” permeating
leachate had low concentrations of organic acids and cations (such as calcium) but the significant clogging occurred when the concentration of organic acids and cations was high ("highly-loaded" leachate). Rowe et al. (2002) demonstrated that for similar flow and dissolved chemical composition of the leachate, columns permeated with synthetic leachate having negligible suspended solids experienced less clogging than those permeated with real landfill leachate (Armstrong 1998) with much higher suspended solids. Thus the composition of the leachate (e.g. organic acids, inorganic cations and suspend solids concentrations) entering the drainage layer has a critical effect on the rate of clogging.

The mass loading of constituents that can contribute to clogging of a drainage layer is the product of the chemical concentration and the flow. For a given leachate, Rowe et al. (2000b) reported that columns with a high flow rate experienced greater clogging rate than those with a low flow rate.

Since the leachate characteristics change as the processes causing clogging occur, the leachate emerging from a drainage layer is not the same as that entering the layer. For example, Rowe et al. (2000b) demonstrated that the clogging of glass beads in the same column was greatest near the inlet where the leachate strength was greatest and that the chemical composition of the effluent from even a short column was quite different to that of the influent. Likewise, the laboratory mesocosms run in series (McIsaac & Rowe 2007) showed that the clog mass in the saturated zone decreased between the influent zone and the effluent zone in the same mesocosm and decreased further between the first and last mesocosm in the series due to the decreased mass loading along the flow path.


The practical implications of these findings regarding mass loading are:

i. reducing the leachate collection pipe spacing would reduce the rate of clogging of the porous media around the pipes since the total volume of leachate collected by one individual pipe, and hence the mass loading on the material around the pipe, is decreased;

ii. the chemical characteristics of leachate at the end of a leachate collection system (the sump) generally will not be representative of the leachate entering the system or migrating through the liner system since it has been “treated” by the biological, chemical and physical processes occurring in the LCS.

**Effect of Temperature**

Armstrong (1998) examined the effect of temperature (10°C, 21°C, and 27°C) on the clogging rate and showed that over the range of temperatures examined, the higher the temperature the greater the rate of clogging (other things being equal). The practical implication of this study is that anything that reduces the temperature in the LCS (and hence on the liner) below that optimal for biological growth (often 30-40°C and 50-60°C) will extend the service of the LCS as the clogging rate of porous medium is decreased. It will also enhance the service life of the liner systems (Rowe 2005).

**Effect of Filter-Separator Layer**

The field exhumation of part of the LCSs at the Keele Valley landfill reported by Fleming et al. (1999) found that the VVO was 30-60% in the upper unsaturated portion of drainage layer without the use of filter-separator layer between the waste and coarse gravel drainage layer, while the VVO was 0-20% in the counterpart zone where there was a geotextile. The clog mass in the unsaturated gravel was mostly from the physical intrusion of waste material into the upper gravel drainage layer, and there was relatively little biologically induced clogging in this unsaturated zone within 4-5 years operation.

McIsaac & Rowe (2006) demonstrated that the amount of clog mass and rate of clogging was reduced when a filter-separator layer was used between the waste material and gravel layer or within the gravel drainage layer. All filter configurations examined prevented any significant intrusion of waste material into the gravel layer. The clogging of the woven geotextile was not significant. Compared with other filter configurations, the woven geotextile was least effective at reducing the clogging of the underlying gravel drainage layer. Some biologically induced clogging of the nonwoven geotextile was observed within the fibrous structure of the geotextile. The reduction of the hydraulic conductivity for the nonwoven geotextile was less than one order magnitude and no significant perching of leachate on the geotextile was observed in 6 years operation. The nonwoven geotextile filtered particulates and passively treated the leachate thereby reducing clogging of underlying gravel layer. When a graded granular filter was used, the entire top layer of the sand was cemented due to the accumulation of clog mass, and a reduced permeable zone was observed within the sand component of the graded granular filter. Of all mesocosms with a filter-separator layer (McIsaac & Rowe 2006), the least clogging of underlying gravel drainage layer was the mesocosm with a graded granular layer.

The practical implications from the filter-separator studies are: (1) a suitable filter-separator layer prevents significant physical intrusion of waste material into the drainage layer and extends the service life of the LCS; (2) a woven geotextile provided a good separator but did not otherwise extend the service life of the LCS whereas both the nonwoven geotextile and graded granular filter served to reduce clogging of the underlying drainage material (especially in the saturated zone).

**Saturated versus Unsaturated Conditions**

Other things being equal, McIsaac & Rowe (2007) found that there was substantially greater clogging in a fully saturated mesocosm (300 mm saturated thickness) than in a partly saturated mesocosm (100 mm saturated thickness). Saturation of the gravel: (i) increased the retention time of leachate in the drainage layer, and (ii) created a more conducive environment for the microbial growth...
on the surface of gravel. This resulted in the formation of a much greater clog mass in the 300 mm of gravel when fully saturated than when only 100 mm was saturated and 200 mm was unsaturated. McIsaac & Rowe (2007) suggested that the LCSs should be designed and operated with a minimum saturated drainage height by regularly pumping leachate out of the landfill and avoiding accumulation of leachate within the LCSs.

The unsaturated column tests on 50mm gravel, reported by McIsaac & Rowe (2008), demonstrated a large reduction in leachate strength (organic and inorganic concentrations) as it permeated through as little as 200-mm thick of unsaturated gravel. Thus significant leachate treatment can occur even before it reaches the saturated zone in the LCSs. This further confirms the finding that the leachate collected at the drainage pipes only represented a fraction of the leachate strength entering the LCSs. Averaged from all the unsaturated gravel columns, about 8% of the initial drainage porosity was reduced after the columns were operated for 8 years. Biofilm was observed only on a small fraction of total surface area of the unsaturated gravel (such as the flat surfaces and the contact points between the gravel particles) where the leachate could be retained long enough for biofilm growth. The practical implications of this study are: (1) the drainage layer in the LCSs should be operated under unsaturated conditions as long as possible; (2) increasing the thickness of unsaturated drainage layer would increase the service life of LCSs.

**Tire Shreds as an Alternative to Gravel**

Rowe & McIsaac (2005) reported that the initial hydraulic conductivity of two types of tire shred (0.007 m/s and 0.02 m/s) at 150 kPa overburden pressure was substantially lower than that of gravel (0.8 m/s). About 600 mm thickness of the unloaded tire shreds was needed to achieve the equal thickness of 300 mm gravel at 150 kPa due to the high compressibility of tire shreds (44-48%). The 38 mm gravel maintained a hydraulic conductivity greater than $10^{-5}$ m/s three times longer than a similar thickness of compressed tire shreds. The hydraulic conductivity of tire shreds reduced to between $10^{-7}$ and $10^{-8}$ m/s after about 1 year of operation, while the hydraulic conductivity of gravel was maintained between $10^{-6}$ and $10^{-7}$ m/s after 2 years operation. Note that all columns were run with accelerated flow to simulate many years of mass loading in the field for each year of the experiment. The much faster clogging of the tire shreds than that of the gravel was attributed to the observed lower initial porosity and numerous narrow and constricted pathways with small pore throats in the tire shreds compared to the much more open structure of the gravel. Even with a 25 mm thickness of drainage material, there is a highly tortuous path for tire shreds compared with the very open path for the gravel (Fig. 5). The practical implications from this study are: (1) gravel should be used in critical zones of the LCSs where the highest leachate mass loading will occur (e.g. especially near leachate collection pipes and sumps); (2) gravel could be replaced by the tire shreds in less critical zones by increasing the thickness of compressed tire shreds to provide a similar service life.

**SOPHISTICATED NUMERICAL MODEL**

Leachate mounding in a LCS is mostly controlled by the:

i. leachate characteristics,

ii. leachate infiltration rate,

iii. drainage pipe spacing and slope to the pipes,

iv. grain size distribution of the granular material (with large, uniformly graded, gravel giving much larger pore throats between voids that need to be clogged before the performance is significantly degraded and relatively lower surface area for biofilm growth than finer grained or more well graded material),

v. hydraulic conductivity of granular porous media, and

vi. continuous geotextile layer (if present). Geotextiles should not be used to wrap individual pipes in a drainage layer.
Several equations based on the simplified assumptions (Giroud et al. 1992, Giroud & Bonaparte 2001, McEnroe 1989, 1993) are used to predict the leachate head acting on the landfill bottom liner for a given infiltration rate, pipe spacing, base slope and initial hydraulic conductivity of the drainage material. However these equations provide no insight regarding the effect of clogging of LCSs or how long the drainage layer will control the leachate head to below the design head. As noted above, both the field and laboratory studies have demonstrated that significant clogging of porous media in the LCSs can occur and that the hydraulic conductivity of drainage layer may drop several orders of magnitude in only a few years (especially if the drainage layer is sand). Thus a means of predicting the leachate head and the time to clogging of LCSs is desired.

Over the past decade, a numerical model (Bioclog) for predicting the clogging of porous media permeated by MSW leachate has been developed (Cooke et al. 1999, Cooke et al. 2005a, Cooke &
Rowe 2008a). Extending the work of Cooke et al. (1999), Cooke et al. (2005a) described the Bioclog-1D model which used the finite element method to predict the fate and transport of nine key leachate constituents (acetate, butyrate, propionate, suspended acetate degraders, suspended butyrate degraders, suspended propionate degraders, suspended inert biomass, suspended inorganic solid particles, and calcium). Bioclog models the growth and loss of five films on the surface of porous media (biofilm arising from acetate, butyrate and propionate degraders, inert biofilm, and inorganic solids film).

The clogging of drainage layer in LCSs reduces the hydraulic conductivity of porous media and further causes leachate mounding on the liner in the landfill. To model this situation, the Bioclog model was extended to 2D conditions by Cooke & Rowe (2008a). With the present writers subsequent extension of the Bioclog model to consider (i) deposition of suspended organic and inorganic particles, and (ii) the effect of inclusion of a filter-separator layer (nonwoven geotextile or graded granular layer) between the waste material and drainage layer, the model is now in a form that it can be used to predict the relative performance of different MSW leachate collection system designs and estimate the service life of the drainage layer for a given design situation.

Modelling of Laboratory Column Tests
Cooke et al. (2005b) modelled the clogging of laboratory columns packed with pea gravel (having a similar nominal grain size as 6 mm glass beads but with a less uniform grain size distribution and a larger and less uniform surface area than the beads) permeated with real landfill leachate. Comparing the Bioclog-1D predictions with the experimental data, it was found that the volatile fatty acids and calcium concentrations for the pea gravel columns were well predicted, and the clog quantities agreed well.

VanGulck & Rowe (2008) reported the use of the Bioclog-1D model to predict clogging of laboratory columns filled with 6 mm glass beads and permeated with both synthetic leachate (with no suspend solids) and real leachate (with significant suspended solids). As well as the distribution of clog mass, the changes of acetate, butyrate, and calcium concentrations in the leachate were reasonably predicted.

Rowe & Babcock (2007) calibrated the Bioclog model using both tire shreds and coarse (38mm) gravel data from the column tests reported by Rowe & MoIsaac (2005) and McIsaacs & Rowe (2005). Using nominal grain size parameters, the model was better at predicting the more uniform gravel than the highly variable tire shreds. However using calibrated parameters, the Bioclog model provided quite reasonable fits to the porosity of the tire shred columns over the test period until column termination.

Modelling of Laboratory Mesocosm Tests
The results from two laboratory mesocosms reported by MoIsaac (2007) were used by Cooke & Rowe (2008b) for examining the effectiveness of Bioclog-2D for modelling well controlled two dimensional laboratory tests involving 38 mm (nominal diameter) gravel and permeated with real landfill leachate. The initial saturated thickness of the gravel layer was 100 mm and the flow length was 565 mm. Two sets of kinetic constants for the volatile fatty acids (lower kinetic rates for case 1 and higher kinetic rates for case 2) were examined based on the calibrated parameters obtained by Cooke et al. (2005b) and Rowe & Babcock (2007) respectively for column tests. Cooke & Rowe (2008b) reported that the predictions of effluent COD and calcium concentrations were reasonably well bracketed by cases 1 and 2. Compared with the measured porosities and total film thicknesses at mesocosm termination, some regions of the drainage layer were well modelled, but the bottom of saturated zone was less well predicted. To address this shortcoming, the Bioclog-2D model was recently revised by the writers to enhance the model’s capacity to consider the settling of suspended solids as they migrate along the flow path and this has substantially improved the predicted clogging of the bottom of the saturated zone as will be reported in detail elsewhere.
Modelling of Field Sand Cases
Cooke & Rowe (2008a) used Bioclog-2D to model a hypothetical field leachate drainage layer (0.3 m thick and 20 m long) with three different types of sand at a slope 1% and a top infiltration rate of 0.2 m/a. This modelling showed that, for the conditions examined, the expected service life of this system with coarse sand (grain size 2mm, initial hydraulic conductivity $1\times10^{-3}$ m/s) was 32 years. At the point when the leachate mound reached the maximum thickness of drainage layer (0.3 m for this system), the most extensively clogged zone was at the downstream end of the drainage layer near where the leachate entered the drainage pipe. This was attributed to the relatively large mass loading at this location which gave rise to a reduction in porosity from the original value of 0.37 to about 0.17 and a decrease in hydraulic conductivity from $1\times10^{-3}$ m/s initially to about $5\times10^{-7}$ m/s at the time the service life was reached.

The calculated service life of medium sand drainage layer (grain size 1 mm, initial hydraulic conductivity $1\times10^{-4}$ m/s) was about 10 years and the porosity and hydraulic conductivity near the pipe at this time were about 0.25 and $2\times10^{-6}$ m/s respectively. For the fine sand drainage layer (grain size 0.75 mm, initial hydraulic conductivity $1\times10^{-5}$ m/s) the calculated service life was about 0.75 years and the porosity and hydraulic conductivity near the pipe at this time were about 0.30 and $3\times10^{-6}$ m/s respectively.

Fig. 6 shows the calculated growth of the leachate mound and the contours of porosity (which started with an initial porosity of 0.37 and hydraulic conductivity $1\times10^{-3}$ m/s) with time for a 30-m long drainage layer with coarse sand for parameters, other than length, similar to those assumed by Cooke & Rowe (2008a) as discussed above. The initial leachate mound was a maximum of 0.005 m above the liner before any clogging. After 5 years, the leachate mound had risen to about 0.12 m and the porosity and hydraulic conductivity near the drain had reduced to about 0.27 and $2\times10^{-5}$ m/s respectively (Fig. 6a). After 15 years, the leachate mound had risen to about 0.22 m and the porosity and hydraulic conductivity near the drain had reduced to about 0.20 and $2\times10^{-6}$ m/s respectively (Fig. 6b). The service life (i.e. when the leachate mound was equal to the maximum design head of 0.3m above the liner) was reached after 25 years. At this time the porosity and hydraulic conductivity near the drain had reduced to about 0.17 and $5\times10^{-7}$ m/s respectively (Fig. 6c). It is noted that, in each case, the failure of the systems was controlled by the loss of hydraulic conductivity near the pipe.

The results for the 30-m long drainage layer examined above and those obtained by Cooke & Rowe (2008a) for an otherwise similar case with a 20-m long drainage length illustrate the effect of drainage length (other things being equal). The increase in drainage lengths from 20 to 30 m (due to a change in pipe spacing) decreased the service life of the drainage layer from about 32 years to 25 years for a coarse sand drainage layer.

If there is a saw-tooth drainage pattern with a high point midway between parallel drainage pipes and sloping (in this case at 1%) down on both sides from the high point to the pipes, then pipe spacing is twice the drainage length. Fig. 7 shows the effect of the drainage length on the service life of LCSs for three different types of sand drainage layer (coarse, medium and fine as described above). As the drainage length increases, the service life is reduced. This is primarily due to the increased mass loading of the sand near the drainage pipe as the drainage length increases. The increased flow is linearly proportional to the increase in length of the drainage length, $L$. However the constituents in the leachate experience a reduction in concentration due to biologically induced clogging in the drainage layer and hence the mass loading itself is slightly non-linear due to this effect. For the conditions considered and a fine sand drainage layer, the service life is 10 years or less for $L \geq 5$ m (Figs. 7 and 8). Similarly, for medium sand the service life is 10 years or less for $L \geq 20$ m and 10-20 years for $20 \geq L \geq 5$ m. Finally under otherwise similar conditions, the service life for coarse sand is greater than 30 years for $L \leq 20$ m and 20-30 years for $20 \geq L \geq 40$ m.
Fig. 6 Porosity within the Saturated Zone of Drainage Coarse Sand Layer at (a) 5 Years, (b) 15 Years, and (c) 25 Years.
Fig. 7  Effect of Drainage Length on the Service Life of LCSs (for parallel pipes on a continuous slope pipe spacing is the same as the drainage path, i.e. \(L\); for a saw-tooth pattern with a high point midway between pipes the pipe spacing is \(2L\)). 1% Slope, Drainage Layer 0.3m Thick, other Parameters as defined by Cooke and Rowe (2008a).
(For colour figure, refer to CD)

Fig. 8  Effect of Nominal Grain Size on the Service Life of LCSs for Uniformly Graded Sand.
(For colour figure, refer to CD)

**Modelling of Field Gravel Case**

As a result of recent improvements by the writers, the Bioclog model can be used to estimate the service life of LCSs with gravel drainage layers and a filter-separator layer between the waste and the drainage layer. Assuming a uniform top infiltration rate 0.2 m/a, a 20-m long drainage layer with gravel (nominal diameter 38 mm, initial porosity and hydraulic conductivity of 0.41 and 0.12 m/s respectively) and other parameters as defined by Cooke & Rowe (2008a), the clogging of the drainage layer was modelled using Bioclog-2D.

The results at 50 years and at the end of the service life (90 years) for the conditions examined are given in Fig. 9. For this case the initial head on the liner was negligible. After 50 years it had increased to about 0.18 m, and the porosity (Fig. 9a) and hydraulic conductivity near the pipe decreased to 0.12 and \(1 \times 10^{-5}\) m/s respectively. The leachate mound reached 0.3 m above the liner after about 90 years. At this time, the porosity (Fig. 9b) and hydraulic conductivity near the pipe had decreased to 0.07 and \(1 \times 10^{-6}\) m/s respectively.
For a 20 m drainage length, the gravel drainage layer increases the service life of LCSs significantly to about 90 years for gravel with nominal diameter 38 mm compared to about 30 years for uniform 2 mm coarse sand (Cooke & Rowe 2008a), about 10 years for 1 mm medium sand, and less than 1 year for 0.75 mm fine sand.

Fig. 9  Porosity within the Saturated Zone of Drainage Gravel Layer at (a) 50 and (b) 90 Years.

PRACTICAL MODEL

Although the Bioclog model is a sophisticated numerical model for predicting the clogging of drainage layer and the service life of LCSs with different configurations, it is not a technique that could easily be used by the engineers who do not have extensive numerical modelling experience.

Based on the field and laboratory finding that calcium carbonate is the dominant fraction in the clog formation under anaerobic conditions in a MSW landfill, Rowe & Fleming (1998) developed a practical model to estimate the service life \( t_c \) of LCSs where relatively uniform gravel material is used for the drainage blanket. It should be noted...
that this model is not appropriate for sand. However since sand should not be used as a drainage material for MSW leachate, for the reasons described above, this is not a major limitation. They conservatively assumed that all calcium entering the drainage layer immediately deposits as calcium carbonate in the system and the fraction \( f_{Ca} \) of the calcium in the clog material is constant with time as well as the bulk density \( \rho_c \) of the clog material.

If the calcium concentration is assumed to be constant with time, the service life of LCSs can be estimated directly from:

\[
t_c = \frac{T_1}{3} - \frac{c_{L1}}{m} \left( \frac{L + 2a}{B} \rho_c f_{Ca} v_f \right)
\]

where \( q_0 \) is the average top infiltration; \( v_f \) is the specific clog mass volume (or porosity reduction) which is the difference between the initial porosity of clean porous medium and porosity of clogged porous medium (e.g. a hydraulic conductivity of \( 10^{-6} \) m/s); \( B \) is the thickness of drainage layer near the perforated drainage pipes; \( L \) is the length of leachate drainage layer (half of the pipe spacing); \( a \) is the length of the zone where clogging is likely to develop to the full thickness of the blanket drain. For their example calculations, Rowe & Fleming (1998) used \( a = 5 \) m but Rowe et al. (2004) indicated that this parameter “may need to be selected on a site specific basis”.

If the calcium concentration was considered to be a constant value \( c_{L1} \) until time \( T_1 \), and then decreased linearly to a steady value \( c_{L2} \) at time \( T_2 \), the service life of LCS can be estimated by the procedure described below.

Step 1 - Use Eq. 2:

\[
t_c = \frac{(L + 2a)B \rho_c f_{Ca} v_f}{3q_0 c_{L1} L} - \frac{c_{L1} - c_{L2}(T_1 + T_2)}{2c_{L2}}
\]

to calculate the service life \( t_c \) for the given parameters. If \( t_c \) is larger than time \( T_2 \), then the service life of this system is \( t_c \); otherwise go to the step 2.

Step 2 - Use Eq. 3:

\[
t_c = \frac{L}{3} - \frac{c_{L1}}{m} \left( \frac{2L + 2a}{B} \rho_c f_{Ca} v_f \right)
\]

where

\[
m = \frac{c_{L2} - c_{L1}}{T_2 - T_1}
\]

to calculate \( t_c \). If \( t_c \) is larger than time \( T_1 \) but smaller than time \( T_2 \), the new \( t_c \) is the service life of this system; otherwise calculate \( t_c \) directly from Eq. 1 and \( t_c \leq T_1 \).


i. the average calcium fraction, \( f_{Ca} \), of the clog material is \( f_{Ca}=25.5\% \) with a standard deviation of 4.5\%, and

ii. the average bulk density of the clog material is \( \rho_c = 1570 \) kg/m\(^3\) with standard deviation 150 kg/m\(^3\).

From the example examined in previous section for a 38mm gravel drainage layer (initial porosity of 0.41 and porosity of 0.07 at a hydraulic conductivity of \( 10^{-6} \) m/s giving \( v_f = 0.41-0.07= 0.34 \) ), a drainage length \( L = 20 \) m, thickness \( B = 0.3 \) m, a top infiltration rate of \( q_0 = 0.2 \) m/a, and assuming that the input calcium concentration is constant with time at \( c_{L1} = 1500 \) mg/L (1.5 kg/L), the service life can be estimated using the “practical model” and compared with the calculated value from BioClog-2D. Using the average parameters specified above for \( f_{Ca} \) and \( \rho_c \), and adopting \( a = 5 \) m as used by Rowe & Fleming (1998), Eq. 1 gives the service life of this system as:

\[
t_c = \frac{(20 + 2 \times 5) \times 0.3 \times 1570 \times 0.255 \times 0.34}{3 \times 0.2 \times 1.5 \times 20}
\]

= 68 years

or, on rounding, about 70 years. This is conservative compared to the 90 years calculated from BioClog. However, inspecting Fig. 9b the
point at which full layer clogging occurs is about 10 m from the pipe and substituting \( a = 10 \text{ m} \) into Eq. 1 gives a service life of 90 years. Considering 9 m < \( a < 11 \text{ m} \) gives a range 86-95 years which is (perhaps fortuitously) very close to the predicted 90 years from the sophisticated numerical model (BioClog). Over the next year the writers will be doing other comparisons to provide additional advice regarding the use of the simplified equations given above. It should be noted that the assumption of a constant calcium concentration for entire period is likely conservative and the actual service life is likely to be longer (potentially considerably longer) than 90 years other things being equal.

**CONCLUSIONS**

The clogging of LCSs has been examined from both the field and laboratory studies. The three major mechanisms for the clogging of porous media in landfills are identified as the: (i) growth of biomass, (ii) precipitation of minerals, and (iii) deposition of suspended solids. Based on the findings from both the field and laboratory studies, a sophisticated numerical model, BioClog, has been successfully developed to examine the clogging of porous media and to predict the service life of LCSs.

Field and laboratory studies were examined to identify the factors that would affect the clogging of porous media. It was found that the leachate drainage layer in a landfill works like the bioreactor under anaerobic conditions. The clogging rate of the drainage layer is increased with: (1) increasing mass loading (i.e. increased leachate strength, increased flow rate, or both); (2) decreasing grain size or uniformity of drainage material; and (3) increasing landfill temperature.

Based on the available data it is concluded that:

- Leachate collection systems should be operated under unsaturated conditions as long as possible to extend the service life of LCSs.
- A filter-separator layer between the waste material and drainage layer minimizes the physical intrusion of waste material into the upper zone of drainage layer.
- Tire shreds should not be used in critical zones (e.g. near pipes of sumps) and, if used elsewhere, the thickness of shreds as placed should give the design thickness once account is made for the significant compression of the shreds under the weight of the waste.

The BioClog model has been developed to the point which can be used for predicting the clogging of drainage media and the service life of LCSs. BioClog predicts the fate and transport of major components in the leachate (COD, calcium, and suspended solid particles) and simulates the accumulation of organic and inorganic clog mass in the porous media. Compared with measured data from laboratory columns and mesocosms, BioClog gives very encouraging predictions of COD and calcium concentrations. The predictions and measurements for porosity also agreed well.

Modelling of field situations using the BioClog model shows that increasing the drainage length decreases the service life of LCSs and increasing the grain size of drainage material increases the service life of LCSs.

Based on both the field and laboratory studies, calcium carbonate is the dominated component in the clog mass in typical MSW landfills. The average calcium fraction of the clog material is \( f_{Ca} = 25.5\% \) and the average bulk density of the clog material is \( \rho_c = 1570 \text{ kg/m}^3 \). These parameters can be used to estimate the service life of LCSs using some simplified equations that were originally published by Rowe & Fleming (1998) and are repeated herein. The prediction from this model is compared with that from BioClog for one case and is in encouraging agreement with the sophisticated model for this case. More work is in progress to refine the approximate model based on information from the more sophisticated BioClog model.

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