Modeling of Leachate Collection Systems with Filter Separators in Municipal Solid Waste Landfills

R. Kerry Rowe, F.ASCE1; and Yan Yu2

Abstract: A numerical model is used to estimate the service life and clogging of gravel leachate drainage layers with a filter separator layer, such as those used in municipal solid waste landfills. A filter separator layer between the waste and the drainage layer is shown to reduce the leachate strength entering the gravel drainage layer and to extend the time that it takes to clog the drainage layer to the point when the leachate level exceeds the maximum design value (the service life). The filter layer is shown to have a far more significant effect in extending the service life when pea gravel (\(d_g = 6\) mm) is used in the drainage layer, and less effect when coarse gravel (\(d_g = 27\) mm) is used in the cases examined, although most of the benefit of a filter separator layer was achieved by using a 3-mm-thick needle-punched nonwoven geotextile. This geotextile may be sufficient for many practical purposes that are similar to those examined. The results from modeling leachate collection systems with filter separator layers subjected to both constant and variable leachate strength show that the characteristics of the leachate entering the drainage layer can substantially affect the service life of the drainage layer, and that high-strength leachate entering the systems for a limited time early in the life (acid phase) of a landfill can greatly reduce the service life of the leachate drainage layer. DOI: 10.1061/(ASCE)EE.1943-7870.0000716. © 2013 American Society of Civil Engineers.

CE Database subject headings: Municipal wastes; Solid wastes; Landfills; Waste management.

Author keywords: Filter separators; Clogging; Service life; Numerical modeling; Leachate collection systems; Municipal solid waste landfill.

Introduction

Typically, the leachate generated within municipal solid waste (MSW) landfills arises from a combination of rainfall infiltration, moisture in the disposed waste, and biodegradation of organic matter. The leachate usually includes both dissolved matter and suspended solids, which, if allowed to escape, may impact the surrounding environment and human health (Rowe et al. 2004). To prevent more than a negligible contaminant escape, a barrier system is generally installed at the base of the landfill. This barrier system includes a leachate collection system (LCS) and a bottom liner (Ontario Regulation 232/98; Ontario Ministry of the Environment 1998). A modern LCS typically has a continuous granular drainage layer with a slope to perforated drainage pipes, which allow leachate within the drainage layer to freely drain to the pipes and through them (under gravity) to the sumps, where it is removed for treatment. The primary objective of the LCS is to minimize the driving force for contaminant transport through the bottom liner by controlling the head to a maximum design level (typically the thickness of the drainage layer), because in design calculations, the leakage through the liner is calculated for a specified leachate mound in the LCS based on the local regulatory requirements. In some cases, a filter separator layer (a geotextile or graded granular layer) is included between the waste and the granular drainage layer to prevent the physical intrusion of the waste into the underlying drainage layer (Rowe 2005).

Field observations (Young et al. 1982; Bass 1986; Brune et al. 1991; Koerner et al. 1993, 1994; McBean et al. 1993; Rowe 1998; Fleming et al. 1999; Craven et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; Levine et al. 2005) and laboratory studies (Brune et al. 1991; Paksy et al. 1995, 1998; Peeling et al. 1999; Rowe et al. 2000a, b, 2002; Fleming and Rowe 2004; VanGulick and Rowe 2004a, b; McIsaac and Rowe 2006, 2007) have shown that both the granular drainage media and filter separators may experience clogging as a result of the permeation of MSW leachate. The movement of leachate through the drainage layer leads to clogging, which typically involves the growth of biomass, deposition of suspended solids, and precipitation of calcium carbonate and other minerals (Rowe 2005). Fleming et al. (1999) found that after approximately four years when an exhumation was conducted, the sand and geotextile present between the waste and the drainage gravel effectively separated the waste and the granular drainage blanket and reduced the clogging of the underlying gravel drainage layer. McIsaac and Rowe (2006) examined the laboratory mesocosms with gravel drainage layers and filter separator layers permeated by MSW landfill leachate for approximately six years. They found that the use of a filter separator layer (woven geotextile, nonwoven geotextile, or graded granular layer) reduced the amount and rate of clogging in the underlying drainage gravel. Specifically, the woven geotextile prevented the intrusion of waste into the upper portion of the unsaturated gravel, but had no other significant effect. The nonwoven geotextile and the graded granular filter both served as separators and prevented the intrusion of waste into the upper unsaturated gravel (like the woven geotextile), but also acted as a filter and a location for biofilm growth and leachate treatment.
which reduced the entrance of both dissolved matter (e.g., short-chain fatty acids and calcium) and suspended solids (e.g., bacteria and fine particles from the waste and daily cover material carried by leachate) into the LCS; therefore, they reduced clogging in the saturated gravel. The graded granular filter reduced clogging of the gravel more than the nonwoven geotextile, but was more prone to clogging itself, and created a greater level of perching of leachate over the filter. Thus, there is empirical evidence of a benefit from the presence of a filter over a period of up to six years, but no study has previously examined to what extent there may be a benefit to the long-term performance of the drainage layer. To do this, there is a need to model the effect of clogging on the long-term performance of drainage layers in MSW landfills and to examine the potential benefit, in addition to separation, that a filter separator layer between the waste and granular drainage layer may have on the long-term performance of the drainage layer, and hence, the LCS.

A one-dimensional (1D) numerical model, BioClog, was developed by Cooke et al. (2005a) and extended to two dimensions (2D) by Cooke and Rowe (2008a) to allow the modeling of the clogging of porous media when permeated with landfill leachate. The model was further enhanced (Yu and Rowe 2012a) by adding the capacity to simulate: (1) the deposition of suspended solid particles within the saturated drainage layer, and (2) the effect of the filter separator layers on the clogging of granular drainage layers. The enhanced BioClog-2D has been shown (Rowe and Yu 2013) to agree between the calculated and observed changes in leachate characteristics and clogging of the porous media in laboratory mesocosm experiments (McIsaac and Rowe 2007; McIsaac 2007). However, the modeling of the service life and clogging of drainage layers with the filter separator layers in MSW landfills has not been examined in the literature at the time of writing.

The objective of this paper is to theoretically examine the effect of the presence of filter separator layers between the waste and granular drainage layer on the long-term performance of drainage layers. Two types of filter separator layers will be considered: (1) a needle-punched nonwoven geotextile, and (2) a sand filter layer. The model simulates the clogging of both the filter separator layer and the granular drainage layer, and estimates the leachate mound within the drainage layer. The effluent leachate characteristics from both the filter separator layer and granular drainage layer will be reported. The service life of drainage layers with different types of filter separator layers and different thicknesses of the sand filter layer will be compared, in which the service life of the LCS is defined as the time when the maximum leachate mound within the LCS reaches the design thickness of the granular drainage layer.

Model Summary

The partial differential equations for the fluid flow and species transport were solved by the finite-element method; full details are provided in the study by Cooke (2007). The same finite-element mesh was used for both flow and transport modeling. Details regarding mesh and checks on mesh refinement are given by Yu (2012). The fluid velocities from the fluid flow equation under the specified boundary conditions were introduced into the transport equations to obtain the nodal concentrations for each species. The modeling of the biogeochemical reactions in leachate and accumulation of clog mass within the saturated drainage layer have been described in detail by Cooke et al. (2005a), Cooke and Rowe (2008a), and Yu and Rowe (2012a), and are briefly summarized in the following.

The fate and transport of nine species (key constituents in leachate) within the porous media were modeled. In leachate from MSW landfills, the biodegradable component of the chemical oxygen demand (COD) is mostly attributable to volatile fatty acids (VFAs; also known as short-chain fatty acids). The modeled VFAs were acetate, butyrate, and propionate, because they are biodegraded relatively easily. Therefore, the suspended acetate, butyrate, and propionate degraders in leachate were also modeled. As suspended active biomass decayed, it was converted to suspended inert biomass. Both the suspended inorganic solid particles (fixed suspended solid: FSS) and suspended inert biomass were modeled. The degradation of VFAs generated carbonic acid, which ultimately provided the carbonate with which the calcium in leachate combined to precipitate as calcium carbonate, the predominant component of the solid clog material (Brune et al. 1991; Fleming et al. 1999). The precipitation of calcium carbonate was controlled by the availability of calcium (Ca) in leachate and the pH of the leachate (VanGulck et al. 2003). The model assumed that the degradation rate of each acid was not affected by any other acids in leachate, although there is some evidence to suggest that the presence of propionate in leachate may decrease the degradation rate of butyrate (James et al. 1998; Taconi et al. 2008).

The accumulation of clog mass within the porous media was simulated in terms of the thicknesses of five different films. Both the organic and inorganic films were modeled. The organic films were comprised of three active biofilms and one inert biofilm. Each of the three active biofilms (acetate, butyrate, and propionate degrader films) increased in mass as a result of the growth of the active biofilm and the deposition of suspended active biomass. The active biofilms lost mass to decay and detachment due to both the shear stress and growth rate. The inert biofilm increased mass because of the decay of active biofilms and the deposition of suspended inert biomass, and lost mass to detachment from shearing. The film of inorganic solids increased mass as a result of the deposition of suspended inorganic solid particles and the precipitation of calcium carbonate and other minerals.

The filter separator layer (nonwoven geotextile or graded granular layer) between the waste and granular drainage layer was modeled in 1D; the granular drainage layer was modeled in 2D (Yu and Rowe 2012a). Because of the formation of a filter cake (McDowell-Boyer et al. 1986; Rollin 1996) on the surface of the filter separator layer, a portion of suspended particles was filtered out of the leachate before it entered the filter separator layer. The effluent from the filter separator layer was the input leachate for the underlying granular drainage layer.

The porosity and specific surface of the granular material were evaluated from the total film thickness (the sum of five film thicknesses) based on a geometric model (Yu and Rowe 2012b). For the nonwoven geotextile with the attached film, the porosity and specific surface were calculated by a geometric model described by Yu and Rowe (2012a). For both the granular material and nonwoven geotextile, a reduction in porosity decreased the hydraulic conductivity according to the following exponential relationship (Rowe et al. 2002; VanGulck and Rowe 2004b; Cooke et al. 2005b):

\[ k = A_k e^{b_k n} \]  

where \( k \) = hydraulic conductivity; \( n \) = porosity; \( A_k \) and \( b_k \) = coefficients of hydraulic conductivity.

Definition and Parameters of the Problem

Fig. 1 shows the profile of an LCS with a filter separator layer present between the waste and granular drainage layers. The filter separator layers examined in this paper consisted of a 3-mm-thick
nonwoven geotextile and a sand filter layer with a thickness of 0.1 to 0.3 m. The sand filter layer was separated from the granular drainage layer by a woven geotextile as a separator to prevent the sand particles from moving into the underlying granular drainage layer. McIsaac and Rowe (2006) found that there was little accumulation of biofilm and little reduction in the hydraulic conductivity of the woven geotextile after six years of permeation by the MSW landfill leachate at realistic flow rates [average percolation (impingement) of 0.2 m/year] in this type of application; therefore, there was little passive treatment of leachate within the system with a sand filter layer.

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The drainage length was \( L = 20 \) m (e.g., 40-m pipe spacing with sawtooth base contouring, as shown in Fig. 1) and the granular drainage layer was 0.3 m thick. The drainage layer was graded to the perforated drainage pipes at a slope of 1%. The diameter of pipes was 0.2 m. The drainage layers were subjected to a uniform leachate impingement rate of 0.2 m/year. For the base case with a constant source of concentration, the leachate characteristics prior to entering the filter separator layer were based on the study by Cooke and Rowe (2008a) and involved, among other things, 22,000 mg/L for the COD concentration (10,000 mg/L of COD each for acetate, Ac, and propionate, Pr, and 2,000 mg/L COD for butyrate, Bu) and 1,500 mg/L for calcium. The concentration of the volatile suspended solids (VSSs; which includes suspended inert biomass and suspended Ac, Bu, and Pr degraders) and FSSs were each 1,000 mg/L. Based on the study by Cooke and Rowe (2008a), a VSS level of 70% was considered to be active, which included equal proportions of Ac, Bu, and Pr degraders. However, the leachate characteristics from the field systems are time-dependent and the difference for the variable source concentration case will be described later, when the change in microbial populations in leachate from the waste at the bottom of the landfill over the service life of the facility is considered. The effective diameters of the VSS and FSS were 0.0001 and 0.0002 cm, respectively (Cooke and Rowe 2008a). The coefficients related to fatty acid and biomass (Table 2) and the parameters for suspended particles and formation of clog mass (Table 3) were based on the study by Cooke and Rowe (2008b) at the temperature of 21°C. The effect of a higher temperature (27°C) on the clogging of saturated gravel layers was examined by Rowe and Yu (2013), who found that an increase in temperature from 21 to 27°C resulted in a higher clogging rate of the filter separator and saturated gravel layers. Details regarding other parameters are given in the study by Yu (2012).

Studies of unsaturated gravel columns (nominal diameter of 50 mm) permeated with MSW leachate have shown very little

### Table 1. Properties of Granular Materials and Nonwoven Geotextile

<table>
<thead>
<tr>
<th>Grain size ( d_g = D_{50} ) or fiber diameter ( d_f ) (mm)</th>
<th>( A_k ) (m/s)</th>
<th>( b_d )</th>
<th>Applicable range in porosity (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_g = 27^a )</td>
<td>( 9.5 \times 10^{-6} )</td>
<td>22.88</td>
<td>( 0.21 \leq n \leq 0.41 )</td>
</tr>
<tr>
<td>( d_g = 6^b )</td>
<td>( 2.4 \times 10^{-8} )</td>
<td>51.03</td>
<td>( 0 &lt; n &lt; 0.21 )</td>
</tr>
<tr>
<td>( d_g = 1^b )</td>
<td>( 1.7 \times 10^{-8} )</td>
<td>38.19</td>
<td>( 0 &lt; n &lt; 0.39 )</td>
</tr>
<tr>
<td>( d_f = 0.03^c )</td>
<td>( 1.6 \times 10^{-9} )</td>
<td>15.69</td>
<td>( 0 &lt; n \leq 0.90 )</td>
</tr>
</tbody>
</table>

| ^a| Cooke and Rowe (2008b). |
| ^b| Cooke and Rowe (2008a). |
| ^c| Yu (2012). |


### Table 2. Fatty Acids and Biomass-Related Coefficients

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Propionate</th>
<th>Acetate</th>
<th>Butyrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic constants</td>
<td>( K_i ) (mg COD/L)</td>
<td>4,700</td>
<td>4,700</td>
</tr>
<tr>
<td> </td>
<td>( q_{Max} ) (mg COD/mg VS/d)</td>
<td>1.0</td>
<td>1.76</td>
</tr>
<tr>
<td> </td>
<td>( A_k )</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td> </td>
<td>( B_k )</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td> </td>
<td>( Y ) (mg VS/mg COD)</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td> </td>
<td>( b_d ) (d (^{-0.5} ))</td>
<td>0.02</td>
<td>0.018</td>
</tr>
<tr>
<td>Diffusion parameters</td>
<td>( D_0 ) (substrate in fluid) (cm(^2)/d)</td>
<td>1.27</td>
<td>1.50</td>
</tr>
<tr>
<td> </td>
<td>( D_f ) (substrate in film) (cm(^2)/d)</td>
<td>0.52</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Note: Data are modified from the study by Cooke and Rowe (2008b); \( K_i \) is the half-maximum rate substrate concentration; \( q_{Max} \) is the maximum value of the specific rate of substrate utilization; VS is volatile solids; \( A_k \) and \( B_k \) are the parameters for the dynamic specific rate of substrate utilization; \( Y \) is the maximum yield coefficient; \( b_d \) is the endogenous decay rate; \( D_0 \) and \( D_f \) are the coefficients of molecular diffusion in the free solution and within the biofilm, respectively.

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Fig. 1. Schematic showing the leachate collection system with a granular drainage layer underlying a filter separator layer: (a) A leachate collection system with a nonwoven geotextile; (b) a leachate collection system with a sand filter layer.
Table 3. Parameters for Suspended Particles and Formation of Clog Mass

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters of clog matter</td>
<td></td>
</tr>
<tr>
<td>Maximum carbonic acid yield coefficient, $Y_{H-Max}$</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbonic acid yield coefficient parameter, $A_{FH}$</td>
<td>80</td>
</tr>
<tr>
<td>Carbonic acid yield coefficient parameter, $B_{FH}$</td>
<td>4</td>
</tr>
<tr>
<td>Film thickness parameter for unsaturated zone, $A_{f}$</td>
<td>Variable</td>
</tr>
<tr>
<td>Film thickness parameter for unsaturated zone, $B_{f}$</td>
<td>247</td>
</tr>
<tr>
<td>Initial film thickness coefficient, $f_{fut}$</td>
<td></td>
</tr>
<tr>
<td>Variable biofilm density parameter, $d_{f}$</td>
<td>72</td>
</tr>
<tr>
<td>Inorganic film density, $X_{IFS}$ (mg NVS/cm³)</td>
<td>2.750</td>
</tr>
<tr>
<td>Other precipitate ratio, $f_{OP}$</td>
<td>0.06</td>
</tr>
<tr>
<td>Fraction degradable by decay, $f_{d}$</td>
<td>0.8</td>
</tr>
<tr>
<td>Parameters of suspended solids</td>
<td></td>
</tr>
<tr>
<td>Active and inert diameter (cm)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Active and inert density (mg VS/cm³)</td>
<td>1030</td>
</tr>
<tr>
<td>Diameter of inorganic particles (cm)</td>
<td>0.0002</td>
</tr>
<tr>
<td>Density of inorganic particles (mg VS/cm³)</td>
<td>1065</td>
</tr>
<tr>
<td>Filter separator coefficient, $f_{FS,SD}$</td>
<td>0.7</td>
</tr>
<tr>
<td>Filter separator coefficient, $f_{FS,SB}$</td>
<td>0.7</td>
</tr>
<tr>
<td>Filter separator coefficient, $f_{FS,IP}$</td>
<td>0.7</td>
</tr>
<tr>
<td>Deposition factor parameter, $A_{IP}$</td>
<td>0</td>
</tr>
<tr>
<td>Deposition factor parameter, $B_{IP}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: Data are modified from the study by Cooke and Rowe (2008b); $X_{IFS}$ is the mass of nonvolatile solids (NVS) per volume of inorganic solids.

clogging within the unsaturated gravel (McIsaac and Rowe 2008). Therefore, the effect of an unsaturated granular drainage layer (the zone between the filter separator layer and saturated granular drainage layer) on the leachate strength was not considered.

The boundary conditions for the fluid flow and species transport (Fig. 1) were as follows. The drainage divide was a zero flow and flux boundary. The leachate mound surface boundary had the specified impingement rate and species flux (Cauchy boundary). At the downstream (pipe) end, the hydraulic head was initially assumed to be 0.005 m, but once the mound exceeded 0.025 m, it was considered to be 20% of the maximum leachate mound thickness within the drainage layer, with a maximum of 0.06 m when the maximum leachate mound reached the full thickness of granular drainage layer (0.3 m). The free exit boundary condition (Frind 1988) was applied for the species transport at the downstream end. The bottom of granular drainage layer was a zero flow and flux boundary.

Taylor and Jaffe (1990) found that a reduction in porosity increased the longitudinal dispersivity of porous media. A power law relationship between the longitudinal dispersivity, $\alpha_L$, and porosity, $n$, was used (Cooke and Rowe 2008a, b):

$$\alpha_L = \alpha_{L,0} \left( \frac{n}{n_0} \right)^{-1.74}$$  \hspace{1cm} (2)

where $\alpha_{L,0} =$ initial longitudinal dispersivity ($\alpha_{L,0} = 0.1$ m); $n_0 =$ initial porosity.

The transverse dispersivity was assumed to be equal to the longitudinal dispersivity as a result of the relatively uniform media in the model. A detailed discussion for other parameters listed in Tables 2 and 3 can be found in VanGulck and Rowe (2008), Cooke and Rowe (2008b), and Yu (2012).

Drainage Layers with Filter Separators Subjected to Constant Leachate Strength

Hydraulic Conductivity of Nonwoven Geotextile

When permeated with MSW landfill leachate, the clog mass that accumulated within the nonwoven geotextile reduced the porosity of the nonwoven geotextile, which resulted in the reduction in hydraulic conductivity of the geotextile from an initial $2 \times 10^{-3}$ m/s to a low of approximately $1 \times 10^{-7}$ m/s (i.e., by approximately four orders of magnitude). This generally agreed with the measured data reported by Koerner et al. (1994).

Effluent Leachate Characteristics for Drainage Layer with Nonwoven Geotextile

Fig. 2 shows the calculated leachate characteristics in effluent from both the 3-mm-thick nonwoven geotextile and 0.3-m-thick granular drainage layer (the grain size was $d_g = 27$ mm and drainage length was $L = 20$ m). The COD in effluent from the nonwoven geotextile decreased to approximately 20,500 mg/L within the first 0.3 years as a result of the treatment of VFAs within the nonwoven geotextile [Fig. 2(a)]. After 0.3 years, the effluent COD from the nonwoven geotextile increased because the reduced surface area within the nonwoven geotextile, due to clogging, was available for VFA treatment. At approximately 1.6 years, the COD in effluent...
was the same as the source COD of 22,000 mg/L, indicating that there was no VFA treatment within the nonwoven geotextile after 1.6 years (although suspended solids were still being removed). Fig. 2(a) also shows that COD in the effluent from the granular drainage layer decreased to approximately 14,500 mg/L within the first 0.4 years. At 0.5 years, the effluent COD from the granular drainage layer was approximately 14,900 mg/L; the slight increase in effluent COD from the granular drainage layer was attributable to the increase in effluent COD from the nonwoven geotextile (the input COD for the granular drainage layer) after 0.3 years. After 0.5 years, the COD in effluent from the granular drainage layer decreased with time, because of biofilm growth in the drainage gravel, to approximately 5,100 mg/L at 15 years. Thus, the modeling shows that the COD entering the leachate collection pipes was different from the COD in leachate before entering the LCS, with most of the COD reduction occurring within the granular drainage layer.

The calcium concentration in the effluent from the nonwoven geotextile decreased to approximately 1,440 mg/L within the first 0.3 years as a result of the deposition of the calcium carbonate within the nonwoven geotextile [Fig. 2(b)]. The effluent calcium concentration from the nonwoven geotextile increased after 0.3 years, and at approximately 0.5 years, the effluent calcium concentration was the same as the source calcium concentration of 1,500 mg/L. The effluent calcium concentration from the granular drainage layer decreased to approximately 1,180 mg/L within the first 0.4 years [Fig. 2(b)]. As a result of the increase in effluent calcium concentration from the nonwoven geotextile after 0.3 years (the input calcium concentration for the granular drainage layer), the calcium concentration in effluent from the granular drainage layer was approximately 1,200 mg/L at 0.5 years (i.e., slightly higher than that at 0.4 years). It decreased with time to approximately 800 mg/L at 15 years due to deposition of calcium as calcium carbonate within the LCS upgradient of the collection pipe.

**Effluent Leachate Characteristics for Drainage Layer with Sand Filter Layer**

The effect of different filter separator layers can be determined by comparing the results for the previously discussed nonwoven geotextile (Fig. 2) with those obtained with the 0.3-m-thick sand filter layer (Fig. 3). In contrast to the geotextile, which had a rapid but short-lived (0.3 years) effect on COD and calcium concentrations, the COD in the effluent from the 0.3-m-thick sand filter layer increased with time to approximately 5,320 mg/L over the first 0.3 years as the leachate percolated through the sand and the microbial colonies became established such that the biological treatment in the sand filter layer resulted in an effluent COD that was only approximately 25% of the influent concentration [Fig. 3(a)] at 0.3 years. After the microbial community became even more established, the COD dropped further, reaching a minimum of approximately 3,400 mg/L at four years. After four years of permeation by the MSW leachate, the clogging of the sand filter layer started to reduce its efficiency in treating leachate (which also happened for the geotextile, but much faster). Thus, after Year 4, the COD in effluent from the sand filter layer gradually increased until, at approximately Years 11–12, it became ineffective in terms of the biological treatment of leachate and the COD in the effluent from the sand approached the influent value of 22,000 mg/L. For the first 7–8 years, most of the biological treatment of the leachate occurred in the sand filter [Fig. 3(a)]. During this period, there was very little clog formation in the gravel layer, and consequently, little reduction in COD within the granular drainage layer, such that the COD in effluent from the drainage layer was almost the same as that in effluent from the sand filter layer. After Years 7–8, the effluent COD from the sand filter layer increased relative to the effluent COD from the drainage layer. With the reduced biological treatment efficiency of the sand layer, after Year 7, the biofilm began to develop in the gravel and the COD in the effluent of the gravel departed from that of the sand layer, but continued to increase until a maximum of approximately 12,200 mg/L was reached at Year 11. Further development of the biofilm in the gravel layer resulted in increased VFA treatment within the drainage layer and the effluent COD from the gravel layer began to approach a steady state value of approximately 5,200 mg/L after approximately 30 years [Fig. 3(a)] with a constant strength influent to the LCS. Because this is just the concentration entering the pipe, further treatment and reduction in VFAs would be expected as the leachate flowed in the pipe to the sump.

Because the precipitation of calcium as calcium carbonate is linked to biological processes that produce carbonic acid, the calcium concentrations in the effluent from the 0.3-m-thick sand filter layer and the gravel layer [Fig. 3(b)] bear many similarities to those described previously for COD. Initially, the calcium concentration was highly attenuated by the sand layer, but increased to approximately 5,200 mg/L by the end of the first year and slightly decreased to approximately 740 mg/L at four years [Fig. 3(b)] for the same reason as discussed previously for COD. The clogging of the sand reduced its ability to assimilate calcium after Year 4, and the calcium concentration in effluent from the sand filter layer increased to almost 1,500 mg/L at Year 11 and asymptoted to 1,500 mg/L at approximately Year 13. As with COD, there was little reduction in calcium concentration in the granular drainage layer within the first four years and the calcium concentration in effluent from the drainage layer was similar to that in effluent from the sand filter layer. The increase in effluent calcium concentration from the

![Fig. 3. Variation in effluent leachate concentrations from both the sand filter layer (0.3 m thick) and drainage layer for: (a) COD; (b) calcium; constant leachate strength entering the LCS, drainage length = 20 m, drainage thickness = 0.3 m, and grain size $d_g = 27$ mm](image-url)
sand filter layer increased the effluent calcium concentration from the granular drainage layer to approximately 1,080 mg/L at Year 11. The calcium concentration in effluent from the granular drainage layer gradually decreased after Year 11 and approached a steady state concentration of approximately 810 mg/L at approximately Year 30.

Because leachate was passing through the filter separator and granular drainage layers, the deposition of suspended solids within the porous media resulted in a reduction in concentrations of both the VSS and FSS (which are separated from calcium, as previously discussed). The effluent VSS and FSS decreased and approached the steady state values of approximately 70 and 10 mg/L, respectively, at approximately Year 2 with a 3-mm-thick geotextile filter and at approximately Year 10 with a 0.3-m-thick sand filter. Thereafter, the effluent concentrations of VSS and FSS decreased and approached the steady state values of approximately 70 and 10 mg/L, respectively, at approximately Year 15 with a 3-mm-thick geotextile filter and at approximately Year 30 with a 0.3-m-thick sand filter. This indicates that the use of a 0.3-m-thick sand filter delayed the accumulation of clog mass within the gravel drainage layer due to deposition of VSS and FSS.

Porosity of Sand Filter Layer

The development of the biofilm that treated COD and caused the precipitation of calcium, discussed in the previous section, resulted in a reduction of porosity within the 0.3-m-thick sand filter layer (Fig. 4). Because of the high surface area in the sand, there was great potential for biofilm growth in the upper part of the sand when the leachate first entered, which caused a reduction in the COD concentrations development (and hence less biofilm growth) at greater depth until clogging became sufficient to inhibit the ongoing treatment near the top of the layer. Thus, by the end of one year, the biofilm growth and development of inorganic film had reduced the porosity in the upper 20 mm of sand (between \( z = 0.28 \) and 0.3 m) to approximately 0.03 from the initial porosity of 0.35. The reduction in leachate strength along the flow path reduced the accumulation of clog mass within the rest of sand filter layer, and there was very little clog mass accumulated within the bottom 150 mm of the sand layer at the end of one year. The clogging of the upper few centimeters of the sand would have resulted in some minor perching of the leachate, but this was sufficient to maintain flow through the underdrained sand and the continuous permeation of leachate after one year, which resulted in a clog mass accumulation at a greater depth within the sand layer. At Year 3, the porosity near \( z = 0.30 \) m was approximately 0.02 and the porosity at \( z = 0.22 \) m had dropped to approximately 0.04, although the porosity in the bottom 60 mm (\( z = 0 \) to 0.06 m) remained essentially unaffected. After Year 5, the porosity of the sand near the surface (\( z = 0.30 \) m) was 0.01, the porosity halfway through the layer (\( z = 0.15 \) m) was approximately 0.04, and the clog mass had started to accumulate near the bottom of the layer (\( z = 0 \)). By Year 7, the porosity to a depth of 0.21 m (\( z = 0.09 \) m) had reduced to 0.04 or less, and at even at the bottom (\( z = 0 \)), it had reduced to approximately 0.31. By Year 11, the entire layer had clogged with a porosity of 0.03 or less. At this point, the sand had no remaining capacity to treat leachate, which caused the results discussed previously and presented in Fig. 3.

Profiles of Leachate Mound

The treatment of leachate and sacrificial clogging of the filter layers that is discussed previously and evident from Figs. 2-4 had a beneficial effect in delaying clogging of the primary drainage gravel. For example, Fig. 5 shows the surface profiles of the leachate mound within the drainage layer (\( d_g = 27 \) mm) at different times for drainage layers: (1) without a filter separator layer, (2) with a 3-mm-thick nonwoven geotextile filter, and (3) with a 0.3-m-thick sand filter layer. Fig. 6 shows the variation in the height of the maximum leachate mound above the base for the same three cases. For the drainage layer without a filter separator layer [Fig. 5(a)], the maximum leachate mound was 0.11 m at Year 30, which increased to 0.21 m at Year 60 and 0.3 m at approximately Year 90. Thus, without a filter, the service life of the drainage layer with the gravel (\( d_g = 27 \) mm) was approximately 90 years for the conditions in the study. After 90 years, this system would still collect most of

![Fig. 4. Porosity distributions in a 0.3-m-thick sand filter layer at different times](image-url)

![Fig. 5. Surface profiles of the leachate mound at different times for: (a) the LCS without a filter separator layer; (b) the LCS with a 3-mm-thick nonwoven geotextile filter; (c) the LCS with a 0.3 mm thick sand filter layer; constant leachate strength entering the LCS, drainage length = 20 m, drainage thickness = 0.3 m, and grain size \( d_g = 27 \) mm](image-url)
the leachate generated within the landfill. However, the leakage through the liner after 90 years would exceed that, based on the assumption of a maximum head of 0.3 m within the granular drainage layer in design calculations.

For identical conditions except for the presence of a 3-mm-thick nonwoven geotextile filter between the waste and the gravel [Fig. 5(b)], the maximum leachate mound at Year 30 was 0.09 m, which increased to 0.17 m at Year 60, 0.25 m at Year 90, and 0.3 m at approximately Year 112. Thus, for these conditions, the nonwoven geotextile extended the service life of the granular drainage layer by more than 20 years. For the drainage layer with a 0.3-m-thick sand filter layer [Fig. 5(c)], the maximum leachate mound was approximately 0.07 m at Year 30, 0.14 m at Year 60, 0.22 m at Year 90, and 0.3 m at Year 120. Thus, the 0.3-mm-thick sand filter extended the service life by approximately 8 years compared to the geotextile filter and by 30 years compared to no filter for the conditions in the study. The reduced clogging due to a continuous filter between the waste and drainage gravel that is evident in these theoretical results is qualitatively consistent with observations from mesocosm tests without a filter, with a geotextile filter, and with a graded granular filter (McIsaac and Rowe 2006) and field observations (Fleming et al. 1999).

**Effect of Filter Layer Thickness and Grain Size of Drainage Material on Service Life of Drainage Layers**

As indicated earlier, the service life of a drainage layer with the gravel \( d_g = 27 \) mm and no filter was approximately 90 years, and with a 3-mm-thick nonwoven geotextile, it was approximately 112 years (a 24% improvement over no filter) for the conditions in the study. Fig. 7 shows that the use of sand filter layers of 0.1 and 0.3 m thick increased the service life to approximately 115 years (a 28% improvement) and 120 years (a 33% improvement), respectively, for the same conditions. Thus, for most practical purposes the 3-mm-thick geotextile was similar to the 0.1-m-thick sand layer in its effect on service life. Because a 0.1-m-thick sand layer is hard to place, a greater thickness may be required for practical reasons, but the improvement in service life attributable to an extra 0.2 m of sand is limited (approximately 5 years or 6%). Thus, although there is a definite advantage in the improvement of service life as a result of the installation of a filter between the waste and the drainage gravel, the 3-mm-thick needle-punched geotextile would be suitable (if properly installed) for conditions similar to those examined. If the woven geotextile between the sand layer and granular drainage layer was replaced by the nonwoven geotextile, it would have only a minor effect on the service life of the granular drainage layer because most of the effect of the filter layer would be provided by the overlying sand and the additional void volume for clog mass accumulation; the reduction in TSS provided by a 3-mm-thick nonwoven geotextile between the sand layer and granular drainage layer would be smaller than that in the overlying sand.

The service life of a drainage layer will also depend on the grain size of the gravel (Yu and Rowe 2013). The service lives calculated for a drainage layer with gravel \( d_g = 6 \) mm and conditions otherwise similar to those examined for gravel \( d_g = 27 \) mm are given in Fig. 7. With no filter, the service-life was approximately 70 years (compared to 90 years for the gravel \( d_g = 27 \) mm). The presence of a 3-mm-thick nonwoven geotextile filter increased the service life to 87 years (a 24% improvement, as was the case of the gravel \( d_g = 27 \) mm). Sand filter layers with thicknesses of 0.1 and 0.3 m increased the service life of the gravel drainage layer with \( d_g = 6 \) mm to approximately 90 years (28% improvement) and 95 years (35% improvement), respectively. Thus, the benefits of the different filters are similar over a wide range of gravel particle size (6 to 27 mm) for the conditions in the study.

**Drainage Layers with Filter Separators Subjected to Variable Leachate Strength**

The modeling results presented in the previous section were based on the assumption that the influent flow rate and leachate concentrations were constant with time. This section examines the effect of both leachate flow rate and concentrations varying with time (Fig. 8) in the modeling of LCSs with filter separator layers to establish how the assumptions regarding influent leachate strength may affect the role of the filter layer and its effect on the service life of the underlying drainage layer.

Field data show that the leachate generation rate is greater before landfill closure than after closure (Bonaparte et al. 2002); hence, it will vary with time. Also, the waste decomposition phase is known to greatly affect the leachate strength for MSW landfills (Kruempelbeck and Ehrig 1999). For example, the leachate concentrations (e.g., COD and calcium) during the acid phase in a young landfill are generally higher than those during the stable methanogenic phase in an old landfill (Ehrig 1988;
on modeling the effect of the biological processes in the LCS that would result in the observed leachate concentrations at the sump, combined with consideration of the limited data available for leachate measured in such a way that the growth of biofilm in the collection layer is likely to have relatively little, or no, effect on the concentrations (Yu 2012).

The analyses described in the list were performed under the following assumptions:

1. The leachate impingement rate into the LCS was 0.3 m³/m²/year for the first 18 years, which linearly decreased to 0.2 m³/m²/year at Year 19, after which it was kept stable by a final clay cover [Fig. 8(a)].

2. The COD of the leachate entering the top of the drainage layer [Fig. 8(b)] increased linearly from 8,000 to 69,000 mg/L over the first four years and remained stable at 69,000 mg/L until Year 12. Between Years 12 and 18, the COD decreased linearly from 69,000 to 8,000 mg/L. The COD was stable at 8,000 mg/L after Year 18. For this case, VFAs contribute 90% of COD with the concentration ratio of Pr:Ac:Bu = 5:5:1.

3. The calcium concentration of the leachate entering the top of the drainage layer [Fig. 8(c)] increased linearly from 200 to 4,000 mg/L over the first four years and remained stable at 4,000 mg/L between Years 4 and 12. It decreased linearly from 4,000 mg/L at Year 12 to 200 mg/L at Year 18 and remained stable at 200 mg/L after Year 18.

4. The concentration of total suspended solids (TSSs, which include both VSS and FSS) in the leachate [Fig. 8(c)] increased linearly from 2,000 to 6,000 mg/L within the first four years and remained stable at 6,000 mg/L until Year 12. The TSS concentration decreased linearly from 6,000 mg/L at Year 12 to 2,000 mg/L at Year 18. After Year 18, it was stable at 2,000 mg/L. The VSS contributes 50% of the TSS (the other 50% of TSS is suspended inorganic solids), and 70% of the VSS is active (the remaining 30% of the VSS is suspended inert biomass) and equally distributed within three groups of bacteria (i.e., the suspended acetate, butyrate, and propionate degraders). Therefore, the change in bacterial populations is considered for this case. For example, the concentration of suspended acetate degraders increased from 233 to 700 mg/L within the first four years. After this, it remained constant at 700 mg/L until Year 12. The concentration of suspended acetate degraders decreased to 233 mg/L at Year 18 and was kept constant thereafter.

All other parameters were the same as those used in the previous section.

For a granular drainage layer with the grain size $d_g = 27$ mm and the variable leachate parameters given in Fig. 8, the service life for the drainage layer with no filter was approximately 65 years, compared to approximately 90 years for the constant strength case considered earlier. As shown in Fig. 9, the maximum leachate mound for the drainage layer without a filter increased to approximately 0.23 m at Year 18 and decreased to approximately 0.20 m at 19 years because the installation of the final cover reduced the leachate generation rate. After 19 years, the leachate mound continued to grow as a result of ongoing clogging, with the maximum leachate mound at 0.27 and 0.3 m at Years 50 and 65, respectively. For a drainage layer with a 3-mm-thick nonwoven geotextile, the maximum leachate mound increased to approximately 0.19 m at Year 18 and reduced to approximately 0.15 m at Year 19 because of the reduced impingement rate. The maximum leachate mound increased again after Year 19 to approximately 0.20, 0.28, and 0.30 m after 50, 100, and 115 years, respectively. For a drainage layer with a 0.3-m-thick sand filter, the maximum leachate mound increased to approximately 0.16 m at Year 18 and reduced
approximately 0.13 m at Year 19. Thereafter, the maximum leachate mound increased with time and reached approximately 0.18, 0.26, and 0.30 m after 50, 100, and 130 years, respectively. This suggests that the high-strength leachate early in the life of a young landfill can have a profound effect of clogging the drainage layer.

The presence of a 3-mm-thick nonwoven geotextile filter separator increased the service life for the gravel with $d_g = 27$ mm to approximately 115 years (77% increase relative to no filter) and for a sand filter layer of 0.1, 0.2, and 0.3 m thickness, the service life increased to approximately 120 years (85% increase), 125 years (92% increase), and 130 years (100% increase), respectively (Fig. 10). Thus the filter plays a far more crucial role in this case with variable leachate strength than it did for the previously discussed case of constant leachate strength. Also, in this case, the sand filter had a more clearly beneficial effect on the service life of the system than the geotextile filter separator.

For the granular drainage layer with gravel $d_g = 6$ mm, the service life of the drainage layer with no filter was only approximately 15 years (Fig. 10). A 3-mm-thick nonwoven geotextile filter layer increased the service life of the drainage layer to approximately 65 years (a 4.3-fold increase) and similar to the geotextile filter), 70 years (a 4.7-fold increase), and 75 years (a 5-fold increase), respectively. Thus, the filter layer is far more critical for the finer ($d_g = 6$ mm) gravel than for the coarser ($d_g = 27$ mm) gravel, but most of the benefit can be gained with a simple needle-punched nonwoven geotextile for the conditions in this study.

### Conclusions

The BioClog model has been used to estimate the service life of gravel drainage layers with a filter separator layer between the waste and the gravel layer. The filter separator layers examined in the study were: (1) a 3-mm-thick needle-punched nonwoven geotextile, and (2) uniformly graded sand with $d_g = 1$ mm and a thickness of between 0.1 and 0.3 m, separated from the gravel by a suitable woven geotextile. It was assumed that the geotextiles were selected to withstand reasonable construction damage and to serve as a suitable filter separator for the nonwoven geotextile and as a separator for the woven geotextile. The uniformly graded gravel drainage layers under consideration had grain sizes of 6 and 27 mm. The maximum linear drainage path in the gravel drainage layer to the collection pipe was 20 m and the drainage layer thickness was 0.3 m. Both constant and variable leachate strength with time were considered. The modeled constituents from leachate were acetate, butyrate, propionate, calcium, suspended acetate, butyrate, and propionate degraders, suspended inert biomass, and suspended inorganic solids. Based on the modeling results, the following conclusions were reached for the specific conditions examined:

1. The biologically mediated treatment of leachate passing through the filter separator layers reduced the concentrations of key leachate constituents entering the underlying granular drainage layer; thus extended the service life of the drainage layer.
2. A sand filter layer was more effective at extending the service life of the drainage layer than a nonwoven geotextile, although the 3-mm-thick needle-punched nonwoven geotextile would be suitable for many practical situations similar to those examined in the study.
3. The filter layer played a far more crucial role in improving the service life of the underlying drainage layer for the variable leachate strength than it did with the constant leachate strength.
4. For the variable leachate strength, the sand filter had a more beneficial effect on the service life of the drainage layer than the nonwoven geotextile filter.
5. The filter layer had a far more significant effect in extending the service life of the finer gravel ($d_g = 6$ mm) than the coarser gravel ($d_g = 27$ mm), although most of the benefit of a filter separator layer was achieved with the 3-mm-thick needle-punched nonwoven geotextile and the improvement in service life attributable to the use of a sand layer was relatively small.

The results presented in this paper further confirmed the findings from field and laboratory studies (Fleming et al. 1999; McIsaac and Rowe 2006) that the use of a filter separator layer between the waste and granular drainage layer can extend the service life of the granular drainage layer. However, the service life of LCSs is dependent on the leachate characteristics and impingement rate; therefore, further research is needed for any full-scale systems, in which the input leachate characteristics and impingement rates are significantly different from those examined in this paper.
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References


