Modelling the clogging of coarse gravel and tire shreds in column tests

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Abstract: A combination of data from laboratory tests and modelling is reported for both coarse gravel (19–38 mm) and two types of tire shred permeated with municipal solid waste leachate. It is suggested that the dispersivity of both the coarse gravel (initially about 4 mm) and tire shreds (initially about 45 mm) increases as the porosity of the drainage media is reduced because of clogging. The detachment of biofilm caused by growth and shear is examined and both are found to influence clogging. The average grain size estimated based on the measured surface area of the particles within a unit volume is shown to provide a good prediction of the rate of clogging for gravel and a conservative prediction for tire shreds. The size and density of suspended solids in leachate is found to significantly influence clogging rates. It is shown that Monod kinetic constants deduced for gravel at 27 °C give a good prediction of clogging for two different types of tire shred at the same temperature. Calibrated parameters used with the BioClog model are shown to give good fits to the porosity of both gravel and tire shred drainage material in laboratory column tests over time periods of up to 2 years.

Key words: leachate collection, coarse gravel, tire shreds, clogging, dispersivity, suspended solids.

Résumé : On fait rapport sur une combinaison de données d’essais de laboratoire et de modélisation de gravier grossier (19–38 mm) de même que de deux types de pneus déchiquetés infiltrés par le lixiviat de déchets municipaux solides. On suggère que la dispersivité tant du gravier grossier (initiallement environ 4 mm) que des pneus déchiquetés (initiallement à 45 mm) s’accroît lorsque la porosité des milieux de drainage est réduite à cause du colmatage. On montre que la granulométrie moyenne estimée basée sur l’aire des surfaces des particules mesurées dans une unité de volume fournit une bonne prédiction du taux de colmatage pour le gravier et une prédiction sécuritaire pour les pneus déchiquetés. On trouve que la grosseur et la densité des solides en suspension dans le lixiviat influencent appréciablement les taux de colmatage. On montre que les constantes cinétiques Monod déduites pour le gravier à 27 °C donnent une bonne prédiction de colmatage pour deux différents types de pneus déchiquetés à la même température. On montre que les paramètres calibrés utilisés avec le modèle BioClog donnent une bonne concordance avec la porosité tant du gravier que du matériau de drainage de pneus déchiquetés dans les essais de colonnes en laboratoire durant des périodes allant jusqu’à deux ans.

Mots-clés : collecte de lixiviat, gravier grossier, pneus déchiquetés, colmatage, dispersivité, solides en suspension.

Introduction

Modern primary leachate collection systems (LCSs) are typically comprised of a network of perforated collection pipes within a drainage layer. Typical drainage materials consist of clean coarse sand or gravel, however, the availability and relatively low cost of shredded tires has increased interest in their use in drainage layers. The LCS is typically designed to control the leachate head acting on the landfill base to about 0.3 m (or less). The ability to maintain the head to this level is controlled by the effectiveness of the piping system and the hydraulic conductivity of the drainage layer. Field studies (e.g., Brune et al. 1991; McBean et al. 1993; Fleming et al. 1999; Rowe 1998, 2005) have shown that the pore space and hydraulic conductivity of the drainage material reduces with time because of an accumulation of organic and inorganic “clog” material. As the hydraulic conductivity of the drainage layer decreases, a leachate mound develops and a system can be said to have reached its service life when it no longer controls the leachate head to the design value. Leachate mounding can both increase advective contaminant transport and the liner temperature, the latter reducing the service life of any geosynthetics in the liner system (Rowe 2005).

Based on the findings of Brune et al. (1991), Rittmann et al. (1996), and Fleming et al. (1999); Cooke et al. (2005a) developed a numerical, multiple species, reactive chemical transport model (BioClog) to predict the clogging rate of the porous media in LCSs exposed to landfill leachate.

VanGulck and Rowe (2004a) conducted a clogging study using columns packed with 6 mm glass beads and permeated with leachate from the Keele Valley Landfill (KVL) in Maple, Ontario. Drainable porosity profiles were measured throughout the duration of the study and results showed that there was far more clogging at the inlet section of the column when compared to the outlet section. VanGulck (2003) used data from these laboratory column experiments to assist in the model parameter calibration of BioClog for 6 mm glass beads.


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McIsaac and Rowe (2005) reported the results of laboratory column studies where two different types of tire shred (irregularly shaped 100 mm × 50 mm × 10 mm clean cut shredded tires, denoted as “G” shreds and rough cut 125 mm × 40 mm × 10 mm with wire protrusions, denoted as “P” shreds) and coarse gravel \( (d_{95} = 37 \text{ mm}, d_{60} = 30 \text{ mm}, d_{10} = 25 \text{ mm}) \) were permeated with KVL leachate. It was shown that as the leachate passed through the drainage material, the loss of chemical oxygen demand (COD) and generation of \( \text{CO}_2 \) caused by methanogenesis of acetic acid \( (\text{CH}_3\text{COOH}) \) facilitated the formation of carbonic acid \( (\text{H}_2\text{CO}_3) \). The net result was an increase in \( \text{pH} \) and carbonate \( (\text{CO}_3^{2-}) \) concentration both of which contributed to the chemical precipitation of calcium carbonate \( (\text{CaCO}_3) \). These results are consistent with the theoretical predictions by Rittmann et al. (1996). The porosity reduction along the columns was measured throughout the duration of this study. Figure 1 shows that the coarse gravel porosity profile, and hence clogging, was relatively uniform along the column at all times. This is very different from the results obtained by VanGulck and Rowe (2004a) for 6 mm glass beads and by McIsaac and Rowe (2005) for the tire shreds (Fig. 2). This begs the question as to why clogging of the coarse gravel was different to that observed for tire shreds or 6 mm glass beads. Since the McIsaac and Rowe columns were designed to mimic a saturated section of a LCS within a drainage layer, they allow for an assessment of the relative rates of clogging for the three different media. They also provide data that can be used to calibrate the BioClog model for coarse material and hence, give parameters that might be used to predict the clogging of leachate collection systems.

The objective of this study was to model the test data reported by McIsaac and Rowe (2005) for the clogging of coarse gravel and tire shreds using the BioClog model (Cooke et al. 2005a). In this paper, particular emphasis will be placed on reporting findings related to (i) dispersion in the drainage material, (ii) the Monod kinetic constants required to predict volatile fatty acid (VFA) fermentation and biomass growth, (iii) the suspended solid properties of leachate needed for modelling the fate and transport of these particles as leachate permeates a gravel size medium, and (iv) the changes in model parameters required to address the pore structure associated with large, nonspherical drainage materials.

The model

BioClog models the leachate flow path as a series of separate fixed film reactors (Cooke et al. 2005a). The fate and transport of nine species are tracked in the model. These include the concentrations of (i) propionate, (ii) acetate, (iii) butyrate, (iv) suspended propionate degraders, (v) suspended acetate degraders, (vi) suspended butyrate degraders, (vii) suspended nonactive biomass, (viii) calcium, and (ix) suspended inorganic solids, such as fixed suspended solids. Substrate utilization, biomass growth, and losses (bacterial detachment and decay) are modelled using a modification of the algorithms developed by Rittmann and McCarty (1981) and Rittmann and Brunner (1984). Biofilm growth was associated with acetogenesis of propionate and butyrate, and the methanogenesis of acetate in anaerobic biofilms. A time marching algorithm models the evolution of the influent and effluent organic concentration, active biofilm, inert biofilm, inorganic film, and porosity at any time and position along a column. By modelling the drainage material as spheres with a nominal diameter, BioClog can track the reduction in porosity (clogging) along a column.
Base case model parameters

Previous literature and model calibration provided the basis for the selection of parameters used to model McIsaac and Rowe’s (2005) columns and the base case model parameters for the coarse gravel, “G” tire shreds, and “P” tire shreds. These parameters are given in Table 1 together with the referenced source of the data. Other relevant parameters to be discussed in the following sections are given in Tables 2, 3, and 4.
Table 2. Summary of Monod kinetic constants used in the modelling study (27 °C).

<table>
<thead>
<tr>
<th>Kₘ (mgCOD/L)</th>
<th>Y (mgVSS/mgCOD)</th>
<th>ᵦ (mgCOD/mgVSSd)</th>
<th>bₐ (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>0.0650</td>
<td>2.000</td>
<td>0.0300</td>
</tr>
<tr>
<td>1789</td>
<td>0.0650</td>
<td>3.000</td>
<td>0.0290</td>
</tr>
<tr>
<td>1233</td>
<td>0.0650</td>
<td>2.000</td>
<td>0.0250</td>
</tr>
</tbody>
</table>

Note: Kₘ, half-maximum rate concentration; ᵦ, maximum specific rate of substrate utilization; bₐ, the biofilm decay coefficient; Y, the true yield coefficient; d, nominal grain size; COD, chemical oxygen demand; VSS, volatile suspended solids.

The 27 °C temperature of the McIsaac and Rowe’s (2005) tests was higher than the 21 °C examined in previous clogging studies (VanGulck and Rowe 2004a, 2004b; Cooke et al. 2005b). Increased temperature is known to increase the rate of biological clogging (Armstrong 1998), and this can be attributed to the effect of temperature on the Monod constants. The values for the half-maximum rate concentration, Kₘ; the maximum specific rate of substrate utilization, ᵦ; the biofilm decay coefficient, bₐ; and the true yield coefficient, Y; deduced from this study by model calibration are listed in Table 2. These parameters, which were deduced for gravel, were subsequently used to predict the response of the tire shreds.

Measured model parameters

McIsaac and Rowe’s (2005) columns involved nonspherical particles, which had a more variable packing arrangement than the glass beads examined by VanGulck and Rowe (2004a, 2004b). To model these columns it is necessary to establish the initial dispersivity (α) and the nominal grain size (d) of the drainage materials as discussed in the following subsections.

Dispersion

The coefficient of hydrodynamic dispersion, D (L²/T), plays an important role in the clogging process as it represents the spreading of contaminants in the column due to the combined effects of mechanical dispersion and diffusion:

\[ D = D_e + D_{md} \]

where Dₑ is the effective (molecular) diffusion coefficient (L²/T) and Dₘd is mechanical dispersion (L²/T).

Dispersion involves mixing that occurs because of local variations in the groundwater velocity. There are three basic phenomena contributing to pore-scale longitudinal dispersion: (i) as fluid moves through pores, it will move faster through the centre of the pore than along the edges; (ii) some of the fluid will travel in longer pathways than other fluid; (iii) fluid that travels through larger pores will travel faster than fluid moving in smaller pores (Fetter 1994). Traditionally, mechanical dispersion is given by:

\[ D_{md} = \alpha \cdot v \]

where α is the dispersivity (L) and v is the average linear groundwater velocity (L/T).

Dispersion has been measured in previous laboratory column experiments and field sites for a range of soils and scales and Table 3 lists a number of published values along with the values deduced in this study. Klotz et al. (1980) stated that dispersivity depends on the effective grain size and uniformity coefficient (d₆₅/d₁₀) of the porous media.

To date, there are no published dispersivity values for the media types of interest in this present study. Thus, laboratory tracer tests were conducted to obtain bromide breakthrough curves for both the coarse gravel and tire shred media, and a finite layer contaminant transport model (Rowe and Booker 2005) was used to back figure the corresponding coefficient of hydrodynamic dispersion. Diffusion was found to be negligible because of the relatively high flow in the column.

Full details regarding the tracer tests are given by Babcock (2005) and only essential details are summarized here. The tracer tests were performed in the same polyvinyl chloride (PVC) columns used by McIsaac and Rowe (2005) for the clogging tests (internal diameter of 287 mm and total length of 813 mm). The columns were packed with the media of interest and saturated with de-ionized water. A bromide solution was fed into the base receptor through four injection ports, located symmetrically around the base receptor. A magnetic stirrer was placed at the centre of the base to maintain a mixed base solution. Seven monitoring ports located vertically along the column were installed to measure the initial drainable porosity and the bromide concentration profile at different times. To ensure that the sample represented the average concentration for a specific section in the column, stainless steel tube inserts were also attached inside these ports extending towards the middle of the column. The injection flow rate of the tests was varied from 300 to 150 L/d to assess whether dispersivity remained constant with a change in flow rate. To verify the consistency of the test results, tests were repeated for nominally identical conditions.

Figure 3a shows the average breakthrough curves for two consecutive gravel tracer tests at a flow rate of 300 L/d (vₛ = 1690 m/a, ̄w = 0.47, v = 3600 m/a) where vₛ is the Darcy velocity; ̄w is the average porosity throughout the column; and v is average linear water velocity. The coefficient of hydrodynamic dispersion and corresponding dispersivity were found to be 14.3 m²/a and 4 mm, respectively. Figure 3b shows the average breakthrough curves for two consecutive tracer tests with a flow rate of 150 L/d (vₛ = 850 m/a, ̄w = 0.47, ̄w = 1800 m/a). It was found that maintaining the dispersivity (α = 4 mm) deduced for a flow of 300 L/d, provided an acceptable prediction of the breakthrough curves at 150 L/d.

Tracer tests conducted for tire shreds compressed in the same manner as described by McIsaac and Rowe (2005) and performed and analyzed as described above for gravel, yielded a dispersivity value of 45 mm for flow rates of 300 (Fig. 4) and 150 L/d (Babcock 2005).

Because of the far more variable void structure of the tire shreds, the dispersivity (α = 45 mm) was an order of magnitude higher than that for gravel (α = 4 mm) over the scale examined. Although the media was modelled in several layers and there was potential to vary the coefficient of hydrodynamic dispersion along the column, a constant D value was found to provide the best fit to the measured data for both materials. Also, in both cases, the dispersivity was the
same, for all practical purposes, over the range of groundwater velocities (and Darcy fluxes) examined.

Nominal grain size
Since BioClog treats the porous medium as an assemblage of packed spheres, the grain diameter is an important model parameter (Cooke et al. 2005a). The drainage materials used in this modelling study had a range of grain sizes and, especially for the tire shreds, were nonspherical in shape. Since the specific surface is an important factor influencing biofilm growth, it is desirable to establish an equivalent grain diameter, $d$, that will give the same surface area per unit volume for spheres for the nonspherical media. To do this, the surface area and volume of the gravel and tire shreds were measured for a representative number of samples as described by Babcock (2005), and the average values are given in Table 4. From this, the surface area per unit volume and, hence, the equivalent diameter of the particles was calculated (Table 4).

Modifications to the model
Since BioClog was calibrated using 6 mm glass beads (VanGulck and Rowe 2004a, 2004b), modifications were made to the model to allow it to reasonably predict the porosity reduction of coarse nonspherical materials. The main physical differences between VanGulck and Rowe’s (2004a, 2004b) and McIsaac and Rowe’s (2005) clogging studies were the nature of the drainage material and the system temperature. The differences in void structure of the drainage material could influence parameters such as detachment and sedimentation of suspended solids out of the system. The increase in temperature would affect the Monod kinetic parameters as discussed later.

Dispersivity
Previous studies have shown that the value of dispersivity increases as the porosity decreases because of clogging. Taylor (1991) found that biofilm-affected sands can experience an increase in dispersivity of three orders of magnitude compared to clean sands. Thus, the dispersivity values calculated earlier for the clean drainage materials serve only as initial values and based on previous research should increase when the void space is reduced due to clogging.

Cooke (2007) incorporated the following function relating dispersivity, $\alpha$, to the $n$, porous media porosity:

$$\alpha = b + m(1/n)$$

where $m$ and $b$ are empirical parameters. Since dispersivity is used to calculate the coefficient of hydrodynamic dispersion ($D = \alpha v_d/n = v_d(b/n + ml^2)$), a maximum coefficient of hydrodynamic dispersion value of 50 m$^2$/d was used as a cap for when severe clogging decreases the porosity to very low values. Dispersivity was varied in the parametric study, which is discussed later, to show its effect on clogging.

Detachment of suspended solids
BioClog models the detachment of suspended solids using two distinct methods: detachment caused by shearing, and detachment caused by growth (sloughing). VanGulck (2003) and Cooke et al. (2005b) only used detachment caused by

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Table 3. Summary of dispersivity values.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Grain size (mm)</th>
<th>Geological material</th>
<th>Scale</th>
<th>Darcy velocity (m/a)</th>
<th>$n$</th>
<th>Initial dispersivity $\alpha$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taylor et al. 1987</td>
<td>0.2–0.33</td>
<td>Sands</td>
<td>2</td>
<td>NG</td>
<td>NG</td>
<td>10*</td>
</tr>
<tr>
<td>Taylor et al. 1987</td>
<td>0.2–0.32</td>
<td>Sands</td>
<td>1</td>
<td>NG</td>
<td>NG</td>
<td>1*</td>
</tr>
<tr>
<td>Novakowski 1992</td>
<td>0.42</td>
<td>Glass beads</td>
<td>1</td>
<td>1261</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Novakowski 1992</td>
<td>0.42</td>
<td>Glass beads</td>
<td>1</td>
<td>1640</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Klotz et al. 1980</td>
<td>1.0</td>
<td>Gravelly sand</td>
<td>2</td>
<td>NG</td>
<td>0.26</td>
<td>25.9</td>
</tr>
<tr>
<td>McIsaac 2007</td>
<td>19–38</td>
<td>Clogged gravel</td>
<td>1</td>
<td>220</td>
<td>0.12</td>
<td>300</td>
</tr>
<tr>
<td>This study</td>
<td>19–38</td>
<td>Clean gravel</td>
<td>1</td>
<td>850</td>
<td>0.48</td>
<td>4</td>
</tr>
<tr>
<td>This study</td>
<td>19–38</td>
<td>Clean gravel</td>
<td>1</td>
<td>1670</td>
<td>0.48</td>
<td>4</td>
</tr>
<tr>
<td>This study</td>
<td>31–62</td>
<td>Tire shreds</td>
<td>1</td>
<td>850</td>
<td>0.25</td>
<td>45</td>
</tr>
<tr>
<td>This study</td>
<td>31–62</td>
<td>Tire shreds</td>
<td>1</td>
<td>1670</td>
<td>0.25</td>
<td>45</td>
</tr>
</tbody>
</table>

Note: 1, laboratory (small) scale; 2, field (large) scale; NG, not given.
* Averaged value.

Table 4. Average surface area and volume of particles, media porosity, and equivalent grain diameter.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>No. of samples</th>
<th>Surface area (mm$^2$)</th>
<th>Volume (mm$^3$)</th>
<th>Porosity</th>
<th>Grain diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse gravel</td>
<td>40</td>
<td>8 391</td>
<td>16 510</td>
<td>0.447</td>
<td>21.3</td>
</tr>
<tr>
<td>Tire shred “G”</td>
<td>40</td>
<td>26 070</td>
<td>40 440</td>
<td>0.248</td>
<td>12.0</td>
</tr>
<tr>
<td>Tire shred “P”</td>
<td>16</td>
<td>22 592</td>
<td>26 890</td>
<td>0.219</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Note: Average surface area and volume calculated per sample.
shearing (none caused by growth). However, in the present work it is hypothesized that both detachment methods act throughout the clogging process. It is likely that the detachment due to shearing is more dominant at higher seepage velocities (i.e., lower porosities) and that detachment caused by growth dominates when seepage velocities are lower (higher porosities). Rittmann (1982) developed an expression, used in BioClog, for detachment as a function of shear stress, on the biofilm, which could be estimated using:

\[
\sigma = \frac{\mu v a (1 - n)^3}{d g^2 n A_s (7.46 \times 10^{10})}
\]

where \(\mu\) is the viscosity of water, \(d g\) is the grain diameter of the porous media, and \(A_s\) is the specific surface of the porous media. Inspection of eq. [4] shows that when the porosity reduces to low values, \(\sigma\) increases rapidly. Some evidence of this is provided by Fig. 1 for porosity values less than 0.10 (599 d), where the porosity profile of the gravel becomes more vertical than previously, suggesting that detachment due to shearing dominates. Compared to glass beads, the coarse gravel has a higher initial average porosity (\(\bar{n} = 0.47\) compared to \(\bar{n} = 0.38\)) and larger grain diameter (\(d_{50} = 29\) mm compared to \(6\) mm), thus one would expect that \(\sigma\) would be significantly less for coarse gravel than for the pea gravel and so detachment due to shear may be far less significant for the coarse gravel than for pea gravel, and hence, detachment due to growth more significant for the coarse gravel. BioClog was modified to allow consideration of both detachment methods acting simultaneously.

**Suspended solid sedimentation from the system**

Given the very open void structure of the coarse gravel, it can be hypothesized that some fraction of suspended solids are lost because of sedimentation along the inlet section of the column. This hypothesis is supported by the high levels of sediment observed in the inlet reservoir at column disassembly (McIsaac 2007). The losses are subtracted from the amount that would be attached to the active, inert, and inactive (FSS and mineral) films resulting in less clogging where the sedimentation process occurs.

VanGulck (2003) and Cooke et al. (2005b) did not incorporate this sedimentation into their modelling study, but because of the more open pore structure of the coarse gravel, the probability that particles in suspension could fall out of the system (and into the base receptor) because of gravitational effects is much greater for materials with large uniform void spaces. It may be anticipated that sedimentation would be greater at the inlet end of the column than at the outlet end since there would be fewer gravel particles onto which the suspended solids could settle and attach.

McIsaac and Rowe (2005) showed transilluminated cross sections of coarse gravel and tire shred material. Their photos provide physical evidence that the coarse gravel had a far more uniform void distribution than the tire shreds. Thus, the probability of sedimentation into the column base receptor (as opposed to onto the porous media itself) is far greater for the gravel than for tire shreds. Less sedimenta-
tion of the suspended solids would result in more attachment, and hence, clogging of the porous media near the inlet of the column, than at points further away from the inlet as was observed for the tire shred columns (see Fig. 2). For this reason, sedimentation of suspended solids out of the column (into the receptor) was not modelled for the tire shred columns.

**Model parametric study for coarse gravel**

Figure 5 shows that the calculated porosity profiles (base case) provided a reasonable fit to the measured values. Because of the assumption of packing of spheres, BioClog can accept initial porosities in the range 0.211 to 0.477. This was adequate for the measured range everywhere except at the top (outlet) of the column where the measured value was 0.546. At the outlet end of the column, the initial value was modelled as 0.477. Inspection of Fig. 5 shows that the measured porosity profile follows the pattern established by the initial porosity. It is not until late times (599 d in Fig. 5) that a relatively straight profile is established (attributed to shear detachment as discussed later).

A parametric study was conducted to show the effects that specific model parameters have on the clogging rate of coarse gravel. The parameters that were analyzed include: dispersivity, nominal gravel grain size, suspended particle size, suspended particle density, method of detachment, and Monod kinetic constant parameters.
Dispersivity

Dispersivity was varied to see what effect mixing had on the clogging rate of the column. The slope and y-intercept in eq. [3] were varied to change the value of dispersivity. The clean gravel ($\bar{n} = 0.47$) had an initial dispersivity of 0.004 m. Analyses were conducted assuming a dispersivity of 0.004 m at the initial porosity and that at a porosity of 0.12 the dispersivity would increase to values of (i) 0.02 m ($b = -0.0108$, $m = 0.0037$), (ii) 0.2 m ($b = -0.1769$, $m = 0.0452$), and (iii) base case: 2.0 m ($b = -0.7285$, $m = 0.3274$). It was found (Fig. 6) that while all three cases gave reasonable fits for the first 100 d (while the porosity remained high) only case (iii) provided a good fit for subsequent times, demonstrating the need to account for an increase in dispersivity with clogging if one is to model the relatively uniform clogging observed in the gravel columns.

Nominal grain size

The grain size of the coarse gravel ranged from a $d_{10}$ of 19 mm to a $d_{100}$ of 38 mm. The calculated equivalent grain diameter of 21.3 mm (see Table 4) was assigned as the base case since it matched the surface area per unit volume of the actual gravel to that of the packed spheres used to model the gravel. Analyses were performed for several particle sizes in the range 19 to 38 mm and it was found (Fig. 7) that the equivalent grain diameter of 21.3 mm gave the best fit to the measured porosity profiles with time. For all times, the porosity reduction (i.e., clogging rate) for the smaller grain size is greater than the larger grain size. Reducing the grain size diameter increases the surface area (per unit volume) available for biofilm development. Numerically, a smaller grain size will increase the attachment coefficient from the Rajagopalan and Tien (1976) filtration model, $K_{Att}$, which will also increase clogging

\[ K_{Att} = \frac{3(1 - n)v_d \eta}{2d_g} \]

where $n$ is the porosity, $v_d$ is the Darcy velocity, $\eta$ is the single-collector efficiency, and $d_g$ is the grain diameter. The single-collector efficiency has been given by Rajagopalan and Tien (1976) as

\[ \eta = 1.5H_p(1 - n)^{2/3}N_R^{2/3}N_L^{1/2}N_R^{-1/8} \]

\[ + (2.25 \times 10^{-3})N_G^{-0.2}N_R^{-2/3} + 4(1 - n)^{2/3}H_p^{1/3}N_P e^{-2/3} \]

where $H_p$ is the Happel parameter, $N_R$ is the interception parameter, $N_L$ is the London force parameter, $N_G$ is the gravitational parameter, and $N_P e$ is the Peclet number. These parameters are outlined in Tien (1989). Reducing $d_g$ also increases the interception parameter, which contributes to attachment:

\[ N_R = \frac{d_s}{d_g} \]

where $d_s$ is the suspended particle diameter.

Suspended particle size

Typical spherical bacteria range in size from 1 to 3 $\mu$m (Metcalfe and Eddy Inc. 1991); therefore, the volatile suspended solid (VSS) particle size was varied within this range (Fig. 8). By visual inspection, comparing the measured porosity reduction to the calculated porosity with time, a VSS particle size of 3 $\mu$m was found to give the best porosity reduction prediction and was chosen as the base case (Fig. 8c). Larger VSS particle sizes have a higher probability of colliding with grains and also occupy more of the void space, thus, giving rise to more rapid clogging than smaller particles. Numerically, the gravitational parameter, $N_G$, in-
Fig. 8. Calculated porosity profiles with time for volatile suspended solid (VSS) particle diameters of (a) 1 μm, (b) 2 μm, and (c) 3 μm – base case for the coarse gravel study (measured data from Rowe and McIsaac 2005). calc., calculated; meas., measured.

Fig. 9. Calculated porosity profiles with time for volatile suspended solid (VSS) particle densities of (a) 1000 kg/m³, (b) 1060 kg/m³, and (c) 1030 kg/m³ – base case for the coarse gravel study (measured data from Rowe and McIsaac 2005). calc., calculated; meas., measured.

corporated into \( \eta \) increases as the diameter of the particle, \( d_p \) increases

\[
N_0 = \frac{2(\rho_p - \rho_l) \left( \frac{d_p}{2} \right)^2}{9 \mu_2}
\]

where \( \rho_p \) is the suspended particle density, and \( \rho_l \) is the density of the leachate.

**Suspended particle density**

A range of VSS particle densities between 1000 and 1060 kg/m³ was examined, and it was demonstrated that the
greater the density of VSS, the greater the clogging rate (Fig. 9). By visual inspection, the VSS particle density that provided the best fit was 1030 kg/m³. As the particle density increases to values much greater than the fluid density (~1000 kg/m³), $N_G$ (eq. [8]) will increase, which increases attachment, $K_{Att}$, hence, clogging of the system increases. The FSS or mineral suspended solids particle density giving the best fit was found to be 1045 kg/m³.

**Method of detachment**

BioClog models the detachment of VSS because of detachment by shearing (Rittmann 1982) and (or) growth (Peyton and Characklis 1993). Both methods of detachment were varied to identify which one of the methods of detachment had the largest effect on clogging. Various combinations of the two clogging mechanisms were considered, and it was found that to obtain good fits the full contribution of both mechanisms was required. Equation [4] shows that the shear stress, $\sigma$, is governed by the ratio $(1-n)^3/n$. As $n$ reduces, the ratio increases, especially for small $n$. Thus, the shear stress is very small for large porosities because of the large constant $(7.46 \times 10^{10})$ in the denominator of eq. [4], and shearing was only found to be significant for the low porosities (<0.10) encountered at late times. In contrast, the detachment because of growth governed the behaviour at higher porosities.

**Model parametric study for tire shreds**

The BioClog model was used to simulate clogging of the tire shreds. The measured porosity along the column with time was found to be reasonably predicted for both the “G” and “P” tire shreds as shown in Fig. 10. The primary differences in the model parameters for the gravel and tire shreds are discussed below.

The equivalent grain sizes for the “G” and “P” quality tire shred estimated in Table 4 (12 and 9 mm, respectively) were found to be too small and, when modelled, resulted in higher calculated clogging rates than those measured. Figure 11 shows that for the “G” shred, the use of a larger grain size (18 mm) resulted in a better fit to the measured porosity profiles with time. The difference in clogging rates is attributed to tire shreds that had significant zones where the direct contact of flat surfaces of different shreds reduced the surface area available for shearing.
face area available for biofilm growth, and, hence, clogging. The calculated clogging rates were based on the individual number of shreds in a unit volume. This was consistent with the clean surfaces observed by McIsaac (2007) at these contact points during disassembly. Thus, it appears that while the approach of calculating the nominal diameter of particles based on the total surface area worked well for gravel (where the area of intimate contact between particles of gravel is quite small and can be neglected), it is overly conservative for tire shreds and resulted in too much clogging. Hence, some increase in diameter is needed to account for the overlapped surface. In this case, about a 50%–80% increase was required (from 12 to 18 mm for “G” shred and from 9 to 16 mm for “P” shred).

It appears that the size of flocs that can develop in a porous media is related to the particle size of that media. VanGulck (2003) used a VSS and FSS particle sizes of 1 and 2 μm, respectively, when modelling the 6 mm glass bead columns. For the coarse gravel examined by McIsaac and Rowe (2005) it was found that the VSS and FSS particle sizes should be increased to 3 and 7 μm, respectively. In the case of the tire shreds, which had much smaller pores for the suspended solid flocs to accumulate, the use of these same values overpredicted clogging (Fig. 12), and the VSS and FSS particle sizes needed to be decreased to 2 and 4 μm to obtain good fits.

**Practical implications**

The size and shape of the void space in the drainage media played an important role in the extent of clogging in the columns. The coarse gravel had relatively uniform void spaces compared to the tire shreds. Uniform void spaces resulted in a less tortuous flow path, fewer small-sized voids and constrictions between pores, and more consistent clogging throughout the column, which would correlate to longer service lives and more effective LCS. The combined effect of the nonuniformities in size and shape, together with the compressibility of the tire shreds, resulted in void spaces that varied extensively in size and shape and were randomly distributed throughout the column. This resulted in more tortuous flow paths and more excessive clogging at the influent end of the columns for the tire shreds than it did for the gravel. These void characteristics all result in a shorter service life and a less effective drainage system.

The modelling suggests that coarse gravel can be simulated using a particle size that gives the correct surface area per unit volume and that this approach will provide a conservative prediction for tire shreds. The kinetic parameters deduced for the gravel were found to give good predictions for the two sets of tire shred columns, suggesting that they can be used in modelling clogging of different media being permeated by municipal solid waste leachate. It was also found that for all three types of coarse media, it was important to model both growth and shear induced detachment, with the former dominating through most of the process, but the latter dominating once the porosity drops below about 10%. This is in contrast to finer-grained media (6 mm glass beads or pea gravel) where only shear-induced detachment played a significant role. This demonstrates the greater effectiveness of the coarser material as a drainage media and the much longer time required (under otherwise similar conditions) for clogging to occur. Although some adjustments to other parameters were required to obtain a good fit to the experimental data, it was evident that except for the size of the suspended particles in the leachate (which appear to get larger as the drainage medium gets coarser), the default values (used by VanGulck 2003) would give conservative predictions of clogging rates.

The size and density of suspended solid particles were shown to significantly affect the rate of clogging. Thus, the presence of a suitable filter over the drainage layer, which would substantially reduce the size of suspended solids reaching the drainage layer, can be predicted to substantially reduce the rate of clogging and increase the service life of the drainage layer. This is consistent with the findings of VanGulck (2003) who showed that there was much less clogging for glass beads permeated with synthetic leachate (with a low concentration of suspended solids) than there was for similar beads permeated with KVL leachate (with much

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higher concentration of suspended solids). It is also consistent with the findings of McIsaac and Rowe (2006) who found that there was less clogging of drainage layers with suitable filters above them than for layers without filters.

Conclusions

Based on a combination of data from laboratory tests and modelling for both coarse gravel (19–38 mm) and two types of tire shred, the following conclusions have been drawn.

1. The dispersivity of both the coarse gravel (initially about 4 mm) and tire shreds (initially about 45 mm) increased as the porosity of the drainage media was reduced because of clogging.

2. In modelling the clogging of both coarse gravel and tire shreds it was necessary to consider detachment due to both growth and shear, with the former dominating at most porosities and the latter dominating as porosities dropped to low values (below about 10%).

3. The average grain size estimated based on the measured surface area of the particles within a unit volume provided a good prediction of the rate of clogging for gravel and a conservative prediction for tire shreds (the latter because of an overestimate of the available surface area caused by intimate contact between the tire shreds that eliminated surface area for biofilm growth).

4. The VSS particle size appeared to increase with increasing size of the porous media through which it passes. Values ranged between 1 μm for 6 mm glass beads to 2 μm for tire shreds to 3 μm for the coarse gravel (with all three being within the range reported in the literature). This suggests that the larger void space within the coarse gravel media allows the suspended solids to maintain larger flocs.

5. Increased size of suspended solids increased clogging (other things being equal) suggesting that a reduction in the size of suspended solids entering a drainage layer, caused by the presence of a suitable filter over the drainage layer, would reduce the rate of clogging of the drainage layer and extend its service life.

6. The Monod kinetic constants deduced for gravel were found to give good predictions of clogging for the two different types of tire shred, suggesting that they may be used for different types of drainage material at 27 °C. Comparison with results of modelling at 21 °C shows that the Monod kinetic constants may be temperature dependent and could give rise to greater clogging at higher temperatures.

7. Calibrated parameters were used with the BioClog model developed by Cooke et al. (2005a) to obtain good fits to the porosity of both gravel and tire shred drainage material in laboratory column tests over time periods of up to 2 years.

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