Change in leachate chemistry and porosity as leachate permeates through tire shreds and gravel

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Abstract: Rubber tire shreds are an attractive potential alternative to conventional gravel in the drainage layer of leachate collection systems at the base of landfills, yet the clogging and thus the long-term performance of tire shreds in this application is not known. This paper presents the results of an experimental investigation into the clogging potential of rubber tire shreds used as part of a leachate collection system at the base of a landfill when permeated with leachate. Experimental columns filled with two different rubber tire shreds and a conventional gravel drainage material were used to study the spatial and temporal variation of leachate characteristics and porosity changes within the drainage materials. It is shown that there are significant differences in the pore structures of the drainage materials and that these differences affect clog development and the length of time it takes for the hydraulic conductivity to drop below a threshold of $10^{-5}$ m/s. The gravel is found to have a service life at least three times greater than that of an equivalent thickness of compressed (at 150 kPa) tire shred.

Key words: tire shreds, landfill, clogging, hydraulic conductivity, porosity, leachate collection.

Introduction

A large number of used scrap tires are landfilled, stockpiled, and illegally dumped every year in Canada. A more productive, economically feasible, and environmentally sound alternative for their disposal would be to find uses for these scrap tires. One possible use that has been suggested is as an alternative to conventional drainage gravel in the construction of leachate drainage layers in sanitary landfill sites. Modern landfills typically have a leachate collection system that includes a system of perforated pipes in a continuous “blanket” of granular material (gravel). This collection system controls leachate mounding and collects and removes contaminant that would otherwise be available for transport to the environment. However, the chemical and biological composition of the leachate that passes through the leachate collection system combined with the presence of microbial activity result in chemical and biological induced clogging (Brune et al. 1994; Fleming et al. 1999; Maliva et al. 2000; Bouchez et al. 2003). Voids within the drainage medium become filled with clog material. The clog that develops decreases the pore space available to transmit leachate, reduces the hydraulic conductivity of the drainage layer, and consequently reduces the efficiency and period of effective functioning of the leachate collection system. Since these systems may be required to collect and remove leachate for extended periods of time, it is important to design them with optimum long-term performance and service life.

Tire shreds are a unique landfill construction material with some similarities to the natural aggregates typically utilized as drainage media. It has been suggested that rubber tire shreds in the blanket drain of a leachate collection sys-
The primary objective of this study is to examine the pore structure of the rubber shred and gravel drainage materials and to discuss how the difference in the pore structures affects clog development in tire shred and conventional gravel drainage materials. A second objective is to design, construct, and operate column experiments to simulate conditions occurring at the base of a landfill in an attempt to replicate reasonable worst-case conditions and to provide insight into the relative performance of the two materials.

Experimental approach and analysis

Four experimental columns were constructed and filled with full sized drainage material (rubber tire shred or conventional gravel) and permeated with leachate for up to two years. A testing program was implemented to monitor and quantify the amount of clogging and changes in leachate composition both temporally and spatially. Water quality testing was performed on leachate samples collected from sample ports located along the length of the columns, before the influent valve, and after the effluent valve. These samples were tested immediately to obtain chemical oxygen demand (COD), calcium (Ca$^{2+}$), pH, total and volatile suspended solids (TSS and VSS, respectively), and volatile fatty acid (VFA) concentrations (specifically acetic, propionic, and butyric acid concentrations). Tests were performed to follow the change in drainable porosity (and hence the change in void volume) with time as clogging developed. Drainable porosity is measured by partially draining the columns and measuring the volume of drained leachate and the change in leachate level. It is calculated by dividing the volume of drained leachate by the total volume of the drained interval. The drainable porosity test will be lower than the actual porosity as a result of incomplete draining of the water under gravity due to fluid adhering to the drainage medium and clog material. Sections (approximately 25 mm thick) cut from compressed drainage material that had been impregnated with fiberglass resin were used to perform a qualitative assessment of the pore structure of the different drainage materials used in the experimental study.

Experimental column and loading frame fabrication and operation

Experimental column and loading frame fabrication

The columns were fabricated from polyvinyl chloride (PVC) (schedule 80) plastic pipe that had an internal diameter of 287 mm and a total length of 813 mm. In addition, a loading frame was constructed to apply a vertical pressure to the compressible rubber tire shred drainage material that would simulate the weight of waste. The loading frame and column are shown in Fig. 1.

The columns had a permanently sealed end cap and a removable sealable lid to allow for the filling and emptying of drainage material. A hole, with an o-ring seal, in the center of the top caps allowed for the passage of the pneumatic ram. The columns had four influent valves, equally spaced around the perimeter of the base of the columns and one large effluent port located above the top surface of the drainage media. Combination sample–piezometer ports (P1, P2, P3, P4, P5, and P6) were equally spaced along the length of the columns (starting at the top of the base grate; Fig. 1) at 100 mm intervals. Leachate collected from sample–piezometer port 1 (P1) is representative of the leachate just before entering the drainage material. Perforated tubular inserts (3.2 mm internal diameter) extending 150 mm into the drainage material were used at each sample port to ensure that a cavity remained open for leachate collection, to increase the accuracy of leachate head measurements during clogging, and to assist in the collection of a representative leachate sample across the diameter of the column.

The loading frame consisted of two square steel plates held apart using four threaded steel rods located in the corners of the plates. A pneumatic cylinder with a 152.4 mm bore and 304.9 mm stroke was centered and hung from the top steel plate. The pneumatic cylinder was connected to a hand control valve to control the up and down movement of the cylinder; a pressure regulator, which allowed for the adjustment of the applied stress; a pressure gauge to monitor the applied pressure; and an air supply line.

Two stainless steel grates with fifty 19 mm perforations were used as bearing surfaces to sandwich the shred material and allow for the free flow of leachate during operation. The top perforated stainless steel plate was attached to the end of the pneumatic ram of the cylinder. The top surface of the base perforated grate was located 51 mm above the base of the column by eight equally spaced supports and created a reservoir in the base of each column that allowed for a uniform distribution of leachate flow into the drainage materials.

A side wall treatment that consisted of four layers of 6 mil plastic sheet was placed between the rubber shreds and the PVC pipe wall to reduce side wall friction and to increase the load transmitted to the base of the columns so as to provide a reasonably uniform stress distribution throughout the columns. Tests indicated that with this treatment approximately 80% of the applied load was transmitted to the base of the columns.

Experimental setup and operation

The four columns, designated R1–R4, were constructed and operated to establish clogging in the more critical regions where flow is concentrated near the leachate collection pipes (Fleming et al. 1999). Two duplicate columns (R1(P) and R3(P)) were filled with a tire shred called “P shred.” One column (R2(G)) was filled with tire shred called “G shred” and the fourth column (R4(Gravel)) was filled with conventional uniformly graded gravel. The drainage materials were dumped loosely into the columns. The loading frame and ram were used to simulate the weight of waste and to compress the tire shreds at a stress of 150 kPa. The compressed height of drainage material ranged between 550 and 610 mm. The dry density of the compressed shreds (at 150 kPa) ranged between 850 and 900 kg/m$^3$ for the G shreds and between 825 and 1000 kg/m$^3$ for the P shreds. The dry density of the gravel in R4 was 1370 kg/m$^3$. The columns were permeated under anaerobic conditions with an upward flow of leachate that was collected regularly from
Fig. 1. (a) Loading frame. (b) Photo. (c) Column.
the Keele Valley Landfill in Toronto, Canada at a design flow rate of 0.4 m$^3$/m$^2$/d at 27 °C.

**Description of drainage material**

Figure 2 shows typical samples of the G and P shreds and 38 mm gravel used for the drainage medium in the study.

The P shreds were relatively flat, irregularly shaped (125 mm × 40 mm × 10 mm) tire chunks from both the sidewall and the tread portions of the tires with jagged edges that appeared to be torn apart rather than cut into pieces. Pieces of metal protruded from both the steel belt and bead wire.

The G shreds were largely flat, irregularly shaped (100 mm × 50 mm × 10 mm) tire chunks with clean-cut edges from the sidewall of the tires, with the bead wire still in place, and therefore relatively smooth and without any deep grooves associated with the tread portion of the tires. Compared to the P shreds, the G shreds had less exposed steel wire (because of the clean cut) and the protruded wire length was shorter but was of heavier gauge bead wire. The size and shape of the G shreds were more uniform than the P shreds.

Crushed dolomitic limestone with a nominal size of 38 mm was used for the drainage layer in column R4.

**Characterization of pore structure**

A qualitative assessment of the drainage material pore structure can be obtained from the successive sections (10 section faces in the gravel and 6 in both the P and G shreds) that were made in each drainage material. Typical sections through the three materials are shown in Fig. 3.

The relatively uniform shape, size, and incompressible nature of the gravel material resulted in large relatively uniform void sizes and generally an open pore structure. Compared to tire shreds, the open pore structure of the gravel produces an unobstructed flow environment where the leachate velocities will remain relatively uniform and low during operation. This would give higher leachate retention times than the shreds which have fewer, and much narrower, flow channels. As a result of the large, relatively uniform, void sizes in the gravel, clog formation must bridge over longer distances and fill larger volumes before the clog material will affect the flow of leachate through the gravel.

Compared to the P shred, the shape, size, and lack of frayed metal of the G shred resulted in a shred volume that was more compressible under vertical loads and also resulted in a more discontinuous distribution of pore volumes that were not systematically connected to each other from section to section. The smallest pore throat openings were observed for the G shreds. The flow regime in the G shred was more tortuous than that in the P shred, and the leachate had to travel through many smaller constrictions and pathways that connect the relatively isolated larger pores. Thus less clog formation would be required to bridge over the narrow constrictions and smaller void spaces in the G shred material before it affects the flow of leachate.

**Leachate quality results**

The normalized COD and calcium concentrations along with the pH shift between the influent and effluent leachate are shown in Fig. 4. Normalized values of COD and calcium were obtained by dividing the effluent and sample–piezometer port concentrations by the concentrations measured at P1. The leachate COD and calcium concentrations decreased between the influent and the effluent ends of the columns as the leachate traveled through the compressed shred (at 150 kPa) and gravel filled columns. Normalized COD and calcium concentrations in the effluent leachate continuously decreased with time until relatively steady state conditions were reached. From approximately 70 days to test completion, the average normalized effluent COD values for R1(P), R3(P), R2(G), and R4(Gravel) were 0.43, 0.44, 0.52, and 0.75, respectively. During steady state removal, average normalized calcium concentrations in R1(P), R3(P), R2(G), and R4(Gravel) were 0.31, 0.32, 0.45, and 0.65, respectively. The G shreds in column R2(G) removed slightly less COD and calcium from the leachate than the P shreds in columns.
Fig. 3. Sections (287 mm in diameter and approximately 25 mm thick) taken through the various drainage materials illustrating differences in the pore structure. Included for each of the gravel, G shred, and P shred is (a) a photo of a typical section face, (b) a trace of the drainage material, and (c) a transillumination of the section.
R1(P) and R3(P). All else being equal, it can be anticipated that the level of clogging will be greater as more COD and calcium are removed. By far the smallest amount of COD and calcium removal occurred for the gravel column.

The pH of the leachate increased as it passed through the drainage material from an average P1 influent pH of 7.0 to an average effluent pH of 7.5, i.e., a shift in pH of about 0.5 pH units at steady state operation. The variations in the leachate characteristics as it passed through the columns are consistent with the findings of Rittmann et al. (1996). An environment conducive to clog development or the precipitation of CaCO₃ is established within the leachate as it passes through both the shred and gravel drainage materials. Rittmann et al. (1996) showed that a reduction in COD concentration due to the biodegradation of VFAs resulted in an increase in leachate pH and carbonate concentration in the leachate, which allowed for the chemical precipitation of CaCO₃.

Once steady state conditions were established, the majority of the removal of COD and calcium from the leachate entering the drainage material occurred within the first 100 mm (section 1) in both the rubber shred and gravel columns, with smaller amounts being removed in subsequent sections as the leachate passed through the columns. For instance, in the rubber shred columns, section 1 was removing approximately 30–40% of the COD concentration, and sec-

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Drainable porosity results

Drainable porosity measurements were performed to assess the decrease of the open void spaces within the drainage medium with time and to estimate the amount of clog development within the voids with time.

The initial average drainable porosity (Fig. 6) measured over the entire length of drainage material was 0.25 for both R1(P) and R3(P), 0.22 for R2(G), and 0.45 for R4(Gravel). Since the gravel column had a much higher initial drainable porosity than the rubber shred columns, much more clog material had to be deposited in the gravel pore space than in the shreds before clogging hindered the ability of the material to transmit leachate. The slight decrease in the initial drainable porosity towards the top of the rubber shred columns is due to the stress being higher at the top of the column relative to the base (because of sidewall friction). The drainable porosity distribution is relatively constant with height in the gravel column.

The development of clog with time was not uniform over the length of any of the rubber shred columns (Fig. 6). Initially, within the rubber shred columns there was a lower drainable porosity at the top of the column than at the bottom (because of higher stress at the top), but after approximately 254 days the opposite trend was observed; i.e., there were lower drainable porosities at the base of the columns. This indicates higher clogging rates at the base of the rubber shred columns. For the gravel column, clog development remained relatively uniform over the entire length of the column. A similar trend in porosity reduction was observed in column experiments conducted by Rowe et al. (2000b) that were filled with 4, 6, and 15 mm beads. Severe clogging was observed at the influent end of the columns with the smaller particles but the change in porosity for the larger particles (15 mm) was far more uniform along the entire column. This was attributed to surface area effects. Since clogging is related to the surface area available for biofilm growth, a greater length of column is required for larger particles to attain the same surface area and hence biofilm area than for smaller particles. Although not as distinct here as in the test by Rowe et al. (2000b), a similar effect was evident.

The porosity reduction with time (Fig. 7) is a measure of the amount of clog development over time within the voids. This porosity reduction \( \nu \) (defined by Rowe and Fleming 1998) represents the porosity that is occupied by clog material at some time \( t \). Porosity reduction can be measured by subtracting the drainable porosity at some time \( t \), from the initial drainable porosity, or similarly, by dividing the volume of clog in each interval at some time \( t \), by the total volume of the interval. The rate of change of \( \nu \) per year, or the slope of the lines in Fig. 7, gives an indication of the rate of clogging within the columns and is provided, in parentheses, for each section in each column in Fig. 7.

Generally, in the shred columns, section 1 had the highest clog formation rates (Fig. 7) with lower measured rates in the top sections. This is likely due to a combination of reduced nutrients and calcium supply needed for clog formation in these upper sections (as discussed earlier) and to the compressed–confined pore structure and tortuous flow regime in the shred columns.

The highest rates of clog formation were measured in the P shred columns with similar rates measured in corresponding sections in the duplicate columns (R1 and R3). In all sections column R2(G) had slightly lower clog formation rates than columns R1(P) and R3(P). Column R2(G) was
Fig. 5. COD and calcium consumption in the columns after significant clog has developed. The hatched area illustrates the sections responsible for the majority of the removal of COD and calcium in the columns after significant clog has developed in the lower sections.
also the least efficient at removing COD and calcium from the leachate. The difference in void structure and flow regime between the two shred types likely caused the difference in clog rates. Constricted–confined pathways that connect relatively isolated larger pores were abundant in the compressed G shred material. This created a more tortuous flow regime than in the P shred and the least exposed surface area in void spaces for unconfined–unrestricted clog deposition and active biofilm growth. The development of clog and the lower observed clog formation rates in R2(G) was thus likely substantially influenced by the high velocity of leachate flow that resulted in lower retention times in the constrictions, higher shear stresses, and thus thinner active biofilm covered surfaces for most of the operation period for this column.

For column R4(Gravel), the rate of clog formation was relatively uniform in all sections, and there was a distinct change in behaviour after about 1.3 years. Clog development occurred at a much faster rate during the first 1.3 years of operation. While maintaining a relatively high porosity and an open pore structure over the first 1.3 years of operation, it is considered that TSS retention and the precipitation of calcium onto fixed suspended solids (FSS) is an important clogging mechanism that contributes significantly to the reduction of the void volume. This results in a uniformly distributed clog throughout the drainage material but may initially develop a clog structure that is not solidly fixed to the gravel drainage medium. Once the majority of the pore volume becomes filled with clog material at a drainable porosity of about 0.05 (after approximately 1.3 years), the potential for this clogging mechanism to form additional clog material is reduced. Although drainable porosities indicate that significant clog formation has occurred by 1.3 years, the clog that has developed does not appear to be able to withstand the shear forces resulting from the higher velocity of the leachate through the occluded pores that occurs after 1.3 years. After 1.3 years, the development of a hard cemented inorganic clog that can resist the steadily increasing shear forces (due to the prescribed flow rate) occurs at a much slower rate.

Once there was significant clogging in a section of the column, the drainable porosity test used to measure void volumes became impractical. Thus, when the drainable porosity dropped much below a value of 0.05, \( \nu_f \) could not be measured. Although not measurable, the change in \( \nu_f \) with time must be lower after a drainable porosity of 0.05 has been reached. This conclusion came from the fact that if clogging continued at the same rate, total occlusion of the voids would have occurred and the test would have terminated earlier than was indeed the case. Flow rates were maintained long after the rate of clog formation would have predicted total occlusion. This suggests that some combination of shearing of biofilm caused by the higher velocities and the lower retention times results in lower clogging rates after

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Fig. 7. Porosity reduction ($v_f$) versus elapsed time.
substantial clogging has occurred. Clogging did not stop however, as is evident from the increasing gradient required to maintain the flow in the bottom sections of the columns after a drainable porosity of 0.05 was reached.

Figure 7 gives a prediction of the clogging rate for these experiments only. The columns were designed to conservatively represent a volume or element of a leachate collection system that would likely experience the greatest potential for clog formation due to the mass loading from the large volume of leachate flowing through it at any given time. This location is adjacent to the leachate collection pipe of the leachate collection system. However, the column experiments provide data that can be used to calibrate predictive models (Rowe et al. 1997; Cooke 1997; Cooke et al. 1999). With the model calibrated for the prediction of the experimental columns, it can further be used to predict the performance and service life of leachate collection systems under similar conditions.

### TSS–VSS results

VanGulck and Rowe (2002) demonstrated that TSS removal from leachate can significantly reduce the space available for leachate transmission. VanGulck (2003) also demonstrated that, in addition to precipitated minerals, the filtration and straining of suspended particles (retention of FSS) from the leachate onto the drainage media surface, especially in a partially clogged medium of low porosity and small pore sizes, can contribute to inert clog mass. The measured TSS and VSS concentrations from P1 (leachate collected just before entering the drainage material) averaged over the operational life of the rubber shred columns were 281 mg/L and 147 mg/L, respectively, and for the gravel column were 574 mg/L and 321 mg/L, respectively. On average, the influent TSS and VSS concentrations in the gravel column were twice those of the shred columns (as discussed later). Average effluent TSS and VSS concentrations over the operational life of the rubber shred columns were 176 mg/L and 123 mg/L, respectively, and for the gravel column were 205 mg/L and 142 mg/L, respectively. Both the rubber shred and gravel columns had similar averaged effluent TSS, VSS, and FSS concentrations.

The amount of FSS is calculated as the difference between the TSS and VSS concentrations in the leachate. The influent P1 TSS, VSS, and FSS concentrations were reduced by approximately 37%, 16%, and 60% in the rubber shred columns and 64%, 56%, and 75% in the gravel column — indicating that although TSS removal is significant in all columns the gravel column was the most efficient at removing TSS from the leachate as it passed through the column. Considering the higher removal efficiencies combined with higher influent TSS concentrations in the gravel column, more FSS will be retained in the gravel column relative to the shred columns. The retained FSS portion of the total clog mass was calculated based on the decrease in FSS concentrations as the leachate passed through the columns (Table 1). Table 1 does not account for the increase in mass due to the precipitation of calcium onto FSS flocs and will therefore underestimate the actual FSS clog mass in the columns. The G and P shreds had approximately 1/4 and 1/2, respectively, as much retained FSS as the gravel column. The high velocity of the leachate in the confined pore structure of the shred columns and thinner active biomass thicknesses, especially once significant clog developed in the void volume, kept the TSS in solution and resulted in a less efficient filtration–straining of TSS from the leachate. Also, lower retention times of the leachate under such conditions would result in less time for calcium to precipitate onto FSS flocs, which would further reduce removal efficiencies of TSS in the shred columns. Both the P and G shreds had similar initial porosities, yet the more confined pore structure and more tortuous flow environment of the G shred resulted in less FSS accumulation, indicating that again the differences in pore structure (in shred material of similar initial porosity) likely had an effect on the amount of FSS clog that accumulated in the material.

Geochemical modeling studies (Owen and Manning 1997; Bennett et al. 2000) have identified numerous calcium-bearing minerals that can potentially form as a result of the precipitation of calcium from supersaturated landfill leachates. Gounaris et al. (1993) and Jensen and Christensen (1999) have shown that calcium in landfill leachates was present in both a dissolved and a suspended solid (colloidal) phase. Samples from the influent, effluent, and along the length of all of the columns were obtained and analyzed for total calcium concentrations before and after filtration to determine what portion of the total calcium was dissolved in the leachate and what portion was undissolved or part of the solid phase FSS. The percentage of undissolved calcium (calcium fixed to the FSS) to the total mass of FSS in the sample in the source leachate was approximately 18%. In the columns it was approximately 36% (average of 16 measures) and is substantially higher than the source leachate, indicating that calcium is precipitating onto the FSS flocs as the leachate flows through the columns. Once appreciable amounts of precipitation have formed on a floc of FSS, the mass of the floc likely becomes too large to be carried by the flow of leachate through the drainage material – and the floc, abundant in calcium carbonate precipitate, will drop out of solution and become part of the soft clog developing on the drainage material (or potentially, could also settle to the bottom of the column if there is an unrestricted path). The accumulation of clog material having the consistency and size of saturated sand was observed during the disassembly of the

<table>
<thead>
<tr>
<th>Column</th>
<th>Measured total dry clog mass (kg)</th>
<th>Calculated FSS retained mass (kg)</th>
<th>Ratio of precipitated mass to FSS retained mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1(P)</td>
<td>5.2</td>
<td>0.73</td>
<td>6.2</td>
</tr>
<tr>
<td>R3(P)</td>
<td>6.6</td>
<td>0.84</td>
<td>6.9</td>
</tr>
<tr>
<td>R2(G)</td>
<td>4.7</td>
<td>0.43</td>
<td>10.0</td>
</tr>
<tr>
<td>R4(Gravel)</td>
<td>9.9</td>
<td>2.10</td>
<td>3.7</td>
</tr>
</tbody>
</table>

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columns. Samples of this clog material were collected and dried and mixed with epoxy and made into thin sections for scanning electron microscope (SEM) imaging (Fig. 8) and also energy dispersive X-ray (EDX) analysis to obtain a semiquantitative analysis of the composition of the clog material. As seen in Fig. 8 the size of the individual grains typically ranges from 0.1 to 0.6 mm in diameter, which corresponds to the size of fine to medium sand. The individual clog particulates were not cemented to each other. The particles appeared to be primarily uniform and homogeneous throughout with no apparent structure (no layering was observed on the cross-sectional plane of the particles). As indicated by the EDX mapping, most of the particles were predominantly composed of calcium, carbon, and oxygen, likely in the form of calcium carbonate. Magnesium, iron, and sulfur were also encountered but in much smaller amounts, along with traces of aluminum and silicon.

The accumulation of this type of clog material was more abundant in the gravel than in the shred columns and was observed within the larger voids in sections 4, 5, and 6 of the P shred material; within a few of the largest voids in the G shred material; and throughout R4(Gravel). The highly compressible nature of the rubber shreds and the resulting confined pore structure and more tortuous flow conditions (than those of the gravel column) combined with the extensive clog development created an environment or conditions in which dissolved calcium cannot as readily or does not have enough time to precipitate onto the FSS flocs in the rubber shred columns and shortened the time in which this clogging mechanism occurred or decreased its effectiveness as a clogging mechanism. In addition, the less abundant supply of calcium in the upper sections of the columns may result in less calcium being available to precipitate onto the suspended flocs. The less aggressive flow environment resulting from the open pore structure allowed the precipitation of calcium onto FSS to occur for longer periods of time within the gravel column than in the rubber columns.

During the majority of the operating life of the gravel column, soft clog was forming because of a clogging mechanism that involved the precipitation of calcium onto the FSS within the gravel. This coincides with the observed nonlinear clog formation rates in the gravel column and the uniform development of clog within all sections of the gravel column (even though the treatment of leachate throughout the column is not uniform). It also relates to the fact that even when the drainable porosities for the gravel filled column indicated significant clog formation had occurred, no significant increase in leachate head was required to maintain flow in the gravel. This is in contrast to the rubber shred columns, where for the same corresponding drainable porosity value, there was mostly hard inorganic clog and little active biofilm at the base of the columns when they were terminated as a result of significant clog development and the consequent need to develop high heads to maintain leachate flow.

Clog material accumulated in the base reservoir of every column. Drainable porosity results indicated that the initially empty reservoir volume of 2.5 L had reduced to less than 0.5 L after approximately 200 days of operation in all of the columns. Also, significant removal of COD and calcium was occurring in the reservoir of each column (Table 2) before the leachate entered the drainage material. The difference in leachate characteristics at P1 relative to the supplied influent characteristics in each column was due to the biological processes occurring in each column. The leachate passing through the base reservoir of R4(Gravel) experienced the greatest reductions. Concentrations of TSS in the leachate at P1 in all columns were substantially higher than in the source leachate, and on average the TSS and VSS concentrations from P1 in the gravel column were twice those of the shred columns. An EDX analysis of the material removed from the reservoir chamber after disassembly confirmed that the material in the reservoir, which had a form similar in size and shape to sand particles, was mainly composed of calcium, carbon, and oxygen. The difference in the leachate characteristics and the clog development process within each column is a consequence of the nature of the material in that column (the source leachate for all columns being the same) and thus is reflected in the hydraulic conductivity and drainable porosity results.

Unlike the very tortuous flow through the rubber shred filled columns, the settling out of FSS flocs from the leachate in the relatively open structure of the gravel drainage material would have a more direct and potentially result in a localized increase in TSS concentrations at the base of the gravel column relative to the rubber shred columns and also result in higher leachate treatment in the gravel reservoir than in the shreds. The tortuous pore structure of the rubber shred filled columns would limit this effect. In a field case scenario this sand sized clog material would settle out and accumulate at the bottom of a gravel drainage layer. As a result of the tortuous flow path in a tire shred drainage layer, this clog material would likely accumulate at the top of the tire shred layer.

Current design practices implemented to reduce the retention time of leachate in the saturated portion of a leachate collection system (through increased slopes of base contours) and to reduce the amount of FSS entering the leachate collection system (such as the use of a filter layer between the drainage material and the waste) will also likely reduce the effectiveness of this clogging mechanism and result in a smaller mass of clog material hence lowering oculde void space in time.

### Table 2: Reduction in COD and calcium concentrations within the reservoir chamber.

<table>
<thead>
<tr>
<th>Column</th>
<th>Average reduction COD %</th>
<th>Absolute (mg/L)</th>
<th>Calcium %</th>
<th>Absolute (mg/L)</th>
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<tbody>
<tr>
<td>R1(P)</td>
<td>26</td>
<td>2511</td>
<td>23</td>
<td>111</td>
</tr>
<tr>
<td>R3(P)</td>
<td>26</td>
<td>2628</td>
<td>23</td>
<td>142</td>
</tr>
<tr>
<td>R2(G)</td>
<td>23</td>
<td>2172</td>
<td>17</td>
<td>95</td>
</tr>
<tr>
<td>R4(Gravel)</td>
<td>45</td>
<td>3691</td>
<td>38</td>
<td>196</td>
</tr>
</tbody>
</table>

**Hydraulic conductivity – drainable porosity relationship**

The hydraulic conductivity drops with decreasing drainable porosity, as shown in Fig. 9. Rowe et al. (2000a) have suggested an empirical relationship between the hy-
Fig. 8. SEM image (top) and EDX map of elements from sand sized clog material removed from R4(Gravel) at termination.
Hydraulic conductivity \( (k) \) and the drainable porosity \( (n) \) as follows:

\[ k = A e^{bn} \]

The rubber shred experiments resulted in coefficients of \( A = 5.26 \times 10^{-6} \text{ m/s} \) and \( b = 32.1 \) \( (r^2 = 0.92) \).

Hydraulic conductivity was calculated from the measured flow rate and the head differences between adjacent piezometers. The highest hydraulic conductivity that could be measured during normal operation of the column experiments at the prescribed flow rate of 0.4 m\(^3\)/m\(^2\)/d was approximately 10\(^{-4} \text{ m/s} \). With an average initial vertical hydraulic conductivity in the gravel column (0.78 m/s) over three orders of magnitude greater than this, there is a large gap in the available data with respect to measured hydraulic conductivities and their associated drainable porosities above hydraulic conductivities of 10\(^{-4} \text{ m/s} \). Sufficient measurements were not attainable from this experimental program to fully define the relationship between hydraulic conductivity and drainable porosity for the gravel column, however, if an exponential relationship is assumed, then the data suggest that \( A = 1.19 \times 10^{-5} \text{ m/s} \), \( b = 24.6 \), and \( r^2 = 0.92 \).  

**Conclusions**

Changes in leachate characteristics and drainable porosity caused by clogging were monitored over a period of up to two years in four experimental test columns filled with full sized drainage material (rubber tire shred or conventional gravel) permeated with real municipal solid waste leachate. Prior to the study, it was not known how the compressed pore structure of the rubber tire shred differed from conventional gravel or what its affect would be on the extent of clog development within the tire shreds. This work has shown the following:

1. The shape and size of the rubber shreds, along with their relatively high compressibility, resulted in a pore structure that differed significantly from the gravel material. The compressible nature of the rubber shred material under vertical loads resulted in numerous narrow constricted–confined pathways and voids that connected relatively isolated larger pores. The gravel drainage material had large relatively uniform void sizes and generally an open void structure.

2. Direct precipitation of calcium to form hard inorganic clog material on the fixed drainage medium formed an important part of the clogging process; especially for the shreds. However, there was also a significant component of clog material (especially for the gravel column) that arose from precipitation of calcium onto FSS that caused flocs to drop out of suspension in the leachate and accumulate as relatively loose sand sized clog material in the pore spaces of the drainage materials.

3. Differences in the pore structure in the rubber tire shred
and gravel drainage materials affected the relative importance of this clog mechanism in each of the drainage materials. The high initial porosity and resulting open void structure and less tortuous flow environment allowed the gravel column to operate for an extensive time wherein clog development caused by precipitation of calcium onto the FSS and TSS retention contributed significantly to occluding the gravel void volume (during this time clog development was fast and uniform). However, once the majority of the pore volume became filled with clog material, the potential for this clogging mechanism to form additional clog material was reduced and the development of a hard inorganic clog material resulting from direct precipitation of calcium occurred at a much slower rate. The clogging rate became nonlinear within the gravel column.

(4) The tortuous flow regime in the shred material was substantially influenced by high velocity leachate flow, short leachate retention times, and high imposed leachate shear stresses in constricted openings between larger pores. Thus the structure also resulted in a nonuniform leachate flow during column operation. The clog material removed from the tire shred columns had less retained FSS clog mass than that from the gravel column, and the clogging was predominantly due to the direct precipitation of calcium, which formed hard inorganic clog material.

(5) Clogging is affected by more than the total void space available to be clogged and is in fact a function of the critical opening sizes, which were substantially smaller for the tire shreds than for the gravel. More clog formation was required to bridge over the longer distances and to fill the larger volumes in the gravel versus the narrow constrictions and smaller pore throats in the shred material (before the clog material affected the flow of leachate through the drainage materials). During the disassembly of the G shred column only the narrow constrictions, voids, and pathways that connect the relatively isolated larger pores were occluded with clog material and not the entire void volume.

(6) The compressible nature of the rubber shreds resulted in a lower percentage of the total exposed surface area in open void spaces where unconfined–unrestricted growth of active biofilm and inactive clog deposition could occur.

Differences in the pore structure of the rubber tire shred and gravel drainage materials had a significant impact on the extent of clogging and relative performance of the different drainage materials. The lower initial porosity combined with the more complex pore structure resulted in substantially faster (i.e., three times) clogging in the tire shreds than in the gravel.

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**References**


