

# Clogging of Tire Shreds and Gravel Permeated with Landfill Leachate

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**Abstract:** The clogging of tire shreds and gravel is based on four column tests permeated with landfill leachate for up to 2 years. Two different types of tire shred (G shred: 100 mm × 50 mm × 10 mm; and P shred: 125 mm × 40 mm × 10 mm with many exposed wires) and a uniformly graded 38 mm gravel were examined. The compressibility of the G and P shreds at 150 kPa were reported to be 48 and 44%, respectively while the initial hydraulic conductivities were 0.007 and 0.02 m/s, respectively (compared to 0.8 m/s for the gravel). The gravel maintained a hydraulic conductivity greater than  $10^{-5}$  m/s for about three times longer than a similar thickness of compressed (at 150 kPa) tire shreds. The tests were conducted at an accelerated flow rate of  $0.4 \text{ m}^3/\text{m}^2/\text{day}$ . At termination of the rubber shred columns after about 1 year the hydraulic conductivity at the influent end of the columns had dropped to between  $10^{-7}$  and  $10^{-8}$  m/s. At termination of the gravel columns after 2 years the corresponding range was  $10^{-6}$ – $10^{-7}$  m/s. The clog was predominantly calcium carbonate, with calcium making up 29–34% of the total clog material. Aluminum, zinc, iron, and copper leached from the P and G shreds when exposed to typical municipal solid waste leachate, however they were not detected in the effluent leachate. The highest concentration of metals was found in the P-shred clog and this is attributed to the greater abundance of exposed steel in these shreds. It is inferred that gravel should continue to be used in critical zones where there is a high mass loading. The results suggest that an increased thickness of compressed tire shred may be used to give a service life similar to that of a given thickness of gravel in noncritical zones.

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## Introduction

Leachate collection systems are extensively used in modern landfills to control the leachate head acting on the landfill base and hence minimize contaminant impact on the environment. These systems commonly comprise perforated leachate collection pipes at regular spacing in a continuous blanket of uniformly graded granular material. Field experience (Brune et al. 1994; Fleming et al. 1999; Maliva et al. 2000; Bouchez et al. 2003) shows that a biological slime (biofilm) grows on the material in the collection layer and that this is followed by biologically induced deposition of inorganic constituents (e.g., calcium carbonate) from the leachate that can cause the collection systems to literally “cement up” and become more like cracked concrete than a drainage layer. The clog that develops decreases the pore space available to transmit leachate, reduces the hydraulic conductivity of the granular layer and consequently reduces the efficiency of the leachate collection system. Since these systems may be required to collect and remove leachate for extended periods of time, it is important

that they be designed to optimize their long-term performance and service life.

One means of extending this service life of leachate drainage systems is to use uniformly graded gravel (Rowe et al. 2004) as the drainage material. Shredded scrap tires have been proposed as an alternative drainage material based on their high hydraulic conductivity (Hall 1991; Edil et al. 1992; Ahmed and Lovell 1993; Duffy 1995). Design considerations such as permeability under high waste fill stresses (Reddy and Saichek 1998b; Benson et al. 2002) and puncture damage to underlying geomembrane component of the composite liner system (Reddy and Saichek 1998a) have been recognized and investigated. However, the potential for clogging of rubber tire shreds, and their performance in transmitting leachate, relative to conventional gravel, has not been previously investigated.

The primary objective of this study is to provide data that could be used to provide insight regarding the extent to which tire shreds will clog and to provide data that could be used to assess how the service life of rubber tire shreds might compare with that of more conventional gravel. A second objective is to characterize the tire shreds examined (in terms of compressibility, dry density, specific gravity, initial porosity, and initial hydraulic conductivity) and examine the potential leachability of contaminants from rubber shred drainage material. Finally, the paper discusses design considerations relating to the use of rubber tire shreds in leachate drainage systems.

## Methodology

Four polyvinyl chloride (PVC) columns were constructed with an internal diameter of 287 mm and a total length of 813 mm (Fig.

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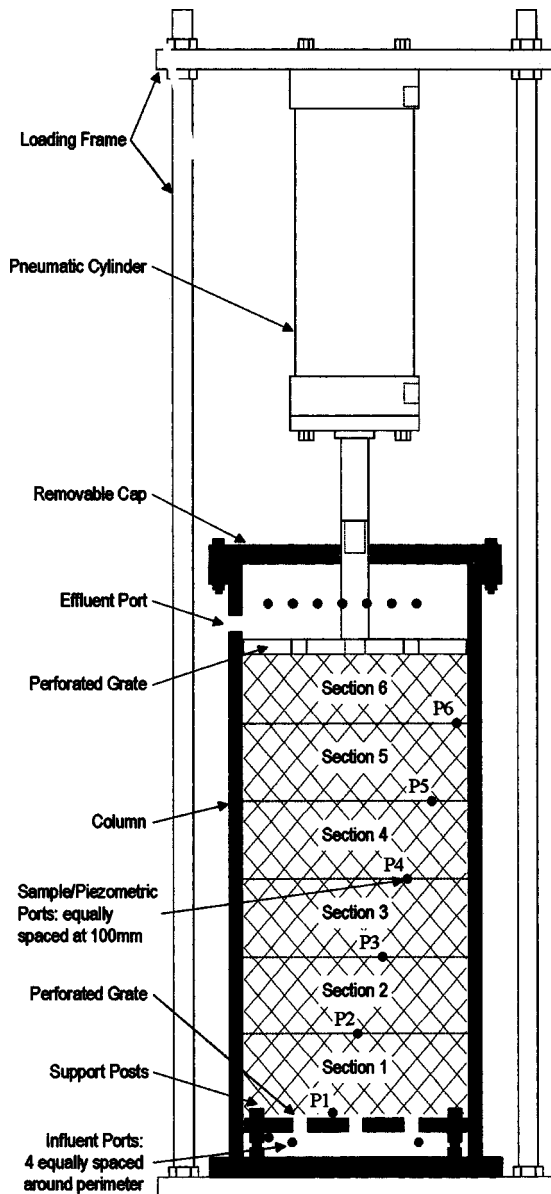


Fig. 1. Experimental column in load frame

1). Two duplicate cells [R1(P) and R3(P)] were filled with a tire shred denoted as "P shred." One column [R2(G)] was filled with tire shred denoted as "G shred" and the fourth column [R4(gravel)] was filled with conventional uniformly graded gravel (the characterization of these materials is provided in the following section). The drainage materials were loosely placed into the columns. A loading frame was used to simulate the weight of waste and to compress the tire shreds at a stress of 150 kPa. To assess the loss in applied load due to side wall friction, load cells were placed at the base of the columns to measure pressures at the base under known applied pressures for differing sidewall treatments. A sidewall treatment consisting of four layers of 6 mil (0.15 mm) plastic placed between the rubber shreds and the PVC pipe wall was selected. It resulted in approximately 80% of the applied load being transmitted to the base of the columns. The compressed height of drainage material ranged between 550 and 610 mm. Fresh leachate was collected weekly from the Keele Valley Landfill (KVL) (Toronto, Canada). The fresh leachate was kept stirred in a series of storage tanks in a room maintained at a

temperature of  $7 \pm 2^\circ\text{C}$ . The leachate was delivered by gravity as required to a manifold which allowed for temperature equalization to that of the columns (i.e.,  $27 \pm 2^\circ\text{C}$ ). Leachate from the manifold was pumped into the base of the columns (each column using a dedicated variable-speed peristaltic pump each with four dedicated pump channels) and flowed upward through the saturated drainage material and exited out the effluent port and discarded. The nominal flow rate of  $0.4 \text{ m}^3/\text{m}^2/\text{day}$  was selected to simulate an accelerated rate of mass loading (to allow experiments to be completed in a reasonable period of time) but not so high as to change the processes occurring in the drainage material. These tests were conducted to establish the rate of clogging in the more critical regions where flow is concentrated near the leachate collection pipes (Fleming et al. 1999). The time required to clog an area of leachate collection system can be approximately estimated knowing the leachate flow rate through that zone and the time to clog at the nominal flow rate in these experiments. More importantly these experiments provide an indication of the relative performance of tire shreds and coarse gravel. Studies of the effect of flow rate and mass loading on clogging have been reported by Rowe et al. (2000a).

The tests were conducted at  $27 \pm 2^\circ\text{C}$  to simulate the conditions anticipated in an active leachate collection system (Rowe et al. 2004). The spatial and temporal changes in leachate characteristics, drainable porosity, and hydraulic conductivity were monitored over a period of up to 2 years using piezometers equally spaced along the columns at 100 mm intervals. This divided the columns into six sample sections as illustrated in Fig. 1. The hydraulic conductivity was calculated from the measured flow rate and the head differences between adjacent piezometers. Apart from the initial values (which could be obtained at flow rates much higher than what could reasonably be used during the clogging tests), the hydraulic conductivity could not be obtained until the clogging was sufficient to create a measurable head difference between adjacent piezometers at the prescribed flow rate. This corresponded to the hydraulic conductivity dropping to about  $10^{-4} \text{ m/s}$  at the specified flow rate of  $0.4 \text{ m}^3/\text{m}^2/\text{day}$  (a decrease in hydraulic conductivity by 2 orders of magnitude for the rubber shred drainage material and over 3 orders of magnitude for the 38 mm gravel).

Since the tire shred clogged much early that the gravel the volumes of leachate that were permeated through the shreds and gravel (and hence the total mass loading) at termination were quite different with cumulative flows at termination of 8,670, 8,440, 9,450, and 16,240 L for Columns R1, R2, R3, and R4, respectively. Once testing was terminated, the columns were disassembled and the clogged drainage material was removed in 50 mm intervals. Mass measurements were used to obtain clog properties such as the amount of wet, dry (weight loss due to evaporated water in an oven at  $105^\circ\text{C}$ ) and ash material (weight loss on ignition in a muffle furnace at  $550^\circ\text{C}$ ). The bulk density of the clog material was measured using a modified *ASTM D854* method. The dry (volatile and nonvolatile solids, excluding water) and ash (nonvolatile solids, excluding water) densities of the clog were calculated using the *ASTM D854* method. Clog samples were sent for elemental analysis.

## Material Characterization

Tire shred samples processed under different operating conditions do not produce the same properties therefore it is important to characterize each tire shred type being considered for use as a

**Table 1.** Material Characteristics

Characteristic	G shred	P shred	Gravel
Length (mm)	50–150	40–300	—
Width (mm)	25–75	25–100	—
Thickness (mm)	3–20	3–20	—
Average dimensions (mm)	100 × 50 × 10	125 × 40 × 10	—
Average aspect ratio	2:1	3:1	—
$D_{85}$ (mm)			37
$D_{10}$ (mm)			25
Uniformity coefficient $D_{60}/D_{10}$ (—)			1.2
Specific gravity [average] (—)	1.13–1.22 [1.17]	1.18–1.35 [1.25]	2.67–2.72 [2.69]
Compression under 150 kPa	48%	44%	—
Dry density—loose ( $\text{kg}/\text{m}^3$ )	440–450	440–480	1,370
Dry density ( $\text{kg}/\text{m}^3$ ) <sup>a</sup>	850–900	825–1,000	—
Initial porosity (—) <sup>a</sup>	0.24	0.27	0.46
Initial hydraulic conductivity ( $\text{m}/\text{s}$ ) <sup>a</sup>	0.007	0.024	0.78

<sup>a</sup>Under test conditions (150 kPa).

leachate drainage material. Initial compressed void space (porosity) and initial compressed hydraulic conductivity values are the primary factors influencing clogging. Compressibility, bulk dry density, and size are important to classify and characterize the tire shred drainage layer.

In general the shredded tire material was comprised of irregularly shaped pieces. The G shreds generally had clean-cut edges and most of the shreds were very similar in size and shape producing a very uniform product. The G shreds consisted mainly of sidewall material with the bead wire still in place. The surfaces of the shreds were relatively smooth and without any deep grooves associated with the tread portion of the tires. Less steel wire was exposed in the G shred due to the cleaner cut and the length of the exposed steel wire was short, however the exposed steel was composed of heavier gage bead wire than that of the P shred.

The P shreds had jagged edges that appeared to be torn apart rather than cut into pieces. There was a significantly greater number of frayed steel wires protruded from the P shred edges than for the G shred. The length of the protruding steel wire was also greater for the P shreds than for the G shreds. The P shred was comprised of a mix of shred from both the sidewall and the tread portions of the tires. The size and shape of the P shreds was far less uniform than the G shred.

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

The distribution of particle size, and range of specific gravity, dry density, porosity, and hydraulic conductivity are given in Table 1 for the tire shreds and gravel. The specific gravity of the G shred, which had less protruding wire, had a narrower range than the specific gravity of the P shred, with the difference in measured values being dependent on the metal content in the shreds. The specific gravity of the gravel was more than twice the average value for the tire shreds. The tire shreds were very compressible and experienced a compression (change in height over initial height) of about 48 and 44% for the G and P shreds, respectively, at an applied vertical stress of 150 kPa. Thus unlike the relatively incompressible gravel, a significant thickness of tire shred (almost twice the design thickness in this case) must be placed in the loose state to ensure that the design thickness of material is present when the vertical stresses due to the waste is applied. As a consequence of the compressibility of the shreds, there was a significant difference in the dry density of the loose shreds and the compressed shreds at 150 kPa (Table 1). Neverthe-

less, the compressed (at 150 kPa) shreds had bulk dry densities approximately 30–40% less than the gravel.

The average initial porosity in the duplicate Columns R1(P) and R3(P) were 0.27. The average initial porosity was 0.24 for Column R2(G) and 0.46 for R4(gravel). Thus the compressed tire shreds (at 150 kPa) had an initial porosity approximately 41–48% of the gravel. All materials had high initial vertical hydraulic conductivities, however the value for gravel (0.78 m/s) was 1–2 orders of magnitude higher than for the P (0.024 m/s) and G (0.007 m/s) shred. The difference between the P and G shred values is primarily attributed to differences in the packing of the shreds related to shred size and shape.

### Influent Leachate Characteristics and Leachate Quality Results

The experimental columns commenced operation in February 2001. The concentration of key raw leachate constituents from KVL were lower in 2001 than in previous years likely due to treatment of the leachate in the KVL leachate collection system before it reaches the collection sump (Rowe and VanGulck 2003). Since the leachate collected had been subjected to treatment it was not representative of young leachate. In order to have a composition [especially in key components such as chemical oxygen demand (COD) and Ca] similar to earlier Keele Valley Landfill leachate, the leachate feedstock for the columns was spiked. Calcium chloride dihydrate ( $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ ) was added to the raw Keele Valley Landfill leachate to increase the calcium concentration. A mixture of acids comprised of acetic, propionic, and butyric acid in a ratio of 20:10:1 was also added to the raw leachate to raise the COD concentration. The leachate supplied to each column was from the same source.

Since the leachate coming from Keele Valley is highly variable, the changes in the influent COD, Ca concentrations, and pH were monitored and the variation in influent leachate concentrations are shown in Fig. 2 (solid symbols). For the first 9 days the average influent COD concentration was below 4,250 mg/L. From 10 to 135 days the influent COD concentration ranged from 4,950 to 9,210 mg/L with an average of 6,900 mg/L. From 135 days to completion, COD ranged from 4,155 to 16,055 mg/L with an average value of 9,820 mg/L. For calcium, the concentration was approximately 100 mg/L for the first 50 days of op-

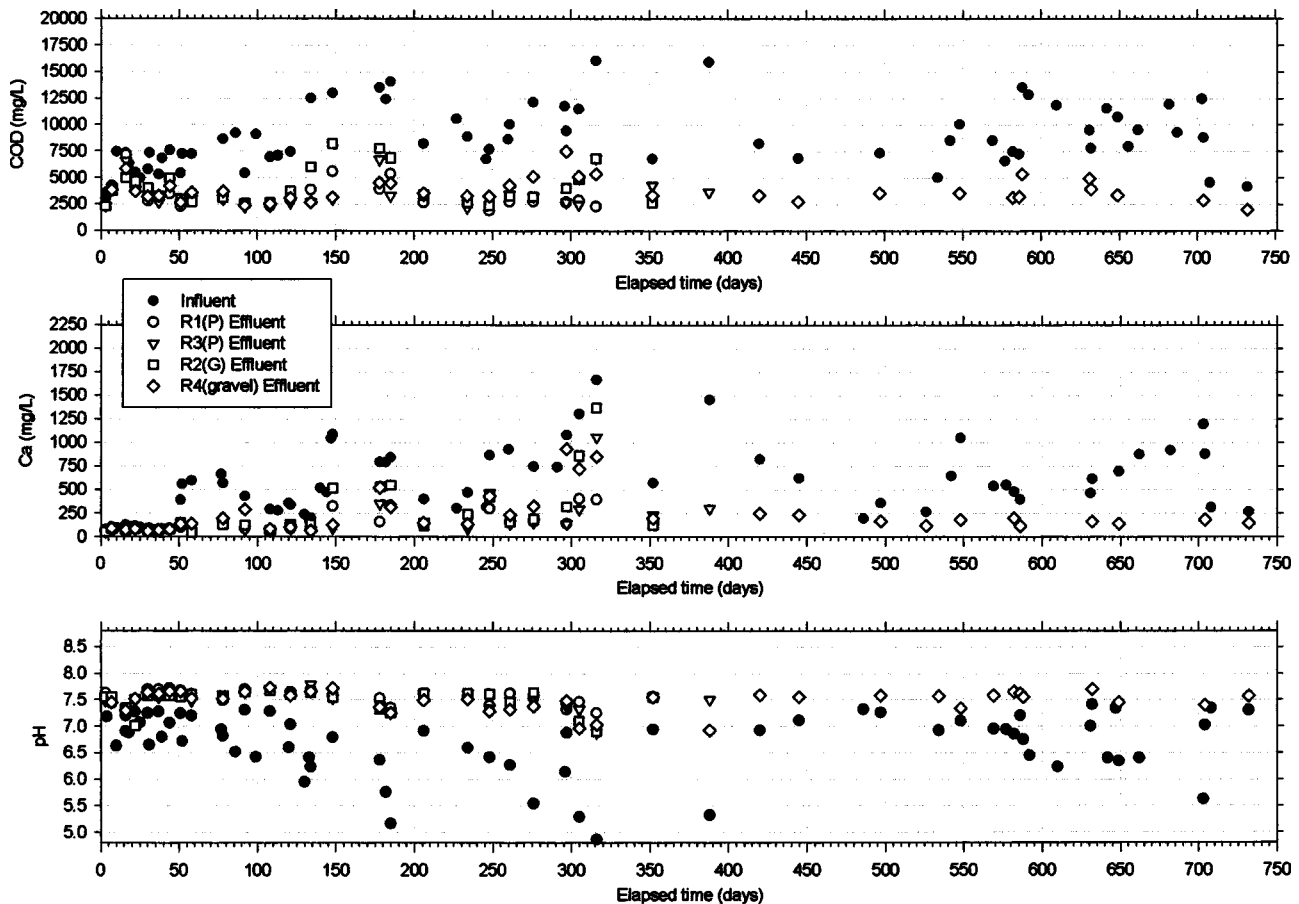


Fig. 2. Variations in chemical oxygen demand and Ca concentrations and pH in influent and effluent leachate with time

eration. From 50 to 135 days the influent concentration ranged from 180 to 665 mg/L with an average concentration of 395 mg/L. Subsequently the Ca concentration ranged from 195 to 1,665 mg/L with an average value of 730 mg/L. For the first 135 days the pH values in the influent leachate ranged from 6.7 to 7.2 with an average value of 7.2. After 135 days the pH ranged from 4.8 to 7.2 with an average value of 6.2.

Since it takes time to establish the biofilm (on the drainage material) needed to cause significant leachate treatment, there is an initial lag period during which there is relatively little difference between influent and effluent concentrations (Fig. 2) and the effluent COD concentrations were generally about 90% or more of the influent concentration. This acclimation period (lag time) was similar for all columns and was less than 50 days for both the gravel and tire shred material. Once the biofilm was established there was a significant reduction in COD and Ca concentrations as the leachate passed through the columns irrespective of the type of drainage material (tire shred or gravel). Thus similar reductions in COD and Ca concentrations were observed for all columns (Fig. 2). In general, constant effluent pH values were measured throughout the operation of the columns despite variations in the influent pH measurements. Likewise, after the acclimation period, relatively stable steady state effluent COD concentrations were measured except at times when the columns had much higher than normal influent organic loading. At these times the effluent concentrations were elevated (i.e. less relative treatment) for all columns. This is likely the result of the inability of the mixed population of bacteria to adapt to the increased concentrations within a short period of time.

Acetic, propionic, and butyric acid concentrations were measured within the influent and effluent leachate with time. Similar reductions in acid concentrations were observed in all of the columns. All of the columns were more efficient at removing acetic acid than propionic acid throughout the testing period.

The variations in the water quality of the leachate as it passed through both the rubber shred and gravel filled columns are consistent with the leachate chemistry study by Rittmann et al. (1996). An environment conducive to clog development or the precipitation of  $\text{CaCO}_3$  is established within the leachate as it passes through the drainage material. Rittmann et al. (1996) showed that the loss in COD (primarily due to fermentation of acetic acid to carbonic acid) and production of carbonate resulted in a shift in pH to higher values. The shift in pH in conjunction with the increased carbonate concentration promoted the development of inorganic clog material (predominantly calcium carbonate).

### Hydraulic Conductivity Results

The change in hydraulic conductivity with time in each section of the columns was monitored to assess how long it would take for clogging to cause a reduction in hydraulic conductivity such that mounding would likely occur in a landfill. The onset of significant clogging was indicated by a notable increase in head at the piezometers along the columns (at the specified flow rate). This typically corresponded to a drop in hydraulic conductivity to

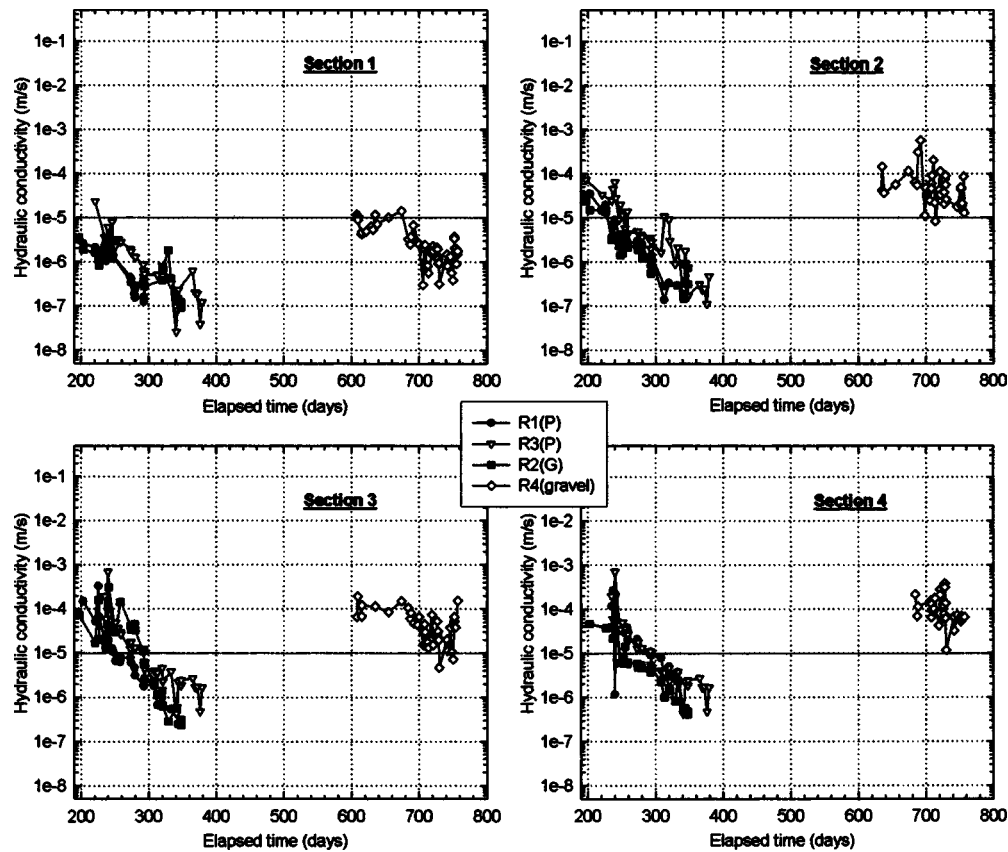


Fig. 3. Hydraulic conductivity versus elapsed time at four sections for each column (Section 1 is at inlet end of column)

about  $10^{-5}$  m/s. A decline in hydraulic conductivities with time was measured in all sections of the rubber tire shred columns and within the first four sections of the gravel column. However the time required to get the drainage material to drop to  $10^{-5}$  m/s (and especially to drop below  $10^{-6}$  m/s) varied significantly between the tire shred and gravel columns. From Figs. 3 and 4, it can be seen that the gravel column outperformed the compressed (at 150 kPa) rubber shred columns by both maintaining a hydraulic conductivity through the material greater than  $10^{-5}$  m/s for approximately three times longer (i.e., requiring passage of approximately three times as much leachate) than the tire shred.

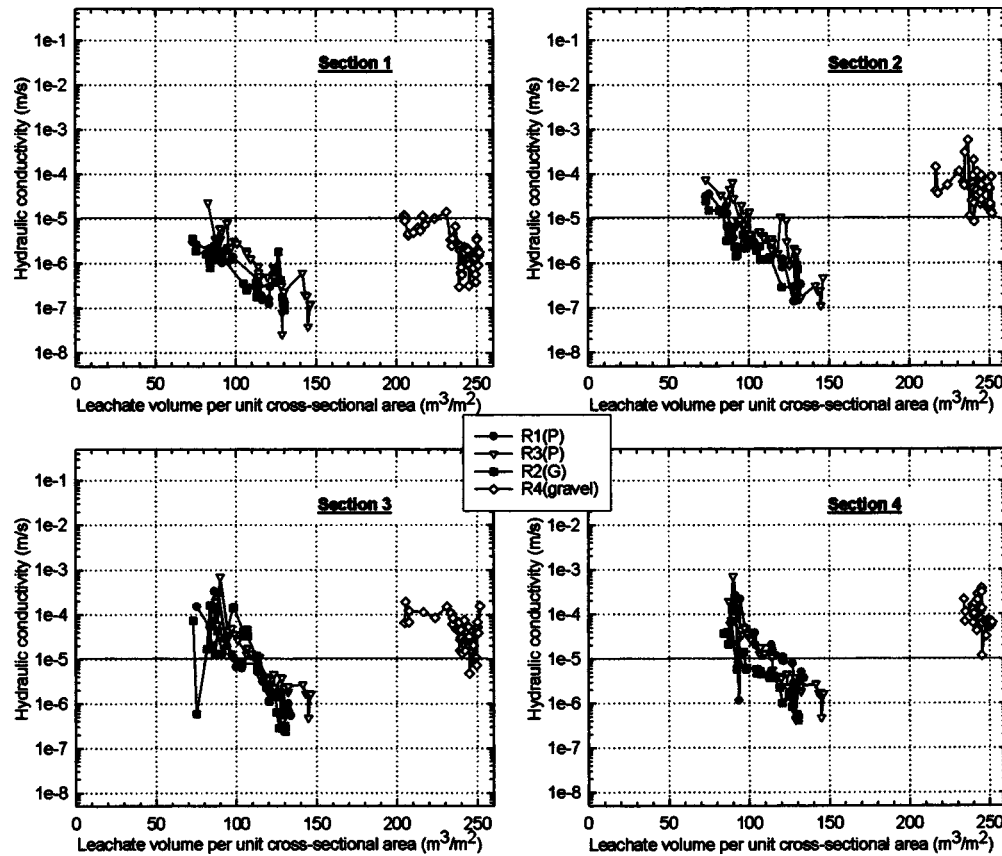
This effect is similar to the effect observed in a column study by Rowe et al. (2000b) that examined different particle bead sizes (15, 6, and 4 mm). In that study the pore spaces between the larger particles (15 mm) remained free of obstructions for a greater period of time than the smaller particles (6 and 4 mm). Although the initial average porosity measured in the compressed shreds [ $R1(P)=0.27, R3(P)=0.27, R2(G)=0.24$ ] was a little less than half that of the gravel drainage material [ $R4(gravel)=0.46$ ], the time required to cause clogging of the gravel to the  $10^{-5}$  m/s level was more than three times as long. Thus the 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 larger and more uniform for the gravel than for the tire shreds (McIsaac and Rowe, private communication, 2003). Assuming similar clogging rates for both the rubber shreds and the gravel drainage material, as has been suggested by some (Duffy 1995), would overpredict the service life of a leachate collection system constructed of rubber tire shreds (similar to those used in this study).

Section 1 (i.e., the section nearest to the influent) experienced

the greatest decrease in hydraulic conductivity for all columns. For the rubber shred filled columns, the hydraulic conductivities decreased to  $10^{-7}$  m/s (or less) and a head difference of approximately 2.95 m ( $i=29.5$ ) could not maintain the design flow rate through the columns. Longer times (larger volumes of leachate) were required to reach equivalent hydraulic conductivities within each section of each column as the distance from the base in the rubber shred or gravel filled columns increased. This is due to the consumption of COD and Ca in the lower sections and less nutrient supply to consecutively higher sections.

Subtle differences in the hydraulic conductivity results with time within the individual sections for the differing shred columns suggest that the development of clog material in the void space may vary due to differences in pore structure that exist between different shred types and sizes. Within the sections illustrated in Figs. 3 and 4, equivalent hydraulic conductivities were measured in R2(G) essentially at the same times as in R1(P), irrespective of the fact that less initial void volume was required to be filled with clog material in R2(G). The development of clog material in the void space with time appears to be slightly dependant of the shred type, either P or G shred, used in a leachate collection system drainage layer. In Sections 1–3 of the duplicate columns filled with P shred, R3(P) required slightly longer times for the hydraulic conductivity to reduce to the same value as in R1(P). Column R3(P) was filled with slightly larger shred material than R1 within these sections and this likely resulted in slightly larger pore throats that needed to fill with clog material.

Defining the onset of significant clog as the time at which the hydraulic conductivity drops to approximately  $10^{-5}$  m/s, the time to reach significant clog is summarized in Table 2 for four sections of each column. Averaging the relative performances over



**Fig. 4.** Hydraulic conductivity versus leachate volume permeated through column at four sections for each column (Section 1 is at influent end of column)

the first 300 mm (Sections 1–3—since Section 4 of the gravel never really dropped below  $10^{-5}$  m/s) it can be seen (Table 2) that the compressed shred (at 150 kPa) is likely to have a service life that is approximately three times less than a gravel drainage material operating under the same conditions.

The column experiments physically represent a very small portion of the drainage blanket of a leachate collection system. The columns are 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. The column experiments are not representative of the entire drainage blanket of a leachate collection system and therefore cannot be used directly to predict the service life of such LCS. However, the data provide an indication of the likely relative performance of similar thicknesses of drainage material in a drainage blanket. Based on the empirical data one can infer that the service life of a given thickness of leachate collection system with 38 mm gravel will be approximately three times longer than a similar (compressed at 150 kPa) thickness of tire shreds. At termination of the rubber shred columns after about 1 year the hydraulic conductivity at the influent end of the columns had dropped to between  $10^{-7}$  and  $10^{-8}$  m/s. At termination of the gravel columns after 2 years the corresponding range was  $10^{-6}$ – $10^{-7}$  m/s.

### Leachability

The principal component of tires is a blend of natural and synthetic rubber (mixture of vulcanized or cross-linked polymers)

**Table 2.** Estimated Times at which Significant Clog Conditions Have Occurred in Each Section of Columns and Relative Performance of Rubber Shreds to that of Gravel

Column	Section	Time to reach significant clog conditions (days) <sup>a</sup>	Relative performance <sup>c</sup>
R1(P shred)	4	295	—
	3	250	3.0
	2	250	3.1
	1	155	3.9
R3(P shred)	4	295	—
	3	290	2.6
	2	255	3.0
	1	210	2.9
R2(G shred)	4	250	—
	3	290	2.6
	2	230	3.4
	1	180	3.3
R4(gravel)	4	<i>N/R</i> <sup>b</sup>	—
	3	750	—
	2	770	—
	1	600	—

<sup>a</sup>The time to reach significant clog is taken to be the time required for the hydraulic conductivity to reduce to approximately  $1 \times 10^{-5}$  m/s.

<sup>b</sup>*N/R*: experiments were terminated after 2 years but before significant clogging occurred at this location.

<sup>c</sup>Relative performance=ratio of the time to reach significant clog conditions in a gravel section to the time to reach significant clog conditions in the same section of the rubber shred.

**Table 3.** Concentration of Metals in Influent and Effluent Leachate of Column R3(P)

Parameter	Influent	Effluent
Aluminum (Al)	0.75	<0.3
Arsenic (As)	0.16	<0.1
Barium (Ba)	0.48	<0.4
Cadmium (Cd)	<0.02	<0.02
Calcium, dissolved (Ca)	1,750	288
Chromium (Cr)	<0.2	<0.2
Cobalt (Co)	<0.2	<0.2
Copper (Cu)	<0.1	<0.1
Dissolved silica as SiO <sub>2</sub>	36.1	37.3
Iron (Fe)	23.5	3.83
Lead (Pb)	<0.3	<0.3
Magnesium, dissolved (Mg)	308	287
Manganese (Mn)	0.24	<0.2
Mercury (Hg)	<0.1	<0.1
Nickel (Ni)	<0.5	0.51
Phosphorus (as P)	9.08	4.25
Potassium, dissolved (K)	1,100	1,060
Sodium, dissolved (Na)	3,020	3,020
Sulfur (S)	32.6	33.8
Zinc (Zn)	<0.1	<0.1

Note: Concentrations are in mg/L.

black, reinforcing agents (silica, resin), curatives (sulfur), softeners and extenders (oils, tackifiers), antidegreasers (paraffin waxes), age resistors (antioxidants), cure activators (zinc oxide, stearic acid, lead oxide), pigments (titanium dioxide), fabrics, and bead and belt structural material (steel, nylon, aramid, fiber, rayon, fiberglass, polyester). Due to the composition and curing process, tires do retain their basic chemical properties and physical shape but obvious concerns are raised by the possible effects of tire shreds on leachate composition and the possible degradation of the tire shreds in contact with the leachate. Leachability tests have shown that low levels of some organic compounds and metals can be released from the tire shreds (Minnesota Pollution Control Agency 1990; Zeliber 1991; Ealding 1992; Humphrey et al. 1997; Humphrey and Katz 2001) but when leaching did occur, the leached compounds were found at low concentrations (i.e., typically below drinking water standards or action levels). This indicates that testing the effects of tire shreds on landfill leachate quality under field conditions was warranted.

To provide initial insight regarding whether metals were being leached from the shred material as the leachate passed through the columns, influent and effluent leachate from the P shred column was sent for analysis. As indicated in Table 3, the P rubber shreds exposed to municipal solid waste leachate for about 4 h (the mean residence time) did not experience an increase in metal concentration. This finding could be the result of a number of factors including insufficient contact time with the rubber shreds, the lack of freshly exposed rubber shred surfaces at the time of sample collection (due to the accumulation of clog material on the shreds), and the accumulation of the metals that are leached at lower levels in the column in the clog material further up the column. Irrespective of which mechanisms were involved, the fact remains that leachate from a municipal solid waste (MSW) facility passing through a partially clogged rubber shred drainage layer did not experience an increase in metal concentrations.

In a separate assessment of whether contaminants were being leached from the shred material, a sample of the influent and

effluent clog material from both the P and G shred columns were analyzed for metal concentrations at termination of the experiments (Table 4). The columns were started at approximately the same time, operated using the same source leachate and were terminated within 2 months of each other [R1(P) was the first column to be terminated]. Increased concentrations of metals were measured in the effluent clog material for almost all metals analyzed. Although higher metal concentrations were measured in the effluent clog, the total mass of clog present in the effluent sections was far less than in the influent sections. The two potential sources of metals are the influent leachate or the shredded tires.

Although numerous studies have indicated that metals can be released from tire shreds (Minnesota Pollution Control Agency 1990; Zeliber 1991; Ealding 1992; Humphrey and Katz 2001) no study has examined the uptake of these metals into the clog material, which could potentially prevent them from being released into the groundwater. Although low metal concentrations were measured in the source leachate as discussed above, the columns operated under high volumes of leachate and for a long duration allowing for potential buildup of metals in the clog material. Tire shreds operating under these conditions could both leach metals from the shreds and accumulate them in the clog material. The total mass of metals in leachate entering the column over the period of the experiment was calculated from the measured volume of leachate and its chemical composition. The total mass of clog within the columns was calculated based on the compositions and total mass of clog material at test termination. Table 5 provides ratios of the mass of elements found in the clog material to that entering the column in the leachate for the P, G, and gravel columns (note that the gravel columns were run for 1 year or more longer than the shred columns so the total potential mass for these columns is much higher). Comparing these estimates (Table 5), it is evident that the total mass of some metals, Al and Zn in the shred clog material of both shred columns and Fe and Cu in the P shred column, is far greater than the estimates based on the leachate analysis. For example, a conservative estimate (overestimate) of the mass of zinc based on the lower detection limit of 0.1 ppm in the source leachate operating for 349 days at a flow rate of 24 L/day would result in a total mass of 838 mg of Zn in the column assuming all is removed from the leachate. However, the mass of Zn in the shred clog is approximately 2–2.6 times this amount. While less clear, comparing the ratios for the shred columns with those for the gravel columns, there is also some evidence of accumulation of Mn and Ni for the P shreds. Comparing the estimated mass of metals in the clog material from the P shred column [R1(P)] to those of the G shred column [R2(G)], it is evident that the masses of iron, manganese, nickel, and copper are much higher for the P shreds than the G shred. This is likely due to the dissolution of the higher amounts of exposed steel wire in the P shred material, than in the G shred. There was much more exposed wire in the P shred and this wire was corroded at the time of disassembly. It is inferred that the majority of the mass of the metals Al, Zn, Fe, Mn, Cu, and Ni originated from other sources other than from the influent leachate (i.e., the tire shreds). Thus the data suggest that aluminum, zinc, iron, manganese, nickel, and copper were leached from the shreds but most became immobilized in the clog material and did not exit the columns in the effluent leachate. Although the data collected in this study provided useful insights, additional work is required to fully define the leachability of tire shreds used in leachate collection systems.

**Table 4.** Total Elemental Analysis of Clog Material from Rubber Shred and Gravel Columns

Parameter	Symbol	Units	Rubber shred columns									
			R1(P shred)		R2(G shred)		Gravel column R4(gravels)					
			Sec. 1	Sec. 6	Sec. 1	Sec. 6	Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sec. 5	Sec. 6
Water content		%/wet	35.31	56.30	40.41	54.74	43.20	62.62	65.45	60.88	71.23	43.20
Organic matter (TVS)		%/dry	11.93	17.24	10.46	15.71	6.85	8.04	8.24	8.33	9.11	9.29
Carbonate as CO <sub>3</sub>		%/dry	50.15	40.42	52.17	50.67	54.81	53.86	54.51	54.12	54.64	54.81
Calcium	Ca	%/dry	29.42	24.72	31.07	29.63	34.55	34.25	33.84	34.17	34.15	34.55
Magnesium	Mg	%/dry	1.15	1.17	1.31	1.44	1.91	1.79	1.74	1.61	1.58	1.91
Silicon	Si	%/dry	0.79	1.63	0.49	0.79	0.15	0.14	0.21	0.17	0.18	0.15
Iron	Fe	%/dry	1.57	10.83	1.01	1.16	0.43	0.45	0.48	0.50	0.51	0.43
Sodium	Na	%/dry	0.39	0.42	0.37	0.57	0.22	0.27	0.26	0.24	0.27	0.22
Aluminum	Al	%/dry	0.26	0.39	0.16	0.23	0.04	0.04	0.05	0.04	0.05	0.04
Potassium	K	%/dry	0.26	0.26	0.18	0.31	0.08	0.08	0.12	0.07	0.10	0.08
Phosphorus	P	%/dry	0.25	0.14	0.24	0.21	0.16	0.16	0.16	0.16	0.16	0.16
Titanium	Ti	%/dry	0.02	0.03	0.01	0.02	0.01	0.01	0.01	0.00	0.00	0.01
Manganese	Mn	%/dry	0.01	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Strontium	Sr	mg/kg	256	244	285	288	282	291	295	299	298	282
Zinc	Zn	mg/kg	227	741	222	562	116.0	—	—	—	99.2	116.0
Copper	Cu	mg/kg	194	464	46	87	122	—	—	—	105	122
Barium	Ba	mg/kg	111	113	113	110	118	124	110	112	105	118
Nickel	Ni	mg/kg	41	698	39	52	16.9	—	—	—	15.7	16.9
Lead	Pb	mg/kg	33	46	8	16	41.7	—	—	—	11.7	41.7
Boron	B	mg/kg	24	36	26	33	14	—	—	—	15	14
Chromium	Cr	mg/kg	18	33	16	32	6.0	—	—	—	5.6	6.0
Zirconium	Zr	mg/kg	16	27	15	23	12	9	15	13	7	12
Vanadium	V	mg/kg	8	12	8	11	5	<5	6	<5	<5	5
Cobalt	Co	mg/kg	7	31	6	6	1.5	—	—	—	1.6	1.5
Yttrium	Y	mg/kg	4	<1	<1	<1	2	1	2	<1	<1	2
Molybdenum	Mo	mg/kg	1	2	1	2	0.6	—	—	—	0.6	0.6
Silver	Ag	mg/kg	1	0	2	1	<0.05	—	—	—	<0.05	<0.05
Cadmium	Cd	mg/kg	0	0	0	0	<0.1	—	—	—	<0.1	<0.1
Scandium	Sc	mg/kg	<1	2	<1	1	<1	<1	1	<1	<1	<1
Beryllium	Be	mg/kg	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ca/CO <sub>3</sub>			0.587	0.612	0.595	0.585	0.630	0.636	0.621	0.631	0.625	0.630

Note: < implies not detected at that lower limit.

## Clog Characterization

### Distribution of Clog Mass

Fig. 5 shows the wet, dry, and volatile masses per unit volume of shred, the percentage of volatile clog, and the water content of the clog material at the time of column disassembly. The clog properties were normalized with respect to the volume of the shred material because the G shreds differed in shape and in size from the P shred, resulting in fewer G shreds per unit volume. Fig. 6 shows the distribution of initial void volume within the columns, volume of clog, the void volume occupancy (VVO) (i.e., the proportion of the original void space that was filled with clog material), and calculated porosity  $n$  at disassembly.

All columns had larger amounts of retained mass at the influent end (base) of the columns. There is a similar trend of a slightly decreasing measured clog mass removed from the different drainage materials with increasing distance from the base influent ports at the time of disassembly. Because the gravel columns started with a much higher initial porosity and were run twice as long as the shred columns, there was a greater accumu-

lation of clog material in the gravel columns and a much more uniform distribution of clog material than in the rubber shred columns.

Higher percentages of active degradable organic material to inactive nondegradable material (percent volatile in Fig. 5) were measured at the top of the shred columns ( $\approx 22\%$ ) compared to the base ( $\approx 11\%$ ). This decrease in percent volatiles toward the base of the column coincides with the relatively absent soft biofilm within the lower sections where significant clog had developed and where leachate velocities were high towards the end of the test. The percent volatiles were lower and more uniform along the gravel column than for the shred columns. The generally lower values are attributed to the much smaller surface area available for biofilm growth (per unit volume) in the gravel than the shred (due to the difference in particle shape and total porosity). The smaller variability is attributed to more uniformly distributed clog along the length as evident from the void volume occupancy values (discussed later) and hydraulic conductivity values within the different sections of the gravel column (especially in Sections 2, 3, and 4) which can be expected to result in

**Table 5.** Total Mass of Metals in Clog Material Relative to Estimated Leachate Influent Mass

Parameter	Rubber shred columns			Gravel column	
	Leachate influent mass (mg)	Ratio of clog mass to leachate mass (—)		Leachate influent mass (mg)	Ratio of clog mass to leachate mass (—)
	R3(P)	R1(P)	R2(G)	R4	R4
Aluminum (Al)	6,282	2.57	1.44	13,626	0.33
Zinc (Zn)	838	2.64	2.02	1,817	0.59
Iron (Fe)	164,756	1.62	0.31	357,365	0.13
Manganese (Mn)	2,010	0.81	0.23	4,360	0.15
Nickel (Ni)	4,188	0.36	0.05	9,084	0.02
Copper (Cu)	838	1.86	0.35	1,817	0.68

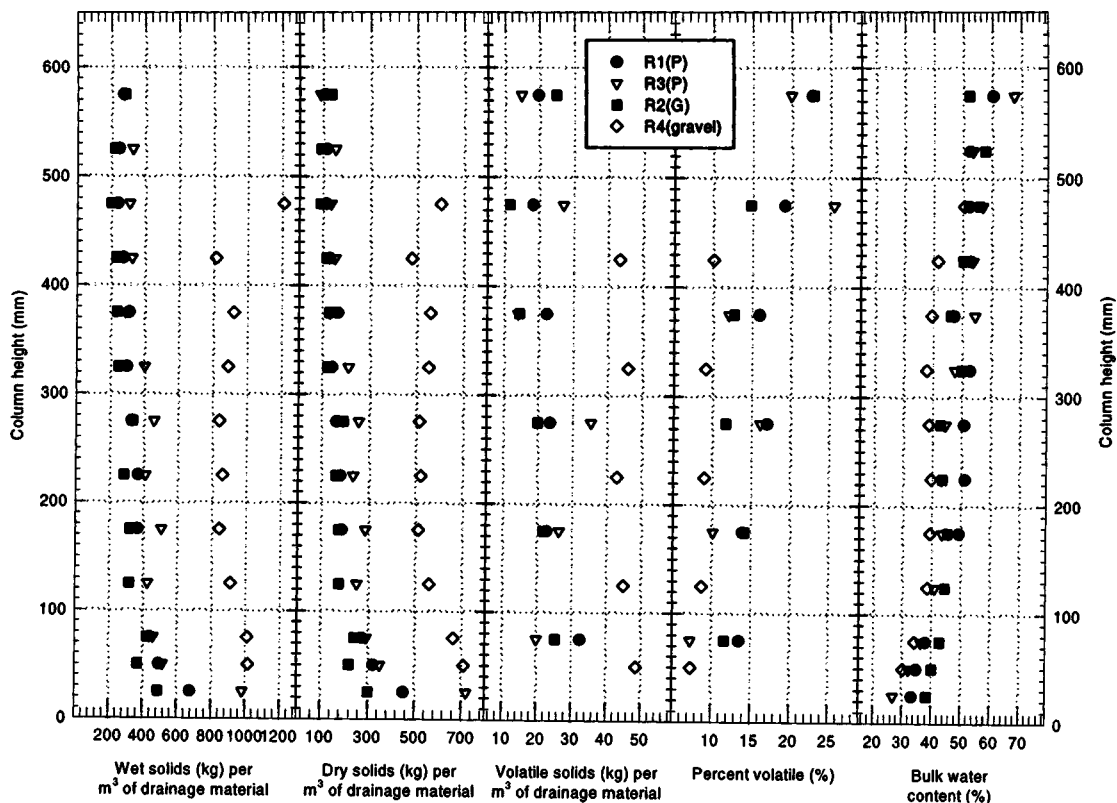
more uniform and smaller leachate velocities (and hence less difference in the shear stresses tending to dislodge biofilm).

The bulk water content (mass of evaporated moisture/wet mass) measured in the clog material increased from a value of approximately 30–60% as one moves from the influent (base) to the effluent end of the columns. This corresponds to the presence of more solid inorganic clog material and less biofilm towards the influent end of the column.

Based on the mass of clog removed from the disassembled columns and the volume of shred material in each section, the volume of clog within each section and the resulting VVO was calculated. Void volume occupancy is the reduction in free pore space and is a ratio of the volume of clog to the initial void volume. Thus a VVO of 100% would indicate that the initial void volume is completely filled with clog material. For the rubber shred filled columns there was a slightly decreasing trend in VVO

values with distance from the influent end of the column (base). For the gravel filled column the VVO values were relatively uniform along the length of the column. Although significant clogging ( $k \leq 10^{-5}$  m/s) occurred in most sections of the different drainage materials, at the time of disassembly the measured hydraulic conductivity within the sections of R4(gravel) were approximately 1–2 orders of magnitude higher than those measured in the rubber shred columns (despite the fact that the gravel test was run for twice as long). The calculated porosity for R4(gravel) were also higher than in the shred columns at test termination. For the shred columns, lower VVO values coincide with the higher hydraulic conductivities measured as one moves up the columns.

At test termination porosities were generally between 5 and 10% for shreds and 15–20% for gravel (VVOs between 55 and 74%). Thus, low hydraulic conductivities ( $6 \times 10^{-8}$ – $7 \times 10^{-7}$  m/s) were obtained at porosities well above zero. The



**Fig. 5.** Clog properties at disassembly of columns

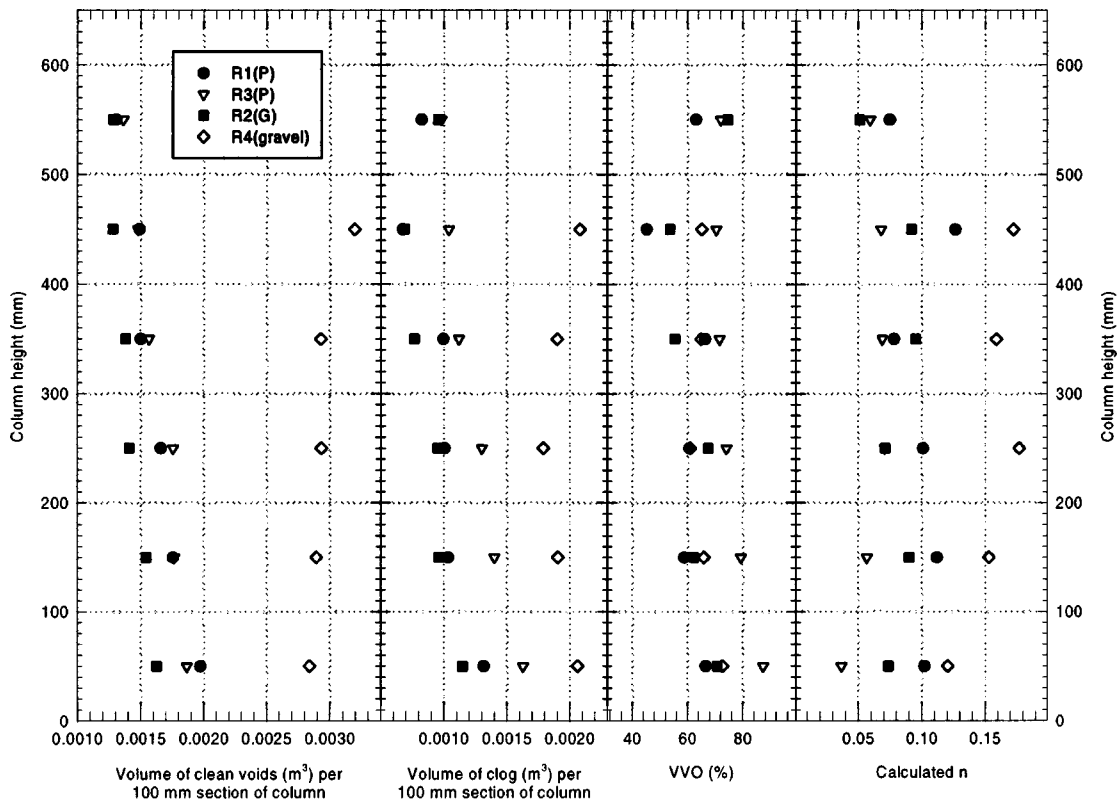


Fig. 6. Variation in initial void volume, volume of clog, void volume occupancy, and calculated total porosity along columns

reason for this was evident at column disassembly where the clog material was observed to fill most of the pore space and, in particular, filling the throat of the pores through which leachate must pass to get between pores. However, it was also observed that the clog material had a secondary porosity as shown in Fig. 7. Thus the clog material reduced the large void opening into numerous smaller constrictions that varied in diameter within the clog structure. Consequently, the flow through this clog material would be far more tortuous than through the initial clean void structure of the drainage material. Furthermore some of the larger voids (Fig. 7) were surrounded by hard clog material and thus the smaller connecting voids would control flow to and through the larger voids.

Columns R1(P) and R2(G), although filled with different shred types, had similar calculated VVO values at disassembly. R3(P) had the highest VVO values distributed along the column length but it also had a longer operating life. However, for an approximately equivalent decrease in hydraulic conductivity only 60–70% of the voids needed to be occluded with clog in R1(P) as compared to 75–85% occlusion for R3(P) and hence this column can be judged to have performed better than the other two shred columns. Thus a slight difference in void structure (i.e., variation in pore sizes) between the P shred columns appears to have given rise to a difference in VVO at disassembly and consequent larger mass of clog per 100 mm section (Fig. 5) for R3(P) than R1(P), although the extent of cementation was less than in R1(P).

### Clog Characteristics

Bulk, dry, and ash film densities were relatively uniform throughout the columns (Fig. 8). Based on dry mass, the majority of the clog material was calcium carbonate ( $\text{CaCO}_3$ ) for all columns (Table 4). The influent section (Section 1) of R1(P) and R2(G)

had 29–31% calcium, 50–52% carbonate, 1–2% iron, and 1% magnesium while the effluent section of R1(P) had 25% calcium, 40% carbonate, 11% iron, and 1% magnesium and the effluent section of R2(G) had 30% calcium, 51% carbonate, 1% iron, and 1% magnesium. As noted earlier there was a much greater accumulation of iron in the clog at the effluent end of the P shred column. The clog composition was relatively uniform along the gravel column with an average of 34% calcium, 54% carbonate,

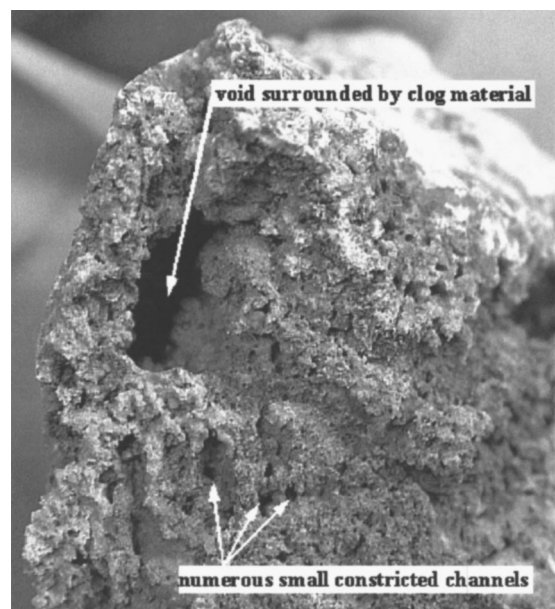


Fig. 7. Photo of clog material removed from R4(gravel)

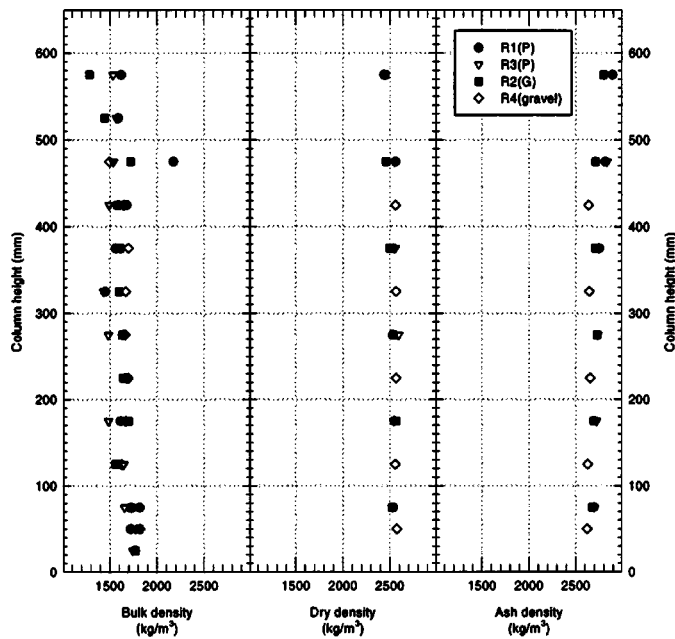


Fig. 8. Clog densities within columns at disassembly

0.5% iron, and 2% magnesium. Thus while there was relatively little variation in the major clog constituent ( $\text{CaCO}_3$ ), there was more variation in the minor metal constituents due to leaching and deposition of material from the tire shreds. This effect was most evident at the effluent end of R1(P) where there was less calcium and carbonate and considerably more iron than in the effluent end of the G shred column (R2) or gravel column (R4). As previously discussed, this difference is attributed to the release of iron from the abundance of frayed wire protruding from the P shreds.

The average fractional value of calcium and carbonate found in the clog material was very similar to values obtained by Rowe et al. (2000a,b) in clogging studies of glass beads using Keele Valley Landfill. The ratio of Ca to  $\text{CO}_3$  ranged from 0.585 to 0.612 for the shred columns and from 0.621 to 0.636 for the gravel column. Since the molecular weight ratio of Ca to  $\text{CO}_3$  is 0.667 for  $\text{CaCO}_3$ , the fact that the observed ratios are less than 0.667 indicates an abundance of  $\text{CO}_3$  with respect to Ca in calcium carbonate and that other metals are likely bound to the carbonate. Based on a mass balance, there was enough  $\text{CO}_3$  to have combined with magnesium and iron found in the clog material (i.e., to allow them to precipitate as carbonates). There was not enough carbonate to account of all of the iron in the effluent clog from the P shreds. Thus the abundant iron at this location has likely precipitated out as iron sulfide.

## Discussion and Practical Implications

Since the tire shreds are highly compressible (48 and 44% at 150 kPa for the two shreds examined), their use for pipe bedding is questionable since they will not provide the lateral support usually relied upon in the design of these systems (Rowe et al. 2004).

Due to their compressibility, a thickness of tire shred of 0.54–0.58 m would need to be placed to achieve a design thickness of 0.3 m under an applied load of 150 kPa. As indicated by this study these shreds have a much lower initial hydraulic con-

ductivity and porosity than the gravel. This combined with the more complex pore structure of the shreds resulted in them clogging much faster than the gravel. The gravel took about three times as long as the compressed (at 150 kPa) shreds to clog to a hydraulic conductivity of  $10^{-5}$  m/s and while the clog tests had to be terminated due to an inability to maintain the design flow rate after about 1 year, the flow rate could still be readily maintained in the gravel columns when they were terminated after 2 years. While these tests were run at accelerated mass loading rates (i.e., 1–2 years will translate into much longer periods of time in field applications), they do indicate that considerable care is required in developing designs that replace gravel with tire shred. In particular, these results suggest that gravel rather than tire shred should be used in the critical zone where there is a high mass loading (e.g., near leachate collection pipes or leachate sumps). In less critical zones the results imply that an increased thickness of compressed tire shred may be used to give a service life similar to that of a given thickness of gravel. The empirical data suggest that to get a similar service life with respect to clogging as 0.3 m of gravel, a (compressed at 150 kPa) tire shred thickness of about 0.9 m would be required. For higher vertical stresses, thicker rubber tire shred layers will likely be required to provide equivalent performance as gravel due primarily to smaller initial void volumes of the rubber tire shreds at the higher stress.

The available evidence (Brune et al. 1994; Rowe et al. 2000b) suggests that clogging is much faster for smaller particles (and hence smaller pore sizes and larger available surface area) than for large particles, and for well graded materials relative to uniformly graded materials. Thus the potential for clogging will be greater for well-graded sands and will be less for the more uniformly graded and larger rubber tire shreds, and will be a minimum for the uniformly graded coarse gravel.

Leachate permeation through the tires was found to leach certain elements (especially Al, Zn, and Fe) from the shreds (especially those with significant amounts of exposed wire) although the data suggest that these metals quickly became captured in the clog material and they were not detected at elevated levels in the effluent leachate. This requires more investigation; however the preliminary indication is that it would not cause a problem with respect to increased risk of metals getting into the groundwater.

## Conclusions

Four columns were permeated with landfill leachate at a nominal flow rate of  $0.4 \text{ m}^3/\text{m}^2/\text{day}$  for up to 2 years in order to investigate the use of tire shreds as a replacement of gravel in the blanket drain of a leachate collection system for a landfill. Two different types of tire shred (G shred:  $100 \text{ mm} \times 50 \text{ mm} \times 10 \text{ mm}$ ; and P shred:  $125 \text{ mm} \times 40 \text{ mm} \times 10 \text{ mm}$  with many exposed wires) and a uniformly graded 38 mm gravel were examined. The following conclusions were drawn from the results of these tests.

1. The compressibility ( $\Delta H/H_0$ ) of the G and P shreds were 48 and 44%, respectively, under a vertical pressure of 150 kPa. Thus the as placed thickness needs to be 1.8–1.93 times the final design thickness to achieve the design thickness at 150 kPa.
2. The initial hydraulic conductivities of the G and P shred (under a load of 150 kPa) and the gravel drainage material were about 0.007, 0.02, and 0.8 m/s, respectively.
3. The 38 mm gravel outperformed the rubber tire shreds by maintaining a hydraulic conductivity greater than  $10^{-5}$  m/s for about three times longer than a similar thickness of com-

pressed (at 150 kPa) tire shreds. At termination of the rubber shred columns after about 1 year the hydraulic conductivity at the influent end of the columns had dropped to between  $10^{-7}$  and  $10^{-8}$  m/s. At termination of the gravel columns after 2 years the corresponding range was  $10^{-6}$ – $10^{-7}$  m/s.

4. The bulk (wet) densities of the clog material ranged from 1,500 to 1,750 kg/m<sup>3</sup>.
5. The clog was predominantly calcium carbonate with calcium making up 29 and 34% of the total clog material for the tire shred clog and the gravel columns, respectively. These parameters can be used in predictive clogging models (e.g., Cooke et al. 1999) to predict clog formation rates and service lives of real scale leachate collection system designs.
6. Some metals leached from both the P and G shreds were exposed to typical MSW leachate. These metals include aluminum, zinc, iron, and copper. However they were not detected in the effluent leachate due either to their very low concentrations or due to the precipitation into the clog material. The clog material for the P shreds was found to contain the highest concentrations of metals and this is attributed to the greater abundance of exposed steel in these shreds than the G shreds. More research is required to fully establish the potential for leaching of metals of tire shred.

The results of these tests suggest that that gravel should continue to be used in critical zones where there is a high mass loading (e.g., near leachate collection pipes or leachate sumps). In less critical zones the results imply that an increased thickness of compressed tire shred may be used to give a service life similar to that of a given thickness of gravel. The empirical data suggest that to get a similar service life with respect to clogging as 0.3 m of gravel, a (compressed at 150 kPa) tire shred thickness of about 0.9 m would be required.

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